A NEW APPROACH TO COMPLETE AIRCRAFT LANDING GEAR NOISE PREDICTION

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Abstract

This thesis describes a new landing gear noise prediction system developed at The Pennsylvania State University, called Landing Gear Model and Acoustic Prediction code (LGMAP). LGMAP is used to predict the noise of an isolated or installed landing gear geometry. The predictions include several techniques to approximate the aeroacoustic and aerodynamic interactions of landing gear noise generation. These include 1) a method for approximating the shielding of noise caused by the landing gear geometry, 2) accounting for local flow variations due to the wing geometry, 3) the interaction of the landing gear wake with high-lift devices, and 4) a method for estimating the effect of gross landing gear design changes on local flow and acoustic radiation.

The LGMAP aeroacoustic prediction system has been created to predict the noise generated by a given landing gear. The landing gear is modeled as a set of simple components that represent individual parts of the structure. Each component, ranging from large to small, is represented by a simple geometric shape and the unsteady flow on the component is modeled based on an individual characteristic length, local flow velocity, and the turbulent flow environment. A small set of universal models is developed and applied to a large range of similar components. These universal models, combined with the actual component geometry and local environment, give a unique loading spectrum and acoustic field for each component. Then, the sum of all the individual components in the complete configuration is used to model the high level of geometric complexity typical of current aircraft undercarriage designs.

A line of sight shielding algorithm based on scattering by a two-dimensional cylinder approximates the effect of acoustic shielding caused by the landing gear. Using the scattering from a cylinder in two-dimensions at an observer position directly behind the cylinder, LGMAP is able to estimate the reduction in noise due to shielding by the landing gear geometry. This thesis com-
pares predictions with data from a recent wind tunnel experiment conducted at NASA Langley Research Center, and demonstrates that including the acoustic scattering can improve the predictions by LGMAP at all observer positions. In this way, LGMAP provides more information about the actual noise propagation than simple empirical schemes.

Two-dimensional FLUENT calculations of approximate wing cross-sections are used by LGMAP to compute the change in noise due to the change in local flow velocity in the vicinity of the landing gear due to circulation around the wing. By varying angle of attack and flap deflection angle in the CFD calculations, LGMAP is able to predict the noise level change due to the change in local flow velocity in the landing gear vicinity. A brief trade study is performed on the angle of attack of the wing and flap deflection angle of the flap system. It is shown that increasing the angle of attack or flap deflection angle reduces the flow velocity in the vicinity of the landing gear, and therefore the predicted noise. Predictions demonstrate the ability of the prediction system to quickly estimate the change in landing gear noise caused by a change in wing configuration.

A three-dimensional immersed boundary CFD calculation of simplified landing gear geometries provides relatively quick estimates of the mean flow around the landing gear. The mean flow calculation provides the landing gear wake geometry for the prediction of trailing edge noise associated with the interaction of the landing gear wake with the high lift devices. Using wind tunnel experiments that relate turbulent intensity to wake size and the Ffowcs Williams and Hall trailing edge noise equation for the acoustic calculation, LGMAP is able to predict the landing gear wake generated trailing edge noise. In this manner, LGMAP includes the effect of the interaction of the landing gear’s wake with the wing/flap system on the radiated noise.

The final prediction technique implemented includes local flow calculations of a landing gear with various truck angles using the immersed boundary scheme. Using the mean flow calculation, LGMAP is able to predict noise changes caused by gross changes in landing gear design. Calculations of the mean flow around the landing gear show that the rear wheels of a six-wheel bogie experience significantly reduced mean flow velocity when the truck is placed in a toe-down configuration. This reduction in the mean flow results is a lower noise signature from the rear wheel. Since the noise from a six-wheel bogie at flyover observer positions is primarily composed of wheel noise, the reduced local flow velocity results in a reduced noise signature from the entire landing
gear geometry.

Comparisons with measurements show the accuracy of the predictions of landing gear noise levels and directivity. Airframe noise predictions for the landing gear of a complete aircraft are described including all of the above mentioned developments and prediction techniques. These show that the nose gear noise and the landing gear wake/flap interaction noise, while not significantly changing the overall shape of the radiated noise, do contribute to the overall noise from the installed landing gear.
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**English**

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<tr>
<td>$a$</td>
<td>Cylinder radius</td>
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<td>$A$</td>
<td>Estimated wing surface area</td>
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<tr>
<td>$B_1$</td>
<td>Cylinder non-dimensional shedding function peak shedding variable</td>
</tr>
<tr>
<td>$B_2$</td>
<td>Cylinder non-dimensional shedding function scaling variable</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of Sound</td>
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<tr>
<td>$C_d'$</td>
<td>Coefficient of fluctuating drag</td>
</tr>
<tr>
<td>$C_l'$</td>
<td>Coefficient of fluctuating lift</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Coefficient of shielding</td>
</tr>
<tr>
<td>$D$</td>
<td>Cylinder diameter</td>
</tr>
<tr>
<td>$D(\theta, \phi)$</td>
<td>Directivity function</td>
</tr>
<tr>
<td>$e$</td>
<td>First cylinder non-dimensional spectrum shape variable</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$f$</td>
<td>Surface definition, $f = 0$ on the surface, $f &gt; 0$ outside the surface</td>
</tr>
<tr>
<td>$F_{ND}(S)$</td>
<td>Non-dimensional spectrum function</td>
</tr>
<tr>
<td>$F_i$</td>
<td>Dipole source strength in Ffowcs Williams-Hawkins equation</td>
</tr>
<tr>
<td>$H_{n}^{(1)}(x)$</td>
<td>Hankel function of the first kind</td>
</tr>
<tr>
<td>$J_n(x)$</td>
<td>Bessel function of the first kind</td>
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<tr>
<td>$k$</td>
<td>Wave number</td>
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<tr>
<td>$k$</td>
<td>Turbulent kinetic energy</td>
</tr>
<tr>
<td>$l$</td>
<td>Cylinder length</td>
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\( l \) Turbulent mixing length scale
\( L_p \) 1/3–Octave Sound pressure level
\( M \) Mach number
\( M_r \) Mach number in the radiation direction, \( M \cdot r \)
\( p \) Second cylinder non-dimensional spectrum shape variable
\( r \) Distance from the source to the observer, \( |x - y| \)
\( S \) Strouhal number, \( S = \frac{fd}{M_\infty c_\infty (1 - M_\infty \cos \theta)} \)
\( S \) Area of sound generating surface
\( u_0 \) Turbulent convection velocity
\( U_0 \) Free stream flow velocity
\( V \) Approximate near field volume around landing gear
\( V \) Volume of flat plate turbulent region or turbulent region
\( V_n \) Incident flow velocity
\( x \) Observer location
\( y \) Source location
\( Z_r \) Ratio of acoustic impedance

**Greek**
\( \alpha \) Turbulent intensity
\( \delta \) Turbulent boundary layer thickness
\( \varepsilon \) Dissipation rate
\( \varepsilon \) Trailing edge calibration variable
\( \theta \) Polar emission angle
\( \lambda \) Wavelength
\( \Lambda \) CFD grid spacing length
\( \rho \) Atmospheric density
\( \tau^* \) Reynolds shear stress
\( \phi \) Polar emission angle
\( \omega \) Angular frequency

**Abbreviations**
**Superscripts/Subscripts**

- \( d \) Drag direction
- \( e \) Emission direction
- \( inc \) Incident value
- \( l \) Lift direction
- \( L \) Loading contribution to noise
- \( M \) Mach direction
- \( n \) Normal direction
- \( r \) Radiation direction
- \( ret \) Retarded time
- \( T \) Thickness contribution to noise
- \( TE \) Trailing edge contribution to noise
- \( sc \) Scattered value
- \( \infty \) Free stream value
- \( ' \) Perturbation quantity
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Dedication

This thesis is dedicated to two very important individuals in my life. First, my grandmother, Mary Grace Lopes, an icon of the Italian home, who told me when I was seven I would achieve this level of success. Memories of her have made sure I stayed focused. And second, Megan Erin Lindsay, my soon to be wife, whose beauty, love, and devotion is beyond measure. My life’s achievements would be meaningless without her.
Chapter 1

Introduction

The noise an aircraft radiates is strictly regulated to limit its annoyance to surrounding communities and considerable effort has been applied to study its reduction [1-3]. An aircraft’s noise emission is a strong design constraint and the aircraft is certified on the basis of three flight conditions: sideline, cutback on takeoff, and approach. Traditionally, engine noise has been the major source of aircraft noise, but over the past several decades engine noise reduction techniques have significantly reduced engine noise. On approach, when the engines are operating at reduced power and the aircraft is in a high-lift configuration, the noise from the flaps, slats, and landing gear become comparable to and can even exceed the engine noise. The noise from these sources is collectively called airframe noise.

Airframe noise is the non-propulsive noise generated by the aircraft, including the landing gear, flaps, and slats, as well as their interaction with each other. Even though each of these noise sources generate sound by different physical mechanisms, the noise generated is similar in amplitude and can have different noise directivity patterns [4]. To demonstrate this, Chow et al. [5] present the directivity of airframe noise sources for an Airbus A340 on approach. Figure 1.1 shows the measured directivity on an arc 150 meters from the aircraft. The figure shows that the landing gear noise is the main noise source at all observer angles. However, the slat noise has similar noise levels at the flyover observer positions and the noise from the flap is on the order of 6 decibels lower than the landing gear noise, which can still affect the total sound level from the aircraft. Chow et al. also report that the measured noise sources scale by different powers of velocity. The landing gear noise scales as velocity to the sixth power, slat noise scales as velocity to the fifth power, the flap noise
scales as velocity to the eighth power, and the overall noise from the aircraft scales as velocity to the 5.5\textsuperscript{th} power. Therefore, all of these noise sources generate noise through different mechanisms and all need to be reduced for a reduction in noise from the total airframe.

A landing gear geometry is composed of bluff bodies with different cross sections, sharp corners, curved hoses, and small fittings. These details make the prediction of the noise from the landing gear different from the other airframe noise sources. None of the various landing gear components are clean cylinders or airfoils, but are connected by flanges, joints, etc., which contribute to a wide range of frequencies in the acoustic signal. Also, small components contribute to the higher frequencies. These higher frequencies are in the range where human hearing is most sensitive; therefore, they are a very significant portion of the perceived noise. Very small components including hoses, nuts, and bolts can be seen in Figure 1.2 which shows a landing gear installed on a Boeing 777. Figure 1.3 demonstrates the difference in noise generated by two landing gear models: a clean and a dirty Boeing 737 scale-model landing gear, tested in the Low Speed Aeroacoustic Facility (LSAF) at Boeing [6]. The clean wind tunnel model does not include hoses and other small features of the landing gear. Note the difference in levels above the 26th octave band, where band is a frequency range over which the sound pressure level has been integrated. The detailed flow and acoustic fields of small components such as wires, hoses, bolts, etc. are nearly impossible to
compute directly. This is due to the difficulty in getting exact geometry and accurate flow fields or measurements. It is challenging to compute the flow around even a simple gear with enough detail for an acoustic prediction because of the range of scales and the high level of turbulence [7].

1.1 Motivation of Current Research

To pass certification, an aircraft must not exceed a minimum noise requirement. On approach, the noise from the landing gear is the dominant factor in total aircraft noise. A landing gear designer must have a system available in order to predict the noise a certain landing gear design may generate. The prediction system must include the noise from all of the main features of the landing gear, including the noise change from a change in design. However, the prediction must be fast enough to provide a quick complete noise prediction. Also, a prediction system should include an approximation for scattering by the landing gear or aircraft wing. By including scattering, a landing
A gear designer is provided with more information on the actual noise propagation.

Although there have been many wind tunnel experiments that measure the noise of isolated landing gear, there has been limited research toward the prediction of landing gear noise when installed on an aircraft. Obviously, to pass noise certification the aircraft must have landing gear down, and therefore the landing gear is operating in an installed configuration, not exposed to the free-stream flow velocity. When installed on an aircraft, the landing gear is embedded in an environment significantly different than would be experienced in a wind tunnel, as shown schematically in Fig. 1.4. The circulation around the wing caused by the lift creates a velocity deficit region that can be significantly lower than the free stream flow velocity. In addition to the noise from the landing gear, an installed landing gear also generates a wake that convects downstream past the trailing edge of the wing/flap system. This results in additional interaction noise, which is a function of the landing gear geometry and relative location with respect to the wing, and is caused by a different mechanism than the landing gear noise alone. It is believed that the noise emitted from the landing gear wake interacting with the wing trailing edges is comparable to landing gear noise in certain frequency ranges and at various observer positions; therefore, it must be predicted in conjunction with landing gear noise if the total installed landing gear noise is to be predicted. However, a prediction system that includes information about wake interactions and shielding effects does not yet exist.
1.2 Originality and Significance of Work

The research presented in this document encompasses a landing gear noise prediction system that is unlike any other noise prediction method or system in existence. The prediction technique can predict the noise from isolated or installed landing gear geometry, including many of the aeroacoustic and aerodynamic interactions. The landing gear is modeled as many sources that account for the acoustic signature and geometric representation of the landing gear geometry. The turn around time from set up to noise prediction is extremely fast, with a 1 day turn around in most cases. Other topics of originality and significant are listed below.

1. A framework for the prediction of noise from a landing gear geometry has been created.

2. A significant update to a prediction tool for landing gear noise (as compared to the author’s original prototype), including an improved cylinder, wheel, and trailing edge acoustic elements has been developed.

3. A frequency domain formulation, able to predict the noise for a landing gear designer in a reasonable amount of time, has been implemented.

4. A first-order approximation to the shielding caused by the landing gear geometry has been
5. A framework for coupling the prediction system with external flow solutions has been implemented.

6. A study on local flow conditions caused by the wing geometry on the predicted landing gear noise has been performed.

7. A method for approximating the noise caused by the landing gear wake impinging on the trailing edge of the aircraft wing/flap system has been developed.

8. A first order approximation to component interaction, in particular, a study on truck angle influence on radiated noise has been conducted.

9. The use of the prediction system on landing gear noise for a complete aircraft has been demonstrated.
1.3 Literature Review

Initial measurements by Smith et al.\cite{8} and Kroeger et al.\cite{9} showed the necessity for the study of airframe noise as a lower limit of aircraft noise. During the late 1970’s and early 1980’s, much aircraft noise research focused on the engine with Federal Aviation Regulations (FAR) Part 36\cite{10} ultimately setting a limit on the amount of noise an aircraft is permitted to generate on take-off and landing. With the reduction of engine noise, it became apparent by the 1980’s that, on landing, the aircraft engines would no longer be the dominant noise source - airframe noise could be an equal contributor, especially for large aircraft. The main body of landing gear noise research during this time followed the work of Heller and Dobrzynski\cite{11}. These studies were limited to two- and four-wheel bogies, typical of commercial aircraft of the time. The experimental models, although scale models of actual landing gear bogies, did not contain many of the small details found on an actual landing gear. It was found that, for observer positions directly below and to the side of the landing gear, the support struts and oleo were the primary noise sources in all frequency ranges. Since that time, research on the noise generated by a landing gear has progressed on three fronts. The first is continued measurements in wind tunnels or by flight tests. The second research front uses empirical models and scaling laws based on wind tunnel tests to predict the noise generated by various landing gear designs. The last front uses computational fluid dynamics to compute the flow variables around the landing gear and, using acoustic formulations, compute the noise generated. This prediction approach has gained considerable attention recently due to the creation of faster and faster computers and larger and larger computational clusters. Each of these prediction approaches has its advantages and disadvantages. In the following three subsections, a brief historical background of each of these techniques is described, along with their advantages and disadvantages.

1.3.1 Experimental Measurements of Landing Gear Noise

Current research in airframe noise includes both experimental and computational studies. The experimental activities involve wind tunnel and flight tests of varying scale, landing gear design and flight conditions. Among the first wind tunnel measurements of landing gear noise is the work of Heller and Dobrzynski\cite{11} where the noise from a simplified two-wheel bogie was measured. The measurements were performed at several observer angles and estimates the contribution of each
landing component was presented. It was determined that sideline noise was generated primarily by the strut assembly, while the noise at flyover microphone positions was found to be mostly from the wheels.

In the past several decades, research has been performed on identifying the noise sources from an aircraft on flyover. The focus of the research has been to identify what noise sources are dominant when the aircraft is in a landing configuration. In the early 1980’s, research with several aircraft at multiple flight speeds reported that the noise from the aircraft with landing gear up scaled like velocity to the fifth power [12, 13]. This is indicative of turbulent boundary layers interacting with the trailing edges of the wing/flap system. In the same experiment, the scaling of noise from the landing gear, when the landing gear were down, were unable to be determined due to wing/flap and propeller noise. In the mid 1980’s, flyover tests of a 747-JT9D demonstrated that the noise from a landing gear does scale as velocity to the sixth power [14]. However, when the flaps were extended, the noise signature from the complete aircraft was altered, and velocity scaling from the landing gear could not be identified. This was thought to be due to the landing gear wake interacting with the flap trailing edges.

Recently, acoustic measurements have been performed on more complicated landing gear designs in order to better measure the mid to high frequency ranges. These include two-wheel [6, 15–20], four-wheel [15, 21, 22], and six-wheel [5, 15, 23–35] bogies, and other configurations [36], to study possible landing gear noise reduction techniques. An example landing gear geometry used in a typical wing tunnel test is shown in Fig. 1.5. In these wind tunnel tests, several important noise characteristics of landing gear have been identified. The first is that the number of wheels changes the noise in the higher frequency ranges as well as the noise at lower frequencies. The second is that the presence of small scale features on the landing gear affects the higher frequencies as originally thought. Once weighting factors are applied to the frequency ranges in the range of human hearing, the perceived noise level increases significantly in the presence of these small details. It is the inclusion of these small details that is vital in making a good acoustic prediction. Also, there is significant interaction between the components on the installed landing gear that must be included in any empirical model or calculated in any flow computation.

The interaction between components, such as struts and wheels, has led to the interest in the
acoustics of tandem cylinder configurations. There has been significant work on this front to estimate the level and intensity of the noise radiated when an upstream component’s downstream wake is interacting with a downstream component. The research on this topic includes both experimental and computational work [37–44]. However, there has not been sufficient correlation between tandem cylinder acoustics and the acoustics from a complicated landing gear.

Experimental methods have been used for many years and improvements in source localization techniques, such as DAMAS [45–47] and LORE [48], have significantly improved their ability to relate source mechanisms to total radiated noise. However, there has been difficulty in achieving total noise signatures from their respective source mappings giving doubt to their overall levels. Some calculations have shown that there is significant interactions between landing gear components [36]. However, these interactions are challenging to measure in a wind tunnel experiment. Also, wind tunnel measurements are extremely expensive and time consuming. It is unrealistic to use wind tunnel measurements for a design process as waiting for measurements, particularly when
they do not give absolute levels, is too time consuming and expensive.

### 1.3.2 Empirical Models of Landing Gear Noise

Experimental work on realistic landing gear geometries guides research into techniques on reducing the noise from current, in use, landing gear geometries. However, the experimentation on landing gear geometries can take a prohibitive amount of time and money to be of use for a developer of new, quieter, landing gear designs. Therefore, much work has been performed on creating empirical models that will quickly provide estimates of landing gear noise.

Fink [4, 49, 50] developed an airframe prediction method for the entire aircraft, which became the basis for NASA’s Aircraft Noise Prediction Program (ANOPP). The ANOPP prediction method separates the landing gear noise into two components: truck noise and strut noise. The spectrum and source strength of each component was determined by comparing to measurements [51]. The noise is determined by two gross length scales: the wheel diameter for the truck noise and the oleo length for the support strut noise. The support strut assembly noise prediction includes the total contributions from the oleo and any support struts as well as any fittings and doors. The truck assembly prediction includes the total noise contributions from the wheels, the hub caps, and any hydraulic brackets and hoses that might be contained on the truck. The noise directivity is described by an empirical function, which is different for each component. Recent flyover measurements by Stoker [6] have shown that although the overall sound pressure level is predicted reasonably well by ANOPP, the noise spectrum is underpredicted at higher frequencies.

At the Boeing Corporation, Guo [52] and Guo et al. [17, 53, 54] developed a purely empirical method for landing gear noise prediction. This method separates all the landing gear components into three categories: namely large, medium and small, which generate noise in the very-low, low and high frequency ranges respectively. All components on a landing gear are placed into one of these categories and some complexity factors are used to calibrate the model. Recently, this method has been improved to estimate the effect of installing the landing gear underneath a lifting wing geometry [55]. Although this prediction method can predict the landing gear noise fairly well for some designs, it does not identify the noise generated by individual components of the landing gear, which is vital when designing a landing gear for low noise emission. Also, this empirical method
includes all of the installation effects by including them in the entire empirical prediction. There has been no individual estimate for reflections, scattering/shielding, or landing gear wake generated trailing edge noise. A landing gear designer using this system is unable to determine what effect these interactions have on the noise.

In the European community, a model has been developed by Smith and Chow \[5,56,57\] that has attempted to identify the noise contributions of individual landing gear components. Each assumed noise source has a spectral function applied to it. Then the sum of the noise sources is calibrated to provide the noise of a complete landing gear. After calibration, the noise functions are modified depending on the type of landing gear geometry. The results for simplified landing gear have matched the shape of measured results under certain configurations, as shown in Fig. 1.6. Although this method has been shown to match measurements for a limited number of landing gear geometries, it is not clear that the method could relate the radiated noise for a general or unique configuration to the new geometry or local flow conditions. The method does not include the aeroacoustic affect of reflection by the wing, scattering from the landing gear geometry, or the additional noise source which occurs when the landing gear wake interacts with the wing/flap system.

Empirical methods are extremely useful to designers because of their very fast turn around time. Unlike wind tunnel measurements, an empirical method takes a very short time to give guidance to a landing gear designer. However, empirical models very rarely include many of the higher-order aerodynamic and aeroacoustic effects individually. The landing gear empirical schemes only include these effects by including them in the entire landing gear noise predictions, not as an addition approximation that can be analyzed independently. These interactions can potentially alter the acoustic signature. Also, in relation to landing gear noise design, it is difficult to create a prediction scheme that can account for many of the small details in a landing gear geometry. A designer may wish to move significant noise generating structures in an unconventional way. Since that may exceed the empirical scheme’s knowledge base, the predictions may not be able to predict any change, and therefore, be significantly inaccurate.
1.3.3 Landing Gear Noise Prediction Using Computational Fluid Dynamics

The last area of landing gear noise research involves high fidelity CFD calculations. Because of the small scale features of a realistic landing gear configuration, the CFD grid resolution must be very fine and the number of grid points required can become overwhelmingly large. It can be shown that to capture the frequency range of the broadband landing gear noise source of a Boeing 777, a computation grid of approximately 13 billion points must be used\footnote{If $V \approx 65m^3$ is the approximate nearfield region for a 4m by 4m by 4m volume, $f_{\text{max}} = 10kHz$ to capture the higher frequency ranges, $\lambda_{\text{max}} = c/f_{\text{max}} = 0.0343m$ is the acoustic wavelength of the highest frequency, and $\Lambda = \lambda/10 = 0.00343$ so there is enough resolution to capture the characteristics. Therefore $N_{\text{pts}} = \frac{V}{\Lambda^3} \approx 1,600,000,000$ in the nearfield region alone. This will increase again when accounting for the farfield region as well.}. The large number of grid points increases the computation time significantly, so that detailed CFD calculations with enough time steps to capture small scale disturbances takes a considerable amount of time even when run on large parallel computers.

The use of CFD to predict landing gear flow has been attempted with computations performed on simplified four-wheel landing gear designs\cite{58,61}. There have been limited earlier attempts on

Figure 1.6: Example from empirical model being developed in the European community to predict landing gear noise. Example shown is for a A340 landing gear [56].
using CFD to predict the flow field around a landing gear due to the complexity of the gear design. A study on different Ffowcs Williams and Hawkings surfaces embedded in the computational mesh was used to predict the noise [58]. It was shown that on body solid surfaces and off body permeable surfaces used in the acoustic calculations predicted different noise in the nearfield, possibly due to short range quadrupole sound sources. These computations also found that the struts significantly affect the noise in the forward and aft observer positions. Other computations show that the upstream strut component sheds vortices that can interact with the downstream strut, causing additional noise [59]. Finally, these early computations [60, 61] have been found to be very dependent on the turbulence model used. Fig. 1.7 shows acoustic predictions using a CFD computation using two different turbulence models around a four-wheel landing gear. The predictions of the noise from the CFD differ significantly depending on the turbulence model used, and only match at very low frequencies. The computation time for these calculations is very large, well beyond a reasonable turn around time in a design cycle, even when performed on computational clusters. To reduce calculation time, attempts have been made to simplify the landing gear geometry. Unfortunately, since the small details, which are removed in the smoothing process, are responsible for generating much of the noise in the mid and high frequency ranges, removing them also removes their contributions to the noise.

Even though it will be a long time before computational calculations mature into a usable form for a designer, some effort has been applied to calculate the noise from a landing gear using multiple techniques. These include two-wheel [62-65] and four-wheel [58-61, 66] bogie designs. There has been little work on larger landing gear configurations because of gear complexity and computational power required. Obviously, considering the difficulties in using experimental and computational methods to predict the noise of a new landing gear design, designers must rely on empirical methods to guide them when creating a low noise landing gear geometry.

1.4 The LGMAP Acoustic Prediction Scheme

A physics-based empirical landing gear noise prediction scheme has been developed at the Pennsylvania State University in conjunction with NASA Langley Research Center and The Boeing Corporation [67-70]. It is a component based noise prediction scheme in some ways similar to
the method developed by Smith and Chow. However, this method differs in many key areas from those developed previously. The method, called the Landing Gear Modeling and Acoustic Prediction (LGMAP) code, uses a small set of scalable acoustic elements to represent the physical components of the landing gear. Each of the acoustic elements is a simple model that depends on local flow properties, such as flow velocity and turbulence level. The noise from each component is scaled by its characteristic length. In this manner, large components generate predominantly low frequency noise while smaller components contribute mainly at higher frequencies. Predictions with this method have demonstrated its potential for predicting changes in noise due to the addition of smaller components.

The research presented in this thesis is based on preliminary studies performed at The Pennsylvania State University by Lopes, et. al. [69]. In this work, the framework for the LGMAP scheme was developed, and the present research is the continuation of that work into a more physics-based prediction scheme that can approximate the influence of aerodynamic and aeroacoustic interactions on the radiated noise from a landing gear. Following, in this section, is a summary of the prelimi-
nary development of LGMAP. The previous work includes implementation and development of the framework of the prediction scheme including the development of acoustic elements. After the description and calibration of these elements, the original LGMAP prediction scheme is demonstrated by comparing the prediction for a dressed and undressed Boeing 737 nose gear geometry.

1.4.1 Introduction to LGMAP

The central feature of LGMAP is a “toolbox” of acoustic elements (or objects), shown schematically in Fig. 1.8. These include cylinder objects (these can be of any size and any cross section), edge objects (used for door edges, flaps, etc.), small fittings and wheels. These objects are the building blocks that are used to construct the LGMAP representation of any landing gear configuration. Each object is a simplified geometric representation of the physical component modeled, which uses the local upstream environment as input to predict the noise. Engineering judgement is required to determine how to represent the complex landing gear components in terms of simple LGMAP acoustic elements, but the object geometry is positioned at the correct location within the landing gear configuration. The upstream environment can include the local flow properties and turbulence levels. Each acoustic element uses the component’s geometry and upstream environment to generate noise and creates a downstream environment. The total noise from the landing gear is simply the sum of noise generated by each of the individual acoustic elements.

1.4.2 Description and Calibration of LGMAP Acoustic Elements

The noise from each physical object is modeled with one or more acoustic elements from the acoustic element toolbox. For instance, the oleo, a support strut, and a hose can all be modeled as collections of cylinders. The door and the wing can be modeled as a combination of a reflective surface and a sharp trailing edge. The noise from fittings, nuts, and bolts might be approximated by an additional source. Each of these acoustic elements are explained briefly in this section.

Cylinder Acoustic Element

The first acoustic element in the toolbox is the cylinder acoustic element. This acoustic element can be used to represent many pieces on the landing gear ranging from the oleo to small hoses. The
acoustic radiation by an isolated cylinder is well understood. The cylinder experiences unsteady forces at frequencies dictated by the Reynolds number. In uniform flow, the cylinder experiences unsteady lift and drag forces, which are somewhat different for different cylinder cross section shapes. Cylinder acoustic elements in the LGMAP model are not intended to represent an isolated cylinder, but to account for the turbulent environment expected in the vicinity of the landing gear. Thus, the loading for the cylinder is modeled as broadband with a distinct peak at the nominal shedding frequency of an isolated cylinder. A broadband loading spectrum on the cylinder-like components of the landing gear also can account for the fact that the physical landing gear components are typically not smooth, nor do they have constant cross section in the spanwise direction.

The unsteady loading on components is the primary source of noise generation for a landing gear geometry. Ideally, a loading noise prediction requires the unsteady surface pressure as input, but for low-frequency noise typical of the unsteady loading on a cylinder, the acoustic wavelength is large compared to the cylinder cross section. Hence, the cylinder can be assumed to be compact in the chordwise (cross section) direction. Therefore, rather than cylinder surface pressures, the loading force as a function of cylinder span can be used as input for the loading noise prediction. The unsteady loads on each cylinder element of the landing gear are modeled using a “universal” non-dimensional loading spectrum. This spectrum is assumed to have a peak frequency, \( S_0 \), which is representative of the shedding Strouhal number for a cylinder in turbulent flow. The non-
dimensional loading spectrum is a broadband loading spectrum which is designed to capture all the effect not captured by the prediction system. These include a non-cylindrical cross section and turbulent flow where the cylinder is placed. The dimensional shedding frequency, and the dimensional fluctuating lift and drag forces are determined by the normal component of the local flow velocity, \( V_n \). The peak frequency of the shedding is determined by \( S_0 = fD/V_n \), where \( D \) is the characteristic length. The amplitude of the loading is determined by Eqn. 1.3. The presence of incoming turbulence or non-uniformity in the cross-section is not modeled explicitly, but rather incorporated indirectly by broadening the loading spectrum. The non-dimensional loading spectrum function is given by,

\[
F_{ND}(S) = B_2 S^{-1}(B_1 + S)^{-e}
\]  (1.1)

\[
B_1 = -S_p^0 \left( \frac{e(1-p) - 1}{e - 1} \right)
\]  (1.2)

\[
B_2 = \left[ \int S^{e-1}(B_1 + S)^{-e} \right]^{-1}
\]

\[
L'(S) = \frac{1}{2} \rho V_n^2 D C_l' F_{ND}(S)
\]

\[
D'(S) = \frac{1}{2} \rho V_n^2 D C_d' F_{ND}(2S)
\]  (1.3)

This non-dimensional spectrum is used as a “universal cylinder spectrum” for all cylinder elements. The peak frequency \( S_0 \), the spectral shape (governed by the parameters \( e \) and \( p \)), and the fluctuating lift and drag coefficients, \( C_l' \) and \( C_d' \), can be varied on the basis of the cross-sectional shape; element location, etc. These are initially calibrated and then left unchanged. In this way there can be several classes of cylinder elements. Once the fluctuating forces on a cylinder are known, Farassat’s Formulation 1A [71] of the Ffowcs Williams and Hawkings equation [72] is used to predict the radiated noise.

It is important to note that the cylinder acoustic element is not a prediction of noise from an isolated cylinder. The cylinder acoustic element is a model for a broadband noise source from a cylindrical type of object in the landing gear geometry. The influence of the geometric complexity of a cylindrical type object in the landing gear and the turbulent inflow velocity onto the cylinder type object on the radiation noise is through a broadband spectrum of loading. This spectrum of

\[2\] In the initial implementation of the cylinder objects, the local upstream velocity has been assumed to be the freestream velocity. This assumption is updated later in this thesis.
loading is significantly different that would be experienced if the cylinder has a smooth cylindrical cross section, and is placed in uniform inflow with low turbulence levels.

To provide an acoustic prediction, the calibration coefficients in the cylinder element \((S_0, e, p, C'_l, \text{ and } C'_d)\) are first determined. To calibrate the cylinder acoustic element, measurements from an acoustic test of a scale model of the DC-10 nose gear was used. The model DC-10 nose gear experiments were performed at the outdoor “Wall-Jet Flow Facility” located at the DFVLR Trauen Test Grounds \([51]\). The nose gear used in the tests did not include all the dressings found on installed aircraft landing gear; hence, the only components that were exposed to the flow were the oleo, a support strut, the doors and a pair of wheels. The noise from each component was determined in the wind tunnel test so they can be compared directly with the LGMAP prediction. The measurements for a sideline observer were reported to be dominated by the oleo or strut noise; thus, the data at this observer position was used to calibrate the spectrum shape and the unsteady loading coefficients for the cylinder model. The wavelength of the noise is assumed to be longer than the diameter, therefore all cylinder elements are assumed to be compact. This results in a wireframe representation of a landing gear. Figure \([1.9]\) shows the LGMAP wireframe representation of the landing gear from various viewing angles. In the figure, the wheel models are black, the support struts are blue and the trailing edges are red. Although each of the components are represented by lines in this drawing, their actual diameters are accounted for in the LGMAP prediction.

Figure \([1.10]\) shows a comparison between the wind tunnel measurements and the LGMAP prediction. The experiments and predictions are plotted as continuous lines, with the symbols representing the 1/3-octave band values. The contribution from the strut or oleo is predicted quite well, as it should be, since the experimental data were used to calibrate the cylinder element model. The calibrated cylinder coefficients are given in Table \([1.1]\) along with reported values of an isolated cylinder. The peak calibrated peak Strouhal number does not vary significantly from the values reported in Zdravkovich \([73, 74]\) at a similar Reynolds number. However, the coefficient of fluctuating lift and drag are significantly less than an isolated smooth cylinder. This may be due to the broadband nature of the loading spectrum inherent in the prediction system.
Figure 1.9: The LGMAP model for the DC 10 nose gear. The oleo and support struts are blue, the wheel models are black, and the trailing edges are red.

Figure 1.10: Comparison of predicted sideline noise with measurements by Heller and Dobrzynski [51]. \( D \) is wheel diameter, \( U \) is 65 m/s, \( U_0 \) is a reference velocity of 100 m/s, \( f \) is frequency and \( r \) is observer position.
Wheel Acoustic Element

The wheels on a landing gear are large physical components, but they also contain small details and have a complex flow field around them. The small details, like the tire tread and hub caps, generate turbulence which is convected downstream to the next wheel. The wake from the first wheel interacts with the second, and so on. This has been shown to significantly dampen the primary low frequency (large object) shedding and generate a more broadband signal. Furthermore, the wheels generate noise that radiates to the side and downward. Therefore, to accurately predict the noise from the wheels, the acoustic model for the wheel needs to account for all these features.

In LGMAP, the wheel is represented by a ring of cylinder segments. The ring has a diameter equal to the tire diameter, and each cylinder segment in the ring has a diameter equal to the tire width. The main reason for using a circle to represent the wheel is that noise is radiated both downward and to the side. Although the flow around a tire has little similarity to flow around a cylindrical ring, this model was chosen because, with suitable calibration, it provided a first estimate to noise radiation that is representative of a the noise radiated by real wheel at certain observer positions. The cylinder segments used to make up the wheel ring use a different loading spectrum than ordinary cylinder elements. The spectrum and corresponding forces on each cylinder were chosen so that this wheel model would have the same peak shedding frequency found in the ANOPP formula.

To calibrate the parameters used in the LGMAP wheel model ($S_0$, $e$, $p$, $C_l^f$, and $C_d^f$), the ANOPP wheel noise contribution was used. ANOPP only includes contributions from the oleo or strut and a wheel. Since the ANOPP prediction for the spectrum shape is known to be poor, particularly at higher frequencies, the primary goal of the calibration was to fix the predicted peak level. In the case considered, the aircraft was flying at 120 meters at a flight Mach number of 0.2. The landing gear is a four wheel, two-axle full-scale model representative of a Boeing 757 main landing gear. The simple model of the gear only includes the wheels, the oleo and support struts. The LGMAP

<table>
<thead>
<tr>
<th>Zdravkovich [73, 74]</th>
<th>$e$</th>
<th>$p$</th>
<th>$S_0$</th>
<th>$C_l^f$</th>
<th>$C_d^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrated Cylinder Acoustic Element Model</td>
<td>2.5</td>
<td>2.15</td>
<td>0.22</td>
<td>0.17</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Table 1.1: Parameters used in the cylinder model.
gear wireframe model is shown in figure 1.11 with the support struts shown in blue and wheel assemblies in black. The predictions are made for two observer locations, one at 45° polar angle, with the aircraft approaching, and one at 135°, when the aircraft is moving away. The ANOPP and LGMAP predictions are shown in Figures 1.12 and 1.13. It should be noted that LGMAP gives a contribution from the oleo, but it is much lower than the wheel contribution and does not contribute significantly to the total noise. It was difficult to match the very low frequencies exactly. Again, the noise levels are presented as 1/3–octave values.

In general the predictions were quite good. However, since it is recognized that the wheel model is very crude, no attempt was made to find the model parameters for the best fit. The values of the model parameters for the wheel are shown in Table 1.2.

<table>
<thead>
<tr>
<th>Wheel Acoustic Element Model</th>
<th>$e$</th>
<th>$p$</th>
<th>$S_0$</th>
<th>$C_f$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.0</td>
<td>1.5</td>
<td>0.18</td>
<td>0.34</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 1.2: Parameters used in the wheel model.
With the acoustic elements calibrated, the next step was to perform noise predictions for another landing gear to evaluate the LGMAP model and its calibration.

1.4.3 Initial Landing Gear Noise Predictions

To assess the effect of adding smaller physical components into the LGMAP representation of a landing gear, an example case is considered: a model scale, uninstalled Boeing 737-400 main gear. Noise predictions are compared with the wind tunnel measurements of Stoker [6]. The test setup, shown in figure 1.14a, was conducted in the Low Speed Aeroacoustic Facility (LSAF) at Boeing. These tests compared a dressed 737 main gear without a door to an undressed gear. The primary difference between dressed and undressed landing gear models was that the dressed configuration included the addition of hoses, shown in figure 1.14b. All acoustic elements in the preliminary results from LGMAP use the freestream velocity as the local upstream velocity, and there are no acoustic interactions between components.
Figure 1.13: Calibration of LGMAP to ANOPP predictions for a simplified 4-wheel landing gear at the aircraft receding microphone.

Figure 1.14: a) The test setup of the wind tunnel results of a Boeing 737-400 main gear at the Low Speed Aeroacoustic Facility (LSAF) at Boeing. b) Close up of landing gear with and without dressings.
**Undressed or “Clean” Boeing 737 Nose Gear**

In Fig. 1.15, the LGMAP wireframe representation of the 737-400 undressed model is shown. The support struts are shown in blue, hydraulic brackets are shown in red, and the wheels are shown in black. Each line is representative of the cylinder axis used to model a particular landing gear component.

LGMAP predictions are compared to the undressed wind tunnel measurements for freestream Mach number of 0.18, 0.20, 0.22 and 0.24 using the same parameters that were determined by calibration with the Heller and Dobrzynski DC-10 nose gear and the ANOPP 757 main gear [67]. The noise predictions from LGMAP should scale like Mach number to the sixth power, i.e. $V^6$, because the noise is generated primarily by unsteady surface loading. The measurements and predicted values are shown in Fig. 1.16 scaled according to Mach number. The LGMAP predictions fall on top of each other when scaled by $V^6$. The agreement between the measurements and predictions is reasonably good, except for an anomalous peak in the experimental data at a Mach number of 0.18 in the 1/3-octave bands 27 and 28. The source of this discrepancy in the measurements is unknown. Also, the difference between prediction and measurement at low frequencies may be due to Reynolds number affects. The undressed LGMAP predictions also collapse to a single line with the appropriate Mach number scaling as shown in the figure. The collapse of the predictions demonstrates that all the acoustic elements have a sixth power dependency on velocity.

Even though the LGMAP model for the 737 is only a very approximate representation of the physical geometry, it still provides good agreement throughout the higher frequencies when compared to the measured undressed gear noise. This shows that LGMAP is predicting the general trend of the noise quite satisfactorily. Nevertheless, the current LGMAP model is unable to predict all of the subtle details in the spectrum. The next step is to increase the fidelity of the prediction geometry and analyze the corresponding noise level difference.

**Dressed or “Dirty” Boeing 737 Nose Gear**

Landing gear geometries installed on aircraft are not as clean as the gear used in the measurements shown above. When installed on an aircraft, the landing gear will have hoses running along the oleo and truck other smaller scale components that generate noise within a certain frequency range. The
measurements conducted by Stoker contained landing gear configurations with and without hoses installed to examine how the noise changes when smaller components are present. To demonstrate how LGMAP can predict this change cylinder models representing these hoses were added and compared to the wind tunnel experiments.

The LGMAP wireframe representation of the dirty configuration of the 737 is shown in figure 1.17. Several hoses of various sizes have been added to the undressed configuration to make it a dressed configuration. These include a large hose parallel to the oleo, several small hoses near the support strut, and a hose in wheel truck area. These hoses are approximately in the position of the actual hoses in the experiment, but all of the smooth curves and complexity of the test geometry have not been modeled here. It was found that changing the position of the hoses in the landing gear geometry did not significantly affect the radiated noise; however, changing the orientation to the freestream flow velocity reduces the noise from the hose. In figure 1.18 the dressed LGMAP prediction is shown at a Mach number of 0.20 and is compared to both the dressed and undressed
Figure 1.16: Undressed 737-400 landing gear wind tunnel measurements (symbols) and LGMAP predictions (lines) for Mach numbers of 0.18, 0.20, 0.22 and 0.24 scaled by $V^6$.

737-400 landing gear measurements.

Predictions of noise from the dirty configuration are presented in Fig. 1.19 for Mach numbers ranging from 0.18 to 0.24. The addition of the smaller components (hoses) in the LGMAP prediction yields an increment in noise very similar to that measured by Stoker. At the highest frequencies, the prediction is lower than the measured data, but this may be due to the lack of some of the smallest components or incorrect hose curvature in the LGMAP representation.

1.5 Shortcomings of LGMAP Version 1

The first version of LGMAP, while predicting the noise for the 737 nose gear with different levels of fidelity had several significant shortcomings than made it less useful for a landing gear designer. First, LGMAPv1 was extremely slow. All acoustic calculations were in the time domain and all modeling of sources and acoustic analysis was performed in the frequency domain. This led to a need for a significant number of Fourier and inverse Fourier transforms. Second, LGMAPv1 was
not thoroughly tested. The only true test of LGMAP’s accuracy was one 2-wheel bogie design of the 737 nose gear. While predicting the noise reasonably well for this design was encouraging, predicting the noise for 4-wheel or 6-wheel designs were often significantly in error. Figure 1.20 shows the prediction of noise for a 777 main gear from LGMAPv1 compared to wind tunnel experiments. The LGMAPv1 predictions were underpredicting the noise by approximately 20dB. Also, LGMAPv1 did not include any of the aeroacoustic or aerodynamic interactions in the landing gear noise prediction. There was no acoustic scattering/shielding, local flow due to the wing or landing gear geometry, and no wake generated trailing edge noise prediction. These shortcomings of LGMAPv1 meant that gross changes in landing gear design led to the same predicted radiated noise. For LGMAP to become a useful tool for designers, better prediction techniques needed to be implemented.
Figure 1.18: Wind tunnel measurement (symbols) and dressed LGMAP prediction (lines) for Mach number of 0.20. Also shown are predictions by Guo [52].

Figure 1.19: Dressed wind tunnel measurement and dressed LGMAP prediction for Mach numbers of 0.18, 0.20, 0.22 and 0.24 scaled by $V^6$. Symbols are wind tunnel measurements and lines are LGMAP predictions.
1.6 Research Objective

The objective of the current work is to improve on the already existing LGMAP framework, and create a landing gear noise prediction system that is useful for a landing gear designer. The purpose of the prediction system is to provide noise predictions for an isolated or installed landing gear, and provide as much information to a designer as possible, in a relatively short amount of time. The system must be able to couple with CFD calculations or flow estimates that may be available when predicting the noise. The input into the prediction system is to be as simple as possible, but provide as much flexibility as possible. The system should include a prediction the noise generated by a landing gear, whether installed or in isolation, including effects for scattering, local flow caused by the presence of the wing, wake impingement on a wing/flap trailing edge, or predictions for the change in noise when changing landing gear design.
1.7 Outline of Thesis

The remainder of this thesis is organized into four chapters.

- Chapter 2 includes improvements to the original LGMAP prediction system. These improvements include a change from time domain to frequency domain integration. Converting from a time domain to a frequency domain integration dramatically reduces computation time allowing for much faster acoustic predictions. The second chapter also includes improvements to the wheel acoustic element, and a new trailing edge acoustic element to account for both turbulent boundary layer trailing edge noise and landing gear wake/flap interaction. In this way LGMAP is able to predict the entire noise difference from an aircraft with and without an installed landing gear.

- Chapter 3 describes several physics-based prediction approximations for installed landing gear acoustic prediction.
  
  - The first approximation, presented in Section 3.1, is an estimate for the acoustic shielding due to the landing gear geometry. The prediction system is able to estimate the reduction in noise due to shielding by the landing gear geometry by using the scattering from a cylinder in two-dimensions. This thesis presents predictions compared to a recent NASA Langley wind tunnel experiment, and shows that including the acoustic scattering improves the predictions.
  
  - The second prediction approximation, presented in Section 3.2, includes using coarse CFD calculations around a representative wing cross section to approximate the flow condition near an installed landing gear. FLUENT CFD calculations around an estimate of the Boeing 777 wing cross section in two-dimensions is used to calculate the flow which is input into the acoustic prediction. The prediction system is able to predict the noise level change due to a change in aircraft angle of attack and/or flap deflection angle.
  
  - The third prediction approximation, presented in Section 3.3, includes using an immersed boundary code to quickly calculate an estimate of the average flow velocity caused by the landing gear. Landing gear wake/flap interaction is predicted through es-
timates of turbulence intensity gained from wind tunnel experiments and application of
the trailing edge noise theory of Ffowcs Williams and Hall.

– The final prediction approximation, presented in Section 3.4 uses an immersed bound-
ary code to estimate the change in local flow velocity due to gross changes in landing
gear design. This thesis presents evidence that a change the truck angle to a toe down
position reduces the landing gear noise because the mean flow velocity around the rear
wheels is reduced significantly.

• Chapter 4 presents LGMAP calculations using all of the above prediction approximations.
Predictions are compared to flyover measurements and demonstrate the prediction system’s
ability to match the measured spectral shape. Acoustic predictions on large observer grids
demonstrate that although the main landing gear are the primary noise sources, the nose gear
and landing gear wake/flap interaction noise can potentially alter the over all acoustic signa-
ture significantly.

• Finally, Chapter 5 presents the conclusions and future work for landing gear noise prediction
using the presented prediction system.
Chapter 2

A Second Generation Landing Gear Noise Prediction Method

The original LGMAP prediction system was largely untested, extremely slow, and did not include significant flow physics that are crucial to predicting the noise from an installed landing gear. To make the LGMAP system a viable option for landing gear designers, these shortcomings had to be addressed and improvements to the system had to be developed. These improvements include implementing a frequency domain formulation to significantly improve computation time, an improved wheel acoustic element to predict the noise from six-wheel landing gear designs, and a trailing edge acoustic element that can predict both boundary layer trailing edge noise and wake/flap interaction noise. These improvements are only the first step to creating a prediction tool capable of predicting the noise from an installed landing gear. Chapter 3 will present prediction approximations that are used in conjunction with these improvements to predict installed landing gear noise.

In the following sections, the improvements to the existing features of the LGMAP system are presented. The first of these features includes implementing a frequency domain formulation. It will be shown that the new formulation significantly improves computation time. The second is an improved wheel acoustic element for six-wheel landing gear designs. The improved wheel acoustic element gives predictions that compare better with measurements performed on the noise from a Boeing 777 landing gear model tested at the NASA Langley Research Center Quiet Flow Facility. The final improvement to the LGMAP system includes the development and implementation of two
types of trailing edge acoustic elements that predict the noise from boundary layer turbulence and the landing gear wake interaction with the wing and flap trailing edges.

2.1 Frequency Domain Formulation

LGMAP version 1 is based on the loading noise component of the aeroacoustic prediction code PSU-WOPWOP [75, 76], which evaluates Farassat’s Formulation 1A [71], shown in Equation 2.1 of the Ffowcs Williams-Hawkings equation [72].

\[
4\pi p'_L(x,t) = \frac{1}{c} \int_{f=0}^{\infty} \left[ \frac{\dot{F}_r}{r^2|1-M_r|^2} \right]_{ref} dS + \int_{f=0}^{\infty} \left[ \frac{F_r - F_M^2}{r^2|1-M_r|^2} \right]_{ref} dS + \int_{f=0}^{\infty} \left[ \frac{F_r(rM_r + cM_r - cM^2)}{r^2|1-M_r|^3} \right]_{ref} dS
\]

(2.1)

The code uses a source-time-dominant algorithm to compute the radiated noise for an arbitrary observer location and source motion [75, 76]. In LGMAP version 1, the element loading magnitude (which is directly related to the noise source strength) is modeled in the frequency domain and, using a random phase for each frequency, is then converted to the time domain. Since landing gear noise is very broadband, both low and high frequencies are needed. The requirement to capture both low and high frequencies in the prediction implies that the time history must be long enough to capture the lower frequencies, but sufficiently resolved to capture the higher frequencies, which leads to a very large number of time samples. This time history of loading is then used in PSU-WOPWOP to predict the radiated acoustic pressure in the time domain. The acoustic pressure from each noise source, many hundreds in a typical landing gear geometry, is then converted back to the frequency domain and then added incoherently to achieve the total acoustic pressure spectrum for a particular observer point. The details of this procedure are presented in Reference [68]. Obviously, when there are many sources in a landing gear geometry, the number of Fourier and inverse Fourier transforms becomes very large, and coupled with the large number of samples, leads to a very high calculation time. This is impractical for a designer who will need the noise prediction quickly to understand the acoustic impact of landing gear design changes.

To eliminate the transformations from the frequency domain to the time domain and back again, the noise formulation has been converted to the frequency domain. This presented a particular
challenge when considering that Farassat’s Formulation 1A of the Ffowcs Williams and Hawkings equation was derived for sources with arbitrary motion. To convert the formulation from the time domain to the frequency domain for an arbitrarily moving source is extremely difficult. To reduce the complexity of the problem an analysis of the source terms was performed. Equation 2.2 shows Farassat’s Formulation 1A expanded into 5 source terms by separating the second term in Eqn. 2.1. The terminology for each of these source terms is introduced in Equation 2.3.

\[ 4\pi p'_L(x,t) = \int_{f=0}^{f=\infty} \left[ \frac{\dot{F}_r}{r|1-M_r|^2} \right]_{ret} dS + \int_{f=0}^{f=\infty} \left[ \frac{F_r}{r^2|1-M_r|^2} \right]_{ret} dS + \int_{f=0}^{f=\infty} \left[ \frac{M_rF_r}{r^2|1-M_r|^2} \right]_{ret} dS - \int_{f=0}^{f=\infty} \left[ F_M \right]_{ret} dS + \int_{f=0}^{f=\infty} \left[ F_M \right]_{ret} dS - \int_{f=0}^{f=\infty} \left[ F_M \right]_{ret} dS + \int_{f=0}^{f=\infty} \left[ M_rF_r \right]_{ret} dS + \int_{f=0}^{f=\infty} \left[ F_M \right]_{ret} dS + \int_{f=0}^{f=\infty} \left[ (r|1-M_r|)^{-1} \right]_{ret} dS \]

(2.2)

To simplify the problem, an investigation of was performed on the source terms shown in Equation 2.3 with the LGMAP version 1 code. Figure 2.1 shows an LGMAP version 1 prediction of noise for observers located a constant distance from the center of a representative cylinder. The observers are in a plane perpendicular to the axis of the cylinder. Since a landing gear geometry is composed of many individual cylinders, using this as a representative landing gear geometry is not unreasonable. The radius of the circular ring is 10 cylinder diameters, which is in the nearfield region for the noise calculation. Each term in Equation 2.3 is compared to the total noise. In the near field region, the \( \dot{F}_r \) term is by far the largest noise source, and the second largest noise source is the \( F_r \) term. Similarly, Fig. 2.2 shows LGMAP version 1 predictions on a circular ring whose radius is 100 cylinder diameters, a sufficient distance to be in the acoustic farfield. Again, the derivative of the loading term is by far the largest with the loading in the radiation direction second. The \( M_rF_r, F_M, \) and derivative \( (r|1-M_r|)^{-1} \) terms are small due to the uniform forward flight velocity of the source. If the source had arbitrary motion these terms might not be negligible. Based upon these results, all terms except the two largest terms—the derivative of the loading term and the loading in the radiation direction term—are no longer included in the acoustic prediction.
Figure 2.1: OASPL on a near field observer ring. Each term from the loading portion of the Ffowcs Williams and Hawkings equation is compared. The derivative term is by far the dominant term.

Eliminating the negligible terms results in the equation for acoustic pressure is shown in Equation 2.4:

\[
4\pi p_L'(x, t) \approx \frac{1}{c_\infty} \int_{f=0}^{f} \left[ \frac{\dot{F}_r}{r |1 - M_r|^2} \right]_{ret} dS + \int_{f=0}^{f} \left[ \frac{F_r}{r^2 |1 - M_r|} \right]_{ret} dS \quad (2.4)
\]

The Fourier transform of this expression can be performed analytically by assuming that the Mach number in the observer direction and the observer position relative the the source does not change
Figure 2.2: OASPL on a far field observer ring. Each term from the loading portion of the Ffowcs Williams and Hawkings equation is compared. The derivative term is by far the dominant term.

significantly over a very short time. This then gives,

$$4\pi p'_L(x, \omega) \approx \frac{1}{c_\infty} \int_{f=0} \left[ \frac{it\omega F_r}{r|1-M_r|^2} \right] dS + \int_{f=0} \left[ \frac{F_r}{r^2|1-M_r|} \right] dS$$

The sources are then discretized into individual cylinder segments, where $S = \pi D l$. Multiplying the equation for pressure by its complex conjugate results in an equation for pressure squared, shown in Equation 2.6, the equation implemented in LGMAP version 2. This equation is much simpler
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>SPL (dB)</th>
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<td>10</td>
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</tr>
</tbody>
</table>

Figure 2.3: A comparison using time domain (LGMAP version 1) and frequency domain (LGMAP version 2) to compute the noise from an isolated cylinder. The frequency domain version provides better noise in the higher frequency and significantly less computational time.

than the complete time domain equation and can be performed entirely in the frequency domain.

\[
P_L^2(f) = \sum_{cyl} \frac{F_r^2 D^2 l^2}{16} \left[ \frac{(1 - M_r)^2 + r^2 \kappa^2}{r^4 |1 - M_r|^4} \right] \quad (2.6)
\]

With this much simpler formulation implemented in LGMAP version 2, a comparison was made between LGMAP version 1 and LGMAP version 2. Figure 2.3 shows a comparison between noise predictions for an isolated cylinder using the time domain and frequency domain integration for an observer position ahead of the cylinder. Timings are also shown for each case. The acoustic results are almost exactly the same. The discrepancy at the higher frequencies is a result of the increase in accuracy of the frequency domain formulation when compared to the time domain. The time domain formulation produces errors in the high frequencies due to the Fourier and inverse Fourier transforms. Figure 2.4 shows predictions made using LGMAP version 1 and LGMAP version 2 for a 777 main gear geometry for a sideline observer position. The frequency domain integration implemented in LGMAP version 2 is many thousands of time faster than the time domain version and gives approximately the same answer.1

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1Calculation of timings were performed on desktop workstation with a dual core 2.41 GHz AMD Athlon(tm) X2 processor and 2GB of RAM.
Figure 2.4: A comparison using time domain (LGMAP version 1) and frequency domain (LGMAP version 2) to compute the noise from an isolated Boeing 777 main gear. The frequency domain version provides better noise in the higher frequency and significantly less computation time.

LGMAP version 2 has removed the hinderance of long computation time by using the frequency domain integration, and is now more useful in a design process. This enables other improvements to the prediction methodology to be made that were more difficult to implement in the time domain integration. These include refining the wheel acoustic element to better predict the noise from a larger bogie design, and the implementation of an improved trailing edge acoustic element. These two improvements are presented in the following sections. After these improvements have been presented, higher order, physics-based, techniques are presented that will allow LGMAP to predict the noise from an installed landing gear.

2.2 Wheel Acoustic Element

Section 1.4 presented noise predictions from LGMAP version 1 for two-wheel landing gear geometries for two levels of fidelity. It was shown that inclusion of the small details in the acoustic prediction resulted in a general increase in noise at higher frequencies and a “hump” in the spectrum in the range of 1/3-octave bands 28 to 36. The predicted increase agrees quite well with the increase seen in the experiment, even though the prediction underpredicted the noise at the higher frequencies by approximately 2 – 3dB. However, when comparing to landing gear geometries with
more than 2 wheels, LGMAP version 1 was significantly in error. Therefore, more calibration of
the wheel acoustic element was needed. Recently, there have been wind tunnel measurements per-
formed in the Quiet Flow Facility at the NASA Langley Research Center. This section will present
recalibration of the wheel element to this new data. It is important to note here this recalibration is
used only for six-wheel landing gear designs. The wheel acoustic element presented in Section 1.4.2
is still used for two- and four-wheel landing gear designs.

Section 1.4.2 presented the LGMAP version 1 wheel acoustic element. The acoustic element
was composed of a ring of cylinders. Each cylinder incorporated the same loading spectrum and
force coefficients, calibrated separately from the cylinder acoustic elements, with each cylinder’s
local flow defined as the normal component of the free stream velocity to the cylinder on the wheel
acoustic element. For cylinders on the top or bottom of the wheel acoustic element, those that
are parallel to the free stream velocity, the resulting incident velocity was nearly zero, meaning no
noise was generated. Using the calibrated coefficients presented in Section 1.4.2, this wheel acoustic
element definition in LGMAP version 2 resulted in an overprediction of the noise. An example of
this is shown in Figs. 2.5 and 2.6 which show a comparison of predictions with measurements
performed in the Quiet Flow Facility at NASA Langley of a 6.3%-scale Boeing 777 main gear [33, 34].
The predictions deviate for most observer positions and frequency ranges by a significant
amount.

To be of use to a designer, the predictions must be able to accurately predict the noise from
two-wheel, four-wheel, and six-wheel landing gear geometries. Hence, to perform better for more
complex landing gear designs, the wheel acoustic element had to be recalibrated so that the pre-
dictions would be better for six-wheel landing gears. As a metric for recalibration, the QFF mea-
surements presented in Fig. 2.5 and 2.6 were used. These single microphone positions provided a
simplified directivity with which the LGMAP prediction method could compare. During calibration
it was determined that incorporating a single model for every cylinder in the wheel acoustic element
was not sufficient to match the directivity for all observer locations. Therefore, two different sets
of coefficients were used: one for cylinders along the front and rear sides of the acoustic element,
and one for cylinders at the very top and bottom, where the incident local flow solution is nearly 0.
For the cylinders located at the very top and bottom, the incident velocity was changed to the local
Figure 2.5: LGMAP version 1 predictions of various azimuthal observer locations compared to measurements performed in the QFF at NASA Langley. Original LGMAP predictions for 6-wheel landing gear geometries did not accurately predict the radiated noise.

Figure 2.6: LGMAP version 1 predictions of various azimuthal observer locations compared to measurements performed in the QFF at NASA Langley. Original LGMAP predictions for 6-wheel landing gear geometries did not accurately predict the radiated noise.
Two-Wheel Element Coefficients

<table>
<thead>
<tr>
<th></th>
<th>$e$</th>
<th>$p$</th>
<th>$S_0$</th>
<th>$C_f$</th>
<th>$C_d$</th>
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</thead>
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<td>1.5</td>
<td>0.18</td>
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<td>1.6</td>
<td>0.25</td>
<td>0.184</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 2.1: Parameters used in the six-wheel acoustic element model. The six-wheel acoustic element incorporates two different sets of coefficients, one for the cylinder along the front and back sides of the wheel, and one for the cylinders at the very top and bottom where the incident flow velocity is near zero.

Figure 2.7: LGMAP version 2 predictions compared to QFF measurements at various azimuthal angles. The new wheel acoustic element does a better job at match overall level and trend better than the wheel acoustic element implemented LGMAP version 1.

The six-wheel acoustic element model implemented in LGMAP version 2 provides a more accurate prediction for larger, more complex landing gear designs when compared to the wheel acoustic element implemented in LGMAP version 1. The current model has so far been untested
against four-wheel landing gears. It is important to note that the current wheel acoustic element can certainly be improved. The prediction framework allows for a refinement of acoustic elements as wind tunnel measurements and flight test data, as well as CFD computations, provide more insight into the noise generating mechanisms in the complex geometry. In the next section, a trailing edge acoustic element is defined that can predict the noise from any sharp trailing edges in the landing gear and wing geometry.

### 2.3 Trailing Edge Acoustic Element

Turbulent flow past sharp edges is known to produce trailing edge noise. In an isolated landing gear geometry, the trailing edge noise is generated from a sharp trailing edge located on the door. The door, if present, is embedded in a turbulent flow region generated by various landing gear components. The size and intensity of the turbulence in this region is a function of the landing gear geometry (not the boundary layer as is the normal case for the isolated wing). There are two trailing edge noise sources for an aircraft with installed landing gear. The first is from the turbulent
boundary layer on the wing or flap surface that convects over the trailing edge of the wing/flap system. This type of trailing edge condition has been studied extensively and requires knowledge of the boundary layer thickness and turbulent intensity [77, 78]. The second trailing edge noise source is from the landing gear wake impinging on the trailing edge of the wing/flap system. This trailing edge noise condition is similar to the trailing edge of the door on the landing gear geometry, and is a function of the impinging wake size, its location in relation to the trailing edge, and turbulent intensity. The second trailing edge noise source, because it only exists if the landing gear is present, is a landing gear noise source.

The prediction system uses two methods for the prediction of the noise from a trailing edge. The first trailing edge noise prediction scheme uses the trailing edge noise equation developed by Ffowcs Williams and Hall [79]. This equation relates the Reynolds shear stress and turbulence mixing length and intensity to radiated acoustic pressure. The second trailing edge acoustic element can be used to predict the noise caused by a turbulent boundary layer interacting with a sharp trailing edge. The boundary layer generated trailing edge noise acoustic element uses the theory of Brooks, Pope and Marcolini [80, 81], as modified by Moriarty [82–84] to allow for airfoils other than the NACA 0012. This semi-empirical scheme uses inputs such as airfoil cross section, angle of attack, boundary layer trip, turbulent inflow intensities and trailing edge bluntness. In the following two sections, each of the trailing edge noise prediction schemes implemented in LGMAP are described.

### 2.3.1 Ffowcs Williams and Hall Trailing Edge Noise Equation

In an installed landing gear, an important noise source may be from interactions between the landing gear wake and the trailing edge of the wing and/or flaps. The wake generated trailing edge noise is caused by an external wake generated by a landing gear component or the entire landing gear geometry convecting over a wing or sharp trailing edge. The primary sharp trailing edge in the vicinity of an installed landing gear is the trailing edge of the wing/flap system, and for an uninstalled landing gear geometry it is from the trailing edge of the landing gear door (if a door is present). The length of the door trailing edge is relatively small, compared to the wing, but the flow in this region typically contains many small turbulent eddy noise generating structures. Even though the landing gear door is significantly different from the wing, both structures generate noise by the same mechanism;
thus one scalable acoustic model can be used.

The equation for the far field acoustic spectrum due to sources in the vicinity of a sharp edge is given by Ffowcs William and Hall[79], shown in Equation 2.7.

\[ 4\pi \rho_T (r, \theta, \phi; \omega) = \frac{2^{\frac{3}{2}}}{\pi^{\frac{1}{2}}} e^{i\left(\frac{1}{4}\pi - kr\right)} \frac{k^\frac{1}{2}}{r} \sin^\frac{1}{2} \phi \cos \frac{\theta}{2} \tau^* \delta^{-\frac{3}{2}} V \]  

(2.7)

The Reynolds shear stress term, \( \tau^* \), can be modeled using the turbulence intensity, \( \alpha \) and some spectrum function \( F(S) \), which is dependent on the turbulence Strouhal number.

\[ \tau^* \approx F(S) \rho_0 U_0^2 \approx F(S) \rho_0 \left( \frac{U_0}{U_0} \right)^2 U_0^2 = F(S) \rho_0 \alpha^2 U_0^2 \]  

(2.8)

In Equation 2.7, \( V \) is the volume of the turbulent source region and can be estimated to be the cube of the turbulence mixing length, \( l \), times an arbitrary constant, \( \varepsilon \), of order O(1). Then the equation for the trailing edge acoustic element is simplified into Equation 2.9. This is the equation implemented in the LGMAP prediction system to predict noise from the trailing edge of a door or wing/flap due to an external turbulent wake.

\[ 4\pi \rho_T (r, \theta, \phi; \omega) = \frac{2^{\frac{3}{2}}}{\pi^{\frac{1}{2}}} e^{i\left(\frac{1}{4}\pi - kr\right)} \frac{k^\frac{1}{2}}{r} \sin^\frac{1}{2} \phi \cos \frac{\theta}{2} \tau^* \delta^{-\frac{3}{2}} l^3 \]  

(2.9)

The directivity function for a trailing edge is different from that of a circular cylinder. \( \theta \) is defined as the angle between the upstream flow direction and the radiation vector, and \( \phi \) is defined as the angle between the spanwise direction of the trailing edge and the radiation vector. Figures 2.9 and 2.10 show how the directivity function, \( D = \sin^\frac{1}{2} \phi \cos \frac{\theta}{2} \), varies according to these two parameters. At this stage of development, only three unknowns need to be modeled: the turbulence intensity, the non-dimensional turbulence spectrum, \( F(S) \), and the thickness of the turbulence mixing region, \( l \).

To predict the spectrum of surface pressure near the trailing edge, the ANOPP trailing edge acoustic spectrum (given in Equation 2.10) is used as a starting point, with coefficients \( e = 4.0, \) \( p = 1.5, \) and \( S_0 = 1.7 \). However, similar to the wheel and cylinder acoustic elements, these were determined empirically using wing tunnel experiments. Equation 2.10 and 2.11 show the non-
Figure 2.9: Directivity of trailing edge source. Flow is from left to right and edge is top to bottom.

Figure 2.10: Directivity of trailing edge source. Flow is from left to right and edge is out of page.

dimensional spectrum for the trailing edge acoustic model.

\[ F(S) = B_2 (10S)^{e-1} [B_1 + (10S)^p]^{-e} \]  (2.10)
Figure 2.11: Turbulence intensity ratio as a function of wake size and location. The curve shown is a best fit of measured values, also shown. Measurements from measurements of wakes impinging on turbine blades [88].

\begin{align*}
B_1 &= -S_0^p \left( \frac{e(1-p) - 1}{e - 1} \right) \\
B_2 &= \left[ \int_0^1 S^{e-1}(B_1 + S^p)^{-e} \right]^{-1}
\end{align*}

To relate the turbulence intensity, \( \alpha \), and turbulence length scale, \( l \), the last two unknowns in the trailing edge acoustic prediction, empirical models based on wind tunnel experiments are used. To estimate these parameters, the prediction system uses the results of wind tunnel studies of wakes impinging on turbine blades [88]. The turbulence intensity curve used by LGMAP, shown in Fig. 2.11, is a function of the ratio of the distance of the wake center to the trailing edge and the wake half width. The turbulence intensity at the trailing edge is found by sampling this curve and using a turbulence level at the center of the wake, \( \alpha_0 \), equal to 0.2.

With the relation between turbulence mixing length and turbulence intensity defined empirically through the curve in Fig. 2.11, the only parameter left unknown is the turbulence mixing length. This parameter is an input into the prediction system and can be found through mean flow calculations,
wake estimates based on gear size, or any other method available to a user. In this thesis, an immersed boundary Euler solver is used with a very approximate representation of an isolated landing gear to achieve mean flow solutions. The details are presented in Section 3.3.

2.3.2 Brooks, Pope, and Marcolini Trailing Edge Noise Model

The second trailing edge prediction technique is used to predict the noise from a turbulent boundary layer convecting over a sharp trailing edge found on a wing or flap. To predict this noise source, LGMAP uses an external program developed by Brooks, Pope, and Marcolini [80, 81], as modified by Moriarty [82–84] to allow for airfoils other than the NACA 0012. The Brooks, Pope, and Marcolini code, with modifications by Moriarty, has been fully coupled with the prediction system. The prediction system calls the external executable when needed, processes the output and sums the noise sources together. Figure 2.12 shows a comparison of the Brooks, Pope, and Marcolini code to LGMAP predictions for an isolated observer position. The comparisons are almost exact. Any differences, particularly in the higher frequencies, is due to the ability of LGMAP to convert an octave band, provided by the Brooks, Pope, and Marcolini code, to narrow band, assuming a simplified spectrum shape, so that it can be added to other noise sources in the LGMAP framework. However, even these differences are very small. Figure 2.13 shows the predictions for the same airfoil measured at observer locations of constant distance from the center of the airfoil. For all observer positions, LGMAP and the Brooks, Pope, and Marcolini code match exactly, any differences are extremely small.

2.4 Summary of Acoustic Element Improvements

In the previous three sections, improvements to the existing LGMAP framework have been presented. The first improvement, shown in Section 2.1, includes a frequency domain formulation for the radiated acoustic pressure. This new formulation drastically reduces the computation time when compared to LGMAP version 1, on the order of many thousands of times faster for large landing gear geometries. It was shown that the frequency domain formulation provides nearly exactly the same result when compared to the time domain formulation. The difference between the two formulations is only apparent in the higher frequency range where the frequency domain formulation
Figure 2.12: Comparison of the Brooks, Pope, Marcolini trailing edge noise prediction code to the incorporated LGMAP prediction code. Airfoil used in the prediction is 1.5 meters long in the spanwise direction, with a 1 meter chord length. The observer is located perpendicular to the flow direction at a distance of 1.22 meters. The angle of attack of the airfoil is 1.516 degrees. Results show that LGMAP compared extremely well with the BPM prediction code.

performs more accurately than the time domain due to numerical errors with Fourier transforms. The frequency domain formulation allows for very fast turn around time, so that a designer can better use the predictions to guide the development of a quieter landing gear design.

The second improvement to the existing LGMAP scheme is an improved wheel acoustic element, presented in Section 2.2. The wheel acoustic element implemented in LGMAP version 1 was untested for six-wheel landing gear geometries. It was shown that the LGMAP version 1 wheel acoustic element overpredicts the radiated noise for this type of design. The wheel acoustic element was therefore recalibrated to better match measurements. These calibrations include polar and azimuthal variations with observer position.

The third improvement to the existing LGMAP framework is the incorporation of two types of trailing edge acoustic elements. The first type of trailing edge acoustic element, presented in Section 2.3.1 uses the Ffowcs Williams and Hall trailing edge noise equation to predict the noise caused by an external wake from a landing gear geometry impinging onto a trailing edge, such as a wing/flap system, or landing gear door. Using an empirical fit to data for turbulence intensity, the only input needed for an acoustic prediction is the turbulence mixing length. In Section 3.3 an immersed boundary code is used to estimate this parameter. The second trailing edge acoustic
Figure 2.13: The overall sound pressure level for a circle around the trailing edge of a NACA 0012 Airfoil and observer configuration same as Fig. 2.12. LGMAP boundary layer trailing edge noise prediction and the Brooks, Pope, and Marcolini code are nearly exactly the same.

element improvement, presented in Section 2.3.2, is the embedded boundary layer generated trailing edge noise prediction code developed by Brooks, Pope, and Marcolini. By using this external function, LGMAP is able to predict the noise caused by a boundary layer convecting over a sharp trailing edge, such as a wing or flap.

In the following section, new physics-based prediction tools incorporated into the LGMAP system will be presented. These new techniques allow LGMAP to predict the noise from an installed landing gear, accounting for the local flow variations due to the wing, scattering of noise from the wing downward to an observer, shielding of noise from landing gear components, boundary layer generated trailing edge noise from the wing/flap system, and the landing gear generated trailing edge noise. It is these prediction tools, along with the improved acoustic elements presented in this section, that allow LGMAP to predict the noise from an installed landing gear.
Chapter 3

The Prediction of Aerodynamic and Aeroacoustic Effects

Chapter 2 presented modifications to existing acoustic elements. These modifications improve the prediction of individual noise sources, such as the landing gear components or trailing edges of the wing. However, these improvements to the existing acoustic elements alone are insufficient to fully predict the noise from an installed landing gear. The aerodynamic or aeroacoustic interactions between landing gear components or between the landing gear and other aircraft structures can potentially alter the radiated sound. When the aircraft is in a landing configuration, flight testing has shown that the landing gear is a major noise contributor [5, 6, 32]. Existing empirical schemes do not directly model the contribution from acoustic interactions or the interaction for the landing gear wake with the wing and flap trailing edges. For aeroacoustic interactions, the impact of acoustic shielding by landing gear components was not directly addressed. This is due to the difficulty in isolating the acoustic scattering caused by the components separately from the direct noise radiation. Existing prediction schemes include the effect of scattering through empiricism. The predicted noise then includes the scattered sound. Individual contributions from the source alone and scattering alone are unknown. For aerodynamic interactions, the contribution of noise from the landing gear wake interacting with the wing and flap trailing edges is often not included. This is because this noise can be 6 or more decibels lower than the noise from the landing gear alone. Empirical landing gear noise prediction tools do not include this as a separate noise source. The prediction of the
landing gear and trailing edge interaction is incorporated into one signature from the landing gear. The noise caused by the landing gear increases when adding small features, such as hoses or small brackets, on the landing gear geometry. However, the wake generated by the landing gear also increases in size and intensity when adding these small features. Flow measurements have shown an increase in landing gear wake size near the wing trailing edge when increasing the landing gear geometry fidelity [23]. Noise measurements of wing structures with landing gear installed show that increasing the fidelity of the landing gear geometry increases the noise in the region of the wing trailing edge, as well as the directly from the landing gear. These small features increase the turbulence levels and size of the wake impinging on the trailing edge. Since a turbulent wake is interacting with a trailing edge, trailing edge noise is generated. However, a metric for modeling the noise from the wing and flap trailing edge/landing gear wake has not previously been created. These interactions must be predicted, at some level, to determine if these sources of noise are an important factor in installed landing gear noise.

This chapter presents the techniques implemented to predict the noise from an installed landing gear. These techniques are estimates of the aerodynamic and aeroacoustic effects mentioned above. This includes an estimate for the acoustic shielding caused by landing gear components; an estimate of the local flow caused by the circulation around the wing; a prediction of landing gear wake generated trailing edge noise; and, finally, a scheme that allows the prediction of noise when the landing gear truck angle is modified.

### 3.1 Line of Sight Shielding Algorithm

The noise emitted from the individual components of the landing gear geometry radiate noise in all directions and may interact with other landing gear components that scatter the noise. This scattering is very difficult to measure in a wind tunnel or flight test because it is difficult to separate the scattered field from the incident field. The effect of acoustic scattering on the radiated landing gear noise is currently unknown. There is presently no prediction system that incorporates a scattering estimate, and no experiment has focused on measuring acoustic scattering for landing gear. Several

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1The total sound from a scattered source is the sum of an incident sound and the scattered sound. The incident sound is the noise generated with the scattering body removed. The scattered sound is the noise from the scattering body caused by the incident field.
methods can be used to directly calculate the scattered sound. For example, the Fast Scattering Code [89] or time-domain methods [90] may be used. A drawback to such methods is the significant amount of computation time even for a single low frequency acoustic source. Since landing gear noise is very broadband, the scattering of noise for many frequencies, low and high, must be calculated. Also, the landing gear is a very complex geometry with many sources and scattering bodies. To be useful for a landing gear designer, a faster method of calculating the scattered field has to be incorporated into a prediction system to estimate the effect of scattering.

A few simple assumptions can be used to simplify the problem of scattering. A first order estimate of the scattering caused by landing gear components is a simple line of sight assumption. This modifies the propagation model from an estimate of scattering to an estimate of shielding. The algorithm is only applied if a component on the landing gear is in the direct line of sight between the source position and the observer position. Although the scattered sound propagates in all directions, a line of sight assumption provides an estimate of the acoustic shielding caused by components in the landing gear geometry. To further simplify the problem, a second simplification is that each component on the landing gear is assumed to scatter like a circular cylinder. The scattering by circular cylinders has been studied extensively and can be derived analytically. This assumption is compatible with the acoustic elements implemented in the prediction system, since each element is assumed to act like a circular cylinder with a broadband loading spectrum. A third simplification is that the scattering of sound by the circular cylinder behaves as if it is in two-dimensions, with the cross section assumed to be perpendicular to the radiation direction. Although the prediction system representation of the landing gear geometry is composed of many cylinders arranged in a complex configuration; when the cylinder is not perpendicular the two-dimensional representation is an ellipse. The scattering by an ellipse is defined by a characteristic length which is equal to the cylinder diameter. For this study, it is assumed that the scattering of an ellipse of low aspect ratio is approximately the scattering from a circle.

Figure 3.1 shows a schematic of the shielding condition that occurs in the prediction system. A scattering body, the circular cylinder, is shielding the observer and scatters the emitted sound from the source. The sound from the source is partially shielded and only a partial signal is received by the observer. Using the scattering from a cylinder in two-dimensions allows noise generated
Figure 3.1: Schematic of shielding in the prediction framework. The source and observer line of sight is blocked by a scattering body, the circular cylinder.

by large objects (long wavelengths) to pass relatively unaffected around small objects. Conversely, the sound generated by relatively small objects (short wavelengths) is shielded and diffracted by large objects. In the following section, the two-dimensional cylinder scattering equations will be presented.

3.1.1 Two-Dimensional Cylinder Scattering

The shielding approximation implemented in the prediction system is based on a derivation of scattering by a porous cylinder in two-dimensions [91]. The total acoustic field is composed of an incident field and scattered field, as shown in Eqn. 3.1. Because all the sources in the prediction framework are line sources in three-dimensions, it is assumed that the individual noise sources act like point sources in two-dimensions. For point sources, the incident and scattered fields have analytical solutions, shown in Eqns. 3.2 and 3.3. The coefficient of shielding used in the prediction system can be derived from the incident and scattered field. This coefficient is shown in Eqn. 3.8.
\[ p_t(r, \theta) = p_{\text{inc}}(r, \theta) + p_{\text{sc}}(r, \theta) \]  

(3.1)

The sound from the point source, called the incident field, has an analytical solution.

\[ p_{\text{inc}}(r, \theta) = (1/4i)H_0^{(1)}(k_0R) \]  

(3.2)

The scattered field is a sum of Hankel functions, each with a weighting coefficient.

\[ p_{\text{sc}}(r, \theta) = A_0H_0^{(1)}(k_0r) + \sum_{n=1}^{\infty}A_nH_n^{(1)}(k_0r)\cos(n\theta) \]  

(3.3)

The coefficients that weight the Hankel functions for the scattered field are shown in Eqns. 3.4 through 3.7.

\[ A_0 = \frac{iH_0^{(1)}(k_0L)}{4\Delta_0}\{Z_rJ_1(k_1a)J_0(k_0a) - J_0(k_1a)J_1(k_0a)\} \]  

(3.4)

\[ A_n = \frac{iH_n^{(1)}(k_0L)}{2\Delta_n}\{(H_n^{(1)}(k_0a) - H_{n+1}^{(1)}(k_0a))J_n(k_0a) - H_n^{(1)}(k_1a)[J_{n-1}(k_0a) - J_{n+1}(k_0a)]\} \]  

(3.5)

\[ \Delta_0 = Z_rJ_1(k_1a)H_0^{(1)}(k_0a) - J_0(k_1a)H_1^{(1)}(k_0a) \]  

(3.6)

\[ \Delta_n = Z_r[J_{n-1}(k_1a) - J_{n+1}(k_1a)]H_n^{(1)}(k_0a) - J_n(k_1a)[H_n^{(1)}(k_0a) - H_{n+1}^{(1)}(k_0a)] \]  

(3.7)

The total pressure field is the sum of the incident field and scattered field. The sum is rearranged into a scattering coefficient, \( C_s \), applied to the incident field.

\[ p_t(r, \theta) = \left[ \frac{p_{\text{inc}}(r, \theta) + p_{\text{sc}}(r, \theta)}{p_{\text{inc}}(r, \theta)} \right] \ast p_{\text{inc}}(r, \theta) = C_s \ast p_{\text{inc}}(r, \theta) \]  

(3.8)

Figure 3.2 shows the incident acoustic pressure field for a point source located three cylinder radii in front of a scattering cylinder. All scattering figures shown in this section have the source located at the same location and with the intensity. Figure 3.3 shows the scattered field, calculated by Eqn. 3.3 at a frequency corresponding to \( ka = 0.1 \). At this low frequency, the scattering cylinder does not significantly alter the acoustic signature because the wavelength of the acoustic wave is much larger than the cylinder diameter. Figure 3.4 shows the shielding coefficient, calculated from
Figure 3.2: Sample incident acoustic pressure field, $p_{\text{inc}}(r, \theta)$. Point source is located 3 cylinder radii from center of scattering cylinder.

Eqn. 3.8 for a frequency corresponding to $ka = 0.1$. The shielding coefficient is near 1 at all observer locations except very near the scattering cylinder. As the frequency of the incident wave is increased, the cylinder begins to scatter the pressure more significantly. Figure 3.5 shows the scattered field for a frequency corresponding to $ka = 1.0$, which corresponds to an acoustic wavelength on the order of the cylinder radius. The incident pressure is scattered in front of and behind the cylinder. Fig. 3.6 shows the scattering coefficient for $ka = 1.0$. Behind the cylinder the scattered field adds coherently, in phase, with the incident field, causing a slight noise increase. Figure 3.7 shows the scattered pressure as the frequency is again increased to $ka = 10.0$. The scattered pressure field becomes much more complicated than the scattering at lower frequencies. At this frequency, noise is scattered in all directions. Figure 3.8 shows the shielding coefficient for $ka = 10.0$. The shielding coefficient behind the cylinder is significantly reduced because the incident pressure is out of phase with the scattered pressure. This is the shadow region caused by the shielding of the cylinder. Once more, the frequency is again increased by a factor of 10, to $ka = 100.0$. Figure 3.9 shows the scattered field for this higher frequency. At this high frequency, the scattered field is significantly reduced when compared to $ka = 10.0$. The shielding coefficient at this frequency, shown in Fig. 3.10 approaches 1 at all observer locations except directly behind the cylinder.
Figure 3.3: Scattered acoustic pressure on half plane around scattering cylinder for $ka = 0.1$. Point source is located 3 cylinder radii from center of scattering cylinder. At low frequency, scattering has minimal effect behind the cylinder.

Figure 3.4: Shielding coefficient on half plane around scattering cylinder for $ka = 0.1$. Point source is located 3 cylinder radii from center of scattering cylinder. Shielding coefficient is near 1 at all observer locations.
Figure 3.5: Scattered acoustic pressure on half plane around scattering cylinder for $ka = 1.0$. Point source is located 3 cylinder radii from center of scattering cylinder. Scattering affect mainly in front of and behind the scattering cylinder.

Figure 3.6: Shielding coefficient on half plane around scattering cylinder for $ka = 1.0$. Point source is located 3 cylinder radii from center of scattering cylinder. Scattered field behind the scattering cylinder coherently adds to incident pressure field causes slight noise increase.
Figure 3.7: Scattered acoustic pressure on half plane around scattering cylinder for $ka = 10.0$. Point source is located 3 cylinder radii from center of scattering cylinder. Scattered field is apparent on all sides of scattering cylinder.

Figure 3.8: Shielding coefficient on half plane around scattering cylinder for $ka = 10.0$. Point source is located 3 cylinder radii from center of scattering cylinder. Significant shadow zone behind scattering cylinder.
Figure 3.9: Scattered acoustic pressure on half plane around scattering cylinder for $ka = 100.0$. Point source is located 3 cylinder radii from center of scattering cylinder. Scattered acoustic pressure is mostly in front of and behind scattering cylinder.

Figure 3.10: Shielding coefficient on half plane around scattering cylinder for $ka = 100.0$. Point source is located 3 cylinder radii from center of scattering cylinder. Shielding coefficient approaches 1 behind cylinder.
3.1.2 Line of Sight, Frequency Dependent, Shielding Function

Instead of using the equations that define the entire scattered field, the prediction system assumes that all sources shielded by a cylinder are directly behind the cylinder. This ensures that the coefficient will only be applied in the acoustic calculation during a line of sight condition. Since the prediction system is only interested in using the shielding coefficient directly behind the cylinder, a limited number of scattering configurations are used to define the scattering coefficient. The limited number of scattering configurations is predetermined before the acoustic calculation, then used as a 'look up' table during the noise computation. Linear interpolation is used to sample the shielding function at particular combinations of distance from the source to the scattering body, the distance from the scattering body to the source, and the frequency of the source acoustic pressure. This significantly reduces the number of calculations in the prediction system. Figures 3.11 and 3.12 show a few configurations of the shielding coefficient as a function of frequency for various combinations of distances from the scattering cylinder to the observer, and scattering cylinder to the source. The curves shown in these figures represent only a small number of the actual curves used in the prediction system. Figure 3.11 shows the shielding coefficient as the distance from the observer to the scattering cylinder is increased. As the observer is moved farther from the scattering body, the shielding coefficient at all frequencies approaches 1. Similarly, Fig. 3.12 shows the shielding coefficient as the distance from the source to the scattering body is increased. As this distance is increased, the scattering body has a smaller affect on the shielding, reducing the shielding coefficient. Also note, the shielding coefficient from approximately $ka > 10$ begins to climb as the frequency is increased. This is due to the diffraction around the cylinder at higher frequencies and is due to the nature of scattering by an infinitely long circular cylinder.

The prediction system calculates the noise radiated by a sound source, as a function of forcing coefficients, non-dimensional loading spectrum, local flow velocity, and source characteristic length scale. The shielding coefficient, $C_s$, is included as a multiplicative factor in the sound equation to include the effect of shielding, shown in Eqn. 3.9.

$$P_L^2(f) = \sum_{cyl} \frac{C_s^2 F_r^2 D^2 l^2}{16} \left[ \frac{(1 - M_r)^2 + r^2 k^2}{r^4 |1 - M_r|^4} \right]$$  \hspace{1cm} (3.9)
Figure 3.11: Shielding coefficient for three values of distance from observer to scattering body. The shielding coefficient decreases as the distance from the observer to scattering body is increased.

Figure 3.12: Shielding coefficient for three values of distance from source to scattering body. The shielding coefficient decreases as the distance from the source to scattering body is increased.
3.1.3 Demonstration of Prediction Using The Shielding Algorithm

Using the approximation described in the previous section for shielding, a landing gear representation similar to one recently tested in the Quiet Flow Facility (QFF) at NASA Langley Research Center [34], is used for a noise prediction to demonstrate the shielding correction to the radiated noise prediction. Figure 3.13 shows a schematic of the observer angle defined in the QFF experiment. The landing gear geometry used in the experiment is representative of a Boeing 777 main gear. For comparison with the present prediction system, Figs. 3.14 and 3.15 show the QFF measurements compared to the prediction scheme developed by Guo [17, 53, 54] at several azimuthal and polar angles defined by $\phi_e$ and $\theta_e$ respectively. Guo’s approach predicts the noise at most frequency ranges and observer positions. However, it is unable to predict the azimuthal level differences from one side of the landing gear to the other. Also, Guo’s method does not have any correction for the shielding caused by the landing gear geometry, except that it is an empirical fit to measured data. Guo’s prediction system is unable to separate the incident noise from the scattered noise. Figures 3.16 and 3.17 show the current prediction system without the shielding correction. The present prediction system overpredicts for most of the low to mid-frequency range, however, it does predict a noise level difference from one side of the landing gear to the other. Figures 3.18 and 3.19 shows the prediction system including the shielding correction defined previously. The levels, particularly where the system was previously overpredicting by a large amount, are reduced to values closer to those measured. This shows that the acoustic scattering by the landing gear influences the noise in a significant way. Including it in a prediction system provides better estimates of the actual physical mechanisms causing the noise.

To get a more complete picture of the noise directivity, Fig. 3.20 shows the measured directivity in selected 1/3rd octave bands, compared to the prediction system with the shielding included. The present system predicts the levels at all observer positions and octave levels relatively well when compared to other prediction schemes [33, 49]. This is compared to Fig. 3.21 which shows the prediction system compared to the QFF directivity without the shielding correction. The directivity from the prediction system is significantly altered when the shielding model is turned off. The difference in predictions with and without shielding are shown in Fig. 3.22. At the low frequencies, where the wavelength is large compared to any shielding component, the shielding correction is
Figure 3.13: Quiet flow facility coordinate system for landing gear. 4-Wheel landing gear geometry shown. However, six-wheel geometry used in acoustic measurements and present predictions.

Figure 3.14: Prediction method developed by Guo [15] compared to measurements performed in the Quiet Flow Facility at NASA Langley for different azimuthal variations in observer position.
Figure 3.15: Prediction method developed by Guo [15] compared to measurements performed in the Quiet Flow Facility at NASA Langley for different polar variations in observer position.

Figure 3.16: LGMAP predictions without the shielding correction compared to measurements performed in the Quiet Flow Facility at NASA Langley for different azimuthal variations in observer position.
Figure 3.17: LGMAP predictions without the shielding correction compared to measurements performed in the Quiet Flow Facility at NASA Langley for different polar variations in observer position.

relatively small. As the frequency increases, this correction becomes much larger, nearing 8 decibels at some observer locations. It is interesting to note that the largest noise decrease coincides with the direction of the truck angle, suggesting that the scattering by the wheels in that direction is significant. The landing gear representation used in the prediction system can be broken down into sub assembly contributions. Figure 3.23 shows the contribution from the strut and wheel assembly with shielding, compared to Fig. 3.24 which shows the same predictions without shielding. The prediction of noise from the strut assembly is significantly shielded in the mid-frequencies. The change in decibel levels caused by the shielding correction for the strut and wheel assemblies is shown in Fig. 3.25.

When compared to other, purely empirical, prediction schemes, the shielding approximation implemented has been shown to significantly alter the predicted noise in the mid-frequency range and compares well to measured wind tunnel noise measurements of a Boeing 777 main gear. The predictions show that shielding is responsible for as much as 6 decibels at some observer locations. It was also shown that the shielding caused by the wheel is a significant factor in noise
Figure 3.18: LGMAP predictions with the shielding correction compared to measurements performed in the Quiet Flow Facility at NASA Langley for different azimuthal variations in observer position.

radiation from the strut assembly. It is important to note that, although the current shielding model predicts noise changes due to a first order approximation of scattering, there is room for future improvements. The framework developed is specifically designed for improvements to each piece of the prediction system. Future improvements might include scattering at all observer positions due to a two-dimensional cylinder, or integration of the acoustic prediction with a higher order three-dimensional scattering code.

The next section will present the ability of the prediction system to use a flow calculation of isolated two-dimensional wing cross sections at the spanwise location of the landing gear, to approximate the local flow caused by the lift of the wing. Flow calculations at several angles of attack and flap deflection angles demonstrate how the system can predict the difference in noise, due to the local flow caused by these different flight conditions.
Figure 3.19: LGMAP predictions with the shielding correction compared to measurements performed in the Quiet Flow Facility at NASA Langley for different polar variations in observer position.
Figure 3.20: Directivity plot of predicted noise to measurements from the QFF for the total assembly with shielding included.
Figure 3.21: Directivity plot of predicted noise to measurements from the QFF for the total assembly with shielding excluded.
Figure 3.22: Directivity plot of difference in noise level when using the shielding correction for the total assembly.
Figure 3.23: Directivity plot of prediction for the strut and wheel components with shielding included.
Figure 3.24: Directivity plot of prediction for the strut and wheel components with shielding excluded.
Figure 3.25: Directivity plot of difference in the prediction for the strut and wheel components when using shielding.
3.2 Local Flow Velocity for an Installed Landing Gear

During flight, an installed landing gear is placed in an environment that is significantly different from that experienced by an isolated landing gear in a wind tunnel experiment. In a wind tunnel experiment, an isolated landing gear is installed on the wall of the testing platform, and the inflow into the landing gear geometry can be assumed to be uniform. In flight, the lift generated by the airfoil causes circulation which alters the local flow in the vicinity of the landing gear. This local flow is significantly lower than the freestream flow velocity, and is not uniform throughout the landing gear region. Lower flow velocity causes the radiated noise from the landing gear to be significantly less than expected when considering the noise generated at the free stream velocity. This complicates the comparison of landing gear noise of wind tunnel experiments to flight tests. The velocity in the region of the installed landing gear must be estimated, and incorporated into any prediction system that predicts the noise from an uninstalled or installed landing gear. Recently Guo’s prediction method has been upgraded to include the effect of local flow velocity in the prediction scheme [55]. However, this prediction requires the flow velocity in three-dimensions in the entire landing gear region without the landing gear present. In fact, a flow solution for the entire aircraft is used in Guo’s prediction scheme, leading to long computation times. Even though a flow computation around an entire aircraft may be available to a landing gear designer, the present prediction scheme is able to use a much simpler, less computationally intensive, flow computation to estimate this installation effect.

The present prediction scheme does not require flow calculations around the entire aircraft. Any compressible or incompressible, two- or three-dimensional flow solution with, or without any turbulence modeling can be used. This is because the present prediction system only uses a rough estimate of the mean flow condition in the landing gear region. It is important to note that the prediction system is specifically designed to use any flow computation available to a designer, as long as it provides an estimate of the mean flow in the landing gear region. As an example, this section presents two-dimensional FLUENT [92] flow calculations for an approximation of an isolated Boeing 777 wing section. The section is at a spanwise location near the installed landing gear without the bogie present and is traveling at a forward flight Mach number of 0.2. These calculations are only representative of example inputs for the acoustic prediction. It should be emphasized that the
geometry of the wing and high lift devices are only estimated, and do not conform to the exact Boeing 777 wing geometry. The average flow velocity will be used in the predictions to provide an estimate of the installed landing gear local flow. Two trade studies are presented for wing angle of attack and flap deflection angle. Calculations show that increasing the angle of attack, or the flap deflection angle, reduces the local flow in the vicinity of the installed landing gear. Noise predictions show that the decrease in local flow velocity directly corresponds to a decrease in the noise caused by the change in flight conditions.

3.2.1 Computational Setup

The FLUENT CFD [92] code is used to compute the flow field, solving the compressible, unsteady, inviscid Euler equations on a two-dimensional, unstructured grid with approximately 500,000 cells. The number of grid cells is intentionally kept to a minimum to enable a fast computation time. All computations are performed using an implicit, second-order-accurate scheme, with at most 25 subiterations, which are then averaged to obtain an estimate of the mean flow velocity. Each computation is performed, in parallel, on the COCOA4 cluster2 at The Pennsylvania State University, and take approximately 24 hours to reach a converged averaged solution when using 8 processors. Four different flap settings are studied, shown in Fig. 3.26, as well as several angles of attack ranging from 0° to 12°. The four flap settings range from 40° to 62.5°, in 7.5° increments, numbered from flap setting 1 to 4. The outer domain of the grid, shown in Fig. 3.27, is similar to that used in a recent NASA Langley Research Center airfoil computation [93]. Figure 3.28 shows the relative position of the wing to the landing gear, and two sampling lines, referred to in the following sections. The sampling lines are chosen to give a representation of the inflow and outflow conditions into the landing gear noise prediction.

3.2.2 Angle of Attack Study: Flow Results

The first study presented here explores the effect of increasing the angle of attack of the airfoil on the radiated noise. To include the effect of the angle of attack on the noise requires a knowledge of the flow conditions in the vicinity of the landing gear. For these computations the landing gear

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2The COCOA4 cluster consists of 52 nodes, each with 2 quad core, 2.66 GHz Intel Harpertown processors, and 8 GB memory, connected with Infiniband network fabric.
Flap Setting 1: $\theta_f \approx 40^\circ$
Flap Setting 2: $\theta_f \approx 47.5^\circ$
Flap Setting 3: $\theta_f \approx 55^\circ$
Flap Setting 4: $\theta_f \approx 62.5^\circ$

Figure 3.26: Four flap settings used in the present study. Flap settings range from $40^\circ$ to $62.5^\circ$.

is not present. Figures 3.29 through 3.33 show the instantaneous Mach number ratio in the vicinity of the airfoil with a flap setting 2 at five different angles of attack: $0^\circ$, $4^\circ$, $6^\circ$, $8^\circ$, and $12^\circ$. Flap setting 2 is defined as $47.5^\circ$. At higher angles of attack the airfoil generates more lift, and therefore, more circulation. This circulation corresponds to a lower flow velocity in the landing gear region. The Mach number ratio is defined as the local Mach number over freestream Mach number, $M/M_0$, where $M_0$ is 0.2 in the current study. Figures 3.34 and 3.35 show the calculated averaged Mach number ratio near the inflow and outflow of the landing gear region. As the angle of attack is increased, the local flow velocity underneath the airfoil in the region of the landing gear decreases by a slight amount. Comparing the flow velocity near the front of the landing gear, Fig. 3.34 and towards the rear of the landing gear, Fig. 3.35 show that the flow slows down approximately $\Delta M/M_0 \approx 0.05$, where $M_0 = 0.2$, as it passes through the landing gear region (i.e. where the gear would be). The results presented here show similar trends to those presented by Guo [55].
Figure 3.27: The outer domain of the flow calculations are similar to that used in a recent NASA Langley airfoil computation [93].

Figure 3.28: Position of two sampling lines used following sections. Sampling lines chosen to give representation of inflow and outflow conditions into the landing gear geometry.
Figure 3.29: Instantaneous flow velocity for flap setting 2 case at 0° angle of attack.

Figure 3.30: Instantaneous flow velocity for flap setting 2 case at 4° angle of attack.
Figure 3.31: Instantaneous flow velocity for flap setting 2 case at 6° angle of attack.

Figure 3.32: Instantaneous flow velocity for flap setting 2 case at 8° angle of attack.
Figure 3.33: Instantaneous flow velocity for flap setting 2 case at 12° angle of attack.

Figure 3.34: Representation of inflow into landing gear region with different airfoil angles of attack. Mach number ratio presented is shown on sampling line 1, shown in Fig. 3.28.
Figure 3.35: Representation of outflow into landing gear region with different airfoil angles of attack. Mach number ratio presented is shown on sampling line 2, shown in Fig. 3.28.
3.2.3 Angle of Attack Study: Acoustic Results

The mean local flow velocities show that as the angle of attack of the airfoil is increased the Mach number ratio decreases. Figure 3.34 shows that increasing the angle of attack from 0° to 12° results in a decrease in Mach number ratio by a factor of $\Delta M/M_0 \approx 0.15$. Using a $6^{th}$ power law for noise, this corresponds to a noise reduction of approximately 5.8dB. Figure 3.36 shows the region of local flow used in the noise predictions for an airfoil at an angle of attack of 4°. The solution on the unstructured grid has been interpolated onto a coarse, structured grid that is used in the acoustic prediction. The coarsened, structured local flow solution is sampled at the center of the acoustic element to obtain the mean flow velocity vector. The flow in the spanwise direction is assumed to be zero. The effect on the prediction is demonstrated by calculating the noise at an observer position 120 meters directly below the landing gear. Figure 3.37 shows a prediction of the 1/3-octave spectrum using the FLUENT calculations for the local flow. As the angle of attack is increased the flow velocity below the airfoil decreases. The decrease in local flow corresponds to a decrease in the predicted noise levels. The predictions also show that using the FLUENT calculations for the local flow results in a maximum noise reduction of approximately 6 decibels, matching the estimate.
3.2.4 Flap Deflection Study: Flow Results

The second trade study presented here explores the effect of flap deflection on radiated noise. Similar to the angle of attack study, Figs 3.38 through 3.41 show the instantaneous Mach number ratio in the vicinity of the airfoil at $0^\circ$ angle of attack and several different flap deflection angles. As the flap deflection angle increases, the airfoil generates more lift and drag. These forces correspond to an increase in circulation, and therefore, a decrease in local flow in the vicinity of the landing gear. Figures 3.42 and 3.43 show the calculated average Mach number ratio along the sampling lines shown in Fig. 3.28. As the flap deflection angle is increased, the local flow velocity underneath the airfoil in the region of the landing gear decreases. Comparing the flow velocity near the front of the landing gear, Fig. 3.42, and towards the rear of the landing gear, Fig. 3.43, show that the flow slows down in the vicinity of the airfoil similar to the angle of attack study.

![Graph](image)

Figure 3.37: Predictions of noise using local flow caused by airfoil at several different angles of attack. Observer located 120 meters directly below landing gear geometry. Predictions show that increasing the flap deflection angle results in a decrease of noise.
Figure 3.38: Instantaneous flow velocity for flap setting 1 case at 0° angle of attack.

Figure 3.39: Instantaneous flow velocity for flap setting 2 case at 0° angle of attack.
Figure 3.40: Instantaneous flow velocity for flap setting 3 case at 0° angle of attack.

Figure 3.41: Instantaneous flow velocity for flap setting 4 case at 0° angle of attack.
Figure 3.42: Representation of inflow into landing gear region with different flap deflection angles. Mach number ratio presented is shown on sampling line 1, shown in Fig. 3.28.

Figure 3.43: Representation of outflow into landing gear region with different flap deflection angles. Mach number ratio presented is shown on sampling line 2, shown in Fig. 3.28.
3.2.5 Flap Deflection Study: Acoustic Results

The mean local flow velocities, presented in Section 3.2.4, show that the Mach number ratio decreases in the region of the landing gear as the flap deflection angle increases. This decrease is a maximum of approximately 0.12 when increasing the flap deflection angle by 22.5°. Using a 6th power law for noise, this corresponds to a noise reduction of approximately 4.2dB. Similar to the angle of attack study, the effect on the prediction for an observer position of 120 meters directly below the landing gear is shown in Fig. 3.44. As the flap deflection angle is increased, the flow velocity below the airfoil decreases which, in turn, decreases the predicted noise levels. The predictions also show that using the CFD results for local flow result is a maximum noise reduction of approximately 3dB. Again, this approximately matches the simple estimate.

This section has presented the capability of the prediction system to incorporate a local flow...
solution into the prediction of landing gear noise. It was demonstrated that increasing the angle of attack or flap deflection angle decreases the flow in the vicinity of the landing gear. The decrease in local flow corresponds to a decrease in predicted radiated noise. It is important to emphasize that the flow calculations used in the present study are only approximations to the flow in the vicinity of the landing gear. These approximations are presented to demonstrate the ability of the prediction system to predict the effect of airfoil configuration on radiated noise. Although FLUENT has been used to calculate the mean flow, the prediction system is able to use any CFD solution or approximation for the mean local flow. Any one-dimensional approximation, such as those presented in Figs. 3.42 or 3.43, or CFD solution may be used. Any higher-order, two- or three-dimensional CFD code, with or without turbulence modeling, could also be used to provide the mean flow for the prediction system. The noise from the prediction system improves with more accurate local flow input. However, faster approximations, like those presented, provide an understanding of the trends in landing gear noise caused by the wing lift. These approximations can guide a designer in creating a quieter landing gear geometry or airfoil landing condition.

3.3 Landing Gear/Wing or Flap Interaction Noise

All noise caused by installing the landing gear on an aircraft must be included in an installed landing gear noise prediction. This includes the noise caused by the landing gear wake interacting with the wing/flap system. The turbulent wake generated by an installed landing gear convects downstream and interacts with the high-lift system of the aircraft. When the wake interacts with a sharp trailing edge, noise is generated. In the case of an installed landing gear, this includes the trailing edges of the wing/flap system. This noise is characteristic of a trailing edge noise source, but it is caused by the landing gear wake. Therefore, this noise source would not be present if the landing gear was removed. This section presents a method for estimating the characteristics of the landing gear wake, as well as predictions of noise when this wake impinges on the trailing edge of the wing/flap system.

Section 2.3.1 presented a method for predicting the trailing edge noise based on a characteristic wake size and location in relation to the trailing edge. The prediction method uses approximations of turbulence intensity and mixing length scale to predict the noise. This method is used to predict
landing gear noise caused by a landing gear wake, which impinges on the wing/flap system. A relatively fast computation is performed on a simplified, isolated landing gear to estimate the wake geometry. The wake geometry is then used to estimate the turbulence intensity and characteristic turbulence mixing length scale. The estimate of turbulence intensity and length scale are then used in the Ffowcs Williams and Hall trailing edge noise equation to arrive at the radiated noise.

This section proceeds as follows: first, the computational fluid dynamics code used to calculate an estimate of the wake geometry is described. Then, flow results performed on a representation of a simplified Boeing 777 main gear are shown. The flow calculations are performed at several forward flight Mach numbers, and approximate the wake geometry dependence on freestream flow velocity. Following that, the CFD solution is used to estimate the turbulence intensity and characteristic length scale. And finally, acoustic calculations using the prediction method are shown.

3.3.1 Computational Setup

In Section 2.3.1, a method was presented for predicting the trailing edge noise from an approximation of the landing gear wake geometry. The prediction uses empirically fit data to correlate the characteristic turbulence mixing length and turbulence intensity. The turbulence intensity and mixing length scale are then used in the Ffowcs Williams and Hall trailing edge noise equation to arrive at the radiated noise. The only unknown in the noise prediction is the turbulence mixing length. The prediction system estimates the turbulence mixing length by performing flow calculations around a simplified landing gear geometry. It is important to emphasize that the purpose of the flow calculation is to arrive at an estimate of the size of the wake geometry only. A flow computation with turbulence modeling around a detailed landing gear geometry would accurately predict the wake geometry at the wavelengths of interest. However, the study presented here is not concerned with the small scale features of the wake, but rather on only the largest wake scales. A fully resolved turbulent calculation that captures all wavelengths of interest for a noise computation would take a very large time to compute, even on very large computational clusters. Even if such a computation were performed, it has been shown that the results may be significantly dependent on turbulence model [7]. Because only the largest wake scales are needed, the computation can be significantly simplified.
The flow around the simplified geometry is calculated using the Immerged Boundary Solver for Environmental Noise (IBSEN) which solves the Euler equations on a set of Cartesian grids with the surface represented by the immersed boundary approach. A second-order-accurate solution to the compressible Euler equations on overset uniform Cartesian grids was used for these computations. Because IBSEN is an immersed boundary method, there is no need for a surface-fitted mesh, making mesh generation much faster than traditional flow calculations. It is important to emphasize that IBSEN has been used because it was readily available, quick and easy to set up, and fast to run. Similar to the calculations for local flow caused by the presence of the wing presented in Section 3.2, any CFD or estimate would be used for the turbulence length scale. The noise prediction system has been structured to use any estimates for length scales or local flow conditions. A more highly resolved calculation that can better predict the flow field can potentially result in a better noise prediction. The results shown here demonstrate the ability of the noise prediction system to couple with a CFD computation.

In the current study, five forward flight Mach numbers are considered: 0.15, 0.175, 0.2, 0.225, 0.25. A representation of a Boeing 777 main gear with a truck angle of 13° without the wing present is used in the IBSEN flow computations. Figures 3.45 and 3.46 show the outer domain of all the CFD computations. The outer domain stretches approximately 10 oleo lengths in each direction. The domain size was intentionally kept to a minimum in order to keep computation time low. Figures 3.47 and 3.48 show the inner domain, where the immersed boundary technique is used. The inner domain grid spacing is one-sixth of an oleo diameter. This spacing was maximized in order to keep the number of grid points and computation time to a minimum. A trade study on grid spacing was performed and the flow solution was found to not change significantly until the grid spacing was reduced below one-sixth of an oleo diameter. This configuration results in a total of 5.4 million grid points. A more resolved flow computation would result in a more resolved wake domain, however, it was found to significantly increase computation time. A minimum grid point configuration was used here only for demonstration. Each computation took approximately 31 hours using 40 processors on the COCOA4 cluster at The Pennsylvania State University. The flow solution was allowed to reach 10,000 time steps before averaging started. The averages are over an additional 10,000 time steps.
Figure 3.45: The outer domain of the IBSEN flow calculations. The domain consists of a cube approximately 10 oleo lengths in each Cartesian direction. Computational grid on plane perpendicular to wing span direction shown. Flow is from left to right.

3.3.2 Flow Result

The IBSEN CFD program provides an approximation for the mean local flow around the landing gear in isolation. The current study involves five forward flight Mach numbers: 0.15, 0.175, 0.2, 0.225, 0.25. Figures 3.49 through 3.53 show the isosurface at a mean Mach number of $M = 0.75M_0$ for each of the five forward flight Mach numbers. The approximate location of the wing geometry with a flap down setting is also shown, but not included in any flow calculations. For all Mach numbers, the wake of the landing gear passes through the region of the aircraft flap system. It is interesting to note that all five cases have approximately the same wake geometry when viewing the same Mach number ratio isosurface. Also shown in Figs. 3.49 through 3.53 is the location of a plane where the flow is sampled for analysis. The wake geometry at this planar location provides the estimate of the wake geometry input into the trailing edge noise model. Figures 3.54 through 3.58 show the local Mach number ratio at the sampling plane for all Mach numbers. The figures also

\[ \text{Mach number ratio is local Mach number over freestream Mach number, } \frac{M}{M_0} \]
Figure 3.46: The outer domain of the IBSEN flow calculations. The domain consists of a cube approximately 10 oleo lengths in each Cartesian direction. Computational grid on plane perpendicular to oleo shown. Flow is from left to right.

Figure 3.47: The inner domain of the IBSEN flow calculations. Grid cell spacing of finest mesh approximately one-sixth oleo diameter. Flow is from left to right.
Figure 3.48: The inner domain of the IBSEN flow calculations. Grid cell spacing of finest mesh approximately one-sixth oleo diameter. Flow is from left to right.

Figure 3.49: Isosurface of mean local Mach number at $M = 0.75M_\infty$ where $M_\infty = 0.15$. Flow is from left to right. Location of sampling plane for Fig. 3.54 and airfoil cross section also shown. Airfoil not included in flow calculation.

show the projection of the landing gear and trailing edges of the wing/flap system. The projection of the vane and flap provide a line on the CFD solution. The location alone this line of the mean Mach number ratio of 0.8 provide the estimate of the wake width for the trailing edges. Figures 3.54 through 3.58 show the location of all measurements used to estimate wake width in the acoustic analysis.

The Mach number ratio presented in Figs. 3.54 through 3.58 contain 4 high speed flow regions towards the outside of the wake region. This high speed flow is believed to be caused by the grid oversetting in IBSEN. This error was not resolved, but even with the error, IBSEN provides
Figure 3.50: Isosurface of mean local Mach number at $M = 0.75M_\infty$ where $M_\infty = 0.175$. Flow is from left to right. Location of sampling plane for Fig. 3.55 and airfoil cross section also shown. Airfoil not included in flow calculation.

Figure 3.51: Isosurface of mean local Mach number at $M = 0.75M_\infty$ where $M_\infty = 0.2$. Flow is from left to right. Location of sampling plane for Fig. 3.56 and airfoil cross section also shown. Airfoil not included in flow calculation.

A reasonable gross estimate of the wake geometry. It is unclear what the effect of the error in IBSEN is on the wake geometry, but it is believed to be small for this type of computation. As with any other coupling of the noise prediction system and CFD computational code, the IBSEN calculation presented here can be replaced by any flow computation. Any CFD computation which provides the estimate of the wake geometry can be used in this analysis, and IBSEN is used only for demonstration.
Figure 3.52: Isosurface of mean local Mach number at $M = 0.75M_\infty$ where $M_\infty = 0.225$. Flow is from left to right. Location of sampling plane for Fig. 3.57 and airfoil cross section also shown. Airfoil not included in flow calculation.

Figure 3.53: Isosurface of mean local Mach number at $M = 0.75M_\infty$ where $M_\infty = 0.25$. Flow is from left to right. Location of sampling plane for Fig. 3.58 and airfoil cross section also shown. Airfoil not included in flow calculation.

### 3.3.3 Demonstration of Landing Gear/Wing Interaction Noise

Figures 3.54 through 3.58 show the measurement locations for the width of the wake interacting with the vane and flap. The wake width values used for each forward flight Mach number case are shown in Table 3.1. As the forward flight Mach number increases, the wake width parameter for the vane increases, while the wake width parameter for the flap decreases. The approximate distance from the sampling plane to the vane trailing edge is 2.66 meters, and from sampling plane to the flap trailing edge is 4.22 meters. These values are used for the wake distance to trailing edge.
Figure 3.54: Local Mach number ratio, $M/M_\infty$, on sampling plane shown in Fig. 3.49 for $M_\infty = 0.15$. Flow is into the page. Projections of landing gear geometry, vane and flap trailing edges, and wake width measurement locations also shown. Coloring for a local Mach number of $M = 0.15 \times 0.75 = 0.1125$.

Fig. 3.59 shows the empirically fit data relating wake distance over wake half width to turbulence intensity. These are found from experimental data of wakes impinging on turbine blades [88]. Using the values of wake distance over wake half width shown in Table 3.1 to sample the curve shown in Fig. 3.59 results in an estimate of turbulence intensity. The turbulence intensity and wake width are used in the trailing edge acoustic element to predict the noise caused by the landing gear wake interacting with the vane and flap trailing edges.

Before analysis, the values for turbulence intensity and turbulence mixing length for the case of forward flight Mach number 0.2 is used for all cases to check scaling of the trailing edge noise prediction. Figure 3.60 shows the noise prediction on an observer arc of 100 meters below the
Figure 3.55: Local Mach number ratio, $M/M_\infty$, on sampling plane shown in Fig. 3.50 for $M_\infty = 0.175$. Flow is into the page. Projections of landing gear geometry, vane and flap trailing edges, and wake width measurement locations also shown. Coloring for a local Mach number of $M = 0.175 \times 0.75 = 0.13125$.

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<td>2.13</td>
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<td>0.23</td>
<td>0.23</td>
<td>0.25</td>
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<td>1.63</td>
<td>1.47</td>
<td>1.43</td>
<td>1.33</td>
</tr>
<tr>
<td>Flap Wake Distance/Wake Half Width</td>
<td>2.21</td>
<td>2.60</td>
<td>2.88</td>
<td>2.96</td>
<td>3.18</td>
</tr>
<tr>
<td>Flap Turbulence Intensity Ratio</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 3.1: Wake parameters used for the trailing edge acoustic elements. The wake width found from Figs. 3.54 through 3.58. The distance from sampling plane to vane trailing edge is 2.66 meters, and from sampling plane to flap edge is 4.22 meters. Turbulence intensity determined from curve shown in Fig. 3.59.
Figure 3.56: Local Mach number ratio, \( M/M_\infty \), on sampling plane shown in Fig.3.51 for \( M_\infty = 0.2 \). Flow is into the page. Projections of landing gear geometry, vane and flap trailing edges, and wake width measurement locations also shown. Coloring for a local Mach number of \( M = 0.2 \times 0.75 = 0.15 \).

Figure 3.56 shows the vane trailing edge noise prediction for all forward flight Mach number cases using their respective turbulence intensity and mixing length parameters. Figure 3.63 shows the noise predictions scaled according to \( V^5 \). The prediction of the trailing edge noise from the
Figure 3.57: Local Mach number ratio, $M/M_{\infty}$, on sampling plane shown in Fig. 3.52 for $M_{\infty} = 0.225$. Flow is into the page. Projections of landing gear geometry, vane and flap trailing edges, and wake width measurement locations also shown. Coloring for a local Mach number of $M = 0.225 \times 0.75 = 0.16875$.

vane using the estimate of turbulence intensity and mixing length deviate from the $V^5$ power law, and at a low Mach number there is a significant deviation. This deviation is due to the different parameters input into the noise model which are based off of IBSEN CFD calculations. The estimate of turbulence intensity for the vane decreases as the Mach number decreases, and increases as the Mach number increases. This does not follow the $V^5$ scaling law, which is derived for an attached turbulent boundary layer. Similarly, Fig. 3.64 shows the noise prediction from the flap trailing edge at all forward flight Mach numbers using their respective turbulence parameters. Figure 3.65 shows the flap trailing edge noise prediction scaled according to $V^5$. The noise predictions for the flap do not collapse onto a single line, which would be the case if the noise followed the turbulent
Figure 3.58: Local Mach number ratio, $M/M_\infty$, on sampling plane shown in Fig. 3.53 for $M_\infty = 0.25$. Flow is into the page. Projections of landing gear geometry, vane and flap trailing edges, and wake width measurement locations also shown. Coloring for a local Mach number of $M = 0.25 \times 0.75 = 0.1875$.

boundary layer/trailing edge noise scaling laws. This is due to the difference in turbulence intensity and mixing length scale. Figures 3.66 and 3.67 show the noise prediction from both the vane and the flap together. Figure 3.67 shows that the predictions at high Mach numbers deviate from the $V^5$ variation, and at low Mach numbers deviate significantly.

It has been reported that trailing edge noise measurements from the flap region of an aircraft during flyover with the landing gear down scale like $V^8\ [5]$. Obviously, the trailing edge noise prediction presented here does not collapse with $V^5$ scaling, which would be characteristic of turbulent boundary layer generated trailing edge noise. Figures 3.68, 3.69, and 3.70 show the predicted noise scaled as $V^6$, $V^7$, and $V^8$ respectively. The figures show that the prediction technique arguably
Figure 3.59: Turbulence intensity ratio as a function of wake size and location. The curve shown is a best fit of measured values, also shown. Measurements from measurements of wakes impinging on turbine blades [88].

Figure 3.60: Vane and flap trailing edge noise prediction for 5 forward flight Mach number cases. Flow is from left to right. Turbulence intensity and mixing length from forward flight Mach number of 0.2 used for all cases.
Figure 3.61: Vane and flap trailing edge noise prediction for 5 forward flight Mach number cases scaled by $V^5$ to forward flight Mach number of 0.2. Flow is from left to right. Turbulence intensity and mixing length from forward flight Mach number of 0.2 used for all cases.

Figure 3.62: Vane trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases. Flow is from left to right.
Figure 3.63: Vane trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases scaled by $V^5$ to forward flight Mach number of 0.2. Flow is from left to right.

Figure 3.64: Flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases. Flow is from left to right.
Figure 3.65: Flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases scaled by $V^5$ to forward flight Mach number of 0.2. Flow is from left to right.

Figure 3.66: Vane and flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases. Flow is from left to right.
Figure 3.67: Vane and flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases scaled by $V^5$ to forward flight Mach number of 0.2. Flow is from left to right.

shows best scaling with $V^6$ or $V^7$. This is closer to the reported scaling from flyover measurements. The inability of the solutions to collapse onto one scale may be due to the CFD solution, sampling method, or estimates of the turbulence intensities. The scaled noise prediction is very dependent on CFD computations and sampling method. It is currently unclear whether the difference in scaling between measurements and the coarse CFD approximations is due to measurement error or the approximation method presented here. More research on this topic is required to fully understand the scaling of this noise source. The method presented here is to give insight into what may be occurring. Higher order CFD computations around a complex landing gear geometry may provide better estimates of turbulence intensity and mixing length. Using a better estimate for the turbulence parameters may provide better scaling.

The trailing edge noise source from the interaction of the landing gear wake and the trailing edge of the wing/flap system remains a difficult source to predict. The presented system requires a method of approximating the landing gear wake region near the trailing edges of the wing. This section has presented the ability of the prediction system to approximate the noise from the landing gear wake interacting with the wing/flap trailing edges on an aircraft. The method presented here is a first
Figure 3.68: Vane and flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases scaled by $V^6$ to forward flight Mach number of 0.2. Flow is from left to right.

Figure 3.69: Vane and flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases scaled by $V^7$ to forward flight Mach number of 0.2. Flow is from left to right.
Figure 3.70: Vane and flap trailing edge noise prediction on observer arc of radius 100 meters for 5 forward flight Mach number cases scaled by $V^8$ to forward flight Mach number of 0.2. Flow is from left to right.

cut prediction at using coarse CFD calculations to approximate the wake region, and empirically fit data to estimate the turbulence intensity. It is important to note that although IBSEN was used here, any CFD package can be used as long as it provides estimates of the wake geometry and turbulence intensity. IBSEN was chosen because it was readily available, easy to use, quick to run, and provided a first cut approximation of the wake region. Using rough estimates of wake size and turbulence intensity, the predictions show a $V^6$ or $V^7$ dependence. This does not follow traditional boundary layer generated trailing edge noise which scales as $V^5$. However, this is similar to recent fullscale flyover measurements which report the noise from the flap system with landing gear down having a $V^8$ dependence. The slight difference in velocity dependence between the flyover measurements and the presented prediction system may be due to measurement inaccuracies or prediction approximations. However, using CFD to estimate the landing gear wake region in the vicinity of the aircraft wing/flap system has been shown to provide a better estimate of trailing edge noise than the traditional $V^5$ scaling laws.
3.4 Landing Gear Influenced Local Flow

A landing gear geometry is not streamlined, and has many small scale features that generate broadband noise. Also, the flow around landing gear components is very turbulent, and the wakes from upstream components convect downstream onto other landing gear components. The present prediction system incorporates the complex geometry and turbulent environment by broadening the loading spectrum on components, and therefore, the sound emitted. This broadening of the sound includes all aerodynamic effects, such as small scale geometric features, turbulence, and landing gear component interactions through wake impingement. However, if the landing gear is operating in a different configuration, such as an off design truck angle, the present model would not be able to predict an altered sound signature caused by a wake impinging on a downstream component unless this is included in the downstream loading spectrum. It is unclear if changing gross features, such as truck angle, significantly alter the radiated noise. However, this is exactly what a low noise landing gear designer may be interested in. Obviously, to be of value for a designer, a prediction system must include an estimate of the noise change caused by a gross geometry change, such as truck angle.

The final prediction demonstration presented in this chapter is an estimate of the changes in noise caused by changing gross landing gear features. The present study includes estimates of the local flow caused by changing the truck angle of the landing gear geometry. Similar to Section 3.3, a computation is performed on a simplified landing gear geometry. Several computations are presented with different landing gear truck angles. By comparing the estimate of local flow between a baseline and an off design configuration, the change in local flow can be estimated. The change in local flow is input into the prediction system, which corresponds to an altered predicted noise signature. It is shown that configuring the landing gear into a toe-down position decreases the local flow in the vicinity of the rear wheel, and therefore decreases the predicted radiated noise.

This section proceeds as follows: first, an explanation of the geometry setup is presented. The geometry variations consist of five truck angles settings: $23^\circ$, $13^\circ$, $3^\circ$, $-7^\circ$, $-17^\circ$. Following the geometry setup, flow calculations, similar to Section 3.3 is presented. It is shown that toeing the truck angle down results in a decrease of the local flow in the vicinity of the rear wheel. And finally, the estimate of local flow is used in a noise prediction. It is shown that toeing the landing gear truck
down results in a decrease in noise.

3.4.1 Geometry and Computational Setup

In the previous section, IBSEN was used to compute the flow field around a simplified Boeing 777 main gear with a truck angle of 13° at several different Mach numbers. The same truck configuration is the baseline of the current study on truck angle variations. Figure 3.71 shows the five truck angles used in the present study: 23°, 13°, 3°, −7°, −17°. A positive truck angle is toed up, negative is toed down. All computations are at a forward flight Mach number of 0.2 with no wing geometry present. The same IBSEN grids presented in Section 3.3 are used in all computations. Each computation is performed in parallel with 40 processors, on the COCOA4 cluster at The Pennsylvania State University and take approximately 31 hours to complete. The computations are allowed to run to 10,000 times steps before averaging starts. The averaged solution uses an additional 10,000 times steps.

Similar to the previous section, it is important to note that these computations are only to estimate the mean local flow condition in the vicinity of the landing gear. Any CFD package can be used to estimate the average flow conditions. IBSEN was chosen because it was readily available, quick and easy to set up, and fast to run. A more highly resolved CFD calculation may perform better at calculating the averaged flow solution. Using a better solution may improve the estimate of flow changes when changing the truck angle. The present study is performed to demonstrate the prediction system’s ability to couple with an external calculation. It is the goal of this coupling to better aid a designer who may have their own computation readily available.

3.4.2 Flow Calculations

Figure 3.72 through 3.76 show isosurfaces of velocity in the region of the landing gear computed by IBSEN. The isosurfaces shown are at a Mach number equal to 0.75$M_\infty$ and represent the wake region generated by the landing gear. Figure 3.73 is the baseline configuration of a landing gear with a truck angle of 13°. Figure 3.72 shows the local flow velocity when the truck angle is toed up by 10° from the baseline configuration. The local wake region caused by the strut assembly remains the same. However, increasing the truck angle exposes the rear wheel to more of the freestream
Figure 3.71: The five truck angles used to study landing gear influenced local flow. The truck angles used are a) 23°, b) 13° as the baseline, c) 3°, d) −7°, and e) −17° truck angle. Flow is from left to right.
Figure 3.72: Isosurface of velocity in the region of a landing gear with a truck angle of 23°. Isosurface shown is for $V = 0.75V_\infty$. Blue color is to emphasize wake surface from landing gear surface.

velocity, increasing the mean inflow into the wheel. Comparatively, Fig. 3.74 shows the local wake region when the truck angle is toed down by 10° from the baseline case, to 3° toe-up. The wake region from the strut assembly remains the same as the baseline configuration. However, the rear wheel is now slightly engulfed in a region of lower mean flow velocity. This represents a reduction to the mean inflow into the rear wheel. Similarly, Fig. 3.75 shows the local wake region when the truck angle is reduced by another 10°, to a truck angle of −7°. Again, the wake caused by the strut assembly does not significantly differ from the baseline case. However, the rear wheel is now almost entirely engulfed in a reduced flow region. Similar to the 3° case, this represents a decrease in the mean inflow into the rear wheel geometry. Finally, Fig. 3.76 shows the wake geometry when the truck angle is decreased by another 10° to −17°. Unlike the −7° case, the rear wheel is no longer almost completely engulfed, but does experience a slightly reduced mean inflow compared to the baseline configuration.
Figure 3.73: Isosurface of velocity in the region of a landing gear with a truck angle of $13^\circ$. Isosurface shown is for $V = 0.75V_\infty$. Blue color is to emphasize wake surface from landing gear surface.

Figure 3.74: Isosurface of velocity in the region of a landing gear with a truck angle of $3^\circ$. Isosurface shown is for $V = 0.75V_\infty$. Blue color is to emphasize wake surface from landing gear surface.
Figure 3.75: Isosurface of velocity in the region of a landing gear with a truck angle of $-7^\circ$. Isosurface shown is for $V = 0.75V_\infty$. Blue color is to emphasize wake surface from landing gear surface.

Figure 3.76: Isosurface of velocity in the region of a landing gear with a truck angle of $-17^\circ$. Isosurface shown is for $V = 0.75V_\infty$. Blue color is to emphasize wake surface from landing gear surface.
Table 3.2: Modified mean local flow into rear wheel acoustic elements. Values found by estimating the grid cells containing immersed rear wheel surface exposed to flow greater than $V = 0.75V_{\infty}$.

<table>
<thead>
<tr>
<th>Truck Angle</th>
<th>$23^\circ$</th>
<th>$13^\circ$</th>
<th>$3^\circ$</th>
<th>$-7^\circ$</th>
<th>$-17^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{mod}$</td>
<td>$1.05V_{in}$</td>
<td>$1.0V_{in}$</td>
<td>$0.8V_{in}$</td>
<td>$0.5V_{in}$</td>
<td>$0.9V_{in}$</td>
</tr>
</tbody>
</table>

### 3.4.3 Demonstration of Truck Angle Influence on Predicted Noise

The present prediction system uses a simple method of adding the mean flow calculations to ensure that any estimate of local flow solution can be used by a landing gear designer. Each acoustic element affected by the landing gear wake uses an altered local inflow. In the current study, immersed boundary CFD calculations around a simplified landing gear geometry demonstrated that the rear wheel may experience a reduction in mean local inflow at certain toe-down truck angles. However, the CFD used here is only used to demonstrate the technique of adding local flow calculations into the prediction system. Any estimate of mean flow available to a landing gear designer can be used.

The mean flow difference caused by changing the truck angle can affect the radiated noise. A lower mean inflow into a landing gear component leads to a reduction in noise, while an increase results in an increase in noise. The maximum mean local inflow reduction was found to be at a toe-down angle of $-7^\circ$. To demonstrate this effect on noise, only the mean local inflow into the rear wheels is altered. Table 3.2 shows the modified local flow into the rear wheels for each of the truck angle configurations. The modified flow input into the rear wheels is found by estimating the grid cells containing the immersed rear wheel surface exposed to flow greater than $M = 0.75M_{\infty}$. The toe-up configuration experiences a slightly increased mean local flow velocity, while the toe-down configurations experience a decreased mean local flow.

Figure 3.77 shows the OASPL from the prediction system with no modification to the rear wheel inflow on an arc of observers with radius 100 meters below the landing gear. The predictions include the shielding effect. However, at 100 meters, the shielding effect is minimal. The local flow modification into the rear wheels is the same for each case, regardless of truck angle. The prediction of OASPL show that toeing the truck up results in more noise, while toeing down results in lower noise. Any change in sound pressure level is due to a change in source position and directivity. Figure 3.78 show the noise predictions using the modified inflow into the rear wheels.
Figure 3.77: OASPL on observer arc 100 meters from center of landing gear with different truck angles without using approximation for rear wheel local flow. Prediction of noise for landing gear with any toe configuration roughly the same.

The predictions differ slightly from those without modification. Figure 3.79 shows the change in OASPL caused by using the modified inflow. The inflow from the toe-up configuration causes a slightly increased predicted noise. The inflow from the toe-down configurations causes a slightly decreased predicted noise. Although the predicted noise change is minimal, this does give a designer insight into any noise reduction techniques that could be implemented.

In this section, the prediction system was coupled with the IBSEN CFD flow solver to estimate the effect of landing gear wake on down stream components. It was shown that toeing the landing gear down results in a slight reduction of predicted noise. The prediction system uses estimates of local flow conditions to modify the radiated noise of the rear wheels. The reduction caused by toeing the truck angle down is only an example of coupling the prediction system to a CFD solution. It should be emphasized that the CFD code used here is only for demonstration. The flow solution was intentionally kept coarse for quick computation time. Any CFD solution could be used to provide estimates of local flow conditions for the prediction system.

An issue left unresolved is that the wakes from upstream components impinging on downstream
Figure 3.78: OASPL on observer arc 100 meters from center of landing gear with different truck angles using approximation for rear wheel local flow.

Figure 3.79: Change in predicted OASPL caused by modified local inflow into rear wheels. Predictions for toe-up configuration increase slightly, while predictions for toe-down decrease slightly.
components is very time dependent. An averaged solution may miss any strong periodic wakes that may significantly alter the sound generated by a downstream component. The interaction, and the affect on the radiated noise, is extremely hard to predict or compute. This interaction can currently only be included by empirically fitting the radiated noise which would include any of these effects. A higher order, time dependent solution may be better at estimating any interactions between components. In principle, a very resolved computation or measurement would provide a prediction with better inputs. However, measuring or computing the interaction with such an order of resolution is very challenging. A time dependent wake impinging on a rear wheel would broaden the loading spectrum and noise emitted. This increase in noise is in contradiction to the method presented here which includes a reduction in noise when the wheel is in a region of low mean flow. It is currently unclear which effect, the noise decrease caused by the reduced mean flow or the noise broadening caused by the time dependent wake impingement, would affect the noise more. This type of interaction has not been included in the current system, and is left for future work on the topic.

3.5 Summary of Prediction Techniques

This chapter has presented techniques of approximating the aeroacoustic and aerodynamic interactions in the landing gear noise prediction system. These techniques include an approximation of the shielding caused by the landing gear components; the effect of local flow caused by the wing on the landing gear noise; the landing gear wake interactions with the trailing edge of the aircraft wing; and an estimate of component interaction within the landing gear geometry. All of the techniques demonstrate first order approximations in the landing gear noise prediction system. Since they are approximations, they are much faster than measurements or fully resolved computations. The coupling with outside CFD computations has intentionally been kept to a few simple parameters from a coarse flow field. This ensures that any outside computation can be used as long as it provides an estimate of the flow conditions. All computations presented here are only to demonstrate the coupling in the noise prediction with CFD solutions.

The shielding approximation included in the prediction system uses the scattering from a cylinder in two dimensions to approximate the shielding caused by the landing gear components. The
approximation of scattering behind the cylinder provides a shielding coefficient as a function of frequency. In this manner, long wavelengths can pass around small objects relatively unaffected, while short wavelengths are shielded by large objects. It was shown that using this approximation to shielding, the prediction system predicted a $3 - 6\text{dB}$ noise reduction at certain observer locations when compared to not using the approximation. The noise reduction was caused by the wheel acoustic elements shielding the noise from observer positions below the landing gear. This approximation is only a first order estimate of the shielding caused by the landing gear. In the future, other, higher-order methods may be used. These could include using a 2D approximation for scattering from all of the landing gear components, or coupling the prediction system with the an external scattering code.

An installed landing gear is housed in an environment that is significantly different than would be experienced in a wind tunnel test. This chapter presented the coupling of the prediction system with coarse two-dimensional FLUENT calculations around an airfoil. The airfoil was representative of a Boeing 777 wing cross section at the span location near an installed landing gear. The FLUENT computations were intentionally left coarse for quick turn around times. Computations were performed for several different airfoil angle of attacks and flap deflections angles. It was shown that increasing the angle of attack or increasing the flap deflection angle reduced the local inflow in the region of the landing gear. Noise predictions using the two-dimensional flow solution were presented. It was shown that using the flow solution as an estimate for the local inflow into the landing gear geometry resulted in a $4 - 6\text{dB}$ reduction in the predicted noise relative to an uninstalled gear.

The third technique presented here includes an estimate for the wake interactions with the trailing edges of the wing/flap system. The IBSEN immersed boundary code was used to provide fast estimates of the wake region for several different forward flight Mach number cases. The immersed boundary code was used because it was fast, easy to set up, and quick to run. Any CFD solution or approximation of the wake region could be used in the prediction system. The coupling of the flow solution to the prediction system is through estimates of the wake region sampled on a plane in front of the high-lift system. The wake size in front of the trailing edge of the vane and flap provide estimates of the turbulence mixing length. Empirical data from wind tunnel measurements of turbine blades provide a relationship between the turbulent mixing length and turbulent intensity.
The Ffowcs Williams and Hall trailing edge noise equation was used to predict the radiated noise. It was shown that using estimates for the turbulence intensity and turbulence mixing length from the coarse CFD solution resulted in a $V^6$ or $V^7$ scaling of radiated noise. This agrees with recent measurements of aircraft flyovers where it is reported that the flap interaction noise scales like $V^8$.

The final prediction presented here includes using coarse CFD calculations to provide insight into the landing gear influenced local flow. An immersed boundary CFD solution around landing gear geometries with several truck angle settings showed that the rear wheel may experience reduced local flow when toeing the landing gear down. Predictions without using the flow solution showed that toeing the landing gear down results in a slightly decreased noise signature. Using the local flow solution to approximate the inflow into the rear wheel resulted in additional noise difference when toeing the landing gear down. When using the local flow solution, the prediction system demonstrated that toeing the landing gear down may result in $2 - 3\,\text{dB}$ noise reduction.

This chapter has presented techniques of approximating the aeroacoustic and aerodynamic interactions of an installed landing gear. Simple approximations for these complex interactions allows the prediction system to estimate their effect. The noise provided by the system demonstrates that approximating these effects may lead to better noise predictions. However, it is important to note that all of the techniques presented here represent only an approximation to the interactions. The prediction system has specifically been designed to allow for improvements to any component of the prediction technique. These improvements could include better input flow solutions or better internal prediction techniques.

In the next chapter, all of the prediction techniques presented here are combined into a single noise prediction for a complete representative aircraft. These noise predictions include the noise from the landing gear accounting for shielding and local flow estimates from the wing and landing gear. The predictions also include the noise from the trailing edges of the aircraft caused by the turbulent boundary layer and the landing gear wake interacting with the trailing edge of the wing.
Chapter 4

Complete Aircraft Landing Gear Noise Prediction

Chapter 3 presented techniques implemented in the prediction system to approximate aerodynamic and aeroacoustic interactions in a landing gear noise prediction. These interactions included an approximation for the shielding caused by the landing gear geometry; the local flow in the region of the landing gear caused by the wing; the noise generated by the landing gear wake interacting with the wing/flap system; and the landing gear influenced local flow affect on the predicted sound. It was shown that a simple shielding approximation can attenuate the predicted noise several dB at close observer positions. Flow calculations around an aircraft wing cross section demonstrated that the noise from the main gear can be significantly reduced due to a reduction in flow velocity in the landing gear region. Coarse CFD calculations approximating the wake size showed that the trailing edge noise scales as $V^6 - V^7$, and can potentially add to the overall sound pressure level. And finally, coarse CFD calculations around a landing gear geometry showed that toeing the landing gear down can result in a reduced noise signature. This chapter will combine some of the prediction techniques presented previously into one acoustic prediction for the all landing gears installed on an aircraft.

This chapter is organized as follows. The first section compares the prediction system to flyover measurements of airframe noise from the Quiet Technology Demonstrator 2 (QTD2) flight test program [32]. It is shown that the predicted spectral shape, particularly in the mid-frequency range,
matches well to measured values at three isolated measurement locations. Similar to the flyover measurements, predictions show that the nose gear noise can be a significant factor in the total airframe noise. Predictions of landing gear wake generated wing/flap trailing edge noise are shown to affect the spectral shape. The second section of this chapter presents directivity plots of OASPL for the main landing gear, nose gear, landing gear wake wing/flap generated trailing edge noise, and boundary layer trailing edge noise. It will be shown that landing gear wake wing/flap generated trailing edge noise and noise from the nose gear are additive factors in the OASPL at most observer positions.

4.1 Isolated Observer Positions

The aircraft noise measured in the QTD2 flight test program was from a Boeing 777-300ER at a forward flight velocity of 170 knots [32]. For all airframe measurements, both engines were set at idle-power to isolate the airframe noise signature. The QTD2 flight test measured the sound of the airframe with three main landing gear designs. These included a baseline landing gear configuration; a landing gear with wheels aligned to the freestream flow direction; and a landing gear with a toboggan fairing. The measurements also included two wing flap configurations: 0° and 30° flap angle. In the present analysis, the predictions are compared to measurements from the aircraft with baseline main landing gear and flaps detent 30°. The predictions use the features presented in Chapter 3. The effects included for the main landing gear are shielding, local flow velocity for an aircraft at zero angle of attack and flap setting 2, and landing gear generated wing/flap trailing edge noise for a forward flight Mach number of 0.25. The local flow velocity caused by the wing in the landing gear vicinity is determined by scaling the Mach number ratio of computations presented in Section 3.2. Since the measurements are for a baseline landing gear, where the truck angle is 13°, a modified inflow into the rear wheel is not included. It should be mentioned that all the features presented in previous chapters have been applied to the main landing gear. However, they can also be applied to the nose gear. For the predictions presented here, this includes shielding and a slightly increased inflow [55]. An infinite, perfectly reflecting wall is used as a first order approximation to the reflections caused by the aircraft. Both main landing gear noise predictions include a reflecting wall to represent the wing, but the nose gear does not include a wall to approximate any reflections.
caused by the fuselage.

The QTD2 measurements did not report absolute levels, but rather spectrum shapes and changes in levels. Therefore, comparison in spectrum shape between prediction and measurements are given. In the current comparison, the measured amplitudes have been shifted in order to compare spectrum shapes in the mid-frequency ranges with best match at approximately 1250 Hz. The predictions were shifted in order to match the mid-frequency range because the lower frequencies of the measurements have been reported to be suspect due to measurement array size. The predictions are at 3 isolated observer angles at a distance of 150 meters from the center of the aircraft. The predictions of SPL from the entire aircraft are separated into four individual noise sources: main gear strut; main gear wheels; nose gear; and landing gear wake generated wing/flap trailing edge. Figure 4.1 shows the noise predictions compared to the QTD2 measurements at a 60° emission angle. It is reported that the measurements above 1/3-octave band 36 should be ignored due to the measurement floor and atmospheric absorption. The predicted spectrum shape for the complete aircraft in the mid-frequency ranges, between octave bands 25 and 36, matches very well to flyover measurements, while the SPL at lower frequencies is overpredicted. The overprediction at the lower frequency ranges may be due to Reynolds number effects or the inability of the measurement directional array to accurately capture the lower frequency noise. This discrepancy is currently left unresolved. The predictions of individual noise sources show that the wheels from the main landing gear are the primary factor at most frequencies. However, in the lower frequencies, the main landing gear struts are predicted to generated noise at approximately the same level as the main landing gear wheels. Also, in the mid- to high-frequency ranges, the nose gear noise is only a few decibels below the main gear noise prediction. Figure 4.2 shows the predictions compared to the QTD2 measurements at an emission angle of 90°. For this emission angle, the predictions compare well with the measurements in the mid-frequency range, between octave bands 24 and 36. Similar to the comparison at emission angle of 60°, the predictions at lower frequency ranges are too high when compared to the measurements. The dominant factor in most of the noise spectrum is the main gear wheel noise. However, at low frequencies, the strut noise is approximately the same as the wheel noise. At higher frequencies, the nose gear is only a few decibels lower than the main gear wheel noise.

Footnote: 1The 1/3-octave frequency is at 1258.93Hz.
Figure 4.1: Comparison between QTD2 flight measurements and prediction at emission angle of 60°. Measurements shifted to match predicted level at approximately 1250Hz. Prediction at 1250Hz is 67.0dB.

is interesting to note that at higher frequencies, the addition of the nose gear prediction slightly decreased the fall off rate of the spectrum, providing a better fit to the measured data. Finally, Fig. 4.3 shows the noise predictions compared to the QTD2 measurement at an emission angle of 140°. At this emission angle, the prediction from the entire aircraft matches very well to measurements for octave bands between 22 and 36. Again, the predicted noise in the lower frequencies is composed of strut and wheel noise. However, in the higher frequency ranges, the nose gear becomes the dominant factor. It is currently unclear whether this is the actual dominant noise source or an artifact of the prediction system.
Figure 4.2: Comparison between QTD2 flight measurements and prediction at emission angle of 90°. Measurements shifted to match predicted level at approximately 1250Hz. Prediction at 1250Hz is 42.7dB.
Figure 4.3: Comparison between QTD2 flight measurements and prediction at emission angle of 140°. Measurements shifted to match predicted level at approximately 1250Hz. Prediction at 1250Hz is 48.8dB.
Figure 4.4: Noise prediction for both main landing gear using FLUENT two-dimensional local flow solution with 0° wing cross section angle of attack and flap setting 2. Observer grid on plane 150 meters below aircraft.

4.2 Noise Contours

The prediction system is able to predict the total directivity generated by the aircraft landing gear. The aircraft in this study is similar to the aircraft in the previous section, but traveling at a forward flight Mach number of 0.2. Figure 4.4 presents a prediction for the main gear installed for an aircraft The predictions are on an observer grid 150 meters below the aircraft. Figure 4.5 shows the nose gear prediction, Figure 4.6 shows boundary layer generated trailing edge noise prediction using the Brooks, Pope, and Marcolini prediction scheme. Figure 4.7 shows the landing gear wake generated wing/flap trailing edge noise prediction using the method presented in Section 3.3. As expected, the boundary layer generated wing/flap trailing edge noise is predicted to be much lower than the wake generated trailing edge noise. Finally, Figure 4.8 shows the total noise generated by the airframe components trailing edge, main landing gears, and nose gear summed on a pressure squared basis. Notice that although the main gears are the primary noise source, both the wake generated wing/flap trailing edge noise and the noise from the nose gear is predicted to be only a few decibels lower, and cause a noise increase over the main gear’s level alone.
Figure 4.5: Noise prediction for nose landing gear using approximate uniform inflow slightly larger than freestream velocity. Observer grid on plane 150 meters below aircraft.

Figure 4.6: Boundary layer generated trailing edge noise using the Brooks, Pope, Marcolini trailing edge noise code. Note that the scale is not the same as previous figures. Observer grid on plane 150 meters below aircraft.
Figure 4.7: Landing gear wake generated trailing edge noise using the Ffowcs Williams and Hall trailing edge noise equation. Wake size and turbulence intensity determined from Table 3.1 Observer grid on plane 150 meters below aircraft.

Figure 4.8: Total acoustic prediction from all landing gear noise sources. Total is determined from sum of nose gear, main gear, and landing gear wake generated trailing edge noise. Observer grid on plane 150 meters below aircraft.
This chapter has presented predictions for all the landing gear noise sources on a complete aircraft using methods for approximating the aerodynamic and aeroacoustic interactions of installed landing gear. It was shown that the prediction system matches the mid-frequency spectral shape of acoustic measurements performed in the QTD2 flight test program at three isolated observer positions. Predictions of flyover directivities were then presented on an observer grid below the aircraft. It was shown that the main landing gears are the primary noise source. However, the nose gear and landing gear wake generated wing/flap trailing edge noise are additional factors in the overall level of noise. In the next chapter, the conclusions from the present work are described, including suggestions for future work on the topic.
Chapter 5

Conclusion

This thesis has presented a method for predicting the noise from the airframe of an entire aircraft. The prediction system includes features which predict the aerodynamic and aeroacoustic interactions involved in landing gear noise generation. The research presented includes improvements to a landing gear prediction system, and new methods for approximating the aerodynamic and aeroacoustic interactions involved in a landing gear noise prediction. The improvements included a much faster formulation, and improved acoustic elements. The new prediction methods include an approximation for shielding caused by the landing gear geometry; an approximation for the local flow in the region of the landing gear caused by the wing; a method for predicting the noise caused by the landing gear wake interacting with the wing/flap system; and a method for estimating the interactions caused by gross landing gear geometry changes. By using these approximations, the presented method predicts the noise effects not included in other landing gear noise prediction schemes. Because these features have been included in the noise prediction, a landing gear designer has better insight into the noise sources caused by a landing gear design. These insights aid the designer in creating a low noise landing gear.

5.1 Summary of Research Effort

The prediction system incorporates a small number of acoustic elements that are applied to a wide range of components on the landing gear geometry. Each acoustic element contains a relatively
simple acoustic formulation. A single acoustic element design is applied to multiple components on a landing gear geometry. For example, a cylinder acoustic element is applied to an oleo or hose, both having a cylindrical shape. A trailing edge acoustic element is applied to a door or an aircraft wing or flap. Each acoustic element applied to a landing gear component has an input of flow conditions, and an output of sound pressure level. The sound pressure level from an acoustic element applied to a landing gear component is a function of the input flow conditions, and the component size and location in the landing gear. The total noise caused by the landing gear is simply the sum of the acoustic output from all acoustic elements.

Initially, several improvements have been made to a preliminary prediction system. These have included the implementation of a frequency domain formulation. The frequency domain formulation significantly reduces computation time. This reduction in computation time allows for a much faster turn around between landing gear designs and predicted noise. Further improvements include the addition of a trailing edge acoustic element, and an improved wheel acoustic element. The improved wheel acoustic element was shown to better predict the noise from a six-wheel landing gear design. Two separate trailing edge acoustic elements were implemented. The first uses an external program developed by Brooks, Pope, and Marcolini to predict the noise from a turbulent boundary layer interacting with a sharp trailing edge. The second trailing edge acoustic element incorporates the Ffowcs Williams and Hall trailing edge noise equation to predict the noise from an external turbulent wake interacting with a trailing edge. These improvements increased the ability of the prediction system to provide a prediction of noise caused by a landing gear.

The inclusion of the aeroacoustic and aerodynamic interactions allow for better noise estimates based on the physics behind landing gear noise. The first additional feature is the scattering caused by the landing gear geometry. A line of sight shielding algorithm was implemented, using the scattering by a cylinder in two-dimensions. The prediction system was compared to measurements of a 6.3% scale Boeing 777 main gear performed in the Quiet Flow Facility at NASA Langley Research Center, and were shown to match well compared to other predictions schemes. It was shown that the shielding can affect the predicted noise by as much as 6-7dB at some observer positions in the near field.

The second feature implemented in the landing gear noise prediction system was an estimate of
the local flow in the vicinity of the landing gear when installed on an aircraft. When installed on an aircraft, the landing gear is placed in an environment that is significantly different than would be experienced if placed in a wind tunnel. The prediction system is able to couple with any external CFD calculation available to a designer. A designer using the presented prediction system may have such a computation or approximation available. Two-dimensional FLUENT calculations of the mean flow field around simplified Boeing 777 aircraft wing cross section were performed to demonstrate the coupling between the prediction system and an external flow computation. Two studies on aircraft operating conditions were presented. The first study involved increasing the angle of attack of the aircraft. When the angle of attack is increased, the flow velocity in the landing gear vicinity is decreased. This decreased the predicted noise. The second study involved increasing the flap deflection angle. When the flap deflection angle was increased, the local flow velocity in the vicinity of the landing gear was decreased. This, again, decreased the predicted noise.

The third approximation implemented in the prediction system was an estimate of the landing gear wake generated trailing edge noise. The prediction system was coupled with an immersed boundary solver, called IBSEN, that provided the mean flow behind the landing gear. The mean flow at a plane behind the landing gear, perpendicular to the freestream flow, provided estimates of the wake width impinging on the trailing edge of the wing/flap system. Estimates of the turbulence intensity based on wake width provided the input into the trailing edge acoustic element placed at the trailing edges of the wing vane and flap. Predictions of noise at several Mach numbers showed that the predicted trailing edge noise did not scale as $V^5$, like traditional boundary layer generated trailing edge noise. The predicted scaling was closer to $V^6$ or $V^7$. This is similar to recent measurements that report a $V^8$ scaling from the trailing edge of the wing when the landing gear are down.

The final new feature implemented in the prediction system was an estimate of the local flow effect on the predicted noise when changing gross landing gear features. The immersed boundary solver IBSEN was used to predict the mean flow velocity around a landing gear with several different truck angles. It was shown that toeing the landing gear up exposed the rear wheel to higher flow velocities, while toeing the landing gear down engulfs the rear wheel in a region of lower mean flow velocity. Using a modified rear wheel noise prediction, it was shown that toeing the landing gear
down results in a slightly decreased noise signature. Although the decrease was small, it may give a designer insight into possible noise reduction concepts.

Using the improved prediction methods and the new features for the aeroacoustic and aerodynamic interactions, the prediction system was able to predict the noise from an entire aircraft. The prediction system was compared to measurements from the Quiet Technology Demonstrator 2 (QTD2) Flight Test Program. The measured spectral shapes were compared to the prediction at three isolated observer positions. It was shown that the spectral shape of the prediction matched measurements very well in the mid-frequencies range. The predicted low-frequency noise was consistently overpredicted, possibly because of Reynolds number effects. It was shown that including the nose gear in a complete aircraft noise prediction affects the spectral shape at certain observer positions. Finally, the noise prediction on a plane below an aircraft was presented. It was shown that the noise at all observer positions is dominated by the main gear. However, including the nose gear and landing gear wake generated wing/flap interaction trailing edge noise were additive factors in the overall prediction.

5.2 Main Contributions, Significance, and Originality of Work

The research presented in this document encompasses a landing gear noise prediction system that is unlike any other noise prediction method or system in existence. The prediction technique can predict the noise from isolated or installed landing gear geometry, including many of the aeroacoustic and aerodynamic interactions. The turn around time from set up to noise prediction is extremely fast, with a 1 day turn around in most cases. Other topics of originality and significant are listed below.

1. A framework for the prediction of noise from a landing gear geometry has been created.

2. An improved prediction tool for landing gear noise, including an improved cylinder, wheel, and trailing edge acoustic elements has been developed.

3. A frequency domain formulation, able to predict the noise for a landing gear designer in a reasonable amount of time, has been implemented.
4. A first-order approximation to the shielding caused by the landing gear geometry has been developed.

5. A framework for coupling the prediction system with external flow solutions has been implemented.

6. A study on local flow conditions caused by the wing geometry on the predicted landing gear noise has been performed.

7. A method for approximating the noise caused by the landing gear wake impinging on the trailing edge of the aircraft wing/flap system has been developed.

8. A first order approximation to component interaction, in particular, a study on truck angle influence on radiated noise has been conducted.

9. The use of the prediction system on landing gear noise for a complete aircraft has been demonstrated.

5.3 Recommendations for Future Work

The presented prediction system is a comprehensive prediction tool able to predict the noise from any landing gear design, including many of the aeroacoustic and aerodynamic interactions. The system includes empirically curve fit or approximations for higher order affects. However, since it is a comprehensive code for landing gear noise, there are many individual schemes involved in the prediction, each of which has its own list of possible improvements. Indeed, the entire prediction system has specifically been designed to allow for improvements of individual schemes. By improving individual noise prediction schemes, the predictions for all landing gear geometries are improved. The following is a list of possible improvements to the prediction system.

1. Comparisons to other landing gear geometries.

The prediction system presented has been compared to a small number of landing gear designs. These include a Boeing 737 nose gear and a Boeing 777 main gear. By comparing the prediction system to other geometries, each component of the prediction scheme can be improved, providing a better overall prediction of landing gear noise.
2. **Frequency dependent correlation length.**

A cylinder acoustic element is segmented into individual incoherent noise sources, the length of which is a function of the cylinder characteristic length. The loading forces at all frequencies across the segment are assumed to have this correlation length. However, this correlation length should be a function of frequency. A frequency dependent correlation length would be a better model to predict the physics behind the broadband loading noise.

3. **Reynolds number dependent loading coefficients.**

All cylinder acoustic elements have been scaled with the same fluctuating lift and drag coefficients. However, the lift and drag coefficients should not all be identical, and should depend on the Reynolds number of the landing gear component being modeled. By creating a better algorithm for determining the fluctuating lift and drag coefficient, a more physics based scaling can be implemented.

4. **Improved wheel acoustic element.**

The current wheel acoustic element is a ring of cylinder acoustic elements, all of which do not have the same fluctuating lift and drag coefficients. The values of the lift and drag coefficients are determined by empirically fitting the predicted noise to wind tunnel measurements. An improved wheel acoustic element should be created that predicts the noise caused by the wheel based on the physics of the flow field around the wheels.

5. **Improved algorithm for acoustic shielding/scattering.**

The acoustic shielding implemented in the prediction system is based on scattering caused by a cylinder in two-dimensions. The shielding function is determined by the noise received by an observer point behind the scattering cylinder. A higher order, three-dimensional approximation would better predict this aeroacoustic interaction.

6. **Higher order flow computations for local flow caused by aircraft wing.**

The FLUENT CFD code was used to approximate the flow around an aircraft cross section at approximately the location of an installed landing gear. The computations of the flow field were presented to demonstrate the ability of the prediction code to incorporate the reduced flow field experienced by a landing gear in the noise prediction. Better flow computations
could provide better insight into the actual noise level difference when changing the aircraft angle of attack or flap deflection angle. Also, an improved knowledge of the actual three-dimensional wing/flap geometry would enable improved predictions.

7. **Improved algorithm for estimating turbulence intensity and characteristic size of landing gear wake impinging on trailing edge.**

In the presented predictions, the IBSEN solution of the mean landing gear wake was used to determine wake size impinging on the wing/flap system. The algorithm to determine the dimensions of the wake is based on wind tunnel measurements of wakes impinging on engine turbine blades. However, a better algorithm would be developed to better estimate the wake size and turbulence intensity impinging on the wing or flap trailing edge.

8. **Improved algorithm for estimating component interactions caused by gross landing gear features.**

An IBSEN computation was performed to estimate the flow around a landing gear at several truck angles. This showed that the rear wheel is engulfed in a region of lower mean flow velocity. This lower mean flow velocity resulted in a lower predicted noise. However, this method does not account for the fluctuating wake that could be causing additional noise. An improved method that accounts for this interaction would provide a better estimate of component interactions when changing gross landing gear features.

9. **Comparisons with nose gear measurements.**

Predictions of noise from a complete aircraft demonstrated that at certain observer positions, the nose gear is as important as both of the main gear. It is currently unclear whether this is an artifact of the prediction system or actually occur. Comparisons with flyover measurements that can isolate the nose gear can resolve this.

10. **Comparisons with measurements of complete aircraft airframe noise.**

More comparisons with full scale flyover measurements will help calibrate the system further and provide additional confidence in it’s accuracy.
Bibliography


[39] Jenkins, Luther N., Neuhart, Dan H., McGinley, Catherine B., Choudhari, Meelan M., and Khorrami, Mehdi R., “Measurements Of Unsteady Wake Interference Between Tandem Cylin-


Appendix A

LGMAP Documentation And Example Cases

This chapter describes the LGMAP code in detail, including explanations coding structure, input and output files, and example cases. LGMAP is implemented in FORTRAN 95 using an object-oriented design. The first chapter will describe the coding philosophy and structure implemented. The input files define what acoustic predictions are going to take place, including what source definitions and observer locations. There are several different types of input files. Each will be described in more detail in Section A.2. After the calculation, LGMAP will write out the acoustic files. Debug files will also be written out if they are turned on in the input files. Section A.3 will go into detail on the output from LGMAP, including the acoustic predictions and debugging surfaces provided.

A.1 LGMAP Structure

This section describes the object-oriented design of LGMAP, the acoustic integrations, and the general layout of the input files.

A.1.1 LGMAP Code Structure

LGMAP contains several ‘pieces’ of code that are developed independently of each other. These include acoustic elements (those ‘pieces’ that model the sources and perform the noise prediction),
flow definitions, acoustic scattering, change of bases, observers, and ‘pieces’ designed to organize
the sources into manageable groups. Basic object-oriented design principles are used throughout
the program to ensure that each ‘piece’ can be developed, refined, or completely replaced without
significant effect on other parts of the code. In this manner, LGMAP is an ongoing developing
project, with each refinement of the individual ‘pieces’ improving the overall noise prediction and
capability of the code.

FORTRAN 95 and Object Oriented Design

Object-oriented program is the coding philosophy of using “objects” and their interactions in a
programming code, rather than focusing on the implementation of a certain design. Features of an
object-oriented design include encapsulation, polymorphism, and inheritance. While FORTRAN
95 is not an object-oriented language in the same sense as C++ or Java, it does have many of the
same capabilities that allow the implementation of the majority of the features of an object-oriented
code. Data structures, or FORTRAN types, can be created. Each type is associated with a list
of functions that are said to operate on the type. These type/function groupings are the objects
in the code and are analogous to classes in C++. A type can have private parameters or private
functions, in an essence hiding parts of the code from others (the principle of least privilege, or
encapsulation). Operator overloading and interfaces allow polymorphism, the ability to perform an
similar operation on multiple different data types by using the same function call. Inheritance, or
the ability of an object to inherent the ability from a more basic object definition, is achieved by
nesting objects together. For example, an object that defines a wing contains an object that defines
the surface of the wing. In this manner, the wing has all the features of a surface.

LGMAP Objects

In LGMAP, the FORTRAN 95 MODULE is used in place of a C++ or Java CLASS. A module contains
a FORTRAN TYPE and functions that operate on the type. Data structures inside the data type
or functions contained in the module can be public or hidden from outside members, limiting the
access of objects that include the data type. Each function in a MODULE takes in the data type as
it’s first argument, simulating class member functions. Below is an example FORTRAN MODULE
simulating an object. The example shows a data type for a dog and a function for barking.

**Dog Object**

```fortran
MODULE DogObject
 PRIVATE
 PUBLIC::Dog, Bark

 TYPE Dog
 PRIVATE
  TYPE(HEADOBJECT)::head
  TYPE(TAILOBJECT)::tail
  TYPE(LEGOBJECT), dimension(4)::legs
  TYPE(FUROBJECT)::fur
 END TYPE

 CONTAINS

  FUNCTION Bark(rover)
   TYPE(Dog)::rover
   call BreathIn(rover)
   call BreathOut(rover)
   ...
  END FUNCTION Bark

  FUNCTION BreathIn(rover)
  ...
  END FUNCTION BreathIn

  FUNCTION BreathOut(rover)
  ...
  END FUNCTION BreathOut

 END MODULE DogObject
```

**Data Organization**

The core of LGMAP is centered around a limited number of acoustic elements. An acoustic element stores the source information and calculates the noise at a particular observer location. The acoustic elements can be organized into groupings or assemblies. These assemblies include a landing gear assembly or an aircraft assembly. Each assembly can have a support structure used by the assem-
bly’s acoustic elements. These include scattering modules or local flow or change of base objects. And finally, observer objects are single points or collections of points (grids) where the noise is calculated.

**Acoustic Elements**  LGMAP implements a limited number of acoustic elements that define different sources. These include a cylinder element, wheel element, or trailing edge acoustic element. Each acoustic element has its own list of input parameters, including necessary or optional arguments. All acoustic elements can be scaled, moved, or rotated within the assembly. Section A.2.2 will go into detail on the exact inputs of each acoustic element.

**Assemblies**  An assembly is a collection of acoustic elements that define a source. There are three types of assemblies defined in the LGMAP system. A cylinder assembly is a collection of cylinder acoustic elements. A cylinder assembly is usually found on a landing gear geometry and can be used to group the support strut or hydraulic hoses into a convenient grouping. A cylinder assembly can also include other cylinder assemblies, creating a linked list of source groupings. The second assembly is a landing gear assembly. This includes any number of cylinder assemblies, and a number of wheel and trailing edge acoustic elements. The landing gear assembly can also include a local flow definition used by the acoustic elements. And finally, the last assembly is an aircraft assembly. An aircraft assembly is a collection of landing gear assemblies and wing trailing edge acoustic elements. It can also include surfaces that define the wing.

**Support Structures**  LGMAP contains several support structures used to add features in the acoustic prediction. These include a change of base object, a local flow object, and a scattering module. The local flow object is used in landing gear assemblies to provide the local flow for the acoustic elements. The scattering module is used in the landing gear assembly to calculate the shielding caused by the landing gear object. And a change of base can be used by any object in LGMAP to translate or rotate it in space.
Observers An observer object contains the acoustic prediction performed by LGMAP. The observer handles the data storage and data write out. An observer can be a single point or a grid, defined in cartesian or spherical coordinates.

A.1.2 Input Files

LGMAP input files stem from an LGMAP namelist file. The LGMAP namelist file contains the location of the source namelist file, the atmosphere namelist file, and the observer namelist file. The source namelist file can potentially contain the location of the landing gear geometry namelist file or the location of a local flow input file.

A.1.3 Output File

LGMAP contains two different output file types. The first is for the acoustic prediction and contains the SPL in narrow band or any octave level specified by a user in the observer namelist. The second type of output is for debugging purposes.

A.2 Input Files

There are several different kinds of input files read in by LGMAP. These include namelists for the source and observer, as well as local flow definitions and atmospheric conditions. This section will list each input file and the options and description of all the inputs of the namelists.

A.2.1 LGMAP Namelist File

The LGMAP namelist file contains paths to the source, observer, and atmosphere input files. It also contains the path to the output file for debugging surfaces and flags to turn on acoustic scattering in the landing gear noise prediction. Below is an example namelist and explanations of each input.

LGMAP Namelist

```
&caseFile
  debugLevel = 10
```
• **debugLevel**
  This sets the amount of write outs to the screen. The higher the number, the more print outs are provided. This is useful for debugging an LGMAP run and is defaulted to a debug level of 3.

• **aircraftFileName**
  This is the location of the source namelist file. The path is in relation to the directory of the LGMAP call and must be specified.

• **observerFileName**
  This is the location of the observer namelist file. The path is in relation to the directory of the LGMAP call and must be specified.

• **atmosphereFileName**
  This is the location of the atmosphere namelist file. The path is in relation to the directory of the LGMAP call and must be specified.

• **outputPlot3D**
  This is the file name trunk of the output plot 3D files. There may be several plot 3D files written out, depending on the configuration of the LGMAP run. If nothing is specified, no output will be written.

• **scatteringLevel**
  This is the type of shielding that will be used in the acoustic prediction. There are several options. If nothing is specified or scatteringLevel=’NONE’, no shielding approximation will be used. Other options include ‘LINEOFSIGHT’ for on/off if not in line of sight, and ‘FREQUENCYDEPENDENT’ for shielding based on scattering from a cylinder in two dimensions.

### A.2.2 Source Namelist File

The source namelist file contains information on the source in the acoustic prediction. The source is defined as an aircraft that may contain any number of landing gear, trailing edges, and wings. In the following sections, the inputs of each type of object will be described.

**Aircraft Object**

The aircraft object contains a number of landing gear, trailing edges and wings, traveling at a specified forward flight Mach number. The aircraft namelist contains the number of the landing gear,
trailing edges, and wings and the value of the flight Mach number. It can also contain a change of base that can be specified to translate or rotate the entire aircraft assembly. A scale can also be specified that would scale the entire assembly.

**Aircraft Namelist**

```
&AircraftIn
  title       = 'Boeing 777 Aircraft'
nBase        = 1
nLandingGear = 2
nTrailingEdge= 16
nWing        = 2
ForwardFlightMachNumber = 0.2
debugLocalFlowFlag = .false.
scale        = 1.0
/
```

- **title**
  The title specifies the name of the aircraft assembly. This is defaulted to ‘Default Aircraft’.

- **nBase**
  This specifies the number of base changes from the ground frame of reference. For example, if the aircraft was flying at an angle of attack, this would be set at 1 and a change of base namelist would follow the aircraft namelist. This is defaulted to 0.

- **nLandingGear**
  This is the number of landing gear installed on the aircraft. After any possible change of base files are read in from the source namelist, LGMAP will then read in this number of landing gear namelists. This is defaulted to 0.

- **nTrailingEdge**
  This is the number of trailing edge sources on the aircraft and include any trailing edge noise sources caused by the interaction of the landing gear wake with the trailing edge of the wing/flap system. After reading in any landing gear namelists, the number of trailing edges specified is read in. This is defaulted to 0.

- **nWing**
  This is the number of wing geometries and does not include any trailing edges on the wing surfaces. This is only used if the plot 3D output is turned on. The number of wing geometry namelists will be read in after any trailing edge namelists. This is defaulted to 0.

- **forwardFlightMachNumber**
  This is the forward flight Mach number of the entire aircraft assembly. The forward flight direction is assumed to be in the positive X direction. This is defaulted to 0.0.

- **debugLocalFlowFlag**
  This is a flag to turn on local flow debugging. If this is set to .true. and a local flow
solution has been specified in any landing gear geometry, the local flow will be read in but not used in the acoustic calculation. If the plot 3D output is turned on, the local flow read in by LGMAP will be written out. This allows fast debugging of local flow placement and orientation without using the local flow solution in the acoustic prediction. This is defaulted to .false.

- **scale**
  This is a scale applied to the entire aircraft assembly including any landing gear assemblies, trailing edges, wheel assemblies, change of bases, or local flow geometries. This is defaulted to 1.0.

**Landing Gear Object**

The landing gear object contains a file name where the landing gear geometry namelist is located and a flag for a local flow solution, if available. It also contains a scale, similar to the aircraft namelist, and a number of change of bases and number of reflective surfaces.

**Landing Gear Namelist**

```plaintext
&LandingGearIn
  title = 'Starboard Side Main Landing Gear'
  landingGearFileName = 'Example_Cases/777_MG_Local_Flow/Main_Gear.nam'
  nBase = 0
  nReflectiveSurfaces = 1
  scale = 1.0
  localFlowSolution = .true.
/
```

- **title**
  This is the title of the landing gear. The default value is 'Default Landing Gear'.

- **landingGearFileName**
  This is the path to the landing gear geometry file. The landing gear geometry file contains the information about the cylinder and wheel acoustic elements found on the landing gear geometry. This must be specified.

- **nBase**
  This is the number of base changes between the aircraft assembly and landing gear assembly. This define the position of the landing gear in the aircraft frame of reference. This is defaulted to 0.

- **nReflectiveSurfaces**
  This is the number of reflective surfaces for this landing gear. An example of this would include the bottom of the wing which is assumed to be a perfectly reflecting infinite wall. This is defaulted to 0.

- **scale**
  This is the scale of the landing gear. This scale is applied to the entire landing gear geometry, change of bases, and local flow solution. This is defaulted to 1.0.
• **localFlowSolution**  This is a logical that is true if this landing gear has a local flow solution that will be used in the acoustic calculation. If this is true then the next namelist read in, after this landing gear namelist is the local flow namelist. This is defaulted to false.

**Local Flow Object**

The local flow object defines the flow in the region of the landing gear. There are several possible ways to define the local flow. It can be a uniform inflow, a one-dimensional velocity profile, a two-dimensional velocity profile, or a three-dimensional velocity flow field. The local flow namelist contains inputs for each of these cases. If multiple definitions are specified the code will exit and print out an error.

**Local Flow Namelist**

```plaintext
&LocalInflow
  title = 'Flow Field'
  dimensionalUnits = 'METRIC'
  nBase = 0
  UniformInflow = 68.6
  OneDInflowLoc = 0.0, -1.0, -2.0
  OneDInflowValues = 50.0, 68.6, 68.6
  tecplot2DFileName = 'two_d_tecplot_profile.tec'
  TwoDLocationFileName = 'two_d_profile.x'
  TwoDValuesFileName = 'two_d_profile.fn'
  ThreeDLocationFileName = 'three_d_flowfield.x'
  ThreeDValuesFileName = 'three_d_flowfield.fn'
  translation = 0.0, 0.0, 0.0
  scale = 1.0
  readInAxis = 1, 2, 3
  readInModifier = 1.0, 1.0, 1.0
/
```

• **title**  
  This is the title of this local flow field. The default value is ‘Default Local Flow Object’

• **dimensionalUnits**  
  These are the units of the local flow. The default is ‘METRIC’.

• **nBase**  
  This is the number of base changes from the landing gear reference frame to the local flow reference frame. The change of bases that define the position of the local flow geometry in relation to the landing gear frame are read in after the local flow namelist.

• **UniformInflow**  
  This sets the inflow into the landing gear geometry as a uniform flow velocity, not dependent on location. If this is set, no other flow specification can be set.
• OneDInflowLoc
This is the locations of the one-dimensional velocity profile along the z-axis. If this is specified, no other local flow definition can be specified.

• OneDInflowValues
These are the values of velocity at the locations specified in OneDInflowLoc.

• tecplot2DFileName
This is a file name for a two dimensional flow field read in from TECPLOT [95]. See LGMAP User’s Manual [96] for more information.

• TwoDLocationFileName
This is a file name for the location of a two-dimensional plot 3d file name. The file contains the XYZ locations of the local flow. If this is specified, the file name of the values must also be specified.

• TwoDValuesFileName
This is the file name for the values of the flow field at the locations specified in TwoDLocationFileName.

• ThreeDLocationsFileName
The grid file for the three-dimensional locations where the flow field is specified. If this is specified TwoDValuesFileName must also be specified.

• translation
A vector translation for the local flow. This moves the local flow in the vicinity of the landing gear. This can be used in addition to a change of base. This is defaulted to (0.0,0.0,0.0).

• scale
This is used to scale the positions of the local flow. This is defaulted to 1.0.

• readInAxis
This setting determines the order of axis being read in. For example (1,2,3) is XYZ order, (2,1,3) is YXZ order. The default for this is (1,2,3).

• readInModifier
This modified the values of the location of one of the axis. For example (1,1,1) applies no modifier, (-1,1,1) applies a -1 factor to the x position of the location. Default values is (1,1,1).

Wall Object
The wall object is used to include an infinite perfectly reflecting surface in the acoustic prediction. This is used to approximate the reflections of the landing gear noise off of an aircraft wing.

Wall Namelist

```
&WallIn
  normalVector = 0.0, 0.0, -1.0
  pointOnPlane = 0.0, 0.0, 0.0
```
units = 'METRIC'
nBase = 0
/

- **normalVector**
  This is a vector that points out of the surface. For an aircraft, this would point down toward the ground.

- **pointOnPlane** This is any point located on the surface of the reflecting plane. The default value is (0.0, 0.0, 0.0).

- **units** These are the units of the pointOnPlane.

- **nBase** This is the number of base changes from the landing gear frame of reference to the wall frame of reference.

### Trailing Edge Acoustic Element

The trailing edge acoustic element defines the noise caused by turbulence interacting with a sharp trailing edge. LGMAP incorporates two different types of trailing edge acoustic elements. The first uses the Brooks, Pope, and Marcolini method to predict the noise from a turbulent boundary layer convecting past a sharp trailing edge. The second uses the Ffowcs Williams and Hall trailing edge noise equation to model the noise from a wake in the free stream interacting with the trailing edge of a wing/flap system. Both trailing edge noise models use same namelist.

### Trailing Edge Acoustic Element Namelist

```
&TrailingEdgeNameList
  title = 'Starboard_Side_Inner_Flap'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = -8.00169, -3.1, -3.37526
  endPoint = -7.95101, -9.0, -3.5415
  endChord = 1.969
  startChord = 1.969
  nBase = 0
  scale = 1.0
  L_c = 10.0
  thickness = 0.001
  noiseModel = 'LGMAP'
  AoA = 0.0
  geometricAoA = -65.05
  surfaceGeometry = 'circle'
  alpha = 0.01
  turblength = 1.47
  FWHConstant = 1.0
/
```
• **title**
  This is the name of the trailing edge. The default value is ‘Default Trailing Edge’.

• **metricUnits**
  This is the units of the input distances such as starting and ending point. Default is ‘METRIC’.

• **angleUnits**
  This is the units of the input angles such as angle of attack or geometric angle of attack. Default is ‘DEGREES’.

• **startPoint**
  The starting point of the trailing edge. Default is (0.0, 0.0, 0.0).

• **endPoint**
  The ending point of the trailing edge. Default is (0.0, 0.0, 0.0).

• **endChord**
  This is the chord length at location of `endPoint`. Default is 0.0.

• **startChord**
  This is the chord length at location of `startPoint`. Default is 0.0.

• **nBase**
  This is the number of base changes from the aircraft or landing gear frame of reference to the trailing edge frame of reference. Default = 0.

• **scale**
  A scale that can be is applied to the entire trailing edge geometry including change of bases. The default value is 1.0.

• **Lc**
  This is the length, in terms of chord, of the segments of the trailing edge. Default is 1.0.

• **thickness**
  This is the thickness of the trailing edge. Default is 0.0.

• **noiseModel**
  This is the type of noise model being used for the trailing edge. Options are ‘BPM’ for the Brooks, Pope, Marcolini method or ‘LGMAP’ for the Ffowcs Williams and Hall noise equation method. Default is ‘BPM’.

• **AoA**
  This is the angle of attack of the airfoil. Default is 0.0.

• **geometricAoA**
  This is the geometry angle of attack. The flow is assumed to be at the same angle of attack. Default is 0.0.
• surfaceGeometry
  This is a surface geometry which can be applied to the trailing edge. This is used in plot 3d output only.

• alpha
  The turbulent intensity used in the Ffowcs Williams and Hall trailing edge noise equation. Default is 0.0.

• turblength
  The turbulent mixing length scale used in the Ffowcs Williams and Hall trailing edge noise equation. Default is 0.0.

• FWHConstant
  An empirical constant used in the Ffowcs Williams and Hall trailing edge noise equation, Equation 2.9. Default is 0.0.

Change of Base

A change of base defines the position of one frame of reference in relation to another [97]. By chaining several change of bases together, complex frame of reference motions can be created. Since LGMAP is only interested in time independent motion, the use of change of bases is relatively simple. Change of bases can define the position and rotation of one object in relation to another object.

Change of Base Namelist

&CB
  axisValue = 0.0, 1.0, 0.0
  angleValue = 0.0
  translationValue = 0.0, 0.0, 0.0
/

• axisValue
  The axis of rotation for a rotation change of base. This is used in tandem with angleValue. Default is (1.0, 0.0, 0.0).

• angleValue
  The angle of rotation for a rotation change of base. This is used in tandem with axisValue. Default is 0.0.

• translationValue
  The value of translation for a change of base. This is the distance between two frames of reference. Default is (0.0, 0.0, 0.0).
Wing Object

The last namelist that can be in a source namelist is a wing surface namelist. These are used to insert a surface in the plot 3D debugging output files and are used only for debugging. The predicted noise will not be affected by a wing surface.

Wing Namelist

```
&WingNameList
  title = 'Starboard Wing'
  wingFileName = 'Starboard_Wing.x'
  nBase = 0
/
```

- **title**
  This is the name of the wing. Default is ‘Default Wing’.

- **wingFileName**
  The path to a multi-grid plot 3d file. The multi-grid file contains all the surfaces that define the wing.

- **nBase**
  A number of base changes to be applied to the wing.

A.2.3 Landing Gear Geometry Namelist File

The landing gear geometry is modeled in LGMAP as a collection of cylinders and wheels. The cylinders can be grouped into any number of cylinder assembly objects. The cylinder assembly objects can then be scaled, rotated, or translated with the modifications being applied to all cylinder contained in the assembly. The first namelist in a landing gear geometry namelist file is a landing gear namelist which defines the number of sources in the landing gear.

Landing Gear Geometry Namelist

```
&LandingGearIn
  title = 'Port Side Main Gear'
  nAssembly = 2
  nWheelAssembly = 6
  nBase = 0
/
```

- **title**
  The name of the landing gear geometry. Default is ‘Default landing gear geometry’.

- **nAssembly**
  The number of cylinder assemblies in the landing gear. This does not include the cylinder assemblies included in other cylinder assemblies. Default is 0.
• \(n_{\text{Wheel Assembly}}\)
  The number of wheels on the landing gear geometry.

• \(n_{\text{Base}}\)
  The number of base changes from the aircraft to this landing gear. Default is 0.

Cylinder Assembly Object

The cylinder acoustic elements can be arranged into groupings called cylinder assemblies. A cylinder assembly can have change of bases or scales applied to it. This then moves or scales all the cylinders in the cylinder assembly. A cylinder assembly can also have other cylinder assemblies, creating a tree-like structure.

Cylinder Assembly Namelist

```plaintext
&AssemblyIn
  title = "Shock Strut Assembly"
  nCylinder = 9
  nAssembly = 0
  scaleFactor = 0.0976923077
  nBase = 1
/
```

• \(title\)
  This is the name of the cylinder assembly.

• \(n_{\text{Cylinder}}\)
  The number of cylinder acoustic elements in this cylinder assembly. Default is 0.

• \(n_{\text{Assembly}}\)
  The number of other cylinder assemblies in this cylinder assembly. Default is 0.

• \(scaleFactor\)
  A scale factor applied to all the cylinder and cylinder assemblies contained in this cylinder assembly. Default is 1.0.

• \(n_{\text{Base}}\)
  The number of change of bases from the parent object to this cylinder assembly frame of reference. Default is 0.

Cylinder Acoustic Element

The cylinder acoustic element is contained in a cylinder assembly. Since the cylinder is assumed to be a compact source, the cylinder has a start and end point defined as the ends of the line source. The diameter is the characteristic diameter associated with the cylinder acoustic element.

Cylinder Acoustic Element Namelist
&CylinderIn
  title = "AHB First Middle Cross Member"
  startPoint = -1.2,-0.9,4.15
  endPoint = -1.2,0.9,4.15
  diameter = 0.15
/

- **title**
  The name of the cylinder acoustic element. Default is ‘Cylinder Acoustic Element’.

- **startPoint**
  One end of the compact line source. Default is (0.0, 0.0, 0.0).

- **endPoint**
  The other end of the compact line source. Default is (0.0, 0.0, 0.0).

- **diameter**
  The characteristic length of the cylinder element. Default is 0.0.

**Wheel Acoustic Element**

The wheel acoustic element predicts the noise caused by a wheel in a landing gear geometry. It is a collection of cylinders formed in a ring shape, similar to a donut.

**Wheel Acoustic Element Namelist**

&WheelAssemblyIn
  title = 'Forward Starboard Wheel Assembly'
  nSegments = 24
  scaleFactor = 0.0976923077
  treadWidth = 3.0
  radius = 6.0
  nBase = 3
  modifier = 1.0
/

- **title**
  The name of the wheel acoustic element. Default is ‘Default Wheel Acoustic Element’.

- **nSegments**
  The number of cylinder segments around the wheel. Default is 24.

- **scaleFactor**
  A scale that can be applied to the tread width and the radius. Default is 1.0.

- **treadWidth**
  The width of the treads on the wheel. Default is 0.0.
• \textit{radius}
  The radius of the wheel. Default is 0.0.

• \textit{nBase}
  Number of base changes from the landing gear frame of reference to the wheel frame of
  reference. Default is 0.

• \textit{modifier}
  A modifier for the local inflow into the wheel acoustic element. Default is 1.0.

\subsection*{A.2.4 Atmosphere Namelist File}

The atmosphere namelist defines the atmospheric conditions like speed of sound as a function of
altitude.

\begin{verbatim}
Atmosphere Namelist
&EnvironmentConstants
    altitude  = 0.0
    tempOffset = 0.0
/

• \textit{altitude}
  The altitude of the aircraft in feet.

• \textit{tempOffset}
  An offset to the temperature of the day. A temperature offset of 0 degrees corresponds to 16
degrees Celsius temperatures.
\end{verbatim}

\subsection*{A.2.5 Observer Namelist File}

The observer can be a single point or a grid. A grid of observers can be one-dimensional, two-
dimensional, or three-dimensional. The observer coordinates can be defined in Cartesian or spher-
ical coordinates. The observer object also sets the limits on the frequency range of the predictions,
and defines the octave output of the results.

\begin{verbatim}
Observer Namelist
&ObserverIn
    OutputFormat    = 'binary'
    OutputFileName  = '777_Results'
    OctaveNumber    = 3
    OctaveApproxFlag = .true.
    SPLSpectrumOutput = .true.
    gridtype        = 'cartesian'
    distanceUnits   = 'meters'
    angleUnits      = 'degrees'
    xMin            = 0.0
\end{verbatim}
\begin{verbatim}
xMax = 0.0
yMin = 0.0
yMax = 0.0
zMin = -100.0
zMax = -100.0
nbx = 1
nby = 1
nbz = 1
phiMin = 0.0
phiMax = 0.0
thetaMin = 0.0
thetaMax = 0.0
rmin = 0.0
rmax = 0.0
nbPhi = 1
nbTheta = 1
nbr = 1
fMin = 10.0
fMax = 20000.0
nf = 1000
logarithmicSpacing = .true.
/
\end{verbatim}

- **OutputFormat**
  The format of the output. Options are ‘binary’, ‘unformatted’, or ‘ASCII’. Default is ‘binary’.

- **OutputFileName**
  The file name trunk of the output file. Default is ‘lgmap_out’. If the observer is a single point, then the results file will be ‘lgmap_out.dat’. If the results are on a grid, then there will be three output files: ‘lgmap_out.x’, ‘lgmap_out.fn’, ‘lgmap_out.nam’.

- **OctaveNumber**
  The octave band number. Example is 3 for 1/3 octave band, 8 for 1/8 octave band. Default is 0, which corresponds to no octave output.

- **OctaveApproxFlag**
  This will approximate the factor in calculating the octave bands. If the flag is false the factor is $10^{0.3}$, if true, the value is 2.0. Default is true.

- **SPLSpectrumOutput**
  This turns on the narrow band spectrum output. This can be a very large file. Default is false.

- **gridType**
  This is the type of coordinate system used for the observer. Options are ‘Cartesian’, ‘Spherical’, or ‘ANOPP’ coordinates. Default is ‘Cartesian’.

• *distanceUnits*
  This sets the units of distance. Options are ‘meter’ or ‘feet’. Default is ‘meter’.

• *angleUnits*
  This sets the units of angle. Options are ‘degree’ or ‘radian’. Default is ‘radian’.

• *xMin*
  If the grid type is ‘cartesian’, this sets the minimum x location of the grid. Default is 0.0.

• *xMax*
  If the grid type is ‘cartesian’, this sets the maximum x location of the grid. Default is 0.0.

• *yMin*
  If the grid type is ‘cartesian’, this sets the minimum y location of the grid. Default is 0.0.

• *yMax*
  If the grid type is ‘cartesian’, this sets the maximum y location of the grid. Default is 0.0.

• *zMin*
  If the grid type is ‘cartesian’, this sets the minimum z location of the grid. Default is 0.0.

• *zMax*
  If the grid type is ‘cartesian’, this sets the maximum z location of the grid. Default is 0.0.

• *phiMin*
  If the grid type is ‘spherical’ or ‘ANOPP’, this sets the minimum $\Phi$ location of the grid. Default is 0.0.

• *phiMax*
  If the grid type is ‘spherical’ or ‘ANOPP’, this sets the maximum $\Phi$ location of the grid. Default is 0.0.

• *thetaMin*
  If the grid type is ‘spherical’ or ‘ANOPP’, this sets the minimum $\Theta$ location of the grid. Default is 0.0.

• *thetaMax*
  If the grid type is ‘spherical’ or ‘ANOPP’, this sets the maximum $\Theta$ location of the grid. Default is 0.0.

• *rMin*
  If the grid type is ‘spherical’ or ‘ANOPP’, this sets the minimum radial location of the grid. Default is 0.0.

• *rMax*
  If the grid type is ‘spherical’ or ‘ANOPP’, this sets the maximum radial location of the grid. Default is 0.0.
• \( f_{\text{Min}} \)
  This sets the minimum frequency in the spectral results. Default is 0.0.

• \( f_{\text{Max}} \)
  This sets the maximum frequency in the spectral results. Default is 0.0.

• \( n_{f} \)
  This sets the number of bins in the frequency output. Default is 1.

• \( \text{logarithmicSpacing} \)
  The frequency array can be evenly or logarithmically spaced. Default is true.

A.3 Output Files

There are two types of output files from the LGMAP prediction code: acoustic results and debugging files. The acoustic results contain the narrow band, octave filtered, or overall sound pressure levels. These can be for a single point or observer grid. The debugging surfaces contain plot 3D, multi-grid surfaces with debugging functions that aid in the setup of an LGMAP landing gear geometry.

A.3.1 Acoustic Files

The acoustic output from LGMAP can be a single file ending in ‘.dat’ for results on at a single observer location, or a set of 3 files ending in ‘.x’, ‘.fn’, and ‘.nam’ for results on an observer grid. The ‘.dat’ file contains a list of sound pressure levels as a function of frequency to be read in by the TECPLLOT [95] program. For an observer grid, the position of the observer points are written in plot 3D format in the grid file ending in ‘.x’. The functions of noise (OASPL, OASPLdBA, SPL, octave filtered SPL, etc) are found in the function file ending in ‘.fn’. The names of the functions in the function file are found in the namelist file ending in ‘.nam’. The format of the plot 3D files are determined by the ‘OutputFormat’ setting in the observer namelist.

A.3.2 Debugging Surfaces

Debugging surface are written out if the ‘OutputPlot3D’ file name has been specified in the LGMAP namelist file. The ‘OutputPlot3D’ string sets the file trunk of the plot 3D files. Three files are written out, including a grid file ending in ‘.x’, a function file ending in ‘.fn’, and a namelist file ending in ‘.nam’.

A.4 Running LGMAP

LGMAP is primarily called from a command line in a Linux environment. This is done by using the command ./lgmapv2 in the folder that contains the executable (assuming the code has been compiled with the makefile default arguments). LGMAP can take several different types of command line arguments. The first is a help command that prints out a short list of options for LGMAP. The help is printed out by calling ./lgmapv2 --help. No acoustic calculation is performed when the help is called. The help printed out from LGMAP is shown below.
LGMAP Help Output

$ ./lgmapv2 --help

Landing Gear Model and Acoustic Prediction (LGMAP)

LGMAP Usage:

    ./lgmapv2 [Verboseness] [Debugging] [Input file]

LGMAP version: 2.1.1

Type 'lgmapv2 --help' to display this print out.
Type 'lgmapv2 --version' to display version and included module versions

Available commands

[Verboseness] OPTIONAL: -q/-v/-s: Default = -s
   -q QUIET command, little to no output written out to command line.
   -s STANDARD command, some output written out to command line.
   -v VERBOSE command, a lot of output written out to command line.

[Debugging] OPTIONAL: --debug=MODULE_DEBUGGING': Default = '--debug='
   Where MODULE_DEBUGGING is the included module specific debugging information.
   Each debugging argument separated by comma.
   Each parameter will print out added debugging information.
   Implemented debugging includes:
   --debug=Debugging    Debugging parameters.
   --debug=IO           All IO in the program.
   --debug=I0Registers  IO register information.
   --debug=MPI          MPI calls by parent modules.
   --debug=MPICalls     MPI calls by MPI module.
   --debug=MultiSurface MultiSurface Object debugging.
   --debug=GridObject   Grid object debugging.
   --debug=LocalFlow    More information about the local flow object.
   --debug=LocalFlowCalc More information about the local flow calculation.
   --debug=CylinderElement Added debugging for cylinder acoustic element.
   --debug=CylScattering Added debugging for cylinder scattering.
   --debug=WheelElement Added debugging for wheel acoustic element.
   --debug=TrailingEdge Added debugging for trailing edge element.
   --debug=Scattering   Scattering module debugging.
   --debug=LGScattering Added debugging for shielding/scattering.
   --debug=LGAssembly   Added debugging for cylinder assemblies.
   --debug=LandingGear  Added debugging for landing gear assembly.
   --debug=Aircraft     Added debugging for aircraft assembly.
   --debug=Observer     All things in observer module.
   --debug=LGMAP        Prints out general code progression.

[Input File] OPTIONAL: 'file.nam': Default = 'LGMAPv2.nam'
   The input file for lgmap. See documentation for more info.
Another command line option is to display the version numbers of the included modules that make up LGMAP. This is printed out by calling LGMAP with `.lgmapv2 --version`. This output is shown below. Similar to the help print out, when calling LGMAP with the version argument no acoustic calculation is performed.

**LGMAP Help Output**

```
$ ./lgmapv2 --version
***********************************************************************
Landing Gear Model and Acoustic Prediction (LGMAP)
Build Number 2643
Developed by Leonard V. Lopes
Faculty advisor Dr. Kenneth S. Brentner
LGMAP Code Version : 2.1.1
Debug Module Version : 1.1.2
Utility Module Version : 1.2.1
IFORTRANCompilerMod Version : 1.0.2
Windows Module Version : 1.0.0
Binary IO Module Version : 1.0.1
ASCII IO Module Version : 1.0.4
Unformatted IO Mod. Version : 1.0.1
IO Helper Module Version : 1.2.0
Serial MPI Module Version : 1.0.1
Units Module Version : 1.0.0
Vector Obj. Version : 2.1.0
Matrix Obj. Version : 1.0.0
Math Module Version : 1.3.0
Observer Obj. Version : 1.0.1
Freq Domain Obj. Version : 1.0.0
Time Domain Obj. Version : 1.1.0
Reference Frame Version : 1.0.0
Multi-Grid Obj. Version : 1.0.1
Grid Object Version : 1.0.1
Local Flow Obj. Version : 1.0.0
Atmosphere Module Version : 1.0.0
Cylinder Elem. Version : 1.1.1
Wheel Elem. Version : 1.0.4
Trailing Edge Elem. Version : 1.1.3
Scattering Module Version : 1.0.0
Landing Gear Assem. Version : 1.2.1
Wall Obj. Version : 1.0.1
Aircraft Assembly Version : 1.2.1
Number of Processors = 1
User is Leonard Lopes
***********************************************************************
```
There are three options to LGMAP when running an acoustic calculation: the verboseness, debugging options, and LGMAP namelist file name. All of these inputs are optional and are defaulted to values stated in the help print out. The verbose argument has three possible values -q, -s, and -v. These stand for quiet, standard, and verbose respectively with standard as the default argument. The quiet option suppresses all outputs to the screen, while the standard prints out some output to the screen. The verbose option, -v, significantly increases the outputs to the screen.

In addition to the verbose setting, the second optional argument to LGMAP is a debugging argument, --debug=. This argument can significantly increase the print outs of a particular section of the LGMAP code. The help print out includes a list of possible debugging arguments. More than one debugging argument can be called during a single run. An example of a run with the cylinder acoustic element and observer object debugging turned on is ./lgmap --debug=CylinderElement,Observer. This will turn on debugging for the cylinder element and the observer object.

The final optional argument to LGMAP is the file name of the LGMAP namelist file. This is defaulted to LGMAPv2.nam. While the order of the verbose and debugging arguments are optional, the file name argument must come at the end of the command line.

A.4.1 LGMAP Timing

The LGMAP system has been designed for quick turn around time so that it can be used in a design process. This section reports on the time it takes to predict the noise using certain features of the LGMAP prediction system. The timings in this section do not include the CFD computation time for any flow solution, only the time for the acoustic prediction are reported. All reports for timings were for LGMAP predictions performed on a desktop workstation with a dual core 2.41 GHz AMD Athlon(tm) X2 processor and 2GB of RAM. The example case used in this analysis is similar to the example case reported in Section A.5.6. This example includes predictions for the boundary layer generated trailing edge noise, landing gear wake/flap interactions, main gear noise with or without shielding or local flow solution due to the aircraft wing, and nose gear. The dirty main gear predictions include predictions of noise from all the small scale features of the landing gear, including the hoses. The clean main gear prediction do not include the small scale details. Including the small scale details significantly increases the computation time. The total landing gear noise prediction also includes a reflective wall representing reflections from the wing for each main gear. This approximately doubles the computation time for a single main gear.

The timings for each acoustic calculation for a single observer point is reported in Table A.1. The time for many observer points, or observer grids, can be estimated by multiplying the number for a single observer point by the number of observers. The trailing edge noise predictions, either by the Ffowcs Williams and Hall equation or by the Brooks, Pope, and Marcolini method, are extremely fast. The nose gear is composed of 65 individual acoustic elements and takes 7 seconds to run when scattering is not included in the prediction. Including scattering increases the computation time by approximately 1 second. Since there are a relatively small number of elements, the line of sight calculation is fast. A clean main gear geometry is composed of 277 individual acoustic elements. The time for a single observer location without shielding or local flow is 8.64 seconds. Including either the scattering or the local flow calculation increases the calculation time. Including the scattering increases the computation time by approximately 5 seconds. The time increase when including the local flow is very small, less than 1 second. The dirty main gear configuration
<table>
<thead>
<tr>
<th>Sound source</th>
<th>N. Elements</th>
<th>Scattering</th>
<th>Local Flow</th>
<th>Wall Clock Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. L. Generated T. E.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.1</td>
</tr>
<tr>
<td>Wake/Flap Interaction T. E.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.02</td>
</tr>
<tr>
<td>Nose Gear</td>
<td>65</td>
<td>No</td>
<td>No</td>
<td>6.98</td>
</tr>
<tr>
<td>Nose Gear</td>
<td>65</td>
<td>Yes</td>
<td>No</td>
<td>8.17</td>
</tr>
<tr>
<td>Single Clean Main Gear</td>
<td>277</td>
<td>No</td>
<td>No</td>
<td>8.64</td>
</tr>
<tr>
<td>Single Clean Main Gear</td>
<td>277</td>
<td>Yes</td>
<td>No</td>
<td>13.69</td>
</tr>
<tr>
<td>Single Clean Main Gear</td>
<td>277</td>
<td>No</td>
<td>Yes</td>
<td>9.00</td>
</tr>
<tr>
<td>Single Clean Main Gear</td>
<td>277</td>
<td>Yes</td>
<td>Yes</td>
<td>14.27</td>
</tr>
<tr>
<td>Single Dirty Main Gear</td>
<td>4125</td>
<td>No</td>
<td>No</td>
<td>13.12</td>
</tr>
<tr>
<td>Single Dirty Main Gear</td>
<td>4125</td>
<td>No</td>
<td>Yes</td>
<td>16.55</td>
</tr>
<tr>
<td>Single Dirty Main Gear</td>
<td>4125</td>
<td>Yes</td>
<td>No</td>
<td>238.5</td>
</tr>
<tr>
<td>Single Dirty Main Gear</td>
<td>4125</td>
<td>Yes</td>
<td>Yes</td>
<td>245.83</td>
</tr>
<tr>
<td>Total Aircraft</td>
<td>8315</td>
<td>Yes</td>
<td>Yes</td>
<td>747.03</td>
</tr>
</tbody>
</table>

Table A.1: Timings for the LGMAP prediction system with different source terms. All reports for timings were for LGMAP predictions performed on a desktop workstation with a dual core 2.41 GHz AMD Athlon(tm) X2 processor and 2GB of RAM. The total aircraft prediction includes reflective surfaces for the main gear which double the number of elements for the main gear.

includes a significantly larger number of acoustic elements, over 4,000. The calculation time for a single observer point is still relatively small, at approximately 13 seconds. However, including the scattering approximation significantly increases the computation time. The wall clock time including the shielding approximation is over 230 seconds, increasing by a factor of 18. This is due to the many small scale features included in the landing gear. Many of the small elements are shielded by the large elements. The total computation time for a complete aircraft prediction including local flow, line of sight scattering, and the reflections off of the wing by the noise from the main gear is 747.03 seconds.

A.5 Example Cases

LGMAP is able to predict the noise from several different mechanisms. These include noise sources from the landing gear and the trailing edges. This section contains several example cases that a new user of LGMAP should attempt to reproduce before generating their own landing gear noise prediction. The list of example cases presented here cover the features of the LGMAP prediction system. The examples range from least complicated to most complicated, with the simplest an isolated airfoil, and last being a representative, full scale Boeing 777 aircraft prediction on a large observer grid.

A.5.1 Isolated Airfoil

The first example is an isolated NACA 0012 airfoil. The only noise source from an isolated airfoil is the turbulent boundary layer interacting with the sharp trailing edge (ignoring end effects). This
is included in the LGMAP framework by calling an external program. The external program is the Brooks, Pope, and Marcolini (BPM) trailing edge noise program \cite{80,81}, modified by Moriarty to include airfoils other than a NACA 0012 \cite{82,83}. This external program calculates the boundary layer thickness and empirically fits measured data to arrive at the resultant noise. For this type of noise source, LGMAP is only an interface into another program and a surface generator for debugging.

Several different types of namelists are needed for each prediction performed by LGMAP. Section A.2 outlined the input namelists into the LGMAP system. For the case of an isolated NACA 0012, the namelists are shown below and include an LGMAP namelist, a source namelist, an observer namelist, and an atmosphere definition namelist. The LGMAP namelist includes debug levels and where to find the source and observer namelists. It also defines where to put the output debugging surfaces. The source namelist defines the sources of the noise, in this case a trailing edge. A wing defining the surface of the NACA 0012 airfoil is also specified in the source namelist, but only used for debugging surfaces. The trailing edge defined is flying at a forward flight Mach number of 0.2. The trailing edge is defined as a line along the $Y$ axis at an angle of attack of 7.5 degrees. The observer is defined as a ring of 201 individual observer locations. The change of base after the observer namelist shifts the observer from centered around the airfoil, to centered around the trailing edge. Finally, the atmosphere namelist sets the atmospheric conditions to see level on a standard day.

**LGMAP Namelist**

```plaintext
&caseFile
  debugLevel = 10
  aircraftFileName = "Example_Cases/Isolated_Airfoil/0012.nam"
  observerFileName = 'Example_Cases/Isolated_Airfoil/SphericalGrid.nam'
  atmosphereFileName = 'Example_Cases/Isolated_Airfoil/sea_level.nam'
  outputPlot3D = 'Example_Cases/Isolated_Airfoil/0012_Surf'
  scatteringLevel = ''
/

Source Namelist

&AircraftIn
  title = '0012 In Isolation'
  nLandingGear = 0
  nTrailingEdge = 1
  nWing = 1
  ForwardFlightMachNumber = 0.2
  nBase = 0
/

&TrailingEdgeNameList
  title = '0012'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
```
endPoint   = 0.5, 0.0, 5.0
startPoint = 0.5, 0.0, -5.0
endChord   = 1.0
startChord = 1.0
nBase      = 0
scale      = 1.0
L_c        = 5.0
thickness  = 0.001
noiseModel = 'BPM'
AoA        = 7.5
gEometricAoA = 0.0
surfaceGeometry = 'circle'
nBase      = 1
/
&CB
  axisValue   = 0.0, 1.0, 0.0
  angleValue  = 0.0
/
&WingNameList
  title       = '0012_Wing_Surface'
  wingFileName = 'Example_Cases/Isolated_Airfoil/0012.x'
nBase      = 1
/
&CB
  axisValue   = 1.0, 0.0, 0.0
  angleValue  = 1.5707
/

Observer Namelist

&ObserverIn
  OutputFormat  = 'binary'
  OutputFileName = 'Example_Cases/Isolated_Airfoil/Isolated_Airfoil'
  OctaveNumber  = 3
  OctaveApproxFlag = .true.
  SPLSpectrumOutput = .false.
  gridtype      = 'spherical'
  distanceUnits = 'metric'
  angleUnits    = 'degrees'
  thetaMin      = -180.0
  thetamax      = 180.0
  phiMin        = 90.0
  phiMax        = 90.0
  rMin          = 100.0
  rMax          = 100.0
During the run, LGMAP prints out several things to the screen depending on debug level and command line arguments. As an example, for the standard, default conditions, the LGMAP screen print outs are shown below. The print outs include code name, version number and developer.

LGMAP writes out information about the atmosphere, source and observer. Since this is the standard print out, these statements are very short and do not include any debugging statements. After the source and observer is created, the noise is calculated, and finally, the noise outputs and debugging surface names are written to the screen. At this point, a new user of LGMAP, running this example case, is urged to run lgmap -v at the command line. This will print out the verbose output from LGMAP. The verbose output is significantly longer than the standard, and is not included here. A new user is also urged to execute lgmap --help to get a complete list of command line arguments.

**LGMAP Screen Print Out**

**************************************************************
Landing Gear Model and Acoustic Prediction (LGMAP)
Developed by Leonard V. Lopes

---

nbTheta = 201
nbphi = 1
nbr = 1
nf = 500
fMin = 10.0
fMax = 20000
logarithmicSpacing = .true.
nBase = 1
/
&CB
title = 'trans'
translationValue = 0.5, 0.0, 0.0
/

Atmosphere Namelist

&EnvironmentConstants
  altitude = 0.0
  tempOffset = 0.0
/
The location of the acoustic output is stated in the LGMAP screen print out. Using the TEC-PLOT plotting software and viewing the results as a a polar plots results in Fig. A.1. The airfoil is flying from right to left at a Mach number of 0.2. The noise signature is a cardioid shape where the noise maximum is toward the front of the airfoil.

A.5.2 Isolated Full Scale Boeing 777 Wing

The second example is an approximation of an isolated wing of a Boeing 777 aircraft without the landing gear present. A wing has several trailing edges that generate noise. The trailing edge of the wing, flap, slat and vane all generate trailing edge noise. Similar to the isolated airfoil example presented previously, LGMAP predicts each of these noise sources by using the external program developed by Brooks, Pope, and Marcolini [80, 81], modified by Moriarty to include airfoils other
Figure A.1: LGMAP noise prediction from isolated 0012 airfoil at 7.5 degree angle of attack. Airfoil is traveling from right to left at Mach 0.2. The observer ring is 201 individual prediction points centered at the trailing edge.

than a NACA 0012 [82–84]. In this scenario, LGMAP is simply an interface that generates the debugging surfaces, calls the external program many times, and combines the noise from each segment of the trailing edge into a complete noise prediction.

The same types of namelists used in the previous example are used here. These include an LGMAP namelist, a source namelist, an observer namelist, and an atmosphere definition namelist. These are listed below. The LGMAP namelist is very similar to the previous example. It lists the files that defined the source (aircraftFileName), the observer (observerFileName), the atmosphere (atmosphereFileName), and a file name for the output plot3D file trunk for debugging. The source namelist lists 6 different trailing edges on the aircraft wing flying at a forward flight Mach number of 0.2. Each of the individual trailing edge namelists define the source line and input parameters
of the noise prediction. A wing geometry is also specified for debugging surfaces. The observer namelist defines a cartesian observer grid of 61x31 observer locations at a distance of 100 meters from the center of the aircraft.

**LGMAP Namelist**

```
&caseFile
  debugLevel = 10
  aircraftFile = "Example_Cases/Isolated_777_Wing/777.nam"
  observerFile = 'Example_Cases/Isolated_777_Wing/CartesianGrid.nam'
  atmosphereFile = 'Example_Cases/Isolated_777_Wing/sea_level.nam'
  outputPlot3D = 'Example_Cases/Isolated_777_Wing/777_Surf'
  scatteringLevel = ''
/

Source Namelist

&AircraftIn
  title = '777 Full Scale Aircraft'
  nLandingGear = 0
  nTrailingEdge = 6
  nWing = 1
  ForwardFlightMachNumber = 0.2
  nBase = 0
/

&TrailingEdgeNameList
  title = 'Starboard_Side_Slat'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = 5.646, -3.124, -0.094
  endPoint = -5.364, -22.6211, -0.001
  endChord = 1.01
  startChord = 1.01
  nBase = 0
  scale = 1.0
  L_c = 10.0
  thickness = 0.001
  noiseModel = 'BPM'
  AoA = 0.0
  geometricAoA = 62.148
  surfaceGeometry = 'circle'
/

&TrailingEdgeNameList
  title = 'Starboard_Side_Outer_Flap'
```
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -7.3789, -10.0, -1.55927
endPoint = -9.55416, -22.63, -0.635158
endChord = 0.98145
startChord = 2.445
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = -45.82
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Starboard_Side_Inner_Upper_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -7.466, -3.21, -1.5
endPoint = -7.47, -9.0, -1.675
endChord = 2.657
startChord = 2.657
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = -43.4
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Starboard_Side_Inner_Lower_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -8.00169, -3.1, -3.37526
endPoint = -7.95101, -9.0, -3.5415
endChord = 1.969
startChord = 1.969
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = -65.05
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
  title = 'Starboard_Side_Inner_Main_Body'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = -5.49731, -3.1, 0.6128
  endPoint = -5.49731, -9.602, 0.4096
  endChord = 11.024
  startChord = 7.35
  nBase = 0
  scale = 1.0
  L_c = 10.0
  thickness = 0.001
  noiseModel = 'BPM'
  AoA = 0.0
  geometricAoA = 0.0
  surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
  title = 'Starboard_Side_Outer_Main_Body'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = -5.4225, -9.675, 0.4065
  endPoint = -8.79846, -22.6144, 0.1866
  endChord = 7.35
  startChord = 3.3
  nBase = 0
  scale = 1.0
  L_c = 10.0
  thickness = 0.001
  noiseModel = 'BPM'
  AoA = 0.0
  geometricAoA = 0.0
  surfaceGeometry = 'circle'
/
&WingNameList
  title = 'Starboard Wing'
  wingFileName = 'Example_Cases/Isolated_777_Wing/Starboard_Wing.x'
  nBase = 0
/
Observer Namelist

&ObserverIn
  OutputFormat = 'binary'
  OutputFileName = 'Example_Cases/Isolated_777_Wing/777_TE'
  OctaveNumber = 3
  OctaveApproxFlag = .true.
  SPLSpectrumOutput = .false.
  gridtype = 'cartesian'
  distanceUnits = 'meters'
  angleUnits = 'degrees'
  xMin = -250.0
  xMax = 250.0
  yMin = -200.0
  yMax = 200.0
  zMin = -100.0
  zMax = -100.0
  nbx = 61
  nby = 31
  nbz = 1
  nf = 500
  fMin = 10
  fMax = 10000
  logarithmicSpacing = .true.

Atmosphere Namelist

&EnvironmentConstants
  altitude = 0.0
  tempOffset = 0.0
/

During the run, LGMAP prints out several things to the screen including version numbers, source definitions, and observer locations. Using the verbose option, lgmap -v, significantly increases the amount of writes outs. All users of LGMAP are urged to run lgmap --help for a listing of command line options. The output from LGMAP using the default command line arguments is listed below. LGMAP first prints out the program information and version number, then lists some inputs and performs the noise calculation. After the noise calculation, LGMAP writes out information about the debugging surfaces. In this particular case, the names of the grid file, function file, and namelist file are written out for each of the 6 trailing edges.
LGMAP Screen Print Out

******************************************************
Landing Gear Model and Acoustic Prediction (LGMAP)
Developed by Leonard V. Lopes
Faculty advisor Dr. Kenneth S. Brentner
LGMAP Code Version : 2.1.0
******************************************************

Reading In Atmosphere From 'Example_Cases/Isolated_777_Wing/sea_level.nam'.
Atmosphere Created.
Reading In Case Setup From 'Example_Cases/Isolated_777_Wing/777.nam'.
Creating Aircraft With Title '777 Full Scale Aircraft'.
Aircraft Created.
Reading In Observer Setup From 'Example_Cases/Isolated_777_Wing/CartesianGrid.nam'.
Observer Minimum Location (m) = -250.000000 -200.000000 -100.000000
Observer Maximum Location (m) = 250.000000 200.000000 -100.000000
Observer Number of Points = 61 31 1
Observer Created.

Case read in, moving to calculate the noise.
Calculating Landing Gear Noise.
Writing Out Binary Plot3D Multigrid Grid File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_1.x'.
Writing Out Binary Plot3D Multigrid function File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_1.fn'.
Function Names For Binary Plot3D Multigrid In
'Example_Cases/Isolated_777_Wing/777_Surf_TE_1.nam'.
Writing Out Binary Plot3D Multigrid Grid File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_2.x'.
Writing Out Binary Plot3D Multigrid function File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_2.fn'.
Function Names For Binary Plot3D Multigrid In
'Example_Cases/Isolated_777_Wing/777_Surf_TE_2.nam'.
Writing Out Binary Plot3D Multigrid Grid File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_3.x'.
Writing Out Binary Plot3D Multigrid function File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_3.fn'.
Function Names For Binary Plot3D Multigrid In
'Example_Cases/Isolated_777_Wing/777_Surf_TE_3.nam'.
Writing Out Binary Plot3D Multigrid Grid File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_4.x'.
Writing Out Binary Plot3D Multigrid function File To
'Example_Cases/Isolated_777_Wing/777_Surf_TE_4.fn'.
Function Names For Binary Plot3D Multigrid In
'Example_Cases/Isolated_777_Wing/777_Surf_TE_4.nam'.
Writing Out Binary Plot3D Multigrid Grid File To
When completed, LGMAP writes out two types of files. The first type is the acoustic results, usually found in a result folder. The second type of file are debugging files, usually found in an output surfaces folder. For this particular example, the output surfaces include one grid file for the wing surfaces and one set of grid file, function file and namelist file for each of the 6 trailing edges.

Using the TECPLOT plotting software to view the wing surfaces results in a plot shown in Fig. A.2. The wing shown is an approximation of a segment of a Boeing 777 wing and does not include the tip region. Figure A.3 shows the wing with each of the trailing edges highlighted in red. Similarly, the noise files are plot3d function files. Typical noise results are shown in Fig. A.4 through A.6.
Figure A.2: Wing surface of approximation of Boeing 777 wing section. Outboard section not included in acoustic computation.
Figure A.3: Wing surface of approximation of Boeing 777 wing section with trailing edges also shown. Outboard section not included in acoustic computations.

Figure A.4: Over-All Sound Pressure Level (OASPL) (dB) on observer grid centered 100 meters below center of approximate Boeing 777. Wing geometry also shown.
Figure A.5: 1/3-Octave SPL (dB) with center frequency of 630Hz on observer grid centered 100 meters below center of approximate Boeing 777. Wing geometry also shown.

Figure A.6: 1/3-Octave SPL (dB) with center frequency of 2500Hz on observer grid centered 100 meters below center of approximate Boeing 777. Wing geometry also shown.
A.5.3 Isolated 0.063%-Scale Model Boeing 777 Main Gear

The third example case presented here is for a representative 0.063%-scale Boeing 777 main gear. Unlike the previous two cases, this case does not involve a trailing edge or call an external program. All predictions of noise are performed by LGMAP. Similar to the previous two examples, LGMAP reads in four types of namelists: the LGMAP namelist, the source namelist, the observer namelist, and the atmosphere namelist. The LGMAP namelist points to the source namelist (aircraftFileName), observer namelist (observerFileName), and atmosphere namelist (atmosphereFileName). The LGMAP namelist is shown below, followed by the source namelist. The source namelist contains one landing gear flying at a forward flight Mach number of 0.17 with one change of base associated with the entire aircraft structure. Following the aircraft namelist (AircraftIn), is the landing gear namelist (LandingGearIn). This namelist contains the landing gear title, scale, the number of any reflective surfaces associated with the landing gear, and the number of base changes from the aircraft frame of reference to the landing gear frame of reference. Since this example is for an isolated landing gear geometry, there are no base changes from the aircraft frame of reference to the landing gear frame. Also specified in the landing gear namelist is the name of the landing gear file name. This file is where the landing gear geometry is specified. Following that namelist is the observer and atmosphere namelist, similar to the previous two cases.

**LGMAP Namelist**

```plaintext
&caseFile
  debugLevel = 10
  aircraftFileName = "Example_Cases/Isolated_0_063_777_MG/777.nam"
  observerFileName = 'Example_Cases/Isolated_0_063_777_MG/P01.nam'
  atmosphereFileName = 'Example_Cases/Isolated_0_063_777_MG/sea_level.nam'
  outputPlot3D = 'Example_Cases/Isolated_0_063_777_MG/777_Surf'
  scatteringLevel = ''
/

Source Namelist

&AircraftIn
  title = '777 Full Scale Aircraft'
  nLandingGear = 1
```
nTrailingEdge = 0
nWing = 0
ForwardFlightMachNumber = 0.17
nBase = 1
/
&CB
    axisValue = 0.0, 1.0, 0.0
    angleValue = 0.0
/
&LandingGearIn
    title = 'Port Side Main Landing Gear'
scale = 0.063
    landingGearFileName = 'Example_Cases/Isolated_0_063_777_MG/777_Port_Main_Gear.nam'
nBase = 0
nReflectiveSurfaces = 0
/

Boeing 777 Port Side Main Landing Gear Namelist

&LandingGearIn
    nAssembly = 2
    nWheelAssembly = 6
    title = 'Full Scale Boeing 777 Port Side Main Gear'
nBase = 0
/
&AssemblyIn
    title = "Shock Strut Assembly"
nCylinder = 9
    scaleFactor = 0.0976923077
    nBase = 1
/
&CB
    translationValue = 0.0,0.0,0.0
/
&CylinderIn
    title = "Oleo"
    startPoint = -3.0, 0.0, 0.0
    endPoint = -3.0, 0.0, -41.0
    diameter = 2.75
/
&CylinderIn
    title = "Upper Hydraulic Actuator"
    startPoint = -1.625,-3.75,0.0
    endPoint = -1.9939,-3.75,-5.5
    diameter = 2.56
"Lower Hydraulic Actuator"
startPoint = -1.9939, -3.75, -5.5
diameter = 0.75

"Drag Strut"
startPoint = 13.93606, -19.07612, -4.0
diameter = 2.75

"Drag Strut Locking Mechanism"
title = "Drag Strut Locking Mechanism"
startPoint = 3.163149, -10.22556, -14.0
diameter = 0.75

"Drag Strut Spacer"
title = "Drag Strut Spacer"
startPoint = 13.93606, -19.07612, 0.0
diameter = 2.0

"Side Strut"
startPoint = -7.26319, -24.806, -4.0
diameter = 2.75

"Side Strut Locking Mechanism"
title = "Side Strut Locking Mechanism"
startPoint = -4.436473, -13.0905, -14.0
endPoint = -3.80488, -1.375, -12.0
diameter = 0.75

"Side Strut Spacer"
title = "Side Strut Spacer"
startPoint = -7.26319, -24.806, 0.0
diameter = 2.0
title = "Truck Assembly"
nCylinder = 7
scaleFactor = 0.0976923077
nBase = 2
nAssembly = 7

/ &CB
    translationValue = -0.68653825,0.0,-40.053843
/
&CB
    angleValue = -0.226893
    axisValue = 0.0, 1.0, 0.0
/
&CylinderIn
title = "Cross Axle"
startPoint = -15.0,0.0,0.0
diameter = 2.0
/
&CylinderIn
title = "Axle-1-1"
startPoint = -15.0,-1.125,0.0
diameter = 1.25
/
&CylinderIn
title = "Axle-1-2"
startPoint = -15.0,1.125,0.0
diameter = 1.25
/
&CylinderIn
title = "Axle-2-1"
startPoint = 0.0,1.125,0.0
diameter = 1.25
/
&CylinderIn
title = "Axle-2-2"
startPoint = 0.0,-1.125,0.0
diameter = 1.25
/
title = "Axle-3-1"
startPoint = 15.0,1.125,0.0
endPoint = 15.0,3.115,0.0
diameter = 1.25
/
&CylinderIn
title = "Axle-3-2"
startPoint = 15.0,-1.125,0.0
endPoint = 15.0,-3.115,0.0
diameter = 1.25
/
&AssemblyIn
title = "Aft Hydraulic Bracket"
nCylinder = 6
nBase = 1
/
&CB
  translationValue = -14.653,0.0,0.0
/
&CylinderIn
title = "AHB Lower Cross Member"
startPoint = -2.0,-0.75,1.5
endPoint = -2.0,0.75,1.5
diameter = 0.25
/
&CylinderIn
title = "AHB First Middle Cross Member"
startPoint = -1.2,-0.9,4.15
endPoint = -1.2,0.9,4.15
diameter = 0.15
/
&CylinderIn
title = "Second Middle Cross Member"
startPoint = -0.4,1.05,6.8
endPoint = -0.4,-1.05,6.8
diameter = 0.15
/
&CylinderIn
title = "AHB Top Cross Member"
startPoint = 0.0,-1.125,8.125
endPoint = 0.0,1.125,8.125
diameter = 0.3275
/
&CylinderIn
title = "Starboard Side Support"
startPoint = -2.0, 0.75, 1.5
endPoint = 0.0, 1.125, 8.125
diameter = 0.15
/
&CylinderIn
  title = "Port Side Support"
  startPoint = -2.0, -0.75, 1.5
  endPoint = 0.0, -1.125, 8.125
  diameter = 0.15
/
&AssemblyIn
  title = "Aft Hydraulic Bracket Dressing"
  nCylinder = 12
  nBase = 1
/
&CB
  translationValue = -14.653, 0.0, 0.0
/
&CylinderIn
  startPoint = -2.0, 0.9, 1.5
  endPoint = 0.5, 1.0, 8.125
  diameter = 0.1
title = 'Hose 1 in Bracket'
/
&CylinderIn
  startPoint = 0.5, 1.0, 8.125
  endPoint = 16.5, 1.0, 13.0
  diameter = 0.1
title = 'Hose 1 to Oleo'
/
&CylinderIn
  startPoint = 16.5, 1.0, 13.0
  endPoint = 22.25, 1.0, 38.0
  diameter = 0.1
title = 'Hose 1 to top'
/
&CylinderIn
  startPoint = -2.0, 0.45, 1.5
  endPoint = 0.5, 0.55, 8.125
  diameter = 0.1
title = 'Hose 2 in Bracket'
/
&CylinderIn
startPoint = 0.5, 0.45, 8.125
endPoint = 16.5, 0.55, 13.0
diameter = 0.1
title = 'Hose 2 to Oleo'
/
&CylinderIn
startPoint = 16.5, 0.55, 13.0
endPoint = 22.25, 0.55, 38.0
diameter = 0.1
title = 'Hose 2 to Top'
/
&CylinderIn
startPoint = -2.0, -0.45, 1.5
endPoint = 0.5, -0.55, 8.125
diameter = 0.1
title = 'Hose 3 in Bracket'
/
&CylinderIn
startPoint = 0.5, -0.55, 8.125
endPoint = 16.5, -0.55, 13.0
diameter = 0.1
title = 'Hose 3 to Oleo'
/
&CylinderIn
startPoint = 16.5, -0.55, 13.0
endPoint = 22.25, -0.55, 38.0
diameter = 0.1
title = 'Hose 3 to Top'
/
&CylinderIn
startPoint = -2.0, -0.9, 1.5
endPoint = 0.5, -1.0, 8.125
diameter = 0.1
title = 'Hose 4 in Bracket'
/
&CylinderIn
startPoint = 0.5, -1.0, 8.125
endPoint = 16.5, -1.0, 13.0
diameter = 0.1
title = 'Hose 4 to Oleo'
/
&CylinderIn
startPoint = 16.5, -1.0, 13.0
endPoint = 22.25, -1.0, 38.0
diameter = 0.1
/title = 'Hose 4 to top'
/
&AssemblyIn
title = "Forward Horizontal Hydraulic Bracket"
nCylinder = 6
nBase = 1
/
&CB
   translationValue = 09.6927,0.0,0.0
/
&CylinderIn
   startPoint = 2.07736,-1.0625,8.93584
   endPoint = -6.211365,-1.0625,10.51332
   diameter = 0.5
   title = 'FHHB Starboard Side Support'
/
&CylinderIn
   startPoint = 2.07736,1.0625,8.93584
   endPoint = -6.211365,1.0625,10.51332
   diameter = 0.5
   title = 'FHHB Port Side Support'
/
&CylinderIn
   startPoint = 2.07736,-1.0625,8.93584
   endPoint = 2.07736,1.0625,8.93584
   diameter = 0.375
   title = 'FHHB Forward Cross Member'
/
&CylinderIn
   startPoint = 1.22627,-1.0625,9.0978165
   endPoint = 1.22627,1.0625,9.0978165
   diameter = 0.325
   title = 'FHHB First Middle Cross Member'
/
&CylinderIn
   startPoint = -1.0138126,-1.0625,9.52414
   endPoint = -1.0138126,1.0625,9.52414
   diameter = 0.325
   title = 'FHHB Second Middle Cross Member'
/
&CylinderIn
   startPoint = -5.5867,-1.0625,10.3944
   endPoint = -5.5867,1.0625,10.3944
diameter = 0.325
title = 'FHHB Aft Cross Member'
/
&AssemblyIn
title = "Forward Horizontal Hydraulic Bracket Dressing"
nCylinder = 4
nBase = 1
/
&CB
  translationValue = 09.76927,0.0,0.0
/
&CylinderIn
  startPoint = 2.07736, -0.75, 8.93584
  endPoint = -6.211365, -0.75, 10.51332
  diameter = 0.1
  title = ""
/
&CylinderIn
  startPoint = 2.07736, -0.25, 8.93584
  endPoint = -6.211365, -0.25, 10.51332
  diameter = 0.1
  title = ""
/
&CylinderIn
  startPoint = 2.07736, 0.75, 8.93584
  endPoint = -6.211365, 0.75, 10.51332
  diameter = 0.1
  title = ""
/
&CylinderIn
  startPoint = 2.07736, 0.25, 8.93584
  endPoint = -6.211365, 0.25, 10.51332
  diameter = 0.1
  title = ""
/
&AssemblyIn
  title = "Forward Vertical Hydraulic Bracket"
nCylinder = 6
nBase = 1
/
&CB
  translationValue = 09.76927,0.0,0.0
/
&CylinderIn
startPoint = 0.0,-0.57845,0.0
diameter = 0.35
title = 'FVHB Lower Starboard Side Support'
/
&CylinderIn
startPoint = 0.0,0.57845,0.0
diameter = 0.35
title = 'FVHB Lower Port Side Support'
/
&CylinderIn
startPoint = 1.2504, -1.125,5.30452
diameter = 0.344
title = 'FVHB Upper Starboard Side Support'
/
&CylinderIn
startPoint = 1.2504, 1.125,5.30452
diameter = 0.344
title = 'FVHB Upper Port Side Support'
/
&CylinderIn
startPoint = 1.2504,-1.125,5.30452
diameter = 0.5
title = 'FVHB Lower Cross Member'
/
&CylinderIn
startPoint = 1.91637,-1.125,8.221403
diameter = 0.4
title = 'FVHB Upper Cross Member'
/
&AssemblyIn
title = "Forward Verticle Hydraulic Bracket Dressing"
nCylinder = 8
nBase = 1
/
&CB
translationValue = 09.76927,0.0,0.0
/
&CylinderIn
startPoint = 1.2504, -0.75, 5.30452
endPoint = 2.07736, -0.75, 8.93584
diameter = 0.1
title = 'FVHB Hose 1'
/
&CylinderIn
startPoint = -6.211365, -0.75, 10.51332
endPoint = 0.0, -0.75, 38.
diameter = 0.1
title = 'FVHB Hose 1 To Oleo'
/
&CylinderIn
startPoint = 1.2504, -0.25, 5.30452
endPoint = 2.07736, -0.25, 8.93584
diameter = 0.1
title = 'FVHB Hose 2'
/
&CylinderIn
startPoint = -6.211365, -0.25, 10.51332
endPoint = 0.0, -0.25, 38.0
diameter = 0.1
title = 'FVHB Hose 2 To Oleo'
/
&CylinderIn
startPoint = 1.2504, 0.75, 5.30452
endPoint = 2.07736, 0.75, 8.93584
diameter = 0.1
title = 'FVHB Hose 3'
/
&CylinderIn
startPoint = -6.211365, 0.75, 10.51332
endPoint = 0.0, 0.75, 38.
diameter = 0.1
title = 'FVHB Hose 3 To Oleo'
/
&CylinderIn
startPoint = 1.2504, 0.25, 5.30452
endPoint = 2.07736, 0.25, 8.93584
diameter = 0.1
title = 'FVHB Hose 4'
/
&CylinderIn
startPoint = -6.211365, 0.25, 10.51332
endPoint = 0.0, 0.25, 38.
diameter = 0.1
title = 'FVHB Hose 4 To Oleo'
/
&AssemblyIn
  title = "Brake Mount Assembly"
  nAssembly = 6
  nBase = 0
  nCylinder = 0
/
&AssemblyIn
  title = "Center Port Brake Mount"
  nCylinder = 9
  nBase = 1
/
&CB
  translationValue = 0.0,0.9307,0.0
/
&CylinderIn
  startPoint = 0.0,1.0,0.0
  endPoint = 0.0,2.355,0.0
  diameter = 1.74
  title = 'Inner mount'
/
&CylinderIn
  startPoint = 0.0,0.0,0.0
  endPoint = 0.0,-0.6575,0.0
  diameter = 6.1
  title = 'Mount plate'
/
&CylinderIn
  startPoint = 0.6235,0.0,-1.439
  endPoint = 0.6235,1.22,-1.439
  diameter = 0.94
  title = 'Mount cylinder 1'
/
&CylinderIn
  startPoint = 0.6235,0.0,-1.439
  endPoint = 0.6235,1.22,-1.439
  diameter = 0.94
  title = 'Mount cylinder 2'
/
&CylinderIn
  startPoint = -0.6235,0.0,-1.439
  endPoint = -0.6235,1.22,-1.439
diameter = 6.1
title = 'Mount plate'
/
&CylinderIn
  startPoint = 0.0,0.0,-1.84
diameter = 0.94
title = 'Mount cylinder 1'
/
&CylinderIn
  startPoint = -0.6235,0.0,-1.439
diameter = 0.94
title = 'Mount cylinder 2'
/
&CylinderIn
  startPoint = 0.6235,0.0,-1.439
diameter = 0.94
title = 'Mount cylinder 3'
/
&CylinderIn
  startPoint = -1.794,0.0,0.2225
diameter = 0.94
title = 'Mount cylinder 4'
/
&CylinderIn
  startPoint = 1.794,0.0,0.2225
diameter = 0.94
title = 'Mount cylinder 5'
/
&CylinderIn
  startPoint = -0.789,0.0,1.658
diameter = 0.94
title = 'Mount cylinder 6'
/
&CylinderIn
  startPoint = 0.789,0.0,1.658
title = 'Mount cylinder 7'
AssemblyIn
  title = "Forward Port Brake Mount"
  nCylinder = 9
  nBase = 1
/

CB
  translationValue = 14.653765,02.9307,0.0
/

CylinderIn
  startPoint = 0.0,1.0,0.0
  endPoint = 0.0,2.355,0.0
  diameter = 1.74
  title = 'Inner mount'
/

CylinderIn
  startPoint = 0.0,0.0,0.0
  endPoint = 0.0,-0.6575,0.0
  diameter = 6.1
  title = 'Mount plate'
/

CylinderIn
  startPoint = 0.0,0.0,-1.84
  endPoint = 0.0,1.22,-1.84
  diameter = 0.94
  title = 'Mount cylinder 1'
/

CylinderIn
  startPoint = 0.6235,0.0,-1.439
  endPoint = 0.6235,1.22,-1.439
  diameter = 0.94
  title = 'Mount cylinder 2'
/

CylinderIn
  startPoint = -0.6235,0.0,-1.439
  endPoint = -0.6235,1.22,-1.439
  diameter = 0.94
  title = 'Mount cylinder 3'
/

CylinderIn
  startPoint = 1.794,0.0,0.2225
  endPoint = 1.794,1.22,0.2225
  diameter = 0.94
  title = 'Mount cylinder 4'
/ &CylinderIn
  startPoint = -1.794,0.0,0.2225
  endPoint = -1.794,1.22,0.2225
  diameter = 0.94
  title = 'Mount cylinder 5'
/
/ &CylinderIn
  startPoint = 0.789,0.0,1.658
  endPoint = 0.789,1.22,1.658
  diameter = 0.94
  title = 'Mount cylinder 6'
/
/ &CylinderIn
  startPoint = -0.789,0.0,1.658
  endPoint = -0.789,1.22,1.658
  diameter = 0.94
  title = 'Mount cylinder 7'
/
/ &AssemblyIn
  title = "Forward Starboard Brake Mount"
  nCylinder = 9
  nBase = 1
/
/ &CB
  translationValue = 14.653765,-02.9307,0.0
/
/ &CylinderIn
  startPoint = 0.0,1.0,0.0
  endPoint = 0.0,-2.355,0.0
  diameter = 1.74
  title = 'Inner mount'
/
/ &CylinderIn
  startPoint = 0.0,0.0,0.0
  endPoint = 0.0,0.6575,0.0
  diameter = 6.1
  title = 'Mount plate'
/
/ &CylinderIn
  startPoint = 0.0,0.0,-1.84
  endPoint = 0.0,-1.22,-1.84
  diameter = 0.94
  title = 'Mount cylinder 1'
&CylinderIn
startPoint = -0.6235, 0.0, -1.439
endPoint = -0.6235, -1.22, -1.439
diameter = 0.94
title = 'Mount cylinder 2'
/
&CylinderIn
startPoint = 0.6235, 0.0, -1.439
endPoint = 0.6235, -1.22, -1.439
diameter = 0.94
title = 'Mount cylinder 3'
/
&CylinderIn
startPoint = -1.794, 0.0, 0.2225
endPoint = -1.794, -1.22, 0.2225
diameter = 0.94
title = 'Mount cylinder 4'
/
&CylinderIn
startPoint = 1.794, 0.0, 0.2225
endPoint = 1.794, -1.22, 0.2225
diameter = 0.94
title = 'Mount cylinder 5'
/
&CylinderIn
startPoint = -0.789, 0.0, 1.658
endPoint = -0.789, -1.22, 1.658
diameter = 0.94
title = 'Mount cylinder 6'
/
&CylinderIn
startPoint = 0.789, 0.0, 1.658
endPoint = 0.789, -1.22, 1.658
diameter = 0.94
title = 'Mount cylinder 7'
/
&AssemblyIn
title = "Rear Port Brake Mount"
nCylinder = 9
nBase = 1
/
&CB
translationValue = -14.653765, 0.29307, 0.0
/üCylinderIn
    startPoint = 0.0,1.0,0.0
diameter  = 1.74
title     = 'Inner mount'
/
/üCylinderIn
    startPoint = 0.0,0.0,0.0
diameter  = 6.1
title     = 'Mount plate'
/
/üCylinderIn
    startPoint = 0.0,0.0,-1.84
diameter  = 0.94
title     = 'Mount cylinder 1'
/
/üCylinderIn
    startPoint = 0.6235,0.0,-1.439
diameter  = 0.94
title     = 'Mount cylinder 2'
/
/üCylinderIn
    startPoint = -0.6235,0.0,-1.439
diameter  = 0.94
title     = 'Mount cylinder 3'
/
/üCylinderIn
    startPoint = 1.794,0.0,0.2225
diameter  = 0.94
title     = 'Mount cylinder 4'
/
/üCylinderIn
    startPoint = -1.794,0.0,0.2225
diameter  = 0.94
title     = 'Mount cylinder 5'
/
startPoint = 0.789,0.0,1.658
diameter = 0.94
title = 'Mount cylinder 6'

&CylinderIn
startPoint = -0.789,0.0,1.658
diameter = 0.94
title = 'Mount cylinder 7'

&AssemblyIn
title = "Rear Starboard Brake Mount"
nCylinder = 9
nBase = 1

&CB
translationValue = -14.653765,-02.9307,0.0

&CylinderIn
startPoint = 0.0,1.0,0.0
diameter = 1.74
title = 'Inner mount'

&CylinderIn
startPoint = 0.0,0.0,0.0
diameter = 6.1
title = 'Mount plate'

&CylinderIn
startPoint = 0.0,0.0,-1.84
diameter = 0.94
title = 'Mount cylinder 1'

&CylinderIn
startPoint = -0.6235,0.0,-1.439
diameter = 0.94
title = 'Mount cylinder 2'
startPoint   = 0.6235,0.0,-1.439
endPoint    = 0.6235,-1.22,-1.439
diameter    = 0.94
title       = 'Mount cylinder 3'
/
&CylinderIn
  startPoint  = -1.794,0.0,0.2225
  endPoint   = -1.794,-1.22,0.2225
  diameter   = 0.94
  title      = 'Mount cylinder 4'
/
&CylinderIn
  startPoint  = 1.794,0.0,0.2225
  endPoint   = 1.794,-1.22,0.2225
  diameter   = 0.94
  title      = 'Mount cylinder 5'
/
&CylinderIn
  startPoint  = -0.789,0.0,1.658
  endPoint   = -0.789,-1.22,1.658
  diameter   = 0.94
  title      = 'Mount cylinder 6'
/
&CylinderIn
  startPoint  = 0.789,0.0,1.658
  endPoint   = 0.789,-1.22,1.658
  diameter   = 0.94
  title      = 'Mount cylinder 7'
/
&WheelAssemblyIn
  title      = 'Center Port Wheel Assembly'
  nSegments  = 24
  scaleFactor = 0.0976923077
  treadWidth  = 3.0
  radius      = 6.0
  nBase       = 3
/
&CB
  translationValue = 0.0,0.3.846,-40.054
/
&CB
  angleValue    = -0.226893
  axisValue     = 0.0, 1.0, 0.0
/
translationValue = -02.68653, 0.0, 0.0

wheelAssemblyIn

title = 'Center Starboard Wheel Assembly'
nSegments = 24
scaleFactor = 0.0976923077
treadWidth = 3.0
radius = 6.0
nBase = 3

translationValue = 0.0,-03.846,-40.054

angleValue = -0.226893
axisValue = 0.0, 1.0, 0.0

translationValue = -02.68653, 0.0, 0.0

wheelAssemblyIn

title = 'Rear Port Wheel Assembly'
nSegments = 24
scaleFactor = 0.0976923077
treadWidth = 3.0
radius = 6.0
nBase = 3

translationValue = 0.0,03.846,-40.054

angleValue = -0.226893
axisValue = 0.0, 1.0, 0.0

translationValue = -17.31, 0.0, 0.0

wheelAssemblyIn

title = 'Rear Starboard Wheel Assembly'
nSegments = 24
scaleFactor = 0.0976923077
treadWidth = 3.0
radius = 6.0
nBase = 3
/
&CB
  translationValue = 0.0, -0.846, -40.054
/
&CB
  angleValue = -0.226893
  axisValue = 0.0, 1.0, 0.0
/
&CB
  translationValue = -17.31, 0.0, 0.0
/
&WheelAssemblyIn
  title = 'Forward Port Wheel Assembly'
  nSegments = 24
  scaleFactor = 0.0976923077
  treadWidth = 3.0
  radius = 6.0
  nBase = 3
/
&CB
  translationValue = 0.0, 0.846, -40.054
/
&CB
  angleValue = -0.226893
  axisValue = 0.0, 1.0, 0.0
/
&CB
  translationValue = 11.981, 0.0, 0.0
/
&WheelAssemblyIn
  title = 'Forward Starboard Wheel Assembly'
  nSegments = 24
  scaleFactor = 0.0976923077
  treadWidth = 3.0
  radius = 6.0
  nBase = 3
/
&CB
  translationValue = 0.0, -0.846, -40.054
/
&CB
  angleValue = -0.226893
 There are two different levels of scattering in the LGMAP system: frequency dependent shielding on or off. In the following two sections, both of these inputs will be demonstrated with example outputs. The first example has the frequency dependent shielding off, followed by an example with the shielding turned on.
Shielding Model Off

The first example has the shielding model turned off. This is set in the LGMAP namelist. The parameter that sets the scattering level is `scatteringLevel = 'NONE'`, this turns off all scattering calculations. Everything else in the prediction input remains the same. Using the default LGMAP command line arguments results in print outs to the screen shown below. The print outs include version numbers, source parameters, observer locations and output locations. As always, a new user is urged to run `lgmap -v` for more screen print outs or `lgmap --help` for a listing of all command line options. The example results are shown in Fig. A.7.

LGMAP Namelist

```plaintext
&caseFile
  debugLevel = 10
  aircraftFileName = "Example_Cases/Isolated_0_063_777_MG/777.nam"
  observerFileName = 'Example_Cases/Isolated_0_063_777_MG/Po1.nam'
  atmosphereFileName = 'Example_Cases/Isolated_0_063_777_MG/sea_level.nam'
  outputPlot3D = 'Example_Cases/Isolated_0_063_777_MG/777_Surf'
  scatteringLevel = 'NONE'
/
```

LGMAP Screen Print Out

```
************************************************************
Landing Gear Model and Acoustic Prediction (LGMAP)
Developed by Leonard V. Lopes
Faculty advisor Dr. Kenneth S. Brentner
LGMAP Code Version : 2.1.0
************************************************************
Reading In Atmosphere From 'Example_Cases/Isolated_0_063_777_MG/sea_level.nam'.
Atmosphere Created.
Reading In Case Setup From 'Example_Cases/Isolated_0_063_777_MG/777.nam'.
Creating Aircraft With Title '777 Full Scale Aircraft'.
Using free stream Mach number as local flow: M = 0.170000
Local inflow created.
Landing Gear Created.
Aircraft Created.
Reading In Observer Setup From 'Example_Cases/Isolated_0_063_777_MG/Po1.nam'.
Observer Location (m) = 0.079760 x 1.505585 x -0.222325
```
Observer Created.
Case read in, moving to calculate the noise.
Calculating Landing Gear Noise.
Writing Out Binary Plot3D Multigrid Grid File To
‘Example_Cases/Isolated_0_063_777_MG/777_0_063_FV_LG_1.x’.
Writing Out Binary Plot3D Multigrid function File To
‘Example_Cases/Isolated_0_063_777_MG/777_0_063_FV_LG_1.fn’.
Function Names For Binary Plot3D Multigrid In
‘Example_Cases/Isolated_0_063_777_MG/777_0_063_FV_LG_1.nam’.
Writing Out Binary Plot3D Multigrid Grid File To
‘Example_Cases/Isolated_0_063_777_MG/777_0_063_IBSEN_LG_1.x’.
Writing Out Binary Plot3D Multigrid function File To
‘Example_Cases/Isolated_0_063_777_MG/777_0_063_IBSEN_LG_1.fn’.
Function Names For Binary Plot3D Multigrid In
‘Example_Cases/Isolated_0_063_777_MG/777_0_063_IBSEN_LG_1.nam’.
Run Time Was 0.000000 seconds
Fortran Pause - Enter command<CR> or <CR> to continue.
\begin{verbatim}
Shielding Model On

The shielding model implemented in LGMAP uses the scattering by a cylinder in two-dimensions to
approximate the shielding affect. The parameter that sets the scattering level is scatteringLevel = 
‘FREQUENCYDEPENDENT’, this turns on the shielding calculations. The LGMAP output is listed be-
low and does not differ from the lgmap run without the shielding estimate. Fig. A.8 shows the noise
prediction by LGMAP.

LGMAP Namelist

&caseFile
    debugLevel = 10
    aircraftFileName = "Example_Cases/Isolated_0_063_777_MG/777.nam"
    observerFileName = ‘Example_Cases/Isolated_0_063_777_MG/Po1.nam’
    atmosphereFileName = ‘Example_Cases/Isolated_0_063_777_MG/sea_level.nam’
    outputPlot3D = ‘Example_Cases/Isolated_0_063_777_MG/777’
    scatteringLevel = ‘FREQUENCYDEPENDENT’
/

LGMAP Screen Print Out
Landing Gear Model and Acoustic Prediction (LGMAP)
Developed by Leonard V. Lopes
Faculty advisor Dr. Kenneth S. Brentner
LGMAP Code Version : 2.1.0

Reading In Atmosphere From ‘sea_level.nam’.
Atmosphere Created.
Reading In Case Setup From ‘777.nam’.
Creating Aircraft With Title ‘777 Full Scale Aircraft’.
Creating Landing Gear With Title ‘Port Side Main Landing Gear’.
Using free stream Mach number as local flow: M = 0.170000
Local inflow created.
Landing Gear Created.
Aircraft Created.
Reading In Observer Setup From ‘Observer/Az4.nam’.
Observer Location (m) = 0.079760 x 1.505585 x -0.222325
Observer Created.
Case read in, moving to calculate the noise.

Figure A.7: Example LGMAP results from 0.063%-scale Boeing 777 port side main gear with shielding model turned off.
Calculating Landing Gear Noise.
Writting Out Binary Plot3D Multigrid Grid File To
'Example_Cases/Isolated_0_063_777_MG/777_0_063_FV_LG_1.x'.
Writting Out Binary Plot3D Multigrid function File To
'Example_Cases/Isolated_0_063_777_MG/777_0_063_FV_LG_1.fn'.
Function Names For Binary Plot3D Multigrid In
'Example_Cases/Isolated_0_063_777_MG/777_0_063_FV_LG_1.nam'.
Writting Out Binary Plot3D Multigrid Grid File To
'Example_Cases/Isolated_0_063_777_MG/777_0_063_IBSEN_LG_1.x'.
Writting Out Binary Plot3D Multigrid function File To
'Example_Cases/Isolated_0_063_777_MG/777_0_063_IBSEN_LG_1.fn'.
Function Names For Binary Plot3D Multigrid In
'Example_Cases/Isolated_0_063_777_MG/777_0_063_IBSEN_LG_1.nam'.
Run Time Was 0.000000 seconds
Fortran Pause - Enter command<CR> or <CR> to continue.

Figure A.8: Example LGMAP results from 0.063%-scale Boeing 777 port side main gear with shielding model turned on.
A.5.4 Isolated Boeing 777 Main Gear Using Local Flow From Wing

The next example is an isolated Boeing 777 main gear including the effect of local flow caused by the circulation around the lifting aircraft wing. The flow in the region of the landing gear when installed on an aircraft is significantly less than the free stream uniform flow, and is not uniform throughout the entire region of the landing gear geometry. LGMAP has the ability to use several different setups for the flow condition around the landing gear. This includes a modified uniform inflow, a one-dimensional velocity profile, several configurations of two-dimensional flow fields, and a fully three-dimensional flow field around the landing gear. Only one example of a two-dimensional flow field will be shown here. See the LGMAP manual for more details on other configurations [96].

Any CFD package can be used to compute the flow field in the landing gear vicinity. Figure A.9 shows a two-dimensional flow field around a representative wing cross section using the FLUENT CFD code [92]. The computation was performed on a coarse unstructured grid stretching 11 wing chords in front, above and below the wing cross section, and 22 wing chords downstream of the wing cross section. LGMAP requires the flow field on a cartesian mesh in the vicinity of the landing gear. Figure A.10 shows an example sampling mesh in the landing gear vicinity. TECPLOT [95] can been used to interpolate from the unstructured CFD mesh to a structured LGMAP sampling mesh. Figure A.11 shows the flow field on the sampling mesh with the LGMAP representation of the landing gear geometry.

Similar to the examples above, LGMAP uses four types of namelists: LGMAP namelist, source namelist, observer namelist, and atmosphere namelist. These four namelists are shown below. The LGMAP, observer and atmosphere namelists are all very similar to cases shown above. The source namelist now includes a local flow definition for the landing gear geometry. The local flow input includes a file where the local flow is defined and optional change of bases to place the local flow in the correct location and orientation. In addition to these namelists two additional files are needed for this case: landing gear geometry namelist (shown in the previous example), and a local flow definition file. The beginning portion of the local flow definition file is shown below and includes a
Figure A.9: Instantaneous flow velocity for flap setting 2 case at 0° angle of attack.

Figure A.10: Example sampling mesh used in TECPLOT to interpolate flowfield. Background flow field on unstructured grid computed by FLUENT. LGMAP requires flow field on structured mesh in landing gear vicinity.
Figure A.11: Sampling mesh created by TECPlot used in LGMAP. LGMAP landing gear geometry also shown.

TECPlot header and then a list of points with the velocity in the X and Y direction.

**LGMAP Namelist**

```plaintext
&caseFile
  debugLevel       = 10
  aircraftFileName = "Example_Cases/777_MG_Local_Flow/777.nam"
  observerFileName = 'Example_Cases/777_MG_Local_Flow/SingleCartesianPoint.nam'
  atmosphereFileName = 'Example_Cases/777_MG_Local_Flow/sea_level.nam'
  outputPlot3D     = 'Example_Cases/777_MG_Local_Flow/777_Surf'
  scatteringLevel  = 'NONE'
/

&SourceNamelist

&AircraftIn
  title                   = '777 Full Scale Aircraft'
```
nLandingGear = 1
nTrailingEdge = 0
nWing = 0
ForwardFlightMachNumber = 0.2
nBase = 1
debugLocalFlowFlag = .false.
/
&CB
  axisValue = 0.0, 1.0, 0.0
  angleValue = 0.0
/
&tLandingGearIn
  title = 'Starboard Side Main Landing Gear'
  scale = 1.0
  landingGearFileName = 'Example_Cases/777_MG_Local_Flow/Main_Gear.nam'
  nBase = 1
  nReflectiveSurfaces = 0
  localFlowSolution = .true.
/
&CB
  translationValue = -3.0,-5.49,-1.0
/
&LocalInflow
  tecplot2DFileName = 'Example_Cases/777_MG_Local_Flow/LocalFlow.dat'
  nBase = 3
/
&CB
  translationValue = 1.5, 0.0, 1.
/
&CB
  angleValue = 3.1415927
  axisValue = 0.0,0.0,1.0
/
&CB
  angleValue = 1.570796326
  axisValue = 1.0,0.0,0.0
/

Observer Namelist
&ObserverIn
  OutputFormat = 'binary'
  OutputFileName = '777_Results'
  OctaveNumber = 3
OctaveApproxFlag = .true.
SPLSpectrumOutput = .true.
gridtype = 'cartesian'
distanceUnits = 'meters'
angleUnits = 'degrees'
yMin = 0.0
yMax = 0.0
xMin = 0.0
xMax = 0.0
zMin = -100.0
zMax = -100.0
nbx = 1
nby = 1
nbz = 1
nf = 1000
fMin = 10.0
fMax = 20000.0
logarithmicSpacing = .true.
/

Atmosphere Namelist

&EnvironmentConstants
    altitude = 0.0
    tempOffset = 0.0
/

Local Flow Definition File

TITLE = "title"
VARIABLES = "X"
"Y"
"x-velocity"
"y-velocity"
ZONE T="Rectangular zone"
    STRANDID=0, SOLUTIONTIME=0
    I=30, J=30, K=1, ZONETYPE=Ordered
    DATAPACKING=POINT
    DT=(SINGLE SINGLE SINGLE SINGLE )
-2.000000000E+000 -5.000000000E-001 0.000000000E+000 0.000000000E+000
-1.724137902E+000 -5.000000000E-001 0.000000000E+000 0.000000000E+000
-1.448275805E+000 -5.000000000E-001 0.000000000E+000 0.000000000E+000
...
Upon execution, LGMAP reads in all the namelists and the local flow file. LGMAP determines the location of the acoustic element in the local flow region, and then uses the local flow at that location for the acoustic element. The acoustic element then predicts the noise as a function of the local flow velocity. An example LGMAP write out is shown below. Figure A.12 shows the noise prediction using the local flow for an observer 100 meters below the landing gear.

**LGMAP Screen Print Out**

```plaintext
Reading In Atmosphere From 'Example_Cases/777_MG_Local_Flow/sea_level.nam'.
Atmosphere Created.
Reading In Case Setup From 'Example_Cases/777_MG_Local_Flow/777.nam'.
Creating Aircraft With Title '777 Full Scale Aircraft'.
Creating Landing Gear With Title 'Port Side Main Landing Gear'.
Reading in local inflow.
Local inflow created.
Reading in wall setup with 1 number of surfaces.
Landing Gear Created.
Aircraft Created.
Reading In Observer Setup From
'Example_Cases/777_MG_Local_Flow/Observer/SinglePointSpherical.nam'.
Observer Location (m) = -114.906731  x  0.000000  x  -96.418068
Observer Created.
Case read in, moving to calculate the noise.
Calculating Landing Gear Noise.
Integrating oberver at: -114.906731, 0.000000, -96.418068
Number 1 of 1
Writting Out Binary Plot3D Multigrid Grid File To
'Example_Cases/777_MG_Local_Flow/777_FV_LG_1.x'.
```
Writing Out Binary Plot3D Multigrid function File To
'Example_Cases/777_MG_Local_Flow/777_FV_LG_1.fn'.
Run Time Was 0.000000 seconds
Fortran Pause - Enter command<CR> or <CR> to continue.

Figure A.12: LGMAP noise prediction using local flow.
A.5.5 Isolated Boeing 777 Wing With Landing Gear Wake Interaction

The next example includes using an approximation for the landing gear generated trailing edge noise caused by the landing gear wake interacting with the trailing edge of a wing/flap system. An approximation of the wake width is needed for the acoustic prediction. This can be determined by a CFD computation, flow measurement, or a simple approximation or guess. In the current example, the IBSEN [94] flow solver is used to approximate the flow field behind the landing gear. The flow is sampled on a plane perpendicular to the flight direction at the leading edge of the flap system. The projections of the trailing edge then provide a sampling line across the plane. The width of flow velocity less than \( M = 0.75M_0 \) along the line is used as the wake width parameter.

Figure A.13 shows the flow sampled on a plane perpendicular to the flow field behind the landing gear. A projection of the landing gear and trailing edge locations are also shown. The flow is sampled along the projections of the trailing edges, and the width of the region where the Mach ratio, \( M/M_0 \), is less than 0.8 is used as the wake width. For the example shown below, forward flight Mach number of 0.2 and landing gear truck angle of 13°, the wake width for the vane is 2.1 meters and for the flap is 1.47 meters. An empirically fit curve relating wake width over distance to trailing edge to turbulence intensity is used to determine the turbulence intensity. The distance to the trailing edge is found by measuring the distance from the sampling plane to the trailing edge location: this distance is 2.66 meters for the vane, and 4.22 meters for the flap. Figure A.14 shows the relationship between the wake geometry and the turbulence intensity. For this case, the turbulence intensity for the vane is 0.23, and for the flap is 0.04.

Similar to the above examples, LGMAP uses four namelists files to run: LGMAP namelist, source namelist, observer namelist, atmosphere namelist. The LGMAP, source, and observer namelists are shown below. The observer namelist defines a line of observers located below the trailing edges at a distance of 100 meters from the center of the aircraft. The source namelist includes two trailing edge elements: one for the vane and one for the flap. A wing grid file is also specified for plotting. The results from LGMAP are plotted in Fig. A.15.

**LGMAP Namelist**

```plaintext
&caseFile
    debugLevel       = 10
    aircraftFileName = "Example_Cases/777_MG_LGGTEN/777.nam"
    observerFileName = 'Example_Cases/777_MG_LGGTEN/SphericalGrid.nam'
    IBMFileName      = ''
    atmosphereFileName = 'Example_Cases/777_MG_LGGTEN/sea_level.nam'
    outputPlot3D     = 'Example_Cases/777_MG_LGGTEN/777_Surf'
    scatteringLevel  = ''
/
```

**Observer Namelist**

```plaintext
&ObserverIn
    OutputFormat   = 'binary'
```
Figure A.13: Local Mach number ratio, $M/M_\infty$, on sampling plane shown in Fig. 3.51 for $M_\infty = 0.2$. Flow is into the page. Projections of landing gear geometry, vane and flap trailing edges, and wake width measurement locations also shown. Coloring for a local Mach number of $M = 0.2 \times 0.75 = 0.15$.

```
OutputFileName = 'Example_Cases/777_MG_LGGTEN/LGGTEN'
OctaveNumber = 3
OctaveApproxFlag = .true.
SPLSpectrumOutput = .false.
gridtype = 'spherical'
distanceUnits = 'metric'
angleUnits = 'degrees'
thetaMin = 0.0
thetamax = 0.0
phiMin = 90.0
phiMax = 270.0
rMin = 100.0
rMax = 100.0
```
Figure A.14: Turbulence intensity ratio as a function of wake size and location. The curve shown is a best fit of measured values, also shown. Measurements from measurements of wakes impinging on turbine blades [88].

nbTheta = 1
nbphi = 37
nbr = 1
nf = 500
fMin = 10.0
fMax = 20000
logarithmicSpacing = .true.
nBase = 0
/

Source Namelist

&AircraftIn
title = '777 Full Scale Aircraft'
LandingGear = 0
TrailingEdge = 2
Wing = 1
ForwardFlightMachNumber = 0.2
Base = 1
debugLocalFlowFlag = .false.
/
&CB
    axisValue = 0.0, 1.0, 0.0
    angleValue = 0.0
/
&TrailingEdgeNameList
    title = 'Starboard_Side_Vane'
    metricUnits = 'METER'
    angleUnits = 'DEGREES'
    startPoint = -7.466, -3.21, -1.5
    endPoint = -7.47, -9.0, -1.675
    endChord = 2.657
    startChord = 2.657
    nBase = 0
    scale = 1.0
    L_c = 10.0
    thickness = 0.001
    noiseModel = 'lgmap'
    AoA = 0.0
    geometricAoA = -43.4
    surfaceGeometry = 'circle'
    alpha = 0.0575
    turblength = 2.10
    FWHConstant = 1.0
/
&TrailingEdgeNameList
    title = 'Starboard_Side_Inner_Flap'
    metricUnits = 'METER'
    angleUnits = 'DEGREES'
    startPoint = -8.00169, -3.1, -3.37526
    endPoint = -7.95101, -9.0, -3.5415
    endChord = 1.969
    startChord = 1.969
    nBase = 0
    scale = 1.0
    L_c = 10.0
    thickness = 0.001
    noiseModel = 'LGMAP'
    AoA = 0.0
    geometricAoA = -65.05
    surfaceGeometry = 'circle'
    alpha = 0.01
    turblength = 1.47
FWHConstant = 1.0
/
&WingNameList
title = 'Starboard Wing'
wingFileName = './Wing_Structures/Starboard_Wing.x'
nBase = 0
/

Figure A.15: LGMAP prediction of landing gear wake generated trailing edge noise. Aircraft moving at forward flight Mach number 0.2, 0° aircraft angle of attack, and 13° landing gear truck angle.
A.5.6 Full Scale Boeing 777 Wing With Landing Gear

The last example included here is a landing gear noise prediction for a complete aircraft. This includes both main landing gear, a nose landing gear, turbulent boundary layer trailing edge noise, and landing gear wake generated trailing edge noise. The prediction will also include the approximation for shielding, reflections caused by the wing, local flow in the landing gear vicinity due to circulation around the wing, and landing gear influenced component interactions. Similar to the above examples, LGMAP reads in four namelists: the LGMAP, source, observer, and atmosphere namelists. These namelists are shown below. The source definition namelist includes three landing gear (two main gear and one nose gear) each with a local flow definition, and 16 trailing edge noise sources. The main gear include reflective walls for acoustic reflections off of the wing geometry, and local flow calculated uses the above system. The nose gear uses a slightly increased uniform local flow velocity. The trailing edges include 12 trailing edge acoustic elements for the boundary layer generated trailing edge noise (6 on each wing). The remaining 4 trailing edges are landing gear wake generated trailing edges (two on each side, one for the vane and one for the flap). Figure A.16 shows the total noise prediction compared to the main gear, nose gear and landing gear wake generated trailing edge noise predictions.

LGMAP Namelist

```plaintext
&caseFile
  debugLevel = 10
  aircraftFileName = "Example_Cases/777_Total/777.nam"
  observerFileName = 'Example_Cases/777_Total/SphericalGrid.nam'
  IBMFileName = ''
  atmosphereFileName = 'Example_Cases/777_Total/sea_level.nam'
  outputPlot3D = 'Example_Cases/777_Total/777_Surf'
  scatteringLevel = ''
/
```

Observer Namelist

```plaintext
&ObserverIn
  OutputFormat = 'ascii'
  OutputFileName = 'Example_Cases/777_Total/total'
  OctaveNumber = 3
  OctaveApproxFlag = .true.
  SPLSpectrumOutput = .true.
  gridtype = 'spherical'
  distanceUnits = 'meters'
  angleUnits = 'degrees'
  thetaMin = 0.0
  thetamax = 0.0
  phiMin = 150.0
```
phiMax = 150.0
rMin  = 150.0
rMax  = 150.0
nbTheta = 1
nbphi  = 1
nbr    = 1
nf     = 300
fMin   = 10.0
fMax   = 10000.0
logarithmicSpacing = .true.
nBase = 0

Source Namelist

&AircraftIn
   title = '777 Full Scale Aircraft'
   nLandingGear = 3
   nTrailingEdge = 16
   nWing = 2
   ForwardFlightMachNumber = 0.2
   nBase = 1
dbdebugLocalFlowFlag = .false.
/
&CB
   axisValue = 0.0, 1.0, 0.0
   angleValue = 0.0
/
&LandingGearIn
   title = 'Port Side Main Landing Gear'
   scale = 1.0
   landingGearFileName = 'Example_Cases/777_Total/Port_Main_Gear.nam'
   nBase = 1
   nReflectiveSurfaces = 1
   localFlowSolution = .true.
/
&CB
   translationValue = -3.0, 5.49, -1.0
/
&LocalInflow
   tecplot2DFileName = 'Example_Cases/777_Total/LocalFlow.dat'
   nBase = 3
/
&CB
translationValue = 1.5, 0.0, 1.
/
&CB
angleValue = 3.1415927
axisValue = 0.0,0.0,1.0
/
&CB
angleValue = 1.570796326
axisValue = 1.0,0.0,0.0
/
&WallIn
normalVector = 0.0, 0.0, -1.0
pointOnPlane = -3.0,-5.49,-0.5
/
&LandingGearIn
title = 'Starboard Side Main Landing Gear'
scale = 1.0
landingGearFileName = 'Example_Cases/777_Total/Starboard_Main_Gear.nam'
nBase = 1
nReflectiveSurfaces = 1
localFlowSolution = .true.
/
&CB
translationValue = -3.0,-5.49,-1.0
/
&LocalInflow
tecplot2DFileName = 'Example_Cases/777_Total/LocalFlow.dat'
nBase = 3
/
&CB
translationValue = 1.5, 0.0, 1.
/
&CB
angleValue = 3.1415927
axisValue = 0.0,0.0,1.0
/
&CB
angleValue = 1.570796326
axisValue = 1.0,0.0,0.0
/
&WallIn
normalVector = 0.0, 0.0, -1.0
pointOnPlane = -3.0,-5.49,-0.5
/
&LandingGearIn
  title         = 'Nose Gear'
  scale         = 1.0
  landingGearFileName = 'Example_Cases/777_Total/Nose_Gear.nam'
  nBase         = 1
  localFlowSolution = .true.
/
&CB
  translationValue = 24.5, 0.0, 0.0
/
&LocalInflow
  UniformInflow = 67.571
/
&TrailingEdgeNameList
  title         = 'Starboard_Side_Slat'
  metricUnits   = 'METER'
  angleUnits    = 'DEGREES'
  startPoint    = 5.646, -3.124, -0.094
  endPoint      = -5.364, -22.621, -0.001
  endChord      = 1.01
  startChord    = 1.01
  nBase         = 0
  scale         = 1.0
  L_c           = 10.0
  thickness     = 0.001
  noiseModel    = 'BPM'
  AoA           = 0.0
  geometricAoA  = 62.148
  surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
  title         = 'Starboard_Side_Outer_Flap'
  metricUnits   = 'METER'
  angleUnits    = 'DEGREES'
  startPoint    = -7.3789, -10.0, -1.55927
  endPoint      = -9.55416, -22.63, -0.635158
  endChord      = 0.98145
  startChord    = 2.445
  nBase         = 0
  scale         = 1.0
  L_c           = 10.0
  thickness     = 0.001
  noiseModel    = 'BPM'
  AoA           = 0.0
geometricAoA = -45.82
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
  title = 'Starboard_Side_Inner_Upper_Flap'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = -7.466, -3.21, -1.5
  endPoint = -7.47, -9.0, -1.675
  endChord = 2.657
  startChord = 2.657
  nBase = 0
  scale = 1.0
  L_c = 10.0
  thickness = 0.001
  noiseModel = 'BPM'
  AoA = 0.0
  geometricAoA = -43.4
  surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
  title = 'Starboard_Side_Inner_Lower_Flap'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = -8.00169, -3.1, -3.37526
  endPoint = -7.95101, -9.0, -3.5415
  endChord = 1.969
  startChord = 1.969
  nBase = 0
  scale = 1.0
  L_c = 10.0
  thickness = 0.001
  noiseModel = 'BPM'
  AoA = 0.0
  geometricAoA = -65.05
  surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
  title = 'Starboard_Side_Inner_Main_Body'
  metricUnits = 'METER'
  angleUnits = 'DEGREES'
  startPoint = -5.49731, -3.1, 0.6128
  endPoint = -5.49731, -9.602, 0.4096
  endChord = 11.024
startChord = 7.35
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 0.0
surfaceGeometry = 'circle'

&TrailingEdgeNameList
title = 'Starboard_Side_Outer_Main_Body'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -5.4225, -9.675, 0.4065
endPoint = -8.79846, -22.6144, 0.1866
endChord = 7.35
startChord = 3.3
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 0.0
surfaceGeometry = 'circle'

&TrailingEdgeNameList
title = 'Port_Side_Slat'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = 5.646, 3.124, -0.094
endPoint = -5.364, 22.6211, -0.001
endChord = 1.01
startChord = 1.01
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = -62.148
surfaceGeometry = 'circle'

/
&TrailingEdgeNameList
title = 'Port_Side_Outer_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -7.3789, 10.0, -1.55927
endPoint = -9.55416, 22.63, -0.635158
endChord = 0.98145
startChord = 2.445
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 45.82
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Port_Side_Inner_Upper_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -7.466, 3.21, -1.5
endPoint = -7.47, 9.0, -1.675
endChord = 2.657
startChord = 2.657
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 43.4
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Port_Side_Inner_Lower_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -8.00169, 3.1, -3.37526
endPoint = -7.95101, 9.0, -3.5415
endChord = 1.969
startChord = 1.969
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 65.05
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Port_Side_Inner_Main_Body'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -5.49731, 3.1, 0.6128
endPoint = -5.49731, 9.602, 0.4096
endChord = 11.024
startChord = 7.35
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 0.0
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Port_Side_Outer_Main_Body'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -5.4225, 9.675, 0.4065
endPoint = -8.79846, 22.6144, 0.1866
endChord = 7.35
startChord = 3.3
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'BPM'
AoA = 0.0
geometricAoA = 0.0
surfaceGeometry = 'circle'
/
&TrailingEdgeNameList
title = 'Starboard_Side_Vane'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -7.466, -3.21, -1.5
dEndPoint = -7.47, -9.0, -1.675
endChord = 2.657
startChord = 2.657
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'lgmap'
AoA = 0.0
geometricAoA = -43.4
surfaceGeometry = 'circle'
alpha = 0.0575
turblength = 2.10
FWHConstant = 1.0
/
&TrailingEdgeNameList
title = 'Starboard_Side_Inner_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -8.00169, -3.1, -3.37526
dEndPoint = -7.95101, -9.0, -3.5415
endChord = 1.969
startChord = 1.969
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'LGMAP'
AoA = 0.0
geometricAoA = -65.05
surfaceGeometry = 'circle'
alpha = 0.01
turblength = 1.47
FWHConstant = 1.0
/
&TrailingEdgeNameList
title = 'Port_Side_Vane'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -7.466, 3.21, -1.5
dEndPoint = -7.47, 9.0, -1.675
endChord = 2.657
startChord = 2.657
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'lgmap'
AoA = 0.0
geometricAoA = 43.4
surfaceGeometry = 'circle'
alpha = 0.0575
turblength = 2.10
FWHConstant = 1.0
/title
&TrailingEdgeNameList
title = 'Port_Side_Inner_Flap'
metricUnits = 'METER'
angleUnits = 'DEGREES'
startPoint = -8.00169, 3.1, -3.37526
endPoint = -7.95101, 9.0, -3.5415
endChord = 1.969
startChord = 1.969
nBase = 0
scale = 1.0
L_c = 10.0
thickness = 0.001
noiseModel = 'LGMAP'
AoA = 0.0
geometricAoA = 65.05
surfaceGeometry = 'circle'
alpha = 0.01
turblength = 1.47
FWHConstant = 1.0
/title
&WingNameList
title = 'Port Wing'
wingFileName = 'Example_Cases/777_Total/Port_Wing.x'
nBase = 0
/title
&WingNameList
title = 'Starboard Wing'
wingFileName = 'Example_Cases/777_Total/Starboard_Wing.x'
nBase = 0
/title
Figure A.16: Noise prediction for both main landing gear using FLUENT two-dimensional local flow solution with 0° wing cross section angle of attack and flap setting 2. Observer grid on plane 150 meters below aircraft.
Leonard Vincent Lopes was born in New York City, New York on July 8th of 1980 and began his undergraduate studies in Computer Engineering at the University of New Mexico in 1998. In 2000, he transferred to The Pennsylvania State University and changed majors to Aerospace Engineering. In 2002, under Dr. Kenneth S. Brentner, he started research in the rotorcraft acoustic community; as one of the primary developers of PSU-WOPWOP, a widely used rotorcraft acoustic prediction code. He received his undergraduate degree in Aerospace Engineering in 2003 and continued his work on rotorcraft acoustics, publishing several papers on maneuvering flight and real-time acoustic prediction. He continued work at The Pennsylvania State University where he received his Masters Degree in Aerospace Engineering with a minor in High Performance Computing on a component based landing gear noise prediction scheme called LGMAP in 2005. After receiving his Masters Degree, he continued to work on landing gear and rotorcraft noise prediction, receiving the American Helicopter Society Vertical Flight Foundation Scholarship in 2008. During his PhD, he published work on the acoustics of tip-jet driven rotors as well as landing gear noise prediction. He has been a member of the American Institute of Aeronautics and Astronautics and of the American Helicopter Society since 2001.