Increased Fidelity in Prediction Methods For Landing Gear Noise

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An aeroacoustic prediction scheme has been developed for landing gear noise. The method is designed to handle the complex landing gear geometry of current and future aircraft. The gear is represented by a collection of subassemblies and simple components that are modeled using "acoustic elements." These acoustic elements are generic, but generate noise representative of the physical components on a landing gear. The method sums the noise radiation from each component of the undercarriage in isolation acounting for interference with adjacent components through an estimate of the local upstream and downstream flows and turbulence intensities. The acoustic calculations are made in the code LGMAP, which computes the sound pressure levels at various observer locations. The method can calculate the noise from the undercarriage in isolation or installed on an aircraft for both main and nose landing gear. Comparisons with wind tunnel and flight data are used to initially calibrate the method, then it may be used to predict the noise of any landing gear. In this paper, noise predictions are compared with wind tunnel data for model landing gears of various scales and levels of fidelity, as well as with flight data on full-scale undercarriages. The present agreement between the calculations and measurements suggests the method has promise for future application in the prediction of airframe noise.

Nomenclature

$< p^2(S,\theta,\phi) >$	Mean-square acoustic pressure
S	Modified Strouhal number, $S = \frac{fd}{M_\infty c_\infty}(1 - M_\infty cos\theta)$
θ	Polar directivity angle, 0^o front of aircraft and 180^0 behind aircraft
ϕ	Azimuthal directivity angle, 0^o below aircraft and 90^0 to the side
ρ_∞	Mean atmospheric density
c_∞	Ambient speed of sound
Π^*	Non-dimensional acoustic power, referenced to $\rho_\infty c_\infty^3 b_w^2$
N	Number of wheels on landing gear
r_s^*	Non-dimensional distance from source to observer, referenced to b_w
b_w	Span of wing
M_∞	Aircaft Mach number

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K	Constant
L	Landing gear strut length
$F(S)$	Spectrum function
$D(\theta, \phi)$	Directivity function
d	Tire diameter
f	Frequency
D	Cylinder Diameter
C_l'	Lift coefficient
C_d'	Drag coefficient
V_n	Incident velocity

I. Introduction

Noise generated by aircraft in high traffic areas is an annoyance to surrounding communities, and the amount of noise an aircraft generates is a strong design limitation in new aircraft. As a result, much effort has been applied to reducing the noise of all aircraft that operate near communities, specifically large civilian transport airplanes. At take-off and overflight conditions, the engines are the major contributor to aircraft noise. On approach, however, the engines operate at reduced power and the aircraft is in a high-lift configuration. With the advances in engine noise reduction and the airframe operating in a dirty configuration, the airframe generates noise comparable with that of the engine.

Airframe noise is the non-propulsive noise generated by the aircraft, including the landing gear, flaps, and slats. Even though each of these noise sources generate sound by different physical mechanisms, the noise generated is similar in strength. Therefore, all of these noise sources need to be reduced if the noise from the total airframe is to reduced by a significant amount. This makes the reduction of landing gear noise essential.

A landing gear geometry is composed of bluff bodies with different cross sections, sharp corners, curved hoses, and small fittings. These details make predicting the noise from landing gear different from other airframe noise sources. The complex geometry includes many small components that contribute to the higher frequencies. Because of weighting factors that emphasize the higher frequency ranges typical of human hearing, the higher frequencies are more significant to the perceived noise. An important task is to identify those components that generate the greatest noise and then suggest local treatments to address noise reduction. Therefore, there is a need for a prediction scheme that can identify and rank the many sources of sound and their mechanisms in the landing gear geometry.

The landing gear is known to be a source of primarily broadband noise. This broadband noise is the summation of the noise generated by all of the various components of the landing gear. Larger components, such as the wheels and the oleo, radiate noise at relatively low frequencies; brackets, struts, and other medium size components radiate noise in the mid-frequency range; and small fittings, hoses, pipes, etc. are known to radiate at higher frequencies. Figure 1 demonstrates the difference in noise generated between two landing gear models: a low and a high-fidelity Boeing 737 scale-model landing gear, tested in the Boeing Low Speed Aeroacoustic Facility (LSAF) at Boeing by Stoker.[1] The clean wind tunnel model does not include hoses and other small features of the landing gear. Note the difference in the high frequencies above the 26th octave band. The detailed flow and acoustic fields of small components such as wires, hoses, bolts, etc. are nearly impossible to compute directly. 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.[2]

One standard for predicting airframe noise is the airframe noise component of the Aircraft Noise Prediction Program (ANOPP),[3] based on the noise prediction scheme developed by Fink.[4,5] This method is based on an experimental database of aircraft flight data as well as wind tunnel tests by Heller and Dobrzynski.[6] The landing gear noise prediction in ANOPP involves a simple empirical prediction method based on wind tunnel and flight noise measurements of simplified landing gear. However, as shown in Eq. 1 and Table 1, the total noise is expressed in variables based on the diameter of the wheels for the truck noise and the length of the oleo for the support strut noise. The support strut assembly includes the oleo and any support struts as well as any fittings and doors. The truck assembly includes 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[1] have shown that although the overall sound pressure level is predicted reasonably well by ANOPP, the noise spectrum is underpredicted in the higher frequencies. Since ANOPP relates the noise sources to the properties of only two gross features of the landing gear, it is clearly not suited for the identification of particular landing gear components or parts of components that are the strongest local noise sources.

$$< p^2(S,\theta,\phi) >= \rho_\infty^2 c_\infty^4 \frac{\Pi^*}{4\pi r^{*2}} \frac{D(\theta,\phi)F(S)}{(1-M_\infty cos\theta)^4} \tag{1}$$

Sound Due To The Wheel	Sound Due To The Strut
$\Pi^*_{wheels} = K_{wheels} M_\infty^6 (\frac{d}{b_w})^2 N$	$\Pi^*_{strut} = K_{strut} M_\infty^6 (\frac{d}{b_w})^2 \frac{L}{d}$
$D(\theta,\phi)_{wheels} = \frac{3}{2} sin^2\theta$	$D(\theta,\phi)_{strut} = 3 sin^2\theta sin^2\phi$
$F(S)_{wheels} = 0.0577 S^2 (1 + 0.25 S^2)^{-1.5}$	$F(S)_{strut} = 1.280 S^3 (1.06 + S^2)^{-3}$

Table 1. The acoustic power, Π^*, directivity function, $D(\theta,\phi)$ and spectrum function, $F(S)$, used in ANOPP for the wheel and strut components of a four-wheel landing gear.

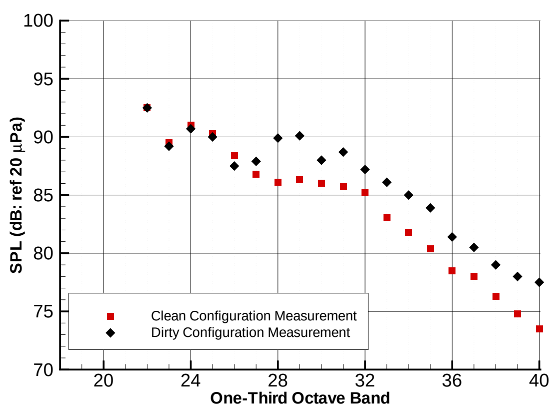

Figure 1. 737-400 landing gear measurements for Mach number = 0.20.

Recently, there has been an attempt to categorize the components of the landing gear into three main frequency ranges depending on their size (namely very-low, low and high frequency).[7,8] This scheme, although predicting each of these frequency ranges, does not provide a direct correlation of the noise generated to geometrical components of the landing gear. The present paper describes an alternative approach to the prediction of landing gear noise, called the Landing Gear Model and Acoustic Prediction (LGMAP) code. LGMAP contains a limited number of simple, generic acoustic elements, which are used to represent the noise generated by geometrically similar parts of a very complex landing gear. Each acoustic element can represent a certain type of component on a landing gear. Each element applied to a component generates an acoustic signal related to the component's size and its local flow environment. This approach retains the simplicity needed to make the noise prediction problem tractable, yet has the geometric flexibility needed to model a realistic landing gear. It also provides detailed information about how each physical component contributes to the overall radiated noise. Finally, the acoustic elements can be improved, with all the landing gear components that use that acoustic element benefiting from such an improvement.

This paper is organized as follows. First, the acoustic elements contained in LGMAP are described. Initial LGMAP noise predictions are compared with experimental results to demonstrate the ability of LGMAP to predict the noise and the future potential of the approach.

II. Description of LGMAP

The computer code LGMAP provides a new approach for predicting landing gear acoustics. The main philosophy guiding the development of LGMAP is to include as much of the geometric complexity of the actual landing gear as possible, but to use simple modeling of the loading and acoustic field for each element to make the noise prediction tractable. This is achieved by recognizing that a landing gear is comprised of components each having a complex geometry. The geometry and positions of all the simple elements, which represent the building blocks for each component, are thus inputs into the code. In addition, details of the local flow characteristics are needed, but these are modeled rather than calculated directly, because computation of the complicated turbulent flow around a complete landing gear by computational fluid dynamics (CFD) is considered impractical. The LGMAP framework allows for flow interference between components to be added later. The code includes installation effects by estimating the acoustic shielding a component would experience when the line of sight to an observer is blocked by a larger component. Based on this framework, the LGMAP code can output the noise from individual components or from the entire gear.

The central feature of LGMAP is a "toolbox" of acoustic elements, as shown in Fig. 2. These include cylinder objects (these can be of any size and any cross section), edge objects (including door edges or flaps), small fittings, and wheels. These objects are the building blocks that are used to construct any landing gear configuration. Each object has a geometric representation and uses an upstream local environment to predict the noise. The geometry includes position in the landing gear configuration and a geometric representation of the object while the upstream environment includes the local flow properties and turbulence levels. Each elemental model uses the component's geometry and upstream environment to generate noise and creates a downstream environment which is passed to the next acoustic element in the geometry as an upstream environment.

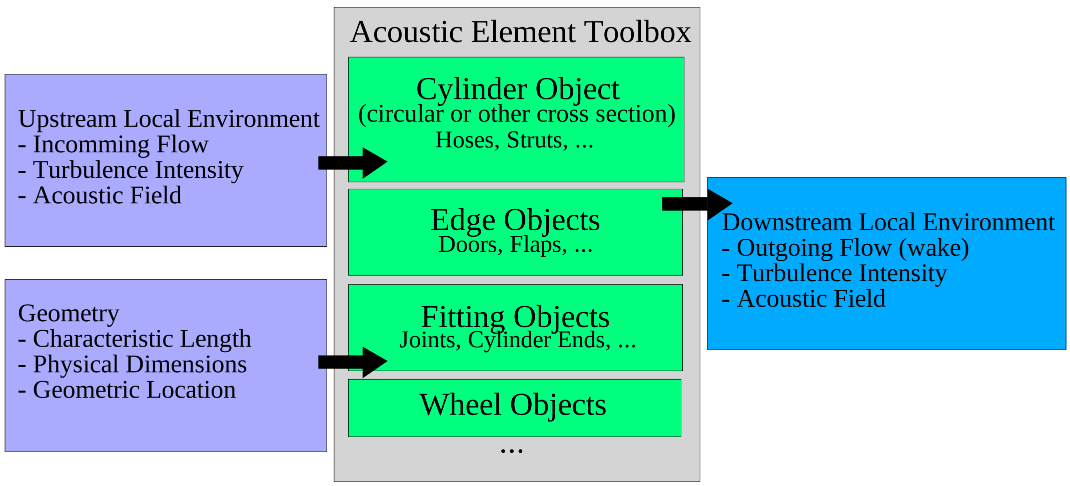

Figure 2. Schematic of the toolbox of acoustic elements implemented in LGMAP.

LGMAP is an extension of the acoustics program PSU-WOPWOP,[9,10] and uses an object-oriented design implemented in Fortran 95. As such, it is a general purpose acoustics prediction code. The code uses a source–time–dominant algorithm to compute the radiated noise using Farassat's Formulation 1A[11] of the Ffowcs Williams–Hawkings equation[12] at an arbitrary observer location. It is shown in Ref. 13 that the loading term of the FW-H equation radiates noise more efficiently than the thickness term: therefore only the loading term is included in LGMAP. The influence of the wing/flap/door trailing edges on the noise radiated from the undercarriage and its wake involves a special model based on the Ffowcs Williams-Hall diffraction theory for acoustic sources in the vicinity of a sharp edge.[14]

A. 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.

1. Cylinder Acoustic Element

A cylinder experiences unsteady forces at frequencies associated with unsteady vortex shedding. In uniform flow, the cylinder experiences shedding at lift and drag shedding frequencies, which are somewhat different for various cross section shapes. But, to account for the turbulent environment, high Reynolds number, and surface roughness expected on and in the vicinity of the undercarriage, the unsteady loading spectrum in the

LGMAP cylinder model is broadened with a distinct peak at the Strouhal frequency based on the cylinder's diameter. Using a broadband loading spectrum on the cylinder-like components of the landing gear also accounts for the fact that the physical landing gear components are typically neither smooth nor of constant cross section in the spanwise direction.

Because of the simple rectilinear motion and the far-field assumption, the unsteady loading on the cylinder is the primary source of noise generation for a landing gear geometry.[13] 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 assumed to be compact in the 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 dimensional shedding frequency, and the dimensional fluctuating lift and drag forces are determined by scaling the loading for each cylinder element using the normal component of the local velocity[a], v_n, and the nominal cylinder diameter, D. 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,

$$F_{ND}(S) = AS^{e-1}(B + S^p)^{-e} \tag{2}$$

$$A = \left[\int_S \frac{1}{A} F_{ND}(S)\right]^{-1} \qquad B = -S_0^p \left(\frac{e(1-p)-1}{e-1}\right)$$

$$L'(S) = \frac{1}{2}\rho V_n^2 D C_l' F_{ND}(S) \qquad D'(S) = \frac{1}{2}\rho V_n^2 D C_d' F_{ND}(2S)$$

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. Two such functions are shown in figure 3.

In principle, the parameters used in the non-dimensional spectrum could determined from available measurements or computations. One potential source for guidance is the extensive collection of cylinder data found in Zdravkovich.[15,16] However, there is little confidence in using the unsteady force coefficient data for a smooth surface cylinder in a low Reynolds number, low-turbulence environment. Instead, initial values found in Zdravkovich have been modified slightly to more closely reproduce results form landing gear noise experiments.

2. 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. Furthermore, the wheels generate noise which 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 the important mechanisms.

The truck wheels are represented in LGMAP by a circular ring of cylinders, which allows noise to be radiated sideways and downwards as proposed by Crighton[17] in his review of the early work of Heller and Dobrzynski.[6] The ring of cylinder elements has a diameter equal to the tire outside diameter, and each cylinder on the ring has a diameter equal to the tire width. Although cylinder segments are used to make up the wheel ring, a different loading spectrum is used for the wheel cylinder segments. The spectrum and corresponding forces on each cylinder are chosen so that this wheel model would have the same peak shedding frequency found in the ANOPP formula for wheels.

[a]In the initial implementation of the cylinder objects, the local upstream velocity is assumed to be the freestream velocity for convenience.

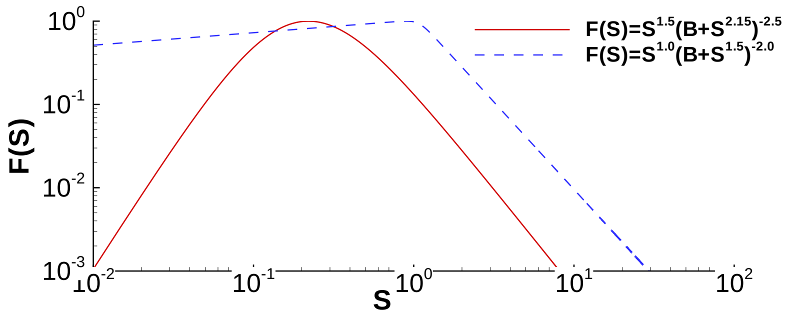

Figure 3. Typical loading spectra for a cylinder acoustic element, $F(S)$ (multiplied by A^{-1} for ease of comparison) red line (———) has a peak value of $S_0 = 0.22$; and the blue line (– – –) has a peak Strouhal number of $S_0 = 1.0$.

The present wheel model is considered crude; hence, more work is needed to refine the wheel model. In the future, alternative wheel models will be developed to better represent the noise generated by the wheels, especially at the higher frequencies. For instance, surface pressure data from a CFD computation could be used to determine the noise radiation of a wheel including small surface features, such as the tire treads, which add to the higher frequencies. Even so, the wheels may not be a prominent noise source because their primary contribution to the spectrum is at lower frequencies.

3. Trailing Edge Acoustic Element

The fluctuating loads on the components of the landing gear are effectively modeled as acoustic dipoles having a velocity dependence of V_∞^6. However when acoustic sources are within an acoustic wavelength of a sharp edge, scattering of the pressure field upstream of the edge leads to a diffraction of the resulting sound by the edge. The noise radiated to the acoustic far field is proportional to V_∞^5. In the case of the landing gear there are three edges to consider:(i) the landing gear door, often attached to the oleo strut, (ii) the wing trailing edge and (iii) the flap trailing edge, which is close to the landing gear wake. The wing and flap interactions only occur for noise predictions for an installed gear. In some installations the distance from the undercarriage to the wing/flap trailing edge is within a wavelength of the lower frequencies generated by the undercarriage. Flight experiments confirm that installed landing gear noise has a mix of noise sources having both velocity scaling laws of V_∞^5 and V_∞^6. Although the current predictions do not include these noise sources, allowances for the diffraction of noise from the landing gear door and from the wing/flag trailing edge are included in LGMAP.

B. Flow Interactions

Because the landing gear geometry has many parts of varying sizes, upstream components have a strong influence on downstream components. Some of these influences include the change in direction and magnitude of the local flow velocity, and an increase in turbulence level experienced by a downstream component. These interactions are challenging to compute directly but can be estimated in the LGMAP model by simple mechanisms. This is accomplished by modifying the downstream components forcing function, $F(S)$, to indicate the upstream component influence. The incoming flow into an acoustic element is used to predict the interaction by means of the upstream and downstream environments in the LGMAP model.

The upstream environment includes the local flow velocity, the incoming turbulence level, and an incident acoustic field. The local flow velocity is likely to be important when considering small scale components adjacent to larger scale parts, large scale components generating wakes which convect into small components, the boundary layer of the wing interacting with the landing gear, or other similar phenomena. The incoming turbulence level potentially affects the loading force spectrum and loading level on the component.

The flow, turbulence, and acoustic properties of the downstream environment are modified versions of the upstream environment. This environment becomes the upstream environment for other elements.

C. Acoustic Interactions

Acoustic interactions are a perticularly interesting and challenging coupling between elements in the landing gear geometry. In a landing gear configuration, there is a large range of component sizes, and a related range of acoustic wavelengths. Although in the current implementation acoustic elements have no direct interaction, clearly the acoustic field from some components may be strongly affected by other components. In particular, it should be expected that when a small component radiates sound at short wavelengths, then a larger object will scatter the sound field of the smaller component. In fact, depending on the relative size and spatial relationship, the acoustic signal from one component may be completely shielded by another component with the result that the small component would not contribute to the total acoustic field at some observer locations. Although LGMAP, at this point, does not include direct acoustic interactions certain code practices, including object orientation, has been performed to facilitate this in future development.

A full prediction of acoustic scattering will be difficult to implement due to the complex geometry of the landing gear. Initial modeling will focus on shielding - depending upon the relative size and proximity of components. The initial implementation of acoustic interactions in LGMAP will not include the noise of smaller components that do not have a direct line of sight to the observer. A simple variation of this might give some approximation to a scattered field: i.e., a fraction of the noise from shielded components might be received by the observer. A parallel implementation of more advanced interaction between acoustic elements could be particularly effective when coupled with an iterative approach to the acoustic scattering problem. Such enhancements are envisioned only in future generations of LGMAP.

III. Calibration

The present version of the code LGMAP has been carefully calibrated against available experimental data on model landing gears tested in wind tunnels and from full-scale flight tests. Refinements to the acoustic models and further calibration as better data becomes available can be used to improve the fidelity of the entire prediction methodology. Comparisons have been made between the calibrated fluctuating loads coefficients in the program and those for the corresponding elements in isolation. In the case of cylindrical elements the load coefficients do not differ significantly from those given by Zdravkovich[15] – even though the cylindrical acoustic elements are actually intended to represent very rough cylinders in the turbulent flow environment surrounding the undercarriage.

A. Cylinder Model Calibration

The model DC-10 nose gear experiments were performed by Heller and Dobrzynski[6] at the outdoor "Wall-Jet Flow Facility" located at the DFVLR Trauen Test Grounds. The measurements for a sideline observer are dominated by the oleo or strut noise. Thus the data at this observer position has been used to calibrate the spectrum shape and the unsteady loading coefficients for the cylinder model. These values are shown in Table 2. See Ref.13 for more details.

e	p	S_0	C_l'	C_d'
2.5	2.15	0.22	0.17	0.085

Table 2. Parameters used in the cylinder model.

B. Wheel Model Calibration

To calibrate the parameters used in LGMAP for wheels, the ANOPP wheel noise model is used. ANOPP only includes contributions from the oleo or strut and the wheels. In the case considered, the aircraft is flying at 120 m 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 the support struts. Using ANOPP to calibrate the wheel model at two observer locations gave the parameters needed for calibration. See Ref.13 and 18 for more details. Table 3 shows the values of the wheel model parameters.

e	p	S_0	C'_l	C'_d
2.0	1.5	0.18	0.34	0.17

Table 3. Parameters used in the wheel model.

IV. 737 Undressed Configuration

To assess the effect of adding smaller physical components into the LGMAP representation of a landing gear, an example case of a model scale, uninstalled Boeing 737-400 main gear is concidered. Noise predictions are compared with the wind tunnel measurements of Stoker.[19] The test stup, shown in figure 4a, 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 includes the addition of hoses, shown in figure 4b. 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.

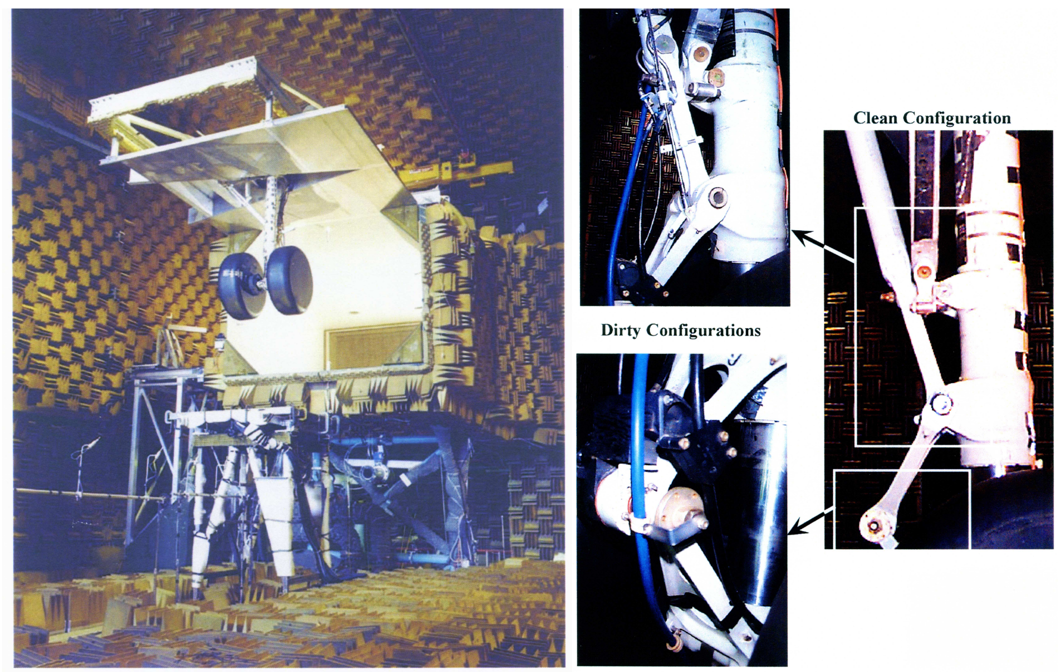

Figure 4. a) The test setup of the wind tunnel results of a Boeing 737-400 main gear at the Low Speed Aeroacoustic Facility (LSAF) at Boeing. b) Close up of landing gear with and without dressings.

In Fig. 5, 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 wheel models 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 with a 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.[18] The noise predictions from LGMAP should scale like Mach number to the sixth power, i.e., V^6. The measurements and predicted values are shown in Fig. 6 scaled according to Mach number. The agreement between the measurements and predictions is 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 is currently unknown. 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 is expected as all the acoustic elements have a sixth power dependency on velocity.

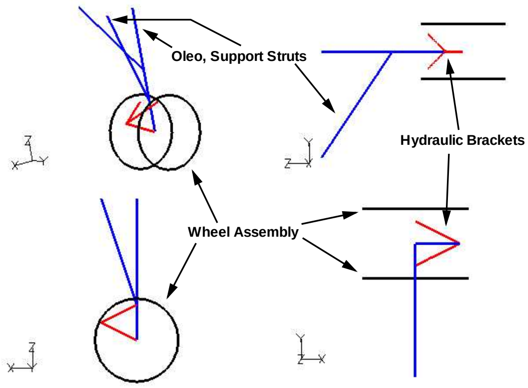

Figure 5. Close up of LGMAP representation of undressed Boeing 737-400. Support assembly models are blue (———), hydraulic bracket models are red (———), and wheel models are black (———).

Even though the LGMAP model for the 737 is 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 at this stage in its development. Nevertheless, the current LGMAP model is unable to predict all of the subtle details in the spectrum. It is unclear whether this discrepancy should be attributed to the LGMAP prediction approach, the LGMAP geometry detail used, or some aspect of the wind tunnel measurements.

V. Increasing Fidelity in LGMAP Model

Landing gear geometries are not usually as clean as the gear used for the measurements shown above. In use, the gear will have hoses running along the oleo and truck other smaller scale components that generate

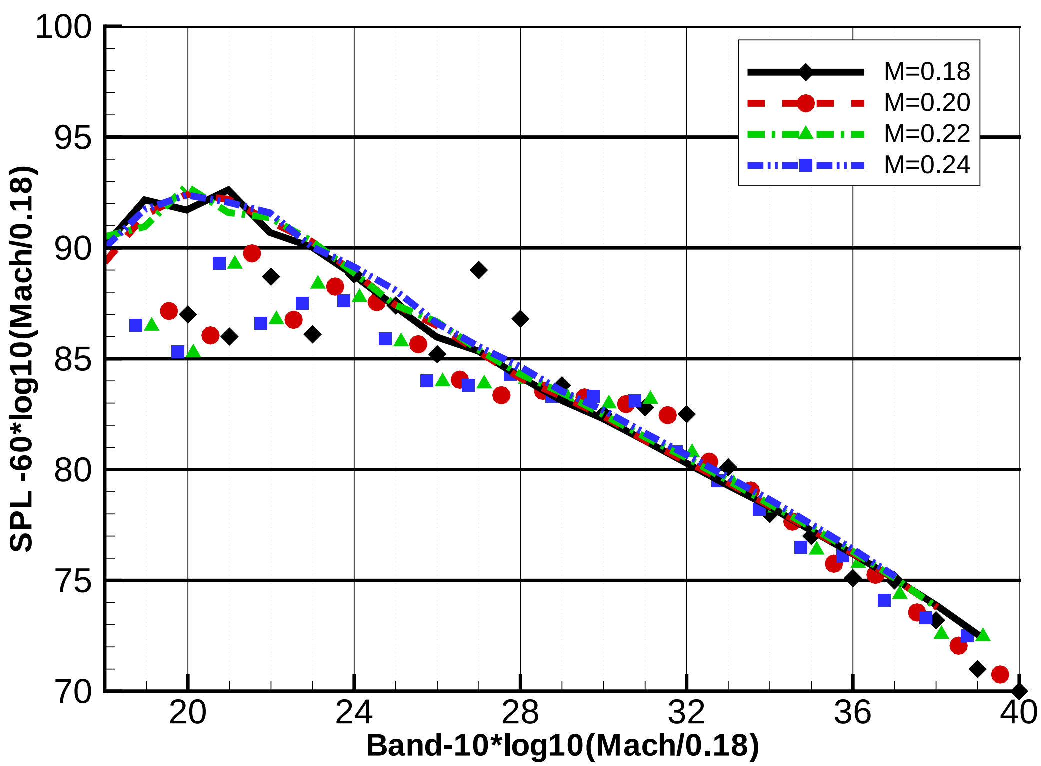

Figure 6. Undressed 737-400 landing gear wind tunnel measurements (symbols) and LGMAP predictions (lines) for Mach numbers of 0.18, 0.20, 0.22 and 0.24 scaled by V^6.

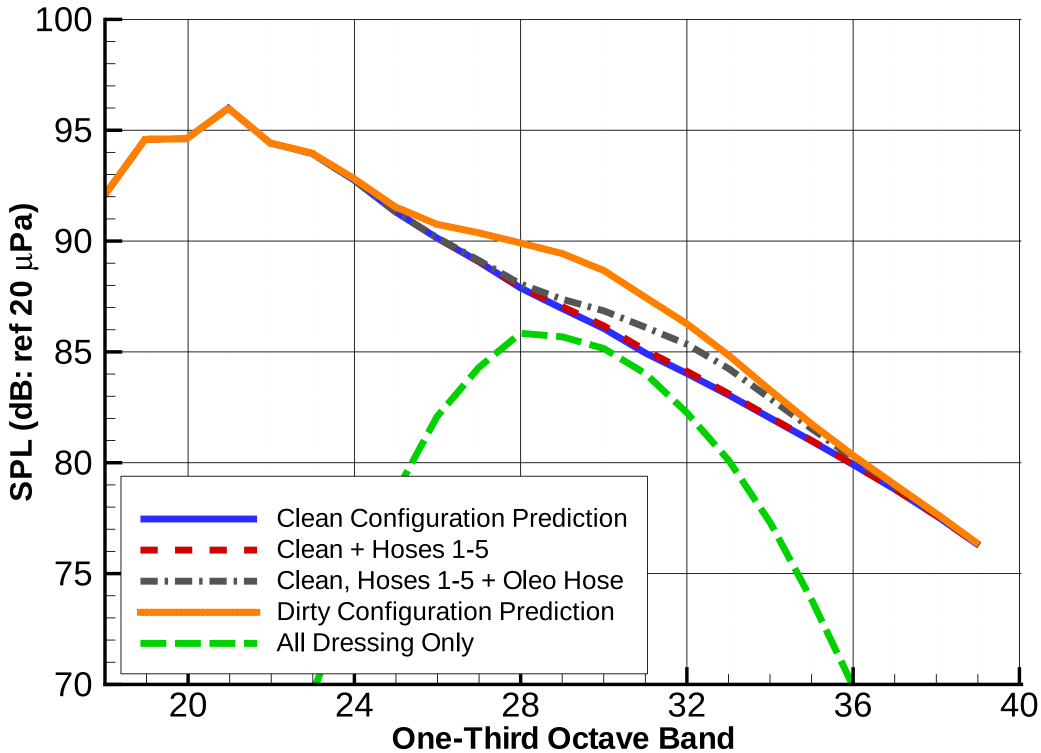

Figure 7. LGMAP 737-400 landing gear prediction for Mach number of 0.20 with various hose configurations.

noise within a certain frequency range. The measurements conducted by Stoker were for a landing gear with and without hoses installed to show how the noise changes. To demonstrate how LGMAP can predict this change cylinder models representing these hoses were added and compared to the wind tunnel experiments. In Fig. 7, the noise from an LGMAP prediction for a Mach number of 0.20 is shown with hoses added sequentially to show how the noise increases with each increase in the fidelity of the gear geometry. The first prediction is for a clean gear. As each hose is added, the levels in the frequency range indicative of the small diameter hoses increases, until the complete dressed prediction is reached. This demonstrates that as more small detailed components are added, the noise prediction improves.

The LGMAP wireframe representation of the dressed configuration of the 737 is shown in Fig. 8a. 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. In Fig. 8b, the dressed LGMAP prediction is shown at a Mach number of 0.20 and is compared to both the dressed and undressed 737-400 landing gear measurements.

It should be noted that as the geometric complexity used in the LGMAP model increases, more complete modeling is implemented. The noise prediction may not continue to increase in amplitude, but because higher-order flow modeling is taken into account, the noise prediction will contain more variation with frequency, possibly predicting the peaks in the wind tunnel measurements. Also, the very short hoses in the truck were replaced by a single hose of the same diameter across the truck. In future predictions, when a more accurate geometric representation of the actual landing gear geometry is known, this will be replaced by each individual hose.

The same comparisons are made in Fig. 9 for a range of Mach numbers from 0.18 to 0.24. Also shown in Fig 8b are the predictions by Guo[8] for a similar configuration and Mach numbers. The predictions by Guo separate the noise sources into three groups based on size. These 3 groups are scaled according to complexity but without insight into what is causing the noise.

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.

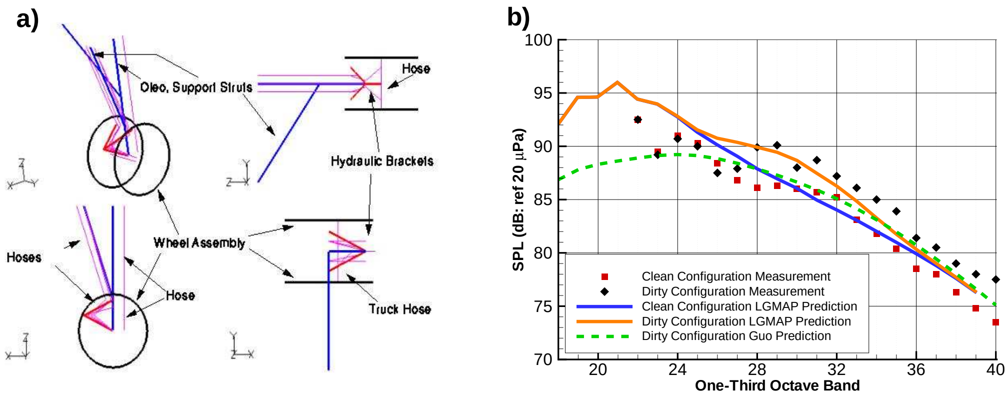

Figure 8. a) Four close-up views of the of LGMAP representation of a dressed Boeing 737-400 Landing Gear. Support assemblies are blue (———), hydraulic brackets are red (———), wheel assemblies are black (———), and hoses are violet (———). b) Wind tunnel measurement and dressed LGMAP prediction for Mach number of 0.20.

VI. Concluding Remarks

The framework for the prediction of noise from a complex geometry landing gear using a toolkit made of simple acoustic elements has been presented. The simple acoustic elements primarily include cylinders with a modeled shedding frequency spectrum both physics and empirically based. The majority of components on the landing gear are modeled as cylinders and the wheels are represented by a ring of cylinders. Each cylinder then generates noise in a frequency range dependent on its shape and local flow. This paper demonstrates that this model can predict the radiated noise of the complete structure at certain observer positions. Previously, this type of design had not been applied to a structure as complex as a landing gear, but it has been shown that this approach can produce adequate results for several Mach numbers and several landing gear designs.

The framework shown is much more robust than a fully empirical model such as ANOPP and is many factors of magnitude less expensive in time and computer cost than a full numerical calculation using CFD. Unlike any previous prediction system, it is also object oriented to allow for expansion and improvement over time as well as detialed enough to allow for component acoustic analysis to identify those components generating the most significant noise. Theses feature will significantly help in the design of future landing gear geometries because designers will have an analytical tool that can make efficient predictions based on small changes in geometry.

It is expected that the fidelity and accuracy of the acoustic elements will evolve over time: initially described by simple acoustic models, validated by comparison with experiments and flight data, and followed by revisions and refinements. This framework is based upon the assumption that that full numerical simulation will be impractical if not impossible to achieve. As further geometric details, additional source mechanisms such as trailing edge scattering, or acoustic effects such as shielding, are predicted, the execution time for the code will increase. However, it is certain to be orders of magnitude less computationally expensive than a direct noise calculation and orders of magnitude less expensive in cost than an experiment.

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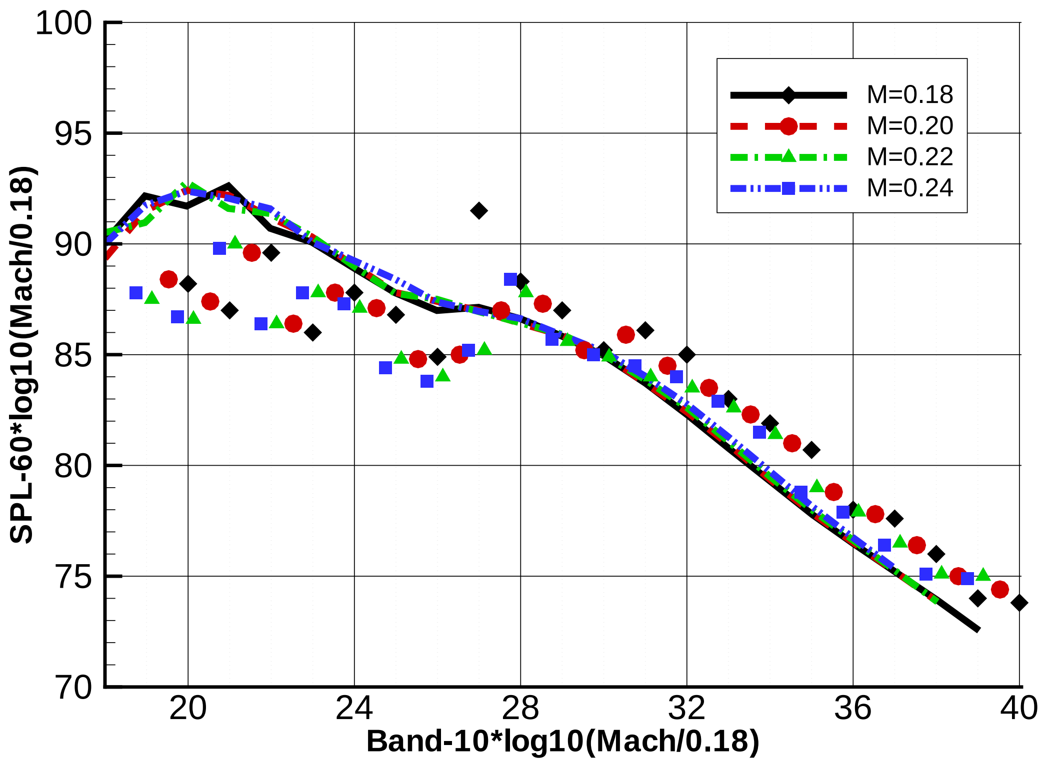

Figure 9. Dressed wind tunnel measurement and dressed LGMAP prediction for Mach numbers of 0.18, 0.20, 0.22 and 0.24 scaled by V^6. Predictions by Guo[8] are also shown.