Complex Landing Gear Noise Prediction Using a Simple Toolkit

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I. Abstract

This paper describes the initial development of a method for the prediction of the noise radiated by aircraft landing gear. Called the Landing Gear Model and Acoustic Prediction (LGMAP), it will eventually include all the geometric complexity of a realistic landing gear. This will be achieved by dividing the gear into a number of elements or objects. The noise from each of these elements is described by a simple acoustic model. Each object has three attributes; its geometry and location, and an upstream and downstream environment. This enables the flow or noise from one element to interact with any other. The method is designed to allow improved element acoustic models to be introduced as they become available. This paper contains some initial examples for two objects; a cylinder element and a wheel model. The landing gear is divided into assemblies made up of these elements. The radiated noise is calculated in the time-domain using a source–time–dominant solution to the Ffowcs Williams–Hawkins equation. This initial, rather crude, model is calibrated by comparison with experiment and existing noise prediction methods. The purpose of this paper is primarily to introduce the modeling philosophy rather than make extensive predictions. Though more than one example is given. The model is still in its early development stages and many important acoustic mechanisms are not included. Some of the future plans and necessary extensions to the model are discussed.

II. Introduction

The goal of NASA’s Advanced Subsonic Technology (AST) Program is a total aircraft noise reduction of 10 EPNdB relative to 1997 levels. Previously, engine noise has been the major source of aircraft noise, but with the introduction of engine noise reduction technologies, it has been found that on approach the airframe noise is comparable with the engine noise and could well exceed it in the future. At take-off the
major component of aircraft noise is still the engine noise since the engine is operating at full power. Whereas, on approach, with the flaps and slats deployed and the landing gear down, the engine is only a little over idle power.

None of the various airframe noise sources are dominant; therefore, the total airframe noise can only be reduced significantly if all of its components are reduced by a similar amount. This makes the reduction of landing gear noise essential. But landing gear components consist of bluff bodies with different cross sections, sharp corners, curved hoses, and small fittings. Each of these features may generate or encounter highly separated turbulent wakes. Any attempt to introduce streamline fairings covering all of the landing gear components would not only be impractical but also operationally unacceptable. Thus an important task is to locate those components or parts of components that generate the greatest noise contributions and then to provide local treatments to reduce the noise. Clearly, there is an important need for a noise prediction method that enables the many components to be ranked on the basis of their contribution to the total noise.

The preliminary stages of the development of such a model are described in this paper.

The landing gear is known to be a source of primarily broadband noise comprised of the noise generated by all of the various components of the landing gear. Large components, such as the wheels and the oleo strut radiate noise due to the turbulent flow around them 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. Therefore, it is critical to include the smaller components in a prediction scheme. Yet the detailed flow and acoustic fields of small components such as wires, hoses, bolts, etc. are nearly impossible to compute directly. Some form of modeling is absolutely required to have any hope of predicting the noise from a typical landing gear.

The airframe noise component of the Aircraft Noise Prediction Program (ANOPP),\textsuperscript{2} based on the noise prediction scheme by Fink,\textsuperscript{3,4} is one such model that has been developed for noise prediction. The method is based on an experimental database of aircraft flight data as well as wind tunnel tests by Heller and Dobrzynski.\textsuperscript{5} The landing gear part of the method is described briefly in the Appendix. It is based on the assumption that the overall noise of a landing gear can be expressed in terms of the dimensions of two major components: the number and diameter of the wheels and the length of the oleo strut. The noise directivity is described by an empirical function, which is different for both components. Recent flyover measurements by Stoker\textsuperscript{6} have shown that although the overall sound pressure level is predicted quite well by ANOPP, the noise spectrum in the higher frequencies is underpredicted. The missing high-frequency noise is presumably generated by the numerous small scale components, such as hydraulic pipes, pins, and flanges, all of which have their own “signature tune” at high frequencies. Since ANOPP relates the noise sources to the properties of 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.

In this paper an alternative approach is taken to model the landing gear noise. A limited number of simple, generic acoustic elements or “objects” are defined, which in turn can be used to build up a very complex model of the landing gear. Each element generates an acoustic signal related to the element size and its local flow environment. This approach retains the simplicity needed to make the noise prediction problem tractable, and yet will contain the geometric complexity of a realistic landing gear. It also will provide detailed information about how each element contributes to the radiated noise. Finally, the acoustic model used in each of the simple acoustic elements can be refined as additional experiments or computations become available, with all the landing gear components benefitting from such an improvement.

The preliminary predictions in this paper are calibrated by comparisons with wind tunnel tests and the present ANOPP method. The case of an installed landing gear is not considered here: but will be a feature of future extensions. Thus, it is expected that the present predictions will scale with $M^6_\infty$, where $M_\infty$ is the aircraft Mach number. Flight data, which include the interference between the landing gear and the airframe, show a scaling of $M^6_\infty$, although the higher frequencies still scale with $M^5_\infty$. At $M_\infty = 0.2$ this results in a 7 dB increase in noise. The landing gear wake interference with the wing and slat trailing edges might add another 3 dB. However, the speed of the flow approaching the main landing gear under conditions of high lift could be reduced to a local Mach number, $M_\infty = 0.15$, giving a reduction of 6 dB.

The present paper is organized as follows. First the general approach is introduced. Then the noise prediction method for each element is described. Both wind tunnel and the ANOPP landing gear noise formula are used to calibrate some of the model parameters. Then an initial noise prediction is compared with a recent experiment to demonstrate the potential of the present approach. Finally, necessary extensions to the present preliminary model are discussed. A discussion and brief description of ANOPP is provided in
the Appendix.

III. Landing Gear Model and Acoustic Prediction (LGMAP)

Given the geometric complexity of the landing gear as well as the complex local flow environment, a methodology is proposed that models the majority of the complex features by a combination of simple acoustic elements. This is appropriate because many of the physical components in a landing gear have geometric similarity and are expected to produce similar acoustic signals - although the relative positions and sizes may vary significantly. It is expected that only a limited number of acoustic elements are needed. The structure of the prediction program has been designed to allow for continuous improvement of the scheme. Model upgrades will be introduced as deficiencies are uncovered or improved element noise models become available. The general characteristics of acoustic elements are now described.

A. Characteristics of Acoustic Elements

The central feature of the LGMAP method is a set or “toolbox” of acoustic elements, shown schematically in Fig. 1. Several element or object types are envisioned including: circular and non-circular cylinders; wheels; edge objects to represent doors; and fittings. These objects are the building blocks that can be used in a variety of sizes to “build up” the entire landing gear geometry. Each acoustic element has three attributes: an upstream environment; a downstream environment; and the element geometry. These attributes provide the key parameters for the element noise prediction and enable the objects to communicate with each other through their upstream and downstream environments. A brief description of the three acoustic element attributes follows.

Upstream Environment

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. The incoming turbulence level affects the loading force spectrum and level on the component. The incident acoustic field is necessary when shielding, scattering, or diffraction effects are included—currently planned for a later stage of development.
Downstream Environment

The properties of the downstream environment are the same as those of the upstream environment. However, the local flow velocity, turbulence level, and acoustic field are those generated by the acoustic element. This environment becomes the upstream environment for other elements.

Element Geometry

The element geometry will be the primary feature used to determine how the landing gear components and assemblies are modeled. The geometry of the element uniquely identifies an element and how that element uses the upstream environment to create the element loading force spectrum, from which the radiated noise is predicted and downstream flow environment is generated. Some elements may have a similar geometry, but the loading spectrum, noise directivity, and velocity scaling will be different.

Element Noise Prediction

Currently the noise prediction for each element is performed in the time domain. Each element has its own loading spectrum, which is converted to a time history by assigning a random phase to each spectral component and applying a Fast Fourier transform. Further details are given below. The noise prediction is then performed using the LGMAP code (which is an extension of PSU–WOPWOP\textsuperscript{7,8}). LGMAP utilizes 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\textsuperscript{9} solution to the Ffowcs Williams–Hawkings equation\textsuperscript{10} for an arbitrary observer location.

It is assumed that, for each element having a spanwise length many times greater than its diameter, the spanwise correlation length is of the order of its diameter. (The precise correlation length is an input parameter.) This is plausible for all components in a turbulent flow, irrespective of the Reynolds number. Thus, at the peak frequency of the loading spectrum and lower frequencies the source can be considered to be acoustically compact with regard to the elements cross section. Elements that are longer than the correlation length are automatically divided in to segments in the acoustic computation. The ability of the code to use a compact cross-section loading model reduces significantly the amount of data that is needed for each of the segments. Only the three components of the unsteady force on each element are required for each segment– not the complete unsteady pressure distribution.

The computed noise from each element is added together assuming that the component sources are uncorrelated. However, the noise calculations are performed in the time domain to allow for the situation where adjacent acoustic elements might interact in a correlated manner. Correlated interactions of elements are planned for future extensions of the present model.

B. Details of Acoustic Element Modeling

In this preliminary version of the prediction program it is assumed that all components of the landing gear can be represented by circular cylinders of length $\ell$ and diameter $d$. This simplistic model will be updated as additional modeling information, from either experiment or computation, becomes available. Also, at this stage, it is assumed that there is no interference between components. Further, it is assumed that each component of the landing gear is exposed to the freestream velocity, equal to the speed of the aircraft or tunnel velocity. The load on each individual element is based on the component of the freestream velocity normal to cylinder, $V_n$. Also, at this stage of the model, the level of the incoming turbulence is not specified. The magnitude of the loading, or the unsteady pressure ($p'$)$_{rms}$, is determined by comparison of the predicted sound pressure levels (SPL) and the experimental values.

The process of building up the landing gear model begins with a detailed description of the landing gear – such as a computer aided design (CAD) representation. From this description, an expert user will construct a representative model based upon the various geometric features in the landing gear. Obviously this will require some judgement from the user because the actual landing gear components can be quite complex; hence some approximate knowledge of the turbulent flow and expected acoustic field will be needed to guide the build-up process. The elements are assumed to radiate noise independently. An example of the acoustic element (wire mesh) representation of a six–wheel landing gear is shown in Fig. 2 along with the detailed CAD description. For the present example, small fittings, and hydraulic pipes and cables, have not been
Figure 2. Detailed CAD Description and Wire Mesh Representation of a Six-Wheel Landing Gear

included. However, some relatively small complex features, such as the hydraulic hose brackets, have been modeled.

Cylinder Element Model

The first acoustic element that has been implemented is the cylinder element model. The unsteady loads on each cylinder element of the landing gear are determined from a nondimensional loading spectrum. The spectrum is assumed to have a peak frequency, $S_0$, which is representative of the shedding Strouhal number for the cylinder. The dimensional shedding frequency, and the dimensional fluctuating lift and drag forces are determined by scaling this spectrum for each cylinder element according to the normal component of the freestream velocity, $V_n$, and the cylinder diameter, $d$. The presence of incoming turbulence is not modeled explicitly at this time, but is incorporated indirectly by a broadening the component spectrum and a modification to the baseline lift and drag coefficients. In the present version of the model, the assumed spectrum has a similar shape to that used in ANOPP, but it has been modified in the light of available new experimental data. The non-dimensional spectrum function is given by,

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

$$L'(S) = \frac{1}{2}\rho V_n^2 DC'_l F_{ND}(S)$$

$$D'(S) = \frac{1}{2}\rho V_n^2 DC'_d F_{ND}(S)$$

$B$ is chosen such that the spectrum peaks at $S = S_0$ and $A$ is chosen such that $\int_0^\infty F(S)dS = 1$. This spectrum is used as a “universal spectrum” for all cylinder elements of a particular type. 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. In this way there can be several classes of cylinder elements. Two such choices of nondimensional loading spectrum are shown in
Fig. 3. The values of the parameters used for the cylinder and wheel spectra and their selection is described below.

In principle, the parameters used in the nondimensional spectrum could be determined from available measurements or computations. One potential source for guidance is the extensive collection of cylinder data found in Zdravkovich.\textsuperscript{11,12} However, we have little confidence in using the unsteady force coefficient data for a smooth surface cylinder at a relatively low Reynolds number, turbulence–free environment. Instead, the values have been determined by comparison of the complete noise prediction with experiments. Interestingly, as described below, the values found in this manner are quite close to the values reported by Zdravkovich. As further calibrations of the model are performed, it is likely that the fluctuating force values for turbulent flows will be somewhat greater than the smooth, low Reynolds number values.

**Wheel Model**

The early data, as recorded in ANOPP, suggest that two wheels in line generate less than twice the noise of the single wheel, but in all cases the noise generated is not associated with vortex shedding (i.e., the flow around the wheel is more complicated than a long circular cylinder). The presence of the truck arch connecting the wheels to the oleo strut is found to generate a strong fluctuating force downwards. Between the wheels there are not only the axles, but also the brakes, bearings, and gearboxes. These components are essentially short bluff bodies, which also significantly effect the flow around the wheels. Furthermore, the end connection of the truck to the oleo strut plays a role. Finally, flow past the front wheel in a multi-axle bogie separates and immediately induces separation on the front face of the second wheel and so on. The noise spectrum for the complete truck peaks at a frequency more related to a Strouhal number based on the diameter of the oleo leg than that of the diameter of the tire. If the truck is at an angle of incidence during the approach to landing the flow and noise measurements show its noise is increased.

Our initial acoustic model for the wheels contains almost none of these features. At present, the wheel is represented by a cylindrical ring of diameter equal to the tire width, and broken up into 24 straight cylinder segments. In Fig. 2, 6 separate wheels are modeled. The main reason for using a circle to represent the wheel is that noise is radiated both downward and to the side. The sideline noise was noted by Crighton\textsuperscript{13} in his review of the early work of Heller and Dobrzynski.\textsuperscript{5} A separate loading spectrum (shown in Fig. 3) was used for wheel cylinder segments.

The wheel model is extremely crude at this point, hence much more work is needed to refine this model. It is unlikely that the final model will be of the form presented here.
Generation of Loading Time History

As noted above, the noise prediction is performed in the time domain and therefore relies on the specification of the element loading time history. To construct a time history of length $T$, the nondimensional loading spectrum, given by Eqn. (1), is sampled at $2^n$ values separated by $dS = D/V_n T$. Each value, $F_i, i = 1, 2^n$, is assigned a random phase and an inverse Fourier transform is used to generate a time history. In order that the time history have a root mean square (rms) value of unity, the rms of the time history is calculated and the record is normalized by this value. This is a consequence of the discrete form of Parseval’s theorem that provides a relationship between the mean square of the time sampled values and the mean square of the spectral coefficients. The dimensional lift and drag loading time histories are then constructed by multiplication by $\rho V_n^2 DC^l$ and $\rho V_n^2 DC^d$ respectively.

IV. Preliminary Results

As noted above, there are many different landing gear configurations. To find the strengths and weaknesses of the current model three different configurations have been examined. The landing gear used in this assessment study range from a simple model of a DC-10 nose gear to a semi-dressed Boeing 777 main gear. This preliminary analysis is used to assess the capability of the model to predict the overall noise level, the spectrum shape, and the contribution of different components.

A. Heller and Dobrzynski\textsuperscript{5} Test Calibration

The model DC-10 nose gear experiments were performed at the outdoor "Wall-Jet Flow Facility" located at the DFVLR Trauen Test Grounds.\textsuperscript{5} The nose gear used in the tests was dressed down so that the only components that were exposed to the flow were the oleo, the door and a pair of wheels. The noise from each component was isolated in the wind tunnel test so they can be compared directly with the current model. This breakdown is given for a sideline observer and the measurements are dominated by the oleo or strut noise. Thus, this data has been used to calibrate the spectrum shape and the unsteady loading coefficients for the cylinder model. The calibration of these parameters for the wheel model is based on comparisons made in the next subsection. Figure 4 shows a comparison between the wind tunnel measurements and our model prediction. It should be noted that $L_p$ is the 1/3–octave SPL. However, in the present paper, the experiments and predictions are shown as continuous lines. 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. However, the contribution from the wheel is over–predicted. The wheel element model has been calibrated based on overhead locations, as described in the next section. It is clear that the present model over–predicts the wheels’ sideline noise radiation and requires further development.

B. ANOPP Calibration

A general discussion of the landing gear component of ANOPP is given in the Appendix. It only includes contributions from the oleo or strut and a wheel model. For an observer located directly below the aircraft flight path, only the wheels radiate noise. So ANOPP is used here to calibrate the the present wheel model. In addition, since the ANOPP prediction for the spectrum shape is known to be poor, particularly at higher frequencies, the primary goal of the calibration is to fix the predicted peak level. The aircraft if 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 support struts. 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. These predictions are shown in Fig. 5. Also shown are the LGMAP predictions. 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. Again, it should be noted that the noise levels are 1/3–octave values. In general the predictions are quite good. However, since it is recognized that the present wheel model is very crude, no attempt has been made to find the model parameters for the best fit. In addition, as additional objects are added to the representation of the landing gear, the spectrum shape and perhaps the level will certainly change. So it should be emphasized that the predictions made here are to provide some confidence that the loading time histories are realistic. The values of the model parameters are shown in Table 1. For the cylinder element, the fluctuating lift and
Figure 4. Comparison of Predicted Sideline Noise With Measurements by Heller and Dobrzynski

Figure 5. Comparison Between ANOPP and LGMAP Predictions for a Simplified 4-Wheel Landing Gear
drag coefficients are very close to the measured values given by Zdravkovich\textsuperscript{11,12} for the highest Reynolds numbers considered with turbulent boundary layers.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & Cylinder Element Model & Wheel Model \\
\hline\hline
$e$ & 2.5 & 2.0 \\
$p$ & 2.15 & 1.5 \\
$S_0$ & 0.22 & 0.18 \\
$C_l'$ & 0.17 & 0.34 \\
$C_d'$ & 0.085 & 0.17 \\
\hline
\end{tabular}
\caption{Parameters Used in Cylinder Element and Wheel Models}
\end{table}

C. 777 Scale Model Comparison

As a final example, a simplified model of a Boeing 777 landing gear is considered. The conditions correspond to the 1/4–scale model tested in the Virginia Tech Acoustic Wind Tunnel. The assemblies included in the model are identified in Fig. 6. They are: the strut assembly including the oleo; the truck assembly; the brake assemblies; the wheels; the aft hydraulic bracket (AHB); the forward vertical hydraulic bracket (FVHB); and the forward horizontal hydraulic bracket (FHHB). Figure 7 shows a comparison of the LGMAP total prediction with the measured data as well as a breakdown of the noise contributions from the different assemblies. The measurements and the predictions are both for a 6.25 Hz constant bandwidth and the measurements are averaged values from an overhead microphone array. Though the general shape of the predicted spectrum is reasonable (the measured data are not shown below 20 kHz because of probable tunnel noise contamination) the level is nearly 20 dB too low. This is surprising, since the predicted levels in the ANOPP calibration were quite good. The authors have no explanation for the discrepancy at this time.

From the predicted breakdown of the assembly contributions to the noise, the largest noise sources, at the overhead location, are the forward horizontal hydraulic bracket and the brake assemblies. At the lowest frequencies the strut assembly is also important. The wheels and the other assemblies are predicted to make little contribution to the total noise. Though the discrepancy in the predicted amplitude remains to be resolved, the predictions in this section should serve to indicate the manner in which the LGMAP methodology will work in the future.
Figure 7. Comparison of LGMAP Results With Wind Tunnel measurements for 1 1/4–Scale 6–Wheel Landing Gear. Both Total Predictions and Breakdown by Assembly are Shown

V. Future Model Improvements

This paper has introduced a new framework for landing gear noise prediction. One of the features of this framework is that from the beginning it is recognized that improvements are both desirable and necessary. Two types of improvements can easily accommodated: 1) add to the toolbox of acoustic elements; and 2) improve the element acoustic modeling. The following is short list of planned features that are needed to provide sufficient elements to fully model a complex landing gear and how such feature enhancements might be implemented.

A. Trailing Edge Noise

It is well known that turbulent flow past sharp trailing edges radiates noise efficiently. Both the directivity of the noise and the velocity scaling are significantly different from typical dipole noise (i.e., trailing edge noise scales as $M^5$ while dipole noise sources scales as $M^6$). The turbulent flow that generates this noise can come from either a turbulent boundary layer or from upstream sources. As nearly all of the landing gear components are bluff bodies and generate a turbulent wake, the fact that these turbulent wakes pass doors and other sharp edges must be properly accounted for. In fact the turbulent wake of the landing gear as a whole typically must pass the trailing edge of the aircraft wing and flaps – resulting in a potent trailing edge noise source.

Initially it is envisioned that a relative simple model will be added to the LGMAP toolbox to account for trailing edge noise. Line source acoustic elements representing trailing edges will be implemented that have the proper velocity scaling and representative acoustic directivity. The upstream environment will be a critical input parameter to determine the trailing edge noise.
B. Acoustic Scattering and Shielding

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 effected 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 complete shielded by another component with the result that the small component would not contribute to the total acoustic field at some observer locations.

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 model 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 allocated. A parallel implementation of the acoustic element noise computations could be particularly effective when coupled with an iterative approach to the acoustic scattering problem. Such a methodology is envisioned only for a second generation implementation of the LGMAP model.

Tunnel Wall or Wing Reflections

It was noted by Crighton\textsuperscript{13} that the “dipole” elements of the landing gear are within an acoustic wavelength of the wing undersurface, which can be represented as a distribution of image dipoles. Thus longitudinal dipoles with axes normal to the wing surface, approximated by an infinite flat horizontal surface, cancel and degenerate to a vertical longitudinal quadrupole. Of course the wing is not an infinite horizontal surface parallel with the ground. ANOPP does not discuss this interference with the wing and assumes that all equivalent acoustic dipoles, representing the unsteady loading on the landing gear, are operating as free-field dipoles.

The approximate effect of reflection from the tunnel walls in a model experiment or from the lower wing surface can be included in the present analysis. For each element segment the acoustic signature is computed at the observer location and at a reflected observer location and then acoustic pressures are added, thus accounting for constructive-destructive interference. The combined signal (segment and image) are then added together with the other segments as uncorrelated signals. At this stage only infinite walls have been implemented and this code feature has not been validated. But, as the model refinement proceeds, shielding and refraction by other aircraft components is planned.

Wheel Model

In the future, alternative wheel models will be tried to attempt to better resolve the clear problem with the directivity seen in the present calculations. Unsteady, compressible, CFD calculations have been completed for an isolated wheel and a cylinder of the same aspect ratio. The results will be used to improve the present wheel model. Also, the effect of upstream turbulence is expected to be particularly important for the wheel models in a landing with 4 or more wheels. Again, experimental and computational studies will be used to model and calibrate this effect. Finally, the tire treads are very small features that again add to the higher frequencies. These will need to be included in future models.

End Effects

In the present model of assemblies such as the oleo or strut, no account is taken of the noise radiation in the direction parallel to the strut axis. This is because the present cylinder element model only includes unsteady loading in the directions normal to the cylinder axis. However, it is expected that some cylindrical assemblies, particularly those with a large cross sectional area, will have a significant loading in the direction parallel to the cylinder axis at their ends. As in the case of the wheel model, unsteady CFD calculations are being conducted for cylinders with different aspect ratios to assess the radiation from the ends of the assembly.
Concluding Remarks

This paper has presented the framework for the prediction of noise from a complex geometry landing gear using a toolkit made of simple acoustic elements. Some predictions have been made to assess the potential of the methodology. These tests have helped to identify shortcomings in the present acoustic element models. These deficiencies will be overcome with improved models based on experimental and computational studies. It is expected that this process of the initial inclusion of a crude acoustic model for an element, followed by a noise prediction and comparison with experiment, leading to guidance on directions for model improvements, will continue. In fact, that is the essence of the present approach: to provide a framework for the prediction of noise from a complex geometry landing gear using simple acoustic models, rather than attempting a full numerical simulation. As further geometric details, additional source mechanisms such as trailing edge scattering, or acoustic effects such as shielding, are included, the execution time for the code will increase. However, it is sure to be orders of magnitude less expensive in computation time than a direct noise calculation and orders of magnitude less expensive in cost than an experiment.

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References


A. The Noise Prediction From ANOPP

The airframe noise component of the Aircraft Noise Prediction Program (ANOPP)\(^2\) is based on the noise prediction scheme by Fink\(^3,4\). The method is based on an experimental database of aircraft flight data as well as wind tunnel tests by Heller and Dobrzynski.\(^5\) A careful and relevant review was given by Crighton.\(^13\) In this formulation landing gear noise is presented only as the landing gear in isolation. Since it is based on an experimental database, it clearly is relevant to the noise prediction of the airframe of a modern commercial airliner, provided allowance is made for large changes in the design of the aircraft components as well as to the overall finish of the modern commercial aircraft. In this paper ANOPP is used to give an
order of magnitude estimate for the practical force coefficients to be used in the more detailed analysis in the LGMAP code.

The ANOPP type formulation can be derived from the Lighthill\textsuperscript{14}-Curle\textsuperscript{15} theory giving the noise intensity at a stationary observer in the far field from a landing gear at rest in a uniform moving fluid of velocity, $V_\infty$. It can be shown that for each “bluff body” component of diameter, $d$, and length, $\ell$, where at high Reynolds number the flow is separated and has a turbulent wake of order $d \times \ell$, with a surface pressure coefficient, $C'_p$, corresponding to an off-surface characteristic turbulent velocity, $u_0/V_\infty$, that the far field sound intensity is given by,

$$I(r, \theta, \phi)(W/m^2) \sim \frac{1}{16\pi} \frac{\pi d \ell}{4\pi^2} \frac{\omega_0^2 \ell_0^2}{u_0^2} \rho_\infty V_\infty^3 \left( \frac{u_0}{V_\infty} \right)^6$$

where $\omega_0$, and $\ell_0$ are the characteristic radian frequency and length scale of the turbulence, which combine to form the turbulent Strouhal number, $s_0 = \omega_0 \ell_0/u_0$, having a value of order 1.7. If the directivity of the far field sound is ignored, the overall acoustic power is found to be given by,

$$P(W) = K \rho_\infty V_\infty^3 M_\infty^3 \left( d^2(\ell/\ell_0) \right)$$

where the constant, $K = (1.7)^2/16 (u_0/V_\infty)^6$ and, as seen below, this is easily recognized as similar to the formulation used in ANOPP, for the contributions to the overall sound from the landing gear, expressed as that from the wheels and the oleo strut but including the effects of all components and interference factors. In this formulation all quantities are dimensional and each component has its own diameter, $d$, and length, $\ell$. The frequency, $f_0$ at the peak in the spectrum for each component is found from $S_0 = f_0 d/V_\infty = 0.2$. From the values of $K$ given in ANOPP for the tire and oleo contribution, expressed with respect to lengths $D$ and $L$, we deduce that in our formulation, $C'_p = 0.12$, corresponding to $u_0/V_\infty = 0.35$. These values for the unsteady pressure coefficient are close to those quoted by Heller and Dobrzynski\textsuperscript{16} in the separated flow around the wheels.

ANOPP considers the case of a fixed observer on the ground as the aircraft flies past at an approach speed of $V_\infty$ and an approach Mach number of $M_\infty = V_\infty/c_\infty$. The slant height between the undercarriage and the observer is $r$ making the angle $\theta$ with respect to the flight direction. In this configuration there exists a Doppler effect between the frequency of sound measured at the moving source and that received by the observer at rest. Thus the frequency, $f$ received by the observer at rest is generated by the moving source with frequency $f_0$, where $f = f_0/(1 - M_\infty \cos \theta)$. Thus for a frequency of $f$ at the observer the Strouhal number for the source of characteristic diameter, $d$, is

$$S = \frac{f d(1 - M_\infty \cos \theta)}{M_\infty c_\infty}$$

where in ANOPP for convenience the reference length is the tire diameter, $D$. The spectral density, in terms of intensity, at the observer is then given by

$$\frac{< (P')^2 > (S)}{\rho_\infty c_\infty} = \frac{P(W)}{4\pi r^4} \frac{D(\theta, \phi)F(S)}{\rho_\infty c_\infty}$$

where $P(W)$ is the total acoustic power in Watts, $D(\theta, \phi)$ is a directivity function, and $F(S)$ is the source spectrum function. $N$ is the number of wheels in a truck.

The frequency of the peak in the observer’s spectrum $f_0$ was found by Fink\textsuperscript{3} and Heller and Dobrzynski\textsuperscript{5} to be related to the diameter of the oleo strut, $d$, and not to the tire diameter, $D$. In fact standard vortex shedding from the truck wheels of the undercarriage at a frequency $f = 0.2V_\infty/D$, which is a very low frequency, is not observed. They observed a peak frequency $f_0 = 0.2 V_\infty/d$.

When the Doppler effect is excluded $S = f D/V_\infty$ and then it is found that the spectral density of the intensity per unit Strouhal number is

$$I_S(S) = \frac{< (P')^2 >}{\rho_\infty c_\infty} (S)$$

with the overall intensity $I = \int_0^\infty I_S(S) dS$. It follows that $D(\theta, \phi)$ must be chosen so that $\int_0^\pi \sin \theta d \theta \int_0^{2\pi} d \phi D(\theta, \phi) = 4\pi$, and $\int_0^\infty F(S) dS = 1$. Thus for the wheels and the oleo strut ANOPP provides respectively

$$\Pi_{\text{wheels}} = \rho_\infty V_\infty^3 D^2_{\text{ref}} M_\infty^3 K_{\text{wheels}} N_{\text{wheels}}$$
and

$$H_{\text{strut}} = \rho_\infty V_\infty^3 D_{\text{ref}}^2 M_\infty^3 \left( \frac{K_{\text{strut}}}{D_{\text{ref}}} \right)$$

where $K_{\text{wheels}} = 4.349 \times 10^{-4}$ for one- or two-wheel trucks and $K = 3.414 \times 10^{-4}$ for four wheel trucks. $N_{\text{wheels}}$ is the number of wheels per truck. For $N_{\text{wheels}}$ greater than 4 it is assumed the value of $K_{\text{wheels}}$ does not depart too much from these values. For the oleo strut ANOPP gives the single value based on the strut length with $K_{\text{strut}} = 2.753 \times 10^{-4}$.

The directivity function for the wheels is given by the empirical relation

$$D(\theta, \phi)_{\text{wheels}} = \left( \frac{3}{2} \right) \sin^2 \theta$$

which assumes symmetry in the longitudinal plane fore and aft. Similarly for the oleo strut

$$D(\theta, \phi)_{\text{strut}} = 3 \sin^2 \theta \sin^2 \phi$$

The spectrum function recommended for the wheels and oleo strut landing gear are given in ANOPP. It should be noted that the ANOPP spectrum functions give the 1/3-octave levels at the band center frequencies. To obtain spectrum functions for which \( \int_0^\infty F(S) dS = 1 \), the ANOPP spectra should be multiplied by the 1/2-octave bandwidth $\Delta f = 0.231 f$.