Towards Noise Prediction for Rudimentary Landing Gear

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Abstract

A four-wheel landing gear truck was designed for research purposes, with the level of complexity which is felt to be manageable in current numerical simulations, and a weak Reynolds-number sensitivity. An experiment is underway, aimed at measuring wall-pressure fluctuations, leading to a meaningful test of unsteady simulations with emphasis on noise generation at a June 2010 workshop. We present two Detached-Eddy Simulations (DES) using up to 18 million points in the high-order NTS code. The first is incompressible and placed in the wind tunnel, as requested for the workshop. The second is at Mach 0.115, with only one wall analogous to a wing (but infinite and inviscid), and is used to exercise far-field noise prediction by coupling the DES and a Ffowcs-Williams/Hawkings calculation (FWH). The results include force, wall-pressure, and noise intensities and spectra. The wall pressure signals in the two simulations are very similar. In the absence of detailed experimental data, the attention is focused on internal quality checks, in particular by varying the permeable FWH surface and outflow-patch treatment. An unexpected finding at this Mach number, well below airliner approach values, is the strong role of the quadrupoles revealed by a difference of up to 7dB between results from the solid and permeable FWH surfaces. The DES system and the FWH utility have proven accurate for jet noise, but landing-gear specific checks will continue. A semi-quantitative estimate of the two terms actually supports the idea that dipoles would not dominate quadrupoles until the Mach number is lowered even further. If confirmed, this finding will complicate airframe-noise calculations, hinder the attribution of noise to a given area or component of the aircraft, and conflict with the classical $U^5$ scaling for acoustic power. Progress appears real, but deep comparisons with experiment or other simulations have yet to occur.

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1. Introduction

The future of noise prediction and some day noise-oriented design belongs to unsteady numerical simulations and first principles, but actual contributions of such methods to industrial activities in aerospace are still years away, and therefore lagging the contributions of CFD to the design of airframes and gas turbines. The extra difficulty, both for engine and airframe noise, resides in the very wide range of scales, first in the geometry with thin free shear layers and/or small components, and eventually in the audible range of sounds. The state of the art is limited to simplified geometries, accessible with “hand-made” structured grids, in contrast with the installed systems which will need to

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be simulated, most probably with adaptive unstructured grids. A problem will be the lower order of accuracy and higher numerical dissipation of such algorithms. We are entering a phase of learning for airframe-noise calculations, which will be most productive if the geometries involved are simple enough for a variety of codes to be compared, with moderate scatter. This is the hope for the NASA-AIAA workshop scheduled for June 10-11 in Stockholm (https://info.aiaa.org/tac/ASG/FDTC/DG/BECA_FILES/Workshop_June_2010_Final_problem_Statements/Contact_Information.pdf); it rests on four geometries, one of which is the present one. Another precursor aspect of this test case at the workshop is that far-field noise predictions are not involved; only wall-pressure fluctuations, which have been recognized as the primary mechanism for noise generation at landing Mach numbers.

This experimental-numerical effort follows those at NASA around 2002 [1], Cambridge in 2008 [2] and the ongoing LAGOON work led by ONERA [3]. DES was performed by Hedges et al. in 2002 [4], and Unsteady RANS and DES by Lockard et al. [5]. Souliez et al. performed Implicit Large-Eddy Simulations [6]. These last two papers used the same, semi-complex model. However, for this workshop a new model was designed and called “rudimentary” (RLG) rather than “simplified,” in the sense that it does not result from stripping a real geometry. A simple analytical definition was desired. The LAGOON geometry was considered more complex than needed, and not fully in the public domain.

The level of complexity here is the same as in the NASA model, with only wheels and primary components, but this geometry was not considered ideal because of its sensitivity to transition on the wheels and the round axles, which had Reynolds numbers very close to the drag crisis. Here, the post and axles are larger and rectangular, in order to produce a more realistic level of blockage and small-scale eddy generation, and to reduce the Reynolds-number sensitivity. The wheel boundary layers are tripped, again for Reynolds-number robustness and to be closer to full-size, rough tires; this is also the approach for LAGOON, and the Cambridge team tripped both the front wheels and the round axles (with Reynolds number under 10^5). In this sense, the geometry and turbulence prescription are “CFD-friendly” and the difficulty resides in the noise generation itself.

The primary experimental task is to obtain unsteady wall-pressure measurements. This is soon to be achieved by NAL in India with Boeing funding, in a closed test section; the work has yet to be published. The model is equipped with trip dots on the front wheels, with location and size suggested by CFD, and tripping was successful. If the model is recognized as useful, it is possible that sound measurements will be made by other institutions, presumably in open tunnels. Moderate Reynolds-number changes should be acceptable, and range of Mach numbers is very desirable. The pressure probes are placed with enough variety, on the wheels and on the fixed parts, to study the flow dynamics in some depth and lead to incisive comparisons between CFD codes and with experiment.

The challenges of landing-gear noise prediction from first principles may turn out to be tall, beyond the known one of an unmanageable range of frequencies. While our experience base with sound prediction from jets using LES and the FWH equation is firm, airframe noise is more uncertain. Again, a key issue is the closing of FWH surfaces downstream, where neglecting the quadrupoles is a severe approximation. The more complex geometry also imposes less favorable grid distributions than jets do, with more block boundaries and stronger stretching. On the other hand, the Mach numbers and temperature ratios are much lower, which may allow some simplifications.

2. Model Description

The figures provide the topology. The geometry is defined by the following dimensions, all normalized with the wheel diameter $D$: wheel width 0.37 and shoulder radius 0.115; wheelbase 1.16 and track 0.88 (these four identical to Lazos); axles square with side 0.3, longitudinal beam 0.3 high and 0.25 wide, vertical post 0.25 square. The model is centered in a tunnel with sides 3.69, and the post reaches the wall; the blockage is deliberately made high to benefit Reynolds number and measurement volumes. Compare with the larger ratio of tunnel size to $D$ needed when noise measurements are made [2]. The diameter Reynolds number is 10^6, and Mach numbers ranging from 0 to 0.2 are acceptable for the wall-pressure exercise.

At the present level of detail, it is sufficient to treat the tunnel walls as inviscid, and the flow on the model itself as “Fully Turbulent.” This means that the inflow conditions for the turbulence variables make the fluid go directly to a turbulent state as soon as it enters the boundary layer. This removes a significant uncertainty.
3. Numerical Elements

The NTS code has been used extensively for jet-noise simulations, as has the FWH utility, and once for landing-gear simulations [4]. It has an efficient incompressible mode. Numerical dissipation is minimized, particularly close to the body, by blending centered and upwind-biased differencing. With the complexity level of the RLG, grid generation is arduous, but can be done with good quality since the code allows overset blocks. In the present work a simple algebraic grid-generator is employed which has a special routine permitting cut-outs for Chimera grids.

The FWH utilities in various studies are similar [4, 5, 6], although all the details have not been cross-checked. We use equation (14.87) in the book Modern Methods in Analytical Acoustics [7], but in frequency space. It contains the far-field approximation. The volume integral outside the FWH surface is neglected. Different approaches to the outflow boundary, at which the assumptions of an FWH formula without external quadrupoles are violated, are in use. Another difference is whether only the far-field approximations are programmed, or the mid-field sound is also provided. All groups have tested permeable and non-permeable (solid) FWH surfaces. Calculating the sound using only the unsteady forces on the model is also an option, proposed by Curle. This will be covered in detail.

In terms of the turbulence treatment, we feel that Detached-Eddy Simulation (DES) [8] is a more promising approach than either URANS, which misses the chance of resolving small eddies at some distance from the walls and therefore the impingement on other components [5], or LES, which is very unlikely to predict separation (or its absence) from smooth surfaces accurately with manageable grid resolution, especially with tripped boundary layers. These weaknesses can be hidden by other errors on grids that are not very fine or with dissipative algorithms, but the improving accuracy of simulations and depth of experimental comparisons will display them clearly, in our opinion. DES and other RANS-LES hybrids are very likely to prevail in this field.

4. Results

4.1. Common Features

Figure 1a shows the surface grid, and the points where spectra will be shown (points 1-3 face backward, and 4-6 forward). The typical surface spacing is 0.02D, requiring 170,000 surface grid points; the multi-block nature of the grid is visible, with patches fit to the wheel treads, sides, and so on. Figure 1b reveals part of the volume grid. The target spacing in the Focus Region is also near 0.02D, and the total number of points is 10 million with 14 blocks in the wind-tunnel section, and 18 million with 16 blocks in free air. The time step is $5\times10^{-3} D/U'_w$, giving fair accuracy up to $St \approx 10$; the Strouhal number is based on $D$ and the freestream velocity $U'_w$. In the compressible simulation the
grid spacing is no larger than 0.08D up to the FWH surfaces. This corresponds to $St = 10$ assuming at least 8-10 cells per wavelength. Spectra will be displayed up to 1/3 of the Nyquist frequency, which is $St = 100$.

Figure 2 vividly illustrates the LES content of the simulation, and the strides made since 2002 [4]. The range of scales is rewarding, for a grid count that is moderate by today's standards, again benefiting from high-order, low-dissipation differencing. The separation from the blunt axle is wide, no doubt deflected by the wheels. Fine-scale turbulence trails the axle and post, gradually coarsening in the Departure Region of the grid.

The drag coefficients for the two runs are 1.70 and 1.39, due to the difference in tunnel blockage. The reference area is $D^2$. The rms coefficients are: $C_x' = 0.047$, $C_y' = 0.064$, $C_z' = 0.065$, and $C_x' = 0.040$, $C_y' = 0.048$, $C_z' = 0.060$ for Runs 1 and 2, respectively.

Figure 3 exhibits the striking 40dB range of the predicted fluctuating pressure levels on the model and on the wall. The distribution is spotty on the wheels, but the fair symmetry suggests a sufficient time sample. Unpublished results, courtesy of E. Gren at CD-adapco, are in fair agreement. The absence of separation on the front half of the front wheels is reflected in very low levels, between 110dB and 114dB. This is expected within the RANS mode of DES; the resolved fluctuations are very weak. The true level due to (attached) boundary-layer fluctuations is estimated to be between 110dB and 120dB, and thus generally slightly higher. An additive model of the resolved fluctuations and the modeled ones, empirically estimated, would allow a meaningful comparison with experiment, with two limitations. First, the simulation in fully-turbulent mode lacks the laminar boundary-layer regions of the experiment; second, the empirical estimates leave an uncertainty of at least ±2dB for the energy, and more for the spectrum, especially with the very strong pressure gradients present on the blunt bodies. Returning to the resolved level, it gradually rises when approaching the rear of the wheel, and separation. The level is high and very uneven all over the rear wheels, which are immersed in turbulence, suggesting intense shear layers and vortices. The peak level is reached under the beam and inside the rear wheel, and caused by the impingement of turbulence created at the blunt leading edge of the axle, and by interference. This level of 150dB can be compared with the dynamic pressure, which is 153dB. Very small spots near corners exceed 160dB.
Figure 3: Wall pressure fluctuation levels.

Figure 4: Wall pressure spectra; refer to Fig. 1 for the points.

Figure 5: Contours of the pressure derivative $\frac{\partial \rho}{\partial t}$ normalized with $\rho_0 c_0^2 / D$. 
Less expected is the 147dB on the ceiling itself, accompanied by a very wide pattern. Turbulence shed by the square post is intensified by the wall proximity. However, spectra on the post do not suggest any “pure” vortex shedding, which may have been expected near $St = 0.6$, based on the drag of the post. Vorticity contours in $x-z$ planes (lower frame in figure 2) confirm this absence of regular shedding. Such shedding was visible and probably too smooth in DES of the LG with a round post [4], partly due to the geometry and partly due to the resolution, noticeably coarser than here. The pressures on the front face may be dominated by sound from other components, or even residual numerical fluctuations as the mottled aspect suggests.

Figure 4 shows the wall-pressure spectra. They are close enough between the two simulations to ascribe the differences to statistical scatter for now. The closed-channel levels may be slightly higher in response to the confinement, but the shapes are very similar and the impact in $dB$ is not large. In the absence of reference results and of grid-resolution studies, it is difficult to establish the accurate frequency range. The fluctuations are far weaker at the front-facing points even at low frequencies, with the spectra less full and even a consistent low point around $St = 3$. The significance of these spectra is uncertain at high frequencies, since DES does not contain the internal fluctuations of the boundary layers. The time samples of $120D/U_\infty$ appear adequate, if only because the low end of the two spectra are quite close, when the simulations are statistically fully independent.

4.2. Compressible Simulation and Sound

4.2.1. Near Field

Figure 5 displays the pressure field, with contour levels adjusted to fit near-field sound, and let turbulent fluctuations saturate. Recall that, depending on the frequency, the sound waves in a simulation may be damped quite rapidly by grid coarsening in the Euler Region. Strong down-directed events have wavelengths near $0.8D$, and therefore a Strouhal number of approximately 11, close to the accuracy limit. This compares moderately well with a broad peak in the model’s lift spectrum (not shown), centered around $St = 7$. In general, the wavelength satisfies $\lambda/D = 1/(MSt)$; a wheel may be considered to be a compact source if $St << 1/M \approx 9$, but the full model including a plausible wall patch or the mirror-image model only if $St << 1/4M \approx 2$. Thus, the bulk of the noise is not at frequencies which make this source globally compact.

4.2.2. Far-Field Sound

Figure 6 details the boundary conditions and position of the FWH surfaces. The sound is calculated for a virtual flow with symmetry across the inviscid ceiling, and therefore no contribution from that surface. This approach is less demanding of ceiling grid spacing than considering the half-space bounded by that ceiling, as was done in the preliminary version of this paper. Results obtained by treating that surface as part of the FWH surface instead of symmetry were reasonably close to the present ones and constituted a somewhat independent check, but their accuracy was limited by the finite area of the ceiling patch used. The FWH-surface tests included: different positions for the closing surface; averaging results with up to four different positions ($x/D = 9, 11, 13, 15$) [9]; omitting or including its contribution; and different lateral positions. Only results in the vertical plane of symmetry are shown, identified with the emission angle $\theta$ for which $0^\circ$ is upstream, $90^\circ$ down, and $180^\circ$ downstream.

A standard test applied to the permeable-surface method is displayed in figure 7. Its upper row shows the effect of “opening” the control surface at the downstream end. It is similar to that observed for jets [9, 10]. Namely, the simulation with open surface exhibits a strong unphysical growth at low frequencies (see [9] for more details). Another problem caused by opening the FWH surface is “missing” part of the sound at observer angles close to $180^\circ$. Note that the coincidence of the spectra from the open and closed surfaces at $St > 0.5$ and $\theta < 120^\circ$ shows that at least in this $\theta$-range the pseudo-sound generated by crossing the downstream end of the closed control surface by turbulent eddies is negligible. An additional argument in favor of this conclusion is provided by the plots in the lower row of Fig. 7. They show the spectra obtained from closed permeable surfaces with the outflow patch placed at different values of $x$, and also the results obtained using averaging over several such FWH surfaces. Moving the closing surface quite close, to $x = 3$, enhances the high-frequency content. Other moves and averaging have a weak effect. Recall that the logic of averaging is that the pseudo-sound which corrupts the closing-surface integral is
carried by turbulent eddies which travel at a velocity far removed from the speed of sound, so that averaging (of the complex Fourier Transforms, not the intensities) allows some degree of cancellation of these errors. A displacement by about $0.3 \, D$ of the lateral faces, always located outside the turbulent region, made a difference of well under $1\, \text{dB}$.

Figure 8 displays the directivity of the Sound Pressure Level and compares the three contenders for sound calculation. The directivity would be stronger in the absence of the plane of symmetry, because it has the effect of combining sound from the model and its mirror image, which raises the sound level by $6\, \text{dB}$ at $\theta = 0$ and $\theta = 180$, but has far less effect near $\theta = 90$. This is a comment on the realism of the configuration chosen, not on the performance of the prediction methods. The difference between the method based only on the force and that based on the solid surface arises from non-compactness of the sources, whereas the difference between the solid and permeable surface arises from the quadrupoles contained inside the permeable surface, at least in theory.

Figures 8 and 9 may contain the most important result of the study so far. The sound “from” the solid surfaces, often called “dipole sound,” is significantly weaker than the sound from the complete closed and averaged permeable surfaces, which we consider as the best treatment. The effect on Sound-Pressure Level (SPL) ranges from about 4 to 6dB, but now examining the spectra, the difference exceeds 10dB in some regions of $(\theta, St)$ space, which is considerable. The spectra also show that the interference between dipole and quadrupole sound is constructive almost everywhere. Plots of the integrated sound energy show that it resides, overwhelmingly, in the $St$ range from 1 to 10; therefore, differences well below $St = 1$ have theoretical interest, but little practical impact.

A further finding is that the sound created by the global forces, in other words from solid-surface integration (with image) but neglecting retarded times, is noticeably different from that with proper retarded times over the oblique $\theta$ angles. The sound produced by this approach is zero at 90 degrees, by symmetry, so that the test is not relevant near that angle. Spectra reveal that the differences begin around $St = 0.4$, which is consistent with the compactness estimates above for the model and image taken together. The strongest differences are in the $St$ range between 2 and 10, and remain moderate. Their importance is minor, in view of the evidence that neither approach is accurate enough.
Figure 7: Spectra of far-field sound with different FWH outflow patches, re-scaled to an emission distance equal to $D$. Upper row: effect of “opening” the control surface at the downstream end; lower row: effect of the position of the outflow patch of closed surface.

Figure 8: Far-field sound intensity, re-scaled to an emission distance equal to $D$.

Figure 9: Far-field sound spectra per unit $St$ with solid and with permeable FWH surfaces, re-scaled to an emission distance equal to $D$.

4.2.3. Discussion of the Quadrupole Effect

Our finding echoes, superficially, that of Lockard et al. [5]. They had differences reaching 10dB for $St < 3$, also with the permeable-surface result higher. There are substantial differences between the two studies, though: they calculated near-field sound and found that at low frequencies the solid-surface result agreed far better with the LES field than the permeable-surface result (without being perfect by any standard). This appears illogical. The integration is not always an easy one, and they suspected a corruption for the permeable-surface result by pseudo-
sound at the outflow surface. Souliez et al. [6] also had higher levels from the permeable surface, but by a smaller margin, especially in the far-field sound. Furthermore, for them the permeable surface agreed better with the LES field (with a very loose-fitting permeable surface), leading them to venture that it was the more correct one; curiously, they preferred the solid-surface output for far-field noise. Therefore, the literature shows this difference between solid and permeable surfaces to be widespread, and that the trends from different groups as not very consistent. The maturity of these methods was poor in 2002-2004, and still is in 2010.

The test they applied, and that of verifying zero values inside the FWH surface, are not possible here because our FWH utility is limited to far-field sound. It is unfortunate, but the cost savings are significant. In addition, we contend that the test of comparing with mid-field sound is instructive, but is not the ultimate test. It is accepted already that comparing with the LES sound near the domain boundaries, much farther from the source, is not correct because the grid in that region cannot support all the frequencies, and numerical dissipation has done its damage. However, mid-field sound already has some of these effects. In some simulations, the sound has already crossed steep increases (if not discontinuities) in grid spacing. Thus, for a point just outside the FWH surface, agreement between the local LES result and that from the permeable surface would be mathematically correct, but would apply to sound that has been somewhat corrupted already, especially with a loose FWH surface [6]. In other words, the concept of “the true far-field sound of the LES” is not an obvious one. When results differ, there is a tendency to blame the ones with weaker sound, assuming they suffered “losses” of some kind. This is not always safe, for instance if pseudo-sound is produced at the outflow surface, or by turbulence crossing the FWH surface on the side.

In a flow which also has turbulence impingement, but Mach 0.2, Greschner et al. [11] had a similar quadrupole contribution, over the Str range corresponding roughly to [1,11] here. The permeable-surface result was higher by 3-5dB, then up to 15dB, and in far better agreement with experiment, a finding they described as “rather surprising.”

We now turn to semi-quantitative reasoning. The noise source is turbulence interacting with solid surfaces. A tentative estimate of the quadrupole and dipole effects, partly borrowed from Crighton and earlier authors, is as follows. Let \( L \) be the size of the strongly turbulent region and \( \delta \) the size of detached eddies which produce a frequency \( f \). Given typical eddy convection velocities \( U_c \), near \( U_c/2 \), we assume \( l = U_c / f = D/(2St) \). The number of eddies in the volume is of order \( L^3/\delta^3 \), and on a surface, \( L^2/\delta^2 \). In the FWH formula (14.87) for \( |x| < p' \), here applied to the solid surface, the quadrupole (volume) term over one eddy has a magnitude of \( \omega^2 \delta l^3 / (4\pi c^2) \); \( \omega \) is the circular frequency. If the eddies are uncorrelated, the product of the group in terms of pressure amplitude is larger than the individual’s by a factor \( (L^3/\delta^3)^{1/2} \; \text{leading to} \; \omega^2 (L^3/\delta^3)^{1/2} / (4\pi c^2) \). This amounts to summing the eddies’ power. The same manipulations for the dipole (solid surface) term give \( \omega^2 \delta l / (4\pi c) \). The gross “quadrupole / dipole” ratio (for amplitude, not energy) is then: \( 2\pi M (S\delta l / 2D)^{1/2} \) with \( M = U_c / c \). The reference length \( D \) has duly dropped out, and \( S\delta l / D \) is the Strouhal number based on \( L \). The ratio \( L / 2D \) is close to 1 in this flow, leaving \( 2\pi M S\delta l / 2D \). This estimate has the expected factor of \( M \), pointing at the dipoles, but also a factor of \( 2\pi \), and a dependence on \( S\delta l / D \), which as mentioned is between 1 and 10 for the bulk of the sound. This dependence brings in the complexity of landing gear (which is even far higher in reality than here). This estimate therefore does not support, at Mach 0.115, the common expectation that the dipole terms should account for the majority of the sound. In fact, taking \( S\delta l / D \) as typical and \( L / 2D \), the quadrupole term would dominate the dipole term by 4dB. Thus the numerical findings appear plausible, except maybe in that the trends at low \( S\delta l / D \) are not very suggestive of a \( S\delta l / D \) dependence.

We now attempt a quantitative estimate for sound level, re-scaled to a distance equal to \( D \). Figure 3 shows levels of the order of 135dB for \( r \). Taking again \( S\delta l / D \) as 5 and \( L = 2D \), this gives 114dB for the quadrupole term and 110dB for the dipole term, in uncanny agreement with figure 8.

As a note, taking 114dB for the SPL re-scaled to \( D \) in all directions gives an acoustic efficiency near \( 5 \cdot 10^{-5} \), which is far higher than the classical \( 10^{-4} \cdot M^2 \) of jets. This may be consistent with the absence of interaction of the jets’ turbulence with solid surfaces.

A final theoretical consideration is the concept of the solid-surface contributions as reflections of “quadrupole sound” rather than self-generated “dipole sound,” notably by Powell [12]. He presented an exact result for a plane inviscid boundary. Here, the model surface is neither plane nor inviscid, so that scattering is possible, but the high-frequency turbulence may approach the plane-boundary regime, especially on the rear wheel which is smooth.
5. Outlook

The work presented here is in progress. There is evidence that its charter, namely producing simulations with extensive LES content past the chosen Rudimentary Landing Gear geometry and calculating far-field sound with the numerical technology that is successful for jets, has been fulfilled. On the other hand, a grid resolution study has not been conducted, and the only affordable grid variation would be coarsening. The quality measures of the LES itself are largely visual, and those of the FWH calculation involve relevant tests, but some unexpected effects suggest applying more thinking and experimentation. The difference between solid and permeable surfaces appears troublesome at first, but no more severe than that found by other groups. It may be too early to answer beyond reasonable doubt the question of whether the difference reveals a strong and unexpected role for the near-field quadrupoles, or numerical errors from a new source in either the DES or the FWH treatment. Lockard et al. voiced concerns over grid block interfaces disturbing the signals. We have such interfaces inside the permeable FWH surface, some with significant steps in grid spacing, but the symmetry set-up avoids this issue for the ceiling contribution proper. Varying the Mach number might distinguish the two putative causes, and we have initiated such a run. Experimental data is expected within weeks for unsteady wall pressures, and may appear within a year for noise. Comparisons with experiment will be helpful, but not replace numerical quality checks or theoretical reasoning. The classical low-Mach-number argument was detailed, and supported the strength of the quadrupoles; it even yielded surprisingly close quantitative agreement with the calculated sound levels. If the quadrupoles indeed dominate, this can create moderate deviations from the $U^2$ scaling, which experiments have strongly supported, albeit with occasional deviations towards powers between 7 and 8 [13]. It could also make the focus of the workshop on wall pressures appear a little narrow. In any case, the most important if tentative consequence is that noise calculations using only wall pressures would be very inaccurate even at Mach 0.115.

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