Detached Eddy Simulation of a Nose Landing-gear Cavity

Robin Langtry and Philippe Spalart

Boeing Commercial Airplane Group, Seattle, WA, USA, 98124

Robin.B.Langtry@boeing.com

Abstract. Some aircraft have exhibited a noticeable vibration and aero-acoustic phenomenon inside the nose landing gear cavity. The goal of the present study was to determine whether unsteady CFD using either unsteady RANS or detached eddy simulation (DES) could predict the cavity oscillation that was measured in a Boeing wind tunnel test. In general the agreement between the experiment and CFD was good. The CFD predicted an aircraft scale cavity tone frequency of 17 Hz compared to the measured value of 15 Hz. As well, the CFD predicted sound pressure level of the tone was within 4 dB of the measurements. From the present results it would appear that CFD can be used as a tool to investigate and possibly mitigate nose gear cavity tone mechanisms on new aircraft designs.

Key words: DES, URANS, cavity, noise, aircraft, landing gear.

1. Introduction

During early flight tests aircraft have occasionally exhibited a noticeable vibration and aero-acoustic phenomenon inside their nose-gear cavity. An oscillation of interest occurred when the gear was partially retracted (wheels up, rear doors closed, front doors open, see Figure 1). These oscillations can often be eliminated through the introduction of various fixes during the development or flight test program. One such fix that proved very effective was to introduce baffles behind the wheels in order to damp out the pressure oscillations. These baffles were designed based on a series of wind-tunnel experiments, and the problem does not occur on production airplanes. Currently, Computational Fluid Dynamics (CFD) has progressed to a point where it is used routinely at Boeing for investigating steady flows. For industrial purposes, unsteady flows are usually only investigated on an experimental basis. The goal of the present study is thus to determine whether unsteady CFD can predict the magnitude and frequency of the pressure oscillations that were measured in a nose gear cavity during flight and wind tunnel testing. A suitable level of accuracy in terms of the oscillation magnitude would be on the order of ±25 percent of the pressure change during one oscillation period.

The problem of intense nose-gear cavity oscillations, among many others, must be avoided in new aircraft designs and CFD is likely to become an essential tool for doing this. It is expected that sooner or later during the early development phase of a landing gear the design will start being checked using CFD. This would include situations where the unsteady loads could potentially be strong enough to raise the noise and vibration contribution from the landing gear to unacceptable levels. The ultimate goal would thus be to rely on unsteady CFD simulations to check the design and reduce the likelihood of having to develop a fix for the cavity oscillation during the flight test program. Very large calculations will probably be needed, however these are expected to be possible in an industrial context within a few years as cluster computing becomes more prevalent.

The CFD technique of choice for the flow physics involved in cavities is Detached Eddy Simulation [1]. The main advantage of DES over either Unsteady Reynolds Averaged Navier-Stokes (URANS) or Large Eddy Simulation (LES) is that the unsteady geometry-specific three-dimensional eddies which constitute turbulence can be resolved, but only where directed by the user through the use of grid density. Consequently, the external fuselage boundary layers can be modeled using a relatively coarse RANS grid (and thus be nearly steady) while the complex flow field inside the cavity can be modeled using Large Eddy Simulation (LES), provided the grid inside the cavity is fine enough. Similar applications have been done for generic cavities and DES has been rather successful, at least for empty cavities but also including the effect of various types of bay doors [2, 3].

The geometry that will be included in the simulation consists of the fuselage from the nose to the beginning of the wing, the cavity, the bay doors, wheels and the main landing-gear strut. It should be noted that a full LES that attempts to resolve the turbulence eddies in the fuselage boundary layers is not currently feasible. This is because the grid and timescale requirements for resolving the turbulent boundary layer eddies would be far too costly on present day computing clusters.

2. Experiment

The wind tunnel test was done in Boeing's Low Speed Aero-acoustic Facility (LSAF). The tunnel consists of a 2.5 by 3.5 m free jet in a large anechoic test chamber which is 20 m long, 23 m wide and 9 m high. The wind tunnel model scale is approximately 1/16th of a typical large passenger aircraft assuming a fuselage diameter 6 m (0.375 m for the wind tunnel model). Noise measurements for frequencies between of 200 Hz and 80 kHz (12.5 Hz and 5 kHz aircraft scale) are possible with the existing foam wedges present in the tunnel [4].

A representative fuselage model was mounted upside down in the test section (see Figure 2). The lifting surfaces were not present in the experiment and their effect on the cavity oscillation is thought to be minimal as the upwash near the nose of the aircraft is only on the order of 0.15 deg. The nose gear cavity is shown in Figure 2 and includes the rear bay doors (which are closed) the front bay doors (open) and a simplified nose landing gear geometry. The free jet for this case had a Mach number of 0.25 and the fuselage angle of attack was 3°. The noise measurements consisted of a number of kulite microphones positioned inside the nose gear cavity (see Figure 2). The frequency and tonal noise levels measured inside the cavity were found to be relatively insensitive to the kulite location.

3. Numerical Method

The CFD code used for this study is the commercial code CFD++ of Metacomp Technologies Inc [5,6]. The code can handle both structured and unstructured grids (hexahedra were used for this study) and has a number of algorithms available for solving steady and transient incompressible and compressible flows. The algorithm selected within CFD++ for this study was the double precision unsteady compressible formulation. This algorithm is a dual time-stepping, second-order backward block-implicit scheme, which uses multi-grid acceleration to converge the linearized systems within each pseudo time iteration step. The time step was selected to give approximately 200 time steps per oscillation period and 15 inner-iterations (i.e. pseudo time steps) were used to converge the equation residuals by two orders of magnitude before moving on to the next time step. The inviscid flux discretization was based on a 2^{nd} order multi-dimensional TVD scheme employing the HLLC Riemann solver to determine the wave interactions at cell faces. Low-speed preconditioning was not used for the unsteady computations.

The computations for this study were run on the NASA Columbia supercomputer which is a 10 240 processor system composed of twenty 512 node Itanium 1.6 Ghz processors. Between 100 and 200 nodes were used for each run. The coarse and fine grids were half-models (in order to reduce the grid size) of the wind tunnel geometry and were generated in ICEM Hexa as a multi-block hex mesh of 5 and 12 million nodes respectively. Based on an oscillation frequency of 15 Hz inside the cavity the coarse grid had approximately 30 grid points per wavelength whereas the fine grid had approximately 58 grid points per wavelength. A symmetry plane was imposed along the centreline of the geometry. The fine grid that was used for the DES runs is shown in Figure 3. The grid near the walls was fine enough to give a y^+ of one or less. The far field boundaries were located 20 fuselage diameters away from the cavity and are not shown in Figure 3.

4. Results

The experimental and CFD predicted sound pressure level vs. the normalized frequency at the back of the nose gear cavity near the closed bay doors (i.e. kulite microphone #1 in the experiment) are shown in Figure 4. The unsteady Reynolds-Averaged Navier Stokes (URANS) computations were done with the SST turbulence model while the DES results were obtained with the S-A DES model [1]. Both the DES and URANS results shown in Figure 4 were obtained on the 5 million node coarse mesh. The coarse grid DES results (as well as URANS) are in relatively good agreement with the LSAF experimental data. In terms of the peak SPL the CFD results differ from the experiment by only about 4 dB. This is considered an acceptable amount of error given the fact that the CFD geometry is considerably simplified (particularly the landing gear) compared to the actual wind tunnel model. The effect of grid refinement on the DES results for the 5 and 12 million node grids are shown in Figure 5. The peak sound pressure levels are virtually identically between the two different grids.

In terms of the tonal frequency there is a small shift in the frequency predicted by the CFD (17 Hz) compared with the measured tone frequency (15 Hz). The measured cavity tone frequency of 15 Hz is very close to the expected frequency of a Rossiter type [8] cavity flow when the length scale (L) is taken as the distance between the start of the cavity and the leading edge of the closed rear bay doors. This is illustrated in the plot shown in Figure 6 for a number of different cavity experiments [7]. The solid lines in Figure 6 correspond to the semi-empirical equation of Heller et al [9].

$$S_m = \frac{f_m L}{U_\infty} \frac{m-\alpha}{\left[M \Big/ \sqrt{1+\frac{\gamma-1}{2}M^2} \right] + 1/k_v} \tag{1}$$

where m is the mode number (equal to 1, 2, 3, …) and $\gamma = 1.4$ is the ratio of specific heats. The quantities α and k_v are empirical constants that were set to $\alpha = 0.25$ and $k_v = 0.57$ in order to match the experimental data in Figure 6 [7].
Assuming a Mach 0.25, Mode 1 type oscillation (i.e. the shear layer consists of only one oscillating wave) corresponds to a Strouhal number of 0.39 in Figure 6. When converted to the normalized length and velocity scales of the experiment this gives a tone frequency of 14.7 Hz. This is very close to the measured value of 15 Hz and would seem to confirm that the nose gear cavity oscillation is a Rossiter type cavity flow with the leading edge of the rear doors dominating the interaction with the shear layer. .

The predicted Mach number contours and instantaneous pressure waves (Pressure – Time averaged pressure) at five points in time during one cavity oscillation period (T) from the URANS results are shown in Figure 7. The contour plots are located in the span wise plane of the landing gear wheel and are useful for illustrating the cavity oscillation physics. At the first point in time (T=0) the cavity shear layer is pointing towards the inner part of the rear bay door leading edge and consequently freestream air is entering the cavity. This raises the pressure inside the cavity and a high pressure wave propagates upstream around the landing gear towards the front of the cavity (T=0.2). Once the high pressure wave reaches the front of the cavity it begins to deflect the shear layer away from the cavity (T=0.4). As the shear layer moves to the outside of the rear bay door leading edge, the air begins to empty out of the cavity (T=0.6). As the air leaves the cavity the cavity pressure is reduced and eventually it is low enough that the shear layer is sucked back towards the inside of the cavity (T = 0.8) at which point the whole cycle repeats.

From the CFD flow visualization there appeared to be only one wave present in the shear layer (i.e. its oscillation to and away from the cavity) and this confirms that the nose gear cavity oscillation was a mode 1 Rossiter type cavity flow. Another point to note is that the magnitude of the cavity tone is expected to be a strong function of the amount of obstructions (i.e. pressure damping) inside the cavity. Certainly the landing gear would act as a partial barrier to the high pressure wave that must propagate towards the front of the cavity in order to trigger the shear layer oscillation. This could also explain how baffles could be used to reduce (or even eliminate) the cavity tone by decreasing the magnitude of the high pressure wave as it propagates towards the front of the cavity and shutting down the mechanism that reinforces the oscillation. Another promising approach to mitigating the cavity tone would be to actually use CFD during the early design phase to determine cavity and bay door shapes that would completely eliminate the cavity oscillation. From the encouraging results obtained in the present study this would appear to be a viable approach.

9. Conclusions

In this study the nose landing gear cavity oscillation measured in the Boeing LSAF tunnel has been computed using both URANS and DES CFD simulations. In general the agreement between the experiment and CFD was good. The CFD predicted a cavity tone frequency of 17 Hz compared to the measured value of 15 Hz. As well, the CFD predicted sound pressure level of the tone was within 4 dB of the measurements. From the present results it would appear that CFD can be used as a tool to investigate and possibly mitigate nose gear cavity tone mechanisms on new aircraft designs. Future work will involve more in depth studies on the effect of grid refinement, time step, Mach number as well as potential modifications to the cavity geometry that would eliminate the oscillation.

Acknowledgements

The authors would like to thank the NASA Advanced Supercomputing Division (NAS) for donating the computing time on the Columbia supercomputer. As well we would like to thank Metacomp Technologies Inc for all of their help with the CFD++ setup on Columbia. Finally the authors would like to thank Cyrille Breard, John Rose, Srini Bhat and Bill Simmons of the Boeing Company for all of their help with the problem setup and experimental data.

References

1. Spalart, P. R., Jou, W.-H., Strelets, M., and Allmaras, S. R., Comments on the Feasibility of LES for Wings and on Hybrid RANS/LES Approach, Advances in DNS/LES, *Proceedings of the First AFOSR International Conference on DNS/LES*, 1997.

2. Nayyar, P., Barakos, G., Badcock, K. and Kirkham, D., Analysis and Control of Transonic Cavity Flow Using DES and LES, *AIAA-2005-5267 35th AIAA Fluid Dynamics Conference and Exhibit*, Toronto, Ontario, June 6-9, 2005

3. Peng, S., Simulation of Flow Past a Rectangular Open Cavity Using DES and Unsteady RANS, *AIAA-2006-2827 24t* D.M. D.M.*h AIAA Applied Aerodynamics Conference*, San Francisco, California, June 5-8, 2006.

4. Guo, Y., Yamamoto, K.J. Stoker, R.W., Experimental Study on Aircraft Landing Gear Noise, *Journal of Aircraft* Paper 0021-8669 vol.43 no.2 pp 306-317, 2006.

5. Batten, P., Leschziner, M.A. and Goldberg, U.C., "Average State Jacobians and Implicit Methods for Compressible Viscous and Turbulent Flows", *JCP*, vol 137, pp 38-78, 1997.

6. Batten, P., Clarke, N., Lambert, C. and Causon, D.M., On the Choice of Wave Speeds for the HLLC Riemann Solver, SIAM J. *Sci.& Stat.Comp*., vol 18, no. 6, pp 1553-1570, 1997.

7. Bliss, D.B. and Hayden, R.E. Landing Gear and Cavity Noise Prediction, *NASA Contractor Report CR-2714*, 1976.

8. Rossiter, J.E., Wind Tunnel Experiments on the Flow Over Rectangular Cavities at Subsonic and Transonic Speeds, *Royal Aircraft Establishment ARC R&M 3438*, 1966.

9. Heller, H.H., Holmes, G., and Covert, E.E., Flow-Induced Pressure Oscillations in Shallow Cavities, *Journal of Sound and Vibration*, Vol 18, No. 4, pp 545-553, 1971.

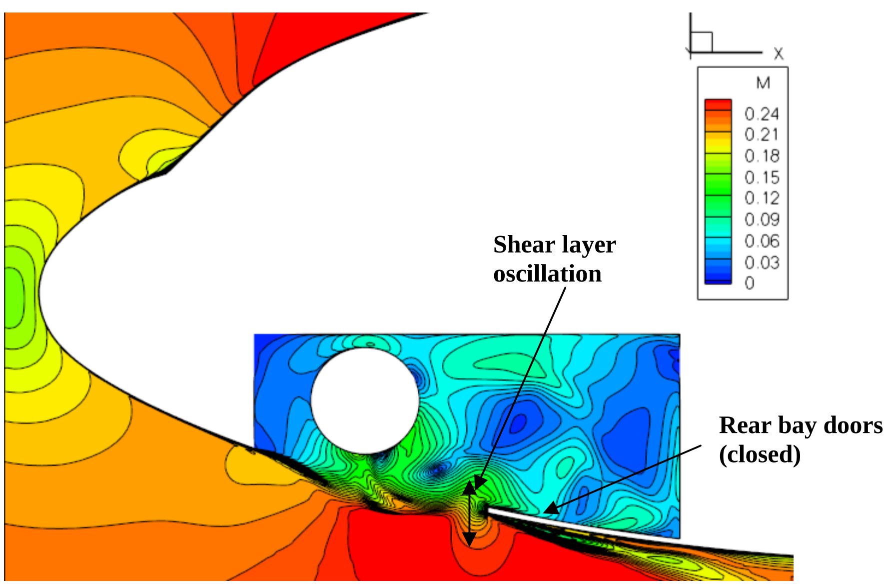

Figure 1 Flow over the nose-gear cavity when the gear is partially retracted with the rear doors closed and the front doors open. Contour plot of Mach number.

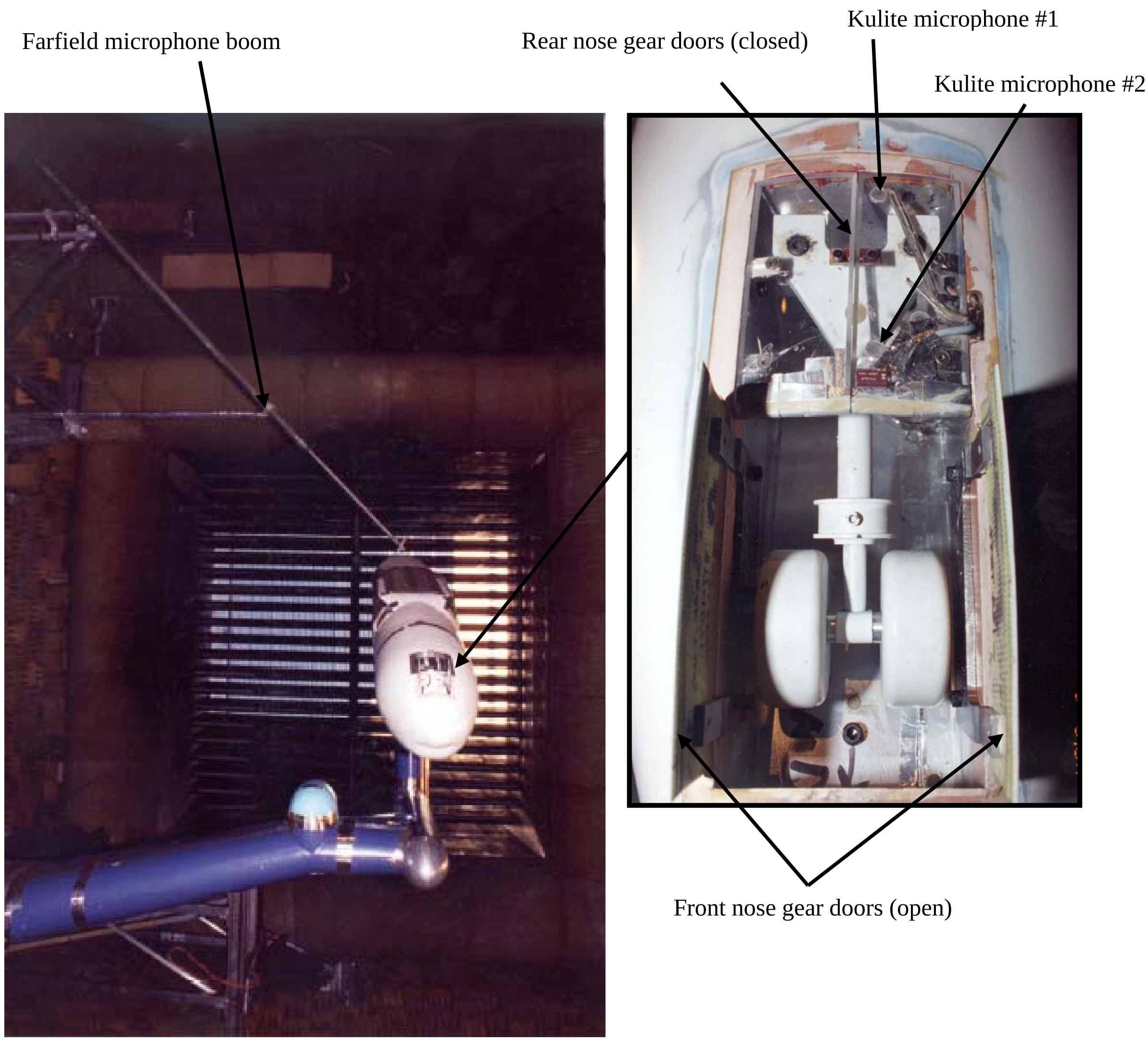

Figure 2 Fuselage model with nose gear cavity, bay doors (front open, rear retracted) and representative landing gear (retracted inside the cavity) installed in LSAF for the noise test (left). Close up view of the nose cavity region (right)

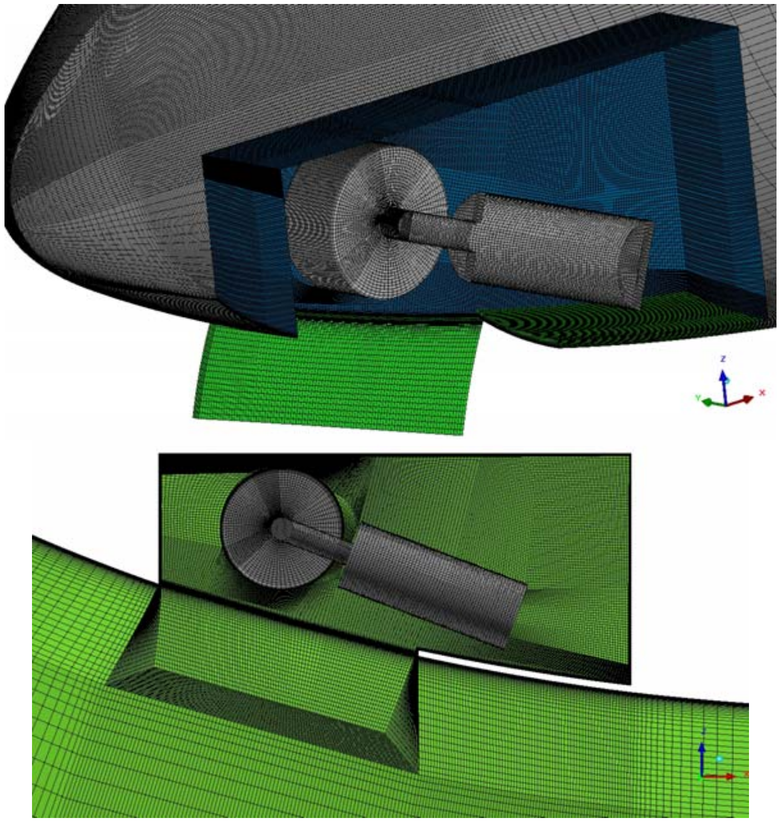

Figure 3 3D half-model view of the nose gear cavity surface grid (top) including the fuselage, cavity walls, landing gear, front nose gear door (open) and rear nose gear door (closed). Volume grid (bottom) near the plane of symmetry.

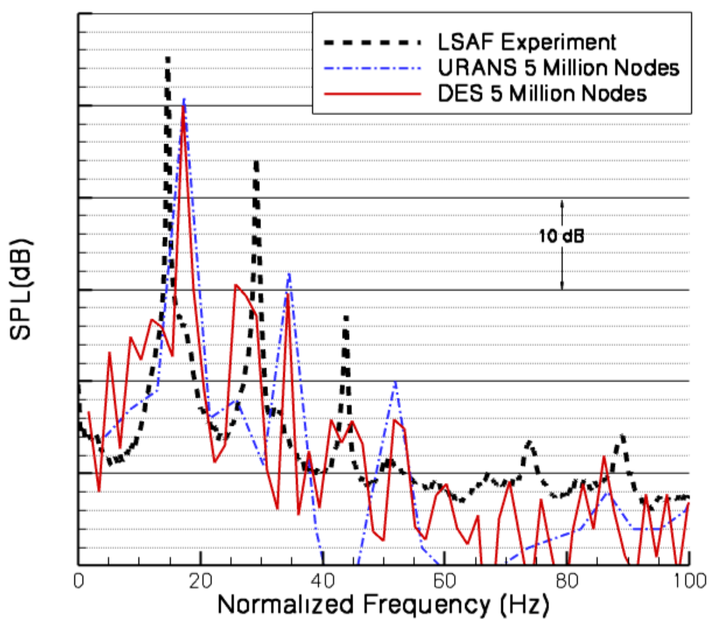

Figure 4 Experimental and predicted Sound Pressure Level (SPL) vs Normalized Frequency inside the cavity at the kulite microphone #1 position.

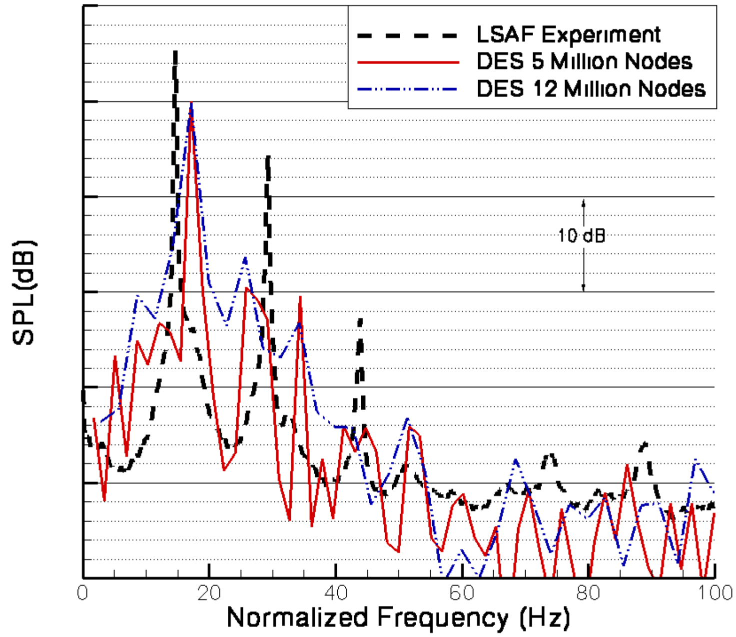

Figure 5 Effect of grid refinement on the predicted Sound Pressure Level (SPL) vs Normalized Frequency inside the cavity at the kulite microphone #1 position.

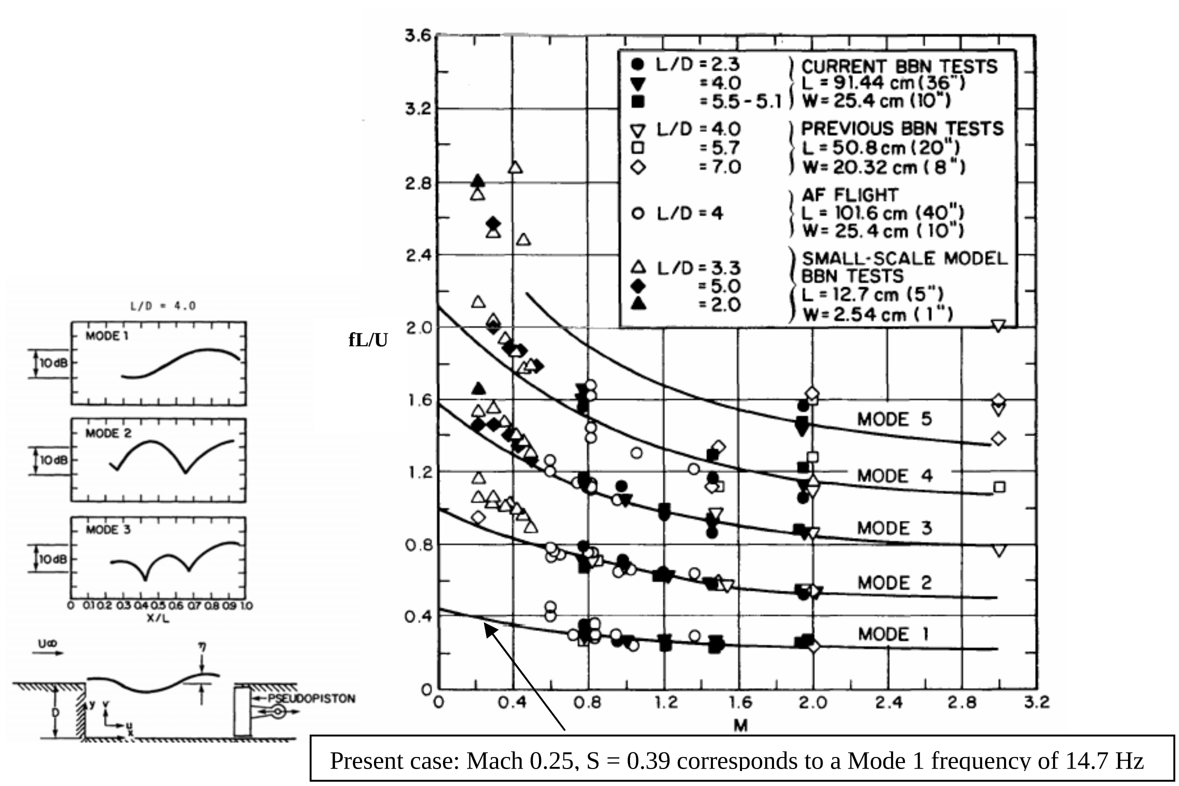

Figure 6 Non-dimensional Rossiter frequencies (fL/U) of various cavity modes as a function of Mach number. (Reproduced from Ref. 7).

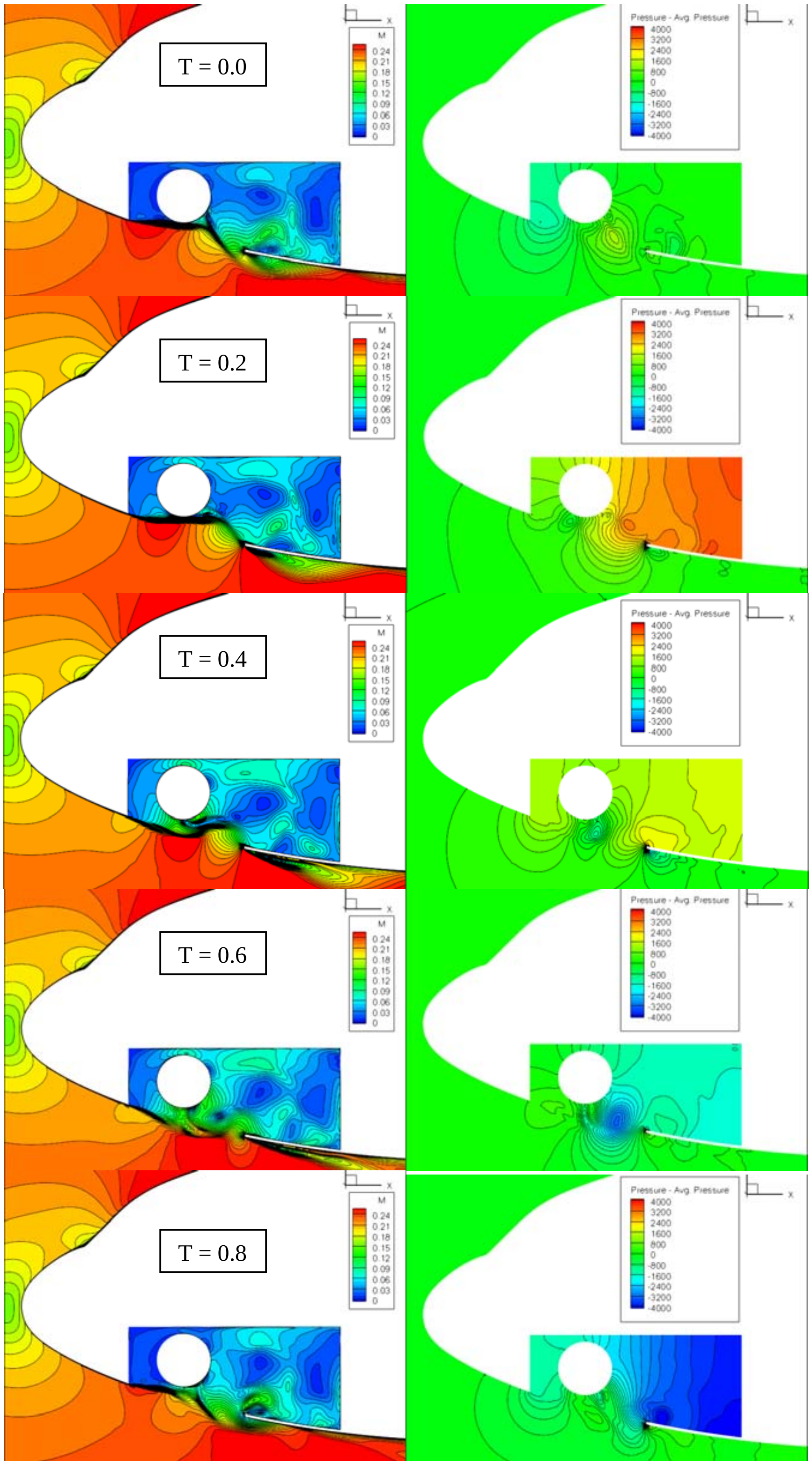

Figure 7 Mach number contours (left) and acoustic pressure contours (right) for five points in time during one cavity oscillation period (T). The contour plots are located in the span wise plane of the landing gear wheel.