Final Technical Report

Project title : A Computational Study of the Flow Physics of Acoustic Liners

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1. Introduction

The present investigation is a continuation of a previous joint project between the Florida State University and the NASA Langley Research Center Liner Physics Team. In the previous project, a study of acoustic liners, in two dimensions, inside a normal incidence impedance tube was carried out. The study consisted of two parts. The NASA team was responsible for the experimental part of the project. This involved performing measurements in an impedance tube with a large aspect ratio slit resonator. The FSU team was responsible for the computation part of the project. This involved performing direct numerical simulation (DNS) of the NASA experiment in two dimensions using CAA methodology. It was agreed that upon completion of numerical simulation, the computed values of the liner impedance were to be sent to NASA for validation with experimental results. On following this procedure good agreements were found between numerical results and experimental measurements over a wide range of frequencies and sound-pressure-level. Broadband incident sound waves were also simulated numerically and measured experimentally. Overall, good agreements were also found.

The primary motivation of the present project is to extend the previous work to three dimensions. The objectives are,

1. To validate DNS as a prediction method for liner impedance taking into account the three-dimensional geometry of the liner configuration.
2. To investigate the flow physics associated with resonators of a liner in three dimensions.
3. To examine the effect of aspect ratio of the openings of resonators on liner impedance.

To meet the above objectives, three-dimensional computations are required. Because the computational domain is three-dimensional, the number of mesh points and memory requirement of the computer code are orders of magnitude more than previous two-dimensional simulation. The complexity of the computer code also increases substantially. The physics of the problem in two and in three dimensions is somewhat different. To illustrate this point, consider the vortex shedding phenomenon at the mouth of a resonator of the liner. In two dimensions, the shed vortices are line vortices (see Figure 1). In three dimensions, the shed vortices are closed ring vortices. Two dimension line vortices are readily shed with relative ease. But three dimension loop vortices are harder to shed especially from small openings with aspect ratio close to one.

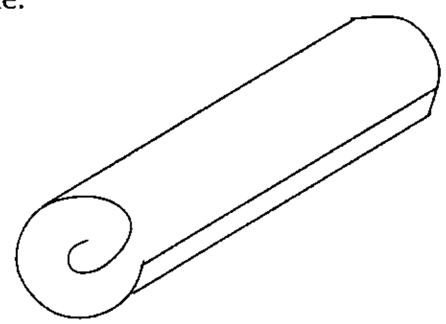


Figure 1. Two dimensional line vortex

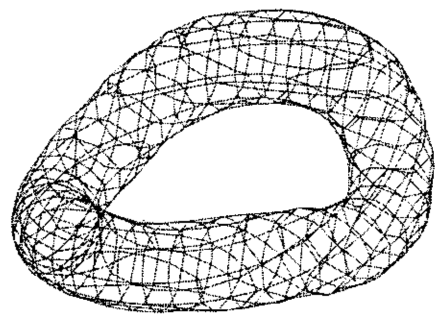


Figure 2. Three dimensional closed ring vortex

2. Computational Model

Experimental measurements were performed at NASA using a 2″ × 2″ normal incidence impedance tube. Six samples of resonator openings were used. The total area of the openings in the face sheet is the same for all six samples but the number of holes is different. The number of holes ranges from one to thirty-two. The hole size of the 32-hole case is 0.0025″ × 0.05″, which gives an aspect ratio of 1.25 (see Figure 2). The present computational work concentrates on this aspect ratio and the next larger aspect ratio of 2.5. It is not feasible to grid all 32 openings for computation. To make the computation reasonable, a computational model is adopted. In this model, the walls of the impedance tube are taken as reflecting boundaries. The face sheet is effectively infinitely wide and long with holes extending to large distances. For an infinitely large face sheet full of holes, a simplification becomes possible by imposing periodic boundary conditions around a single hole. This is shown in Figure 3.

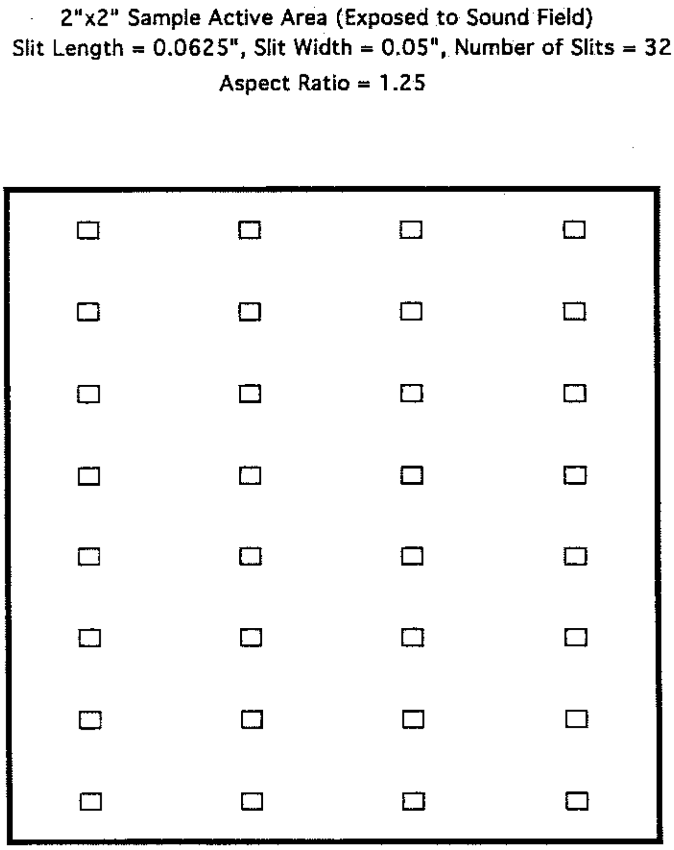


Figure 2. Sample six with 32 aspect ratio 1.25 holes.

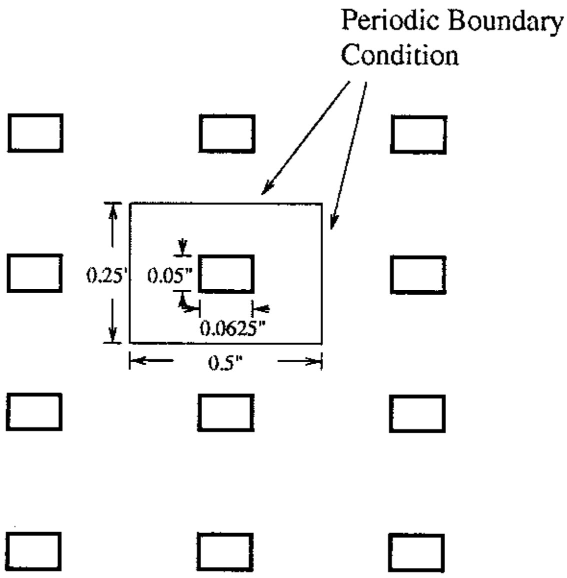


Figure 3. Plan view of an aspect ratio 1.25 opening enclosed by periodic boundary conditions

Figure 4 shows the computational domain of the normal incident impedance tube problem. The dimensions are exact replicas of those of the experiment. The cavity is at the bottom. It is separated from the incident sound waves by the liner surface with a hole at the center. At the top of the computational domain is an acoustic driver. The acoustic driver is simulated in the computation by the use of a perfectly matched layer (PML) combined with a split-variable arrangement. The lateral four sides of the computational volume are formed by the imposition of periodic boundary conditions.

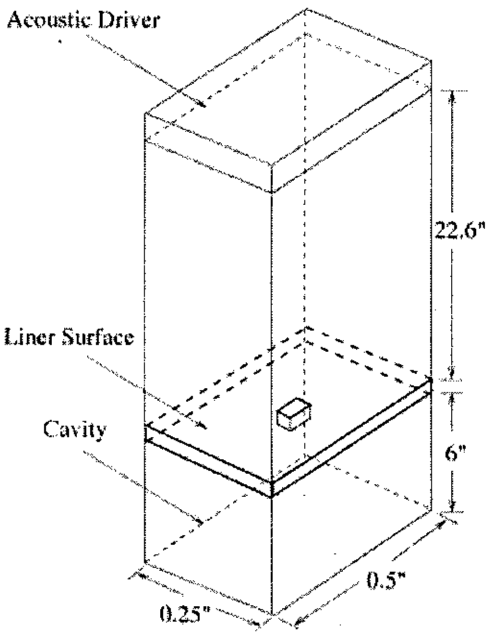


Figure 4. Three dimensional computation domain

It is, however, possible to conceive a situation when the flows in adjacent holes are not exactly synchronized. When this happens, the use of periodic boundary conditions might not be appropriate. To test this possibility, a two-hole simulation code is developed. The two-hole configuration is as shown in Figure 5. Test runs yield results identical to those of a single hole; within numerical accuracy of the algorithm. This gives confidence to the use of periodic boundary conditions in simulating the NASA experiments.

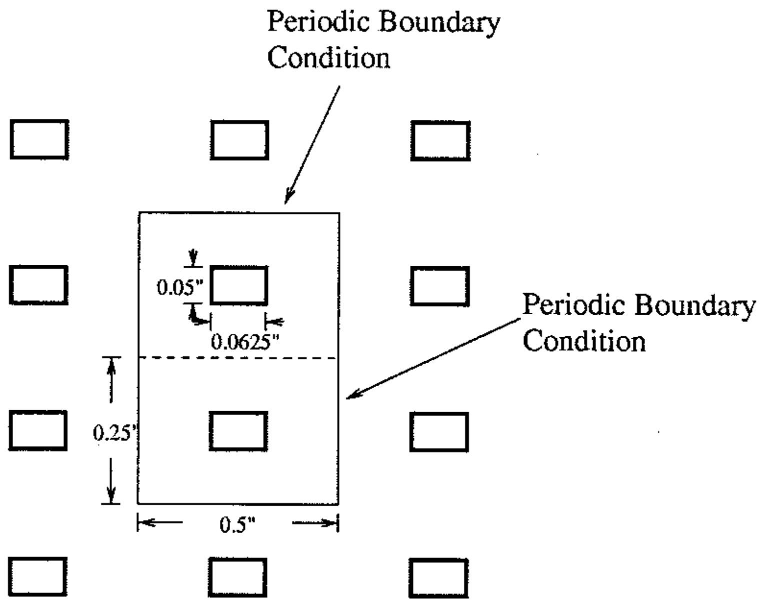
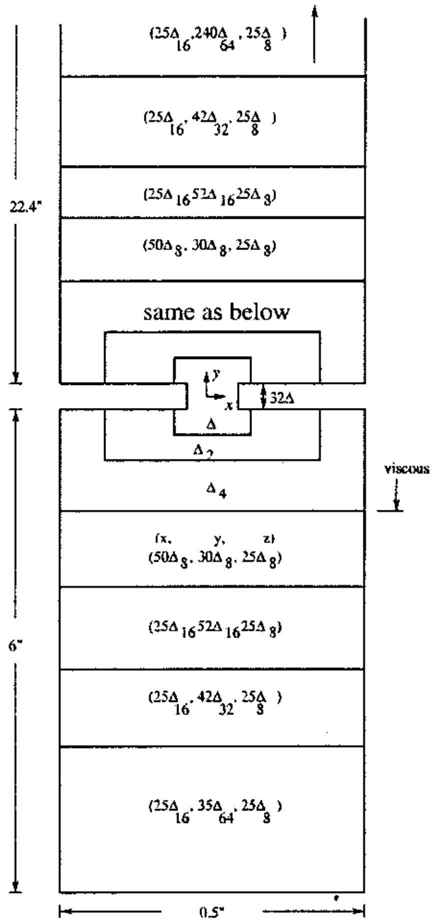


Figure 5. Two-slit computational model.

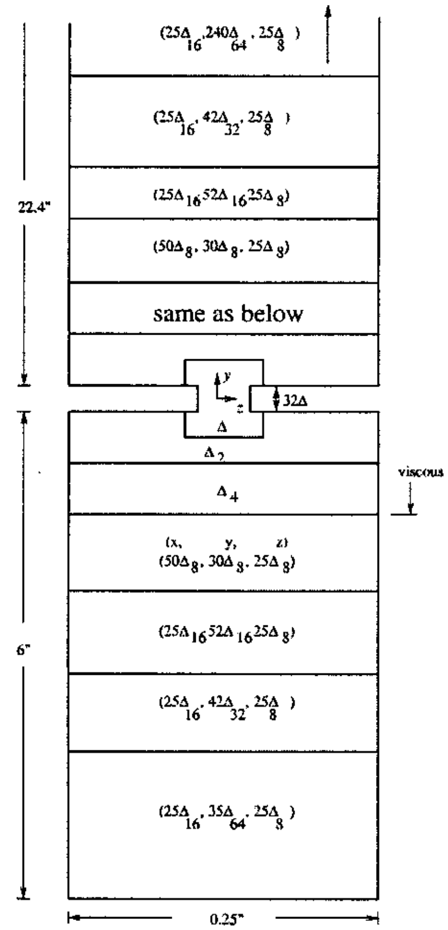
3. Mesh Design and Computation Algorithm

The flow around an acoustic liner is a multi-scales problem. This arises because near the openings of the resonators, viscous effect dominates the fluid motion. However, away from the openings, compressibility dominates the flow dynamics. This change in the dominant flow physics leads to a change in characteristic length scale in different regions of the computation domain. Adjacent to the walls that form the opening of a resonator, an oscillatory viscous Stokes layer is developed. The Stokes layer is very thin. But it exerts a strong influence on the vortex shedding process at the corners of the rectangular opening. Vortex shedding is a crucial mechanism by which a liner damps out sound. At some distance from the resonator openings, viscosity is not important. The fluid motion is driven primarily by acoustics or compressibility. The length scale of acoustics is the wavelength. It is very long compared to the thickness of the Stokes layer.



Sample 6 Grid (x–y section)

Figure 6. Grid design x-y plane.



Sample 6 Grid (z–y section)

Figure 7. Grid design y-z plane.

To provide accurate numerical resolution in simulating the impedance tube problem, a multi-size mesh is used. The idea is to use very fine mesh at the mouth of the resonator. This is to resolve the Stokes layer as well as to capture the shed vortices. The computational domain is divided into a number of subdomains as indicated in Figures 6 and 7. In each subdomain, a uniform size mesh is used. The mesh size of adjacent subdomain is increased by a factor of 2 starting from the mouth region of the resonator. The mesh design of Figures 6 and 7 required a total of 2.2 million mesh points. The code for simulating two holes requires 4.4 million mesh points. This is a fairly large size computation. In the present investigation, 26 parallel processors are used to run the code. 60 processors are used to run the code for two-hole simulation.

The simulations solve the Navier-Stokes equations computationally. These equations are,

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u_j}{\partial x_j} + u_j \frac{\partial \rho}{\partial x_j} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial p}{\partial t}+u_j\frac{\partial p}{\partial x_j}+\gamma p\frac{\partial u_j}{\partial x_j}=0$$

$$\tau_{ij}=\frac{1}{R_D}\left(\frac{\partial u_i}{\partial x_j}+u_j\frac{\partial u_j}{\partial x_i}\right)$$

where $R_D = Da_0/n$ is the Reynolds number. The no-slip boundary condition is enforced in the three blocks with the smallest size mesh. Computationally, this is implemented by the ghost point method. The multi-size-mesh multi-time-step DRP scheme is used to discretize the Navier-Stokes equations. This computation scheme has specially designed stencils to transfer information across a subdomain interface. Also artificial selective damping is imposed to eliminate spurious short waves in the computation. Spurious short waves are often generated at subdomain interfaces and wall boundaries. In this way, numerical stability of the computation is assured. The multi-size-mesh multi-time-step DRP scheme has the unique advantage that different size time steps are used in different subdomain. This reduces unnecessary computation in comparison with single time step method. This method reduces the computer run time significantly.

4. Some Numerical Results and Comparisons with Experiments

Numerical simulations for Sample 6 with aspect ratio 1.25 holes have been completed for some time. Computed liner resistance and reactance at selected frequencies and incident sound pressure levels agree reasonably well with experimental measurements. Figures 8, 9, 10 and 11 show sample comparisons over frequency range of 6.5 kHz to 3.0 kHz and SPL from 116 dB to 148 dB.

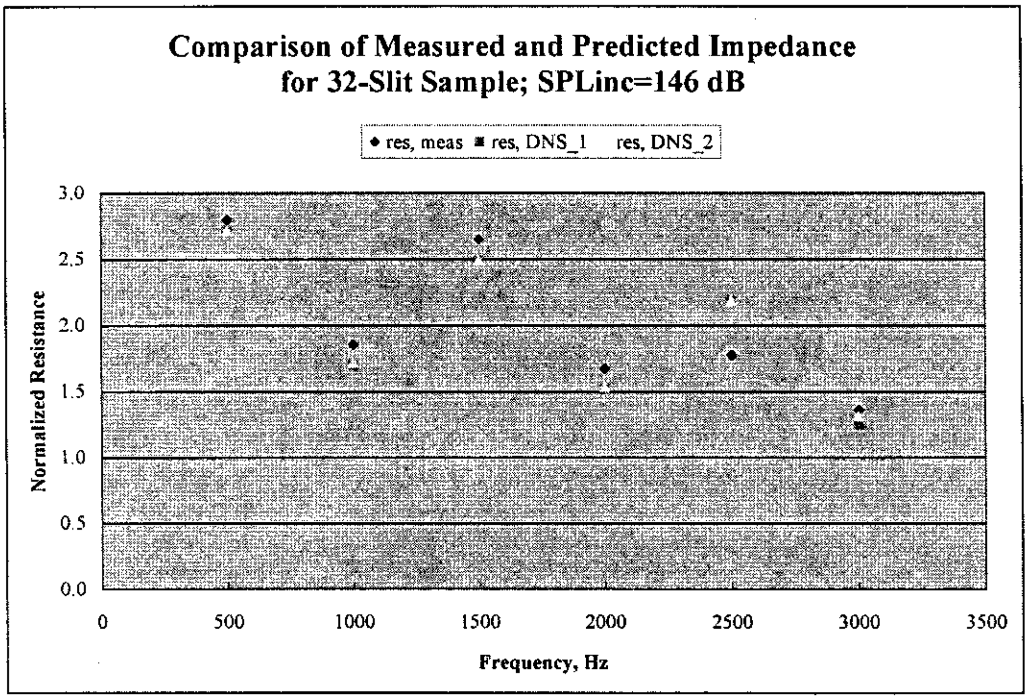


Figure 8. Normalized resistance at 146 dB SPL

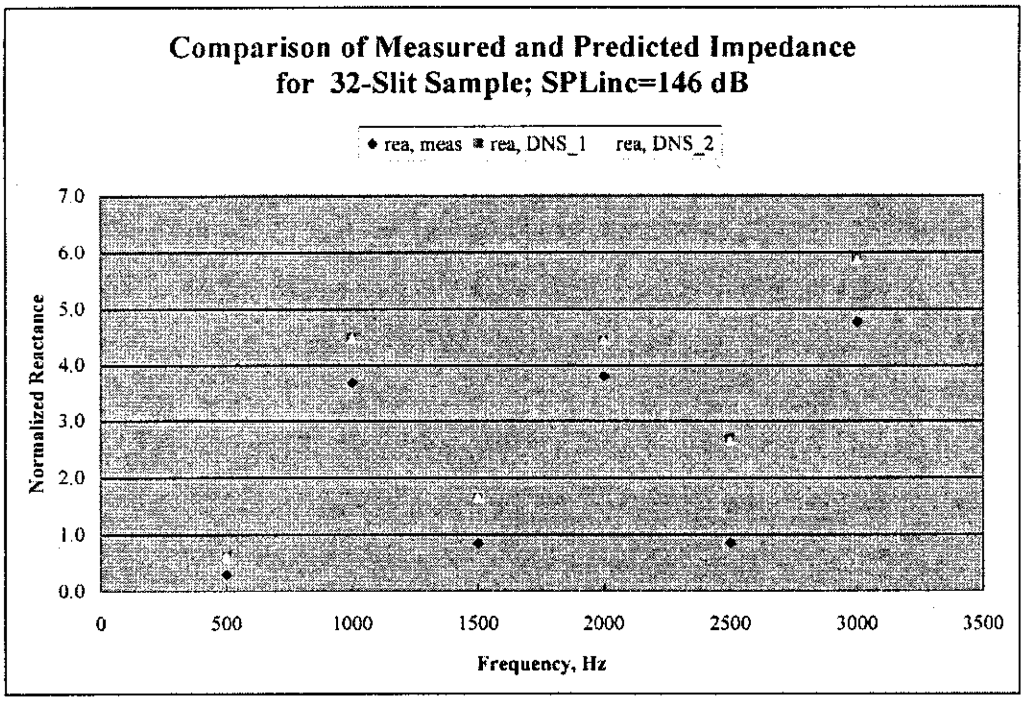


Figure 9. Normalized reactance at 146 dB SPL

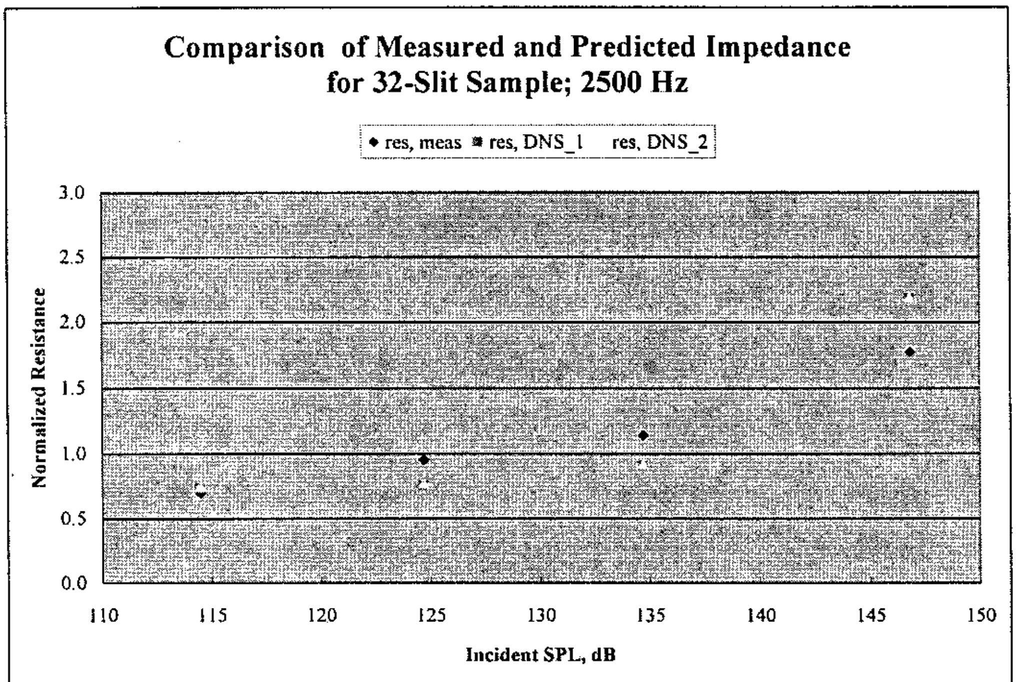


Figure 10. Normalized resistance at 2500 Hz incident sound frequency

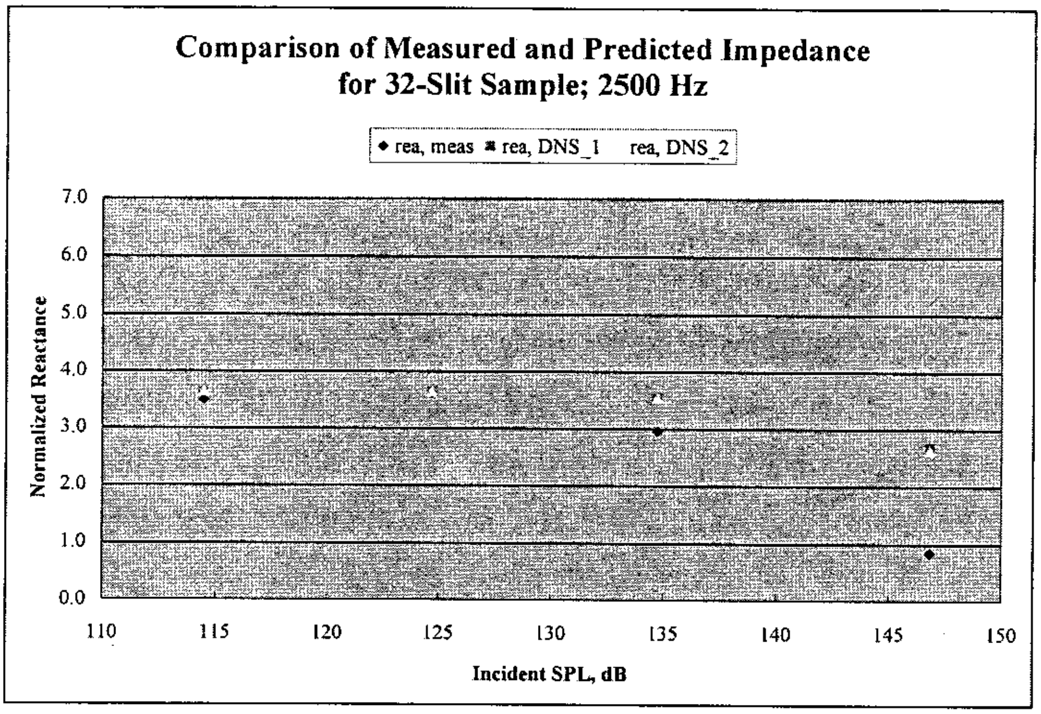


Figure 11. Normalized reactance at 2500 Hz incident sound frequency.

To visualize the flow around he opening of the resonator and the acoustic field inside the impedance tube movies of the numerical simulations are made. Figure 12 shows the vortex trains shed from the corners at the mouth of a resonator. These vortex trains are fairly regular and highly organized. They are very different from the two-dimensional simulation results. In the two-dimensional cases, the vortices are shed randomly. The positions of the shed vortices are chaotic. There is no organized vortex train. Figure 12 suggests that there are fundamental differences between line vortices in two dimensions and closed loop vortices in three dimensions.

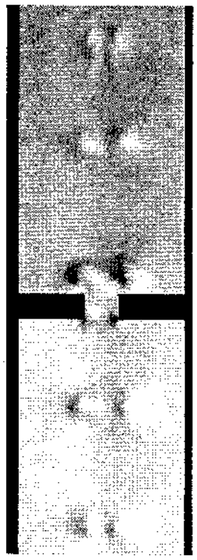


Figure 12. Vortex trains shed from 3D openings of a resonator in an impedance tube.

5. Future Work

At the present time, computations for Sample 6 are completed. Computations for Sample 5 are 60% complete. The work is continuing at this time.

In practical application, an acoustic liner is exposed to broadband sound as well as tones. Simulating the response of a liner to broadband sound is important. It is our plan to repeat a simulation of broadband incident sound waves using narrower bandwidth model. Previous simulation, as a part of the present project, using wide bandwidth yields good results for reactance. But the computed resistance is too high. It is suspected that the problem is caused by the fact that a wide bandwidth model makes the level of the discrete frequency wave representing the energy in the band too high. Even though the total energy is the same but concentrating the energy at a discrete frequency might lead to larger dissipation and hence higher resistance.

This project is to be officially terminated on 30 September 2006. However, the work will continue at FSU until all the simulations for Sample 5 and the case of broadband incident sound are completed and validated. It is the principal investigator's intention to present the results of this project at the 13th AIAA/CEAS Aeroacoustics Conference.