"Optimization and Control of Acoustic Liner Impedance with Bias Flow"

Final Report

Tunable Acoustic Liner Investigations

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Submitted by

Houston Wood, Associate Professor
Jesse Follet, Graduate Research Assistant

Mechanical & Aerospace Engineering
University of Virginia
Charlottesville, VA 22904

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1 Introduction:

Because communities are impacted by steady increases in aircraft traffic, aircraft noise continues to be a growing problem for the growth of commercial aviation. Research has focused on improving the design of specific high noise source areas of aircraft and on noise control measures to alleviate noise radiated from aircraft to the surrounding environment. Engine duct liners have long been a principal means of attenuating engine noise. The ability to control in-situ the acoustic impedance of a liner would provide a valuable tool to improve the performance of liners. The acoustic impedance of a liner is directly related to the sound absorption qualities of that liner. Increased attenuation rates, the ability to change liner acoustic impedance to match various operating conditions, or the ability to tune a liner to more precisely match design impedance represent some ways that in-situ impedance control could be useful. With this in mind, the research to be investigated will focus on improvements in the ability to control liner impedance using a mean flow through the liner which is referred to as bias flow.

Aircraft engine liners are located in the inlet and aft fan duct and attenuate engine noise as the acoustic waves propagate fore to aft of the engine. Figure 1 illustrates the liner placements in the aircraft engine nacelle both fore and aft of the turbofan. As shown in Figure 2, typical aircraft engine liners consist of two layers, which corresponds to two "tuned" frequencies. The liner sound absorption is maximized at its "tuned" frequencies. Each layer consists of a cavity with honeycomb channels and a thin perforated sheet. The liner impedance is dependent upon the geometry of each layer, specifically, its perforate plate thickness, hole diameter, and percent open area (POA) and the cavity length. The honeycomb is purposely for structural stiffness and it minimally affects the impedance of the liner.

Bias flow is aspirated through the back surface of the liner and creates a bias to the incoming parallel grazing flow.

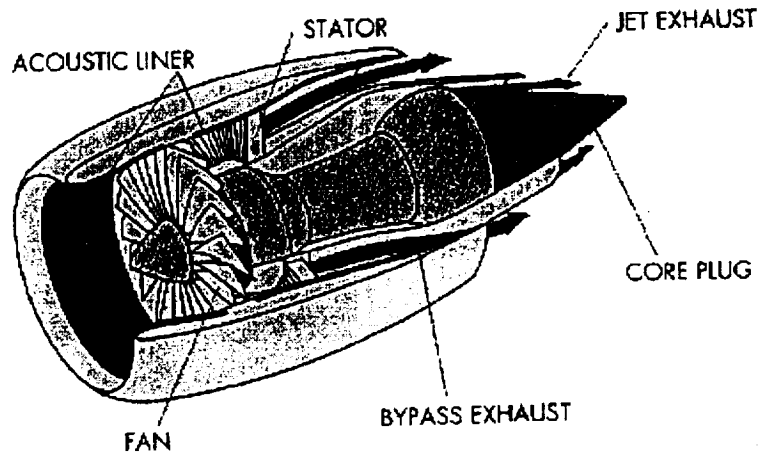**PRIMARY ACOUSTIC ELEMENTS**

Figure 1. Illustration of liner placement in the aircraft engine nacelle. The liners are located in the inlet and aft-fan duct of the nacelle.
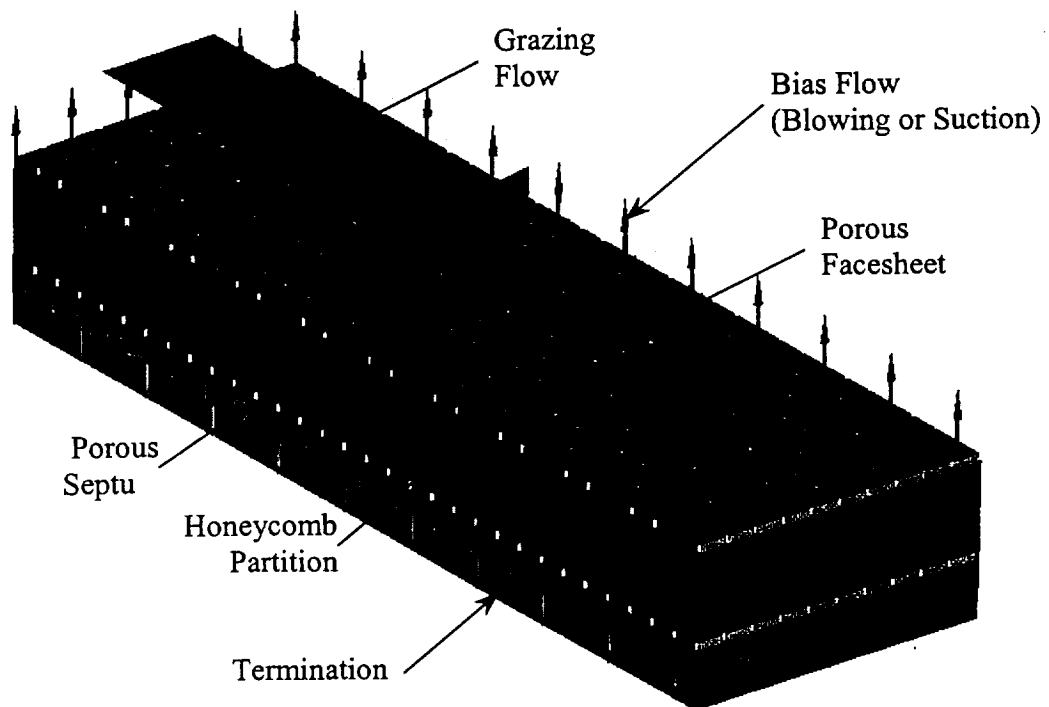

Figure 2. Illustration of a typical 2-DOF acoustic liner with bias flow in a grazing flow environment.

Utilizing the effects of bias flow to improve and control liner impedance has been studied with varying degrees of interest since the early 1970's. The first notable look at using bias flow to control liner impedance is by Dean[1]. Dean performed a rigorous study of the effects of bias flow on the impedance of various perforate liners. The results were used to design bias flow liners that target the optimum impedance curve that varies with grazing flow. Much like most liner design practices, Dean looked narrowly at designing "tuned" liners that only targeted certain engine operating frequencies and ignoring the added benefit of bias flow discussed recently by Cataldi, Ahuja and Gaeta[2]. Cataldi *et al.* showed how bias flow also improves broadband liner absorption. A third advantage to bias flow is its effects on the nonlinear behavior of the liner impedance to changing sound pressure level. As the sound pressure level changes the liner impedance deviates from the optimum design impedance. Melling[3] discusses nonlinear behavior of liners in great detail. With careful design of the bias flow liner, a near perfectly absorbing liner could potentially be achieved for a broad range of frequencies, grazing flow Mach numbers and sound pressure levels.

1.1 Objectives:

This research involves the investigation of the bias flow mechanism in order to change the impedance of an acoustic liner. In several studies[1,2,4] in the past, it has been shown that adding a flow through an acoustic liner in either direction can significantly change the impedance of the liner as compared to impedance without bias flow. Therefore, bias flow offers a mechanism for in-situ control of liner impedance, which could be potentially beneficial for at least two reasons. First this would provide the ability to tune the installed liner impedance to better obtain the design value, this can be an issue arising from many factors including manufacturing tolerances. The second potential benefit of a liner im-

pedance control mechanism would be the ability to change the liner impedance during operation in order to optimize the liner performance at different operating conditions.

While the potential of bias flow to change the liner impedance and the possible benefits are clear, basic questions must be addressed and these form the objectives of this research. The overall objective of this research is to compare the performance of a conventional passive liner with a liner that has been designed to operate with bias flow. With this in mind, the central part of the study is the optimization of the liner geometry and bias flow rates to target the necessary impedance values for maximum broadband absorption. This will provide an indication of the possible performance that can be achieved with bias flow over a conventional liner. It will also demonstrate the range of control of impedance possible with bias flow.

2 Approach:

The approach is primarily experimental in several phases. The first phase involves the evaluation of impedance models using normal incidence tube and d.c. (direct current) raylometer measurements. A normal incidence tube measures normal incidence acoustic impedance and a d.c. raylometer measures the flow resistance of porous material. This model evaluation phase includes the effect of bias flow.

In the second phase, using the validated models, optimum double degree of freedom liners will be designed for both passive (no bias flow) and bias flow cases. The liners will be tested in the normal incidence tube and performance compared to predictions. Figure 3 shows the experimental setup with bias flow. The acoustic wave is incident upon the perforate test sample and the bias flow is introduced through a highly resistive fibermetal sheet that is acoustically opaque but allows flow through.
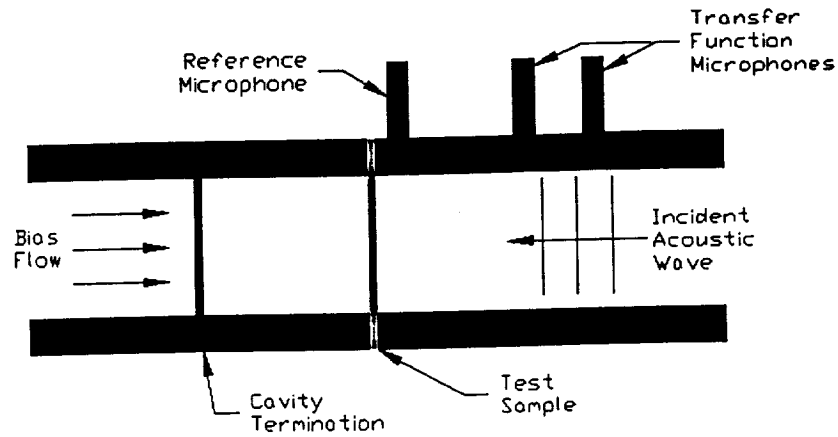
Figure 3. Experimental setup for bias flow normal incidence impedance measurements.
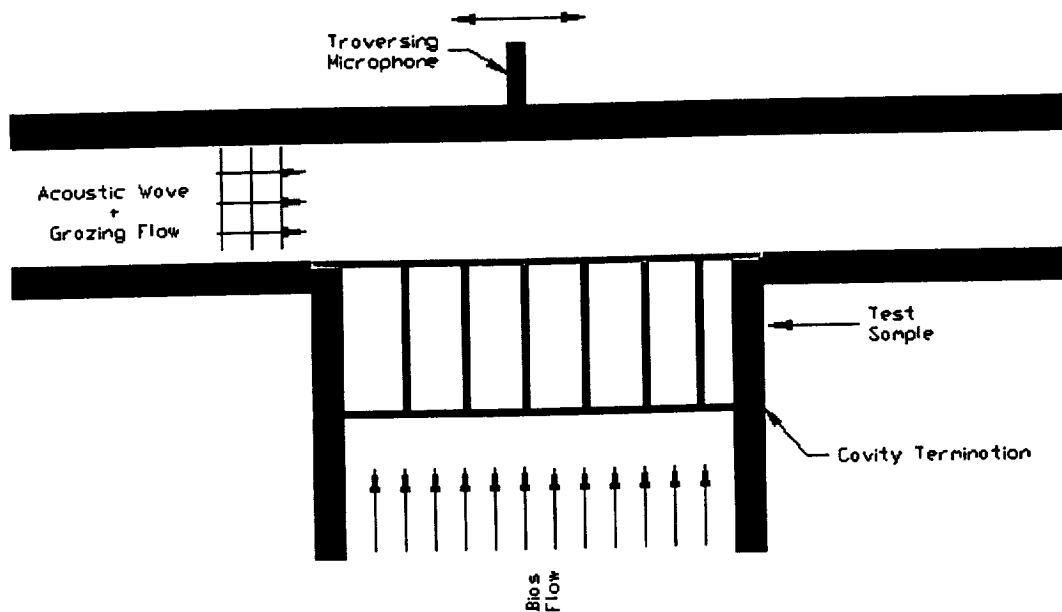
Figure 4. Experimental setup for grazing flow/bias flow impedance measurements.

In the third phase, preliminary impedance models for grazing flow will be validated using some impedance measurements. Again, two optimally designed liners will be built and tested for performance comparison between passive liners and bias flow liners in the grazing flow environment. Figure 4 shows the experimental setup for the grazing flow case. The acoustic wave and grazing flow are parallel to the liner with bias flow again being introduced

through the back wall. The test sample is a perforate with honeycomb cells added for structural support.

2.1 Phase I – Perforate Impedance Database and Modeling

The initial phase of this study is the experimental determination of liner impedance and the evaluation of impedance models using data obtained from the NASA Langley Normal Incidence Tube (NIT). An experimental database was produced which included both fibermetal and perforate samples tested with and without bias flow in a single-degree-of-freedom (SDOF) liner configuration. The database was used to validate available impedance models and develop improvements in order to produce the best available frequency domain impedance model that includes the effect of bias flow.

2.1.1 Normal Incidence Impedance Experimental Database

The NASA Langley Normal Incidence Tube (NIT) was used to make impedance measurements of lumped element single-degree-of-freedom liners with bias flow (see Figure 5). Six acoustic drivers generate an acoustic pressure field, which upon reflection from the perforate sample sets up a standing wave inside the 5.08x5.08 cm² tube. The perforate sample is placed at the end of the tube and supported with a short 5.08x5.08-cm2-cavity length with a termination face. Three microphones are used to measure the sound pressure level near the surface of the perforate, and determine the standing wave pattern in the tube. The microphone closest to the specimen is a stationary microphone that is used to set the sound pressure level at the surface of the specimen. The other two microphones measure the frequency dependent acoustic pressure magnitude and phase differences between the microphones to determine the standing wave pattern in the tube. Since the acoustic wave patterns depend on the surface impedance of the perforate sample, this impedance can be determined

assuming only plane waves exist in the duct. A least square method is used to calculate the incident and reflected acoustic wave related to the acoustic impedance[5,6].
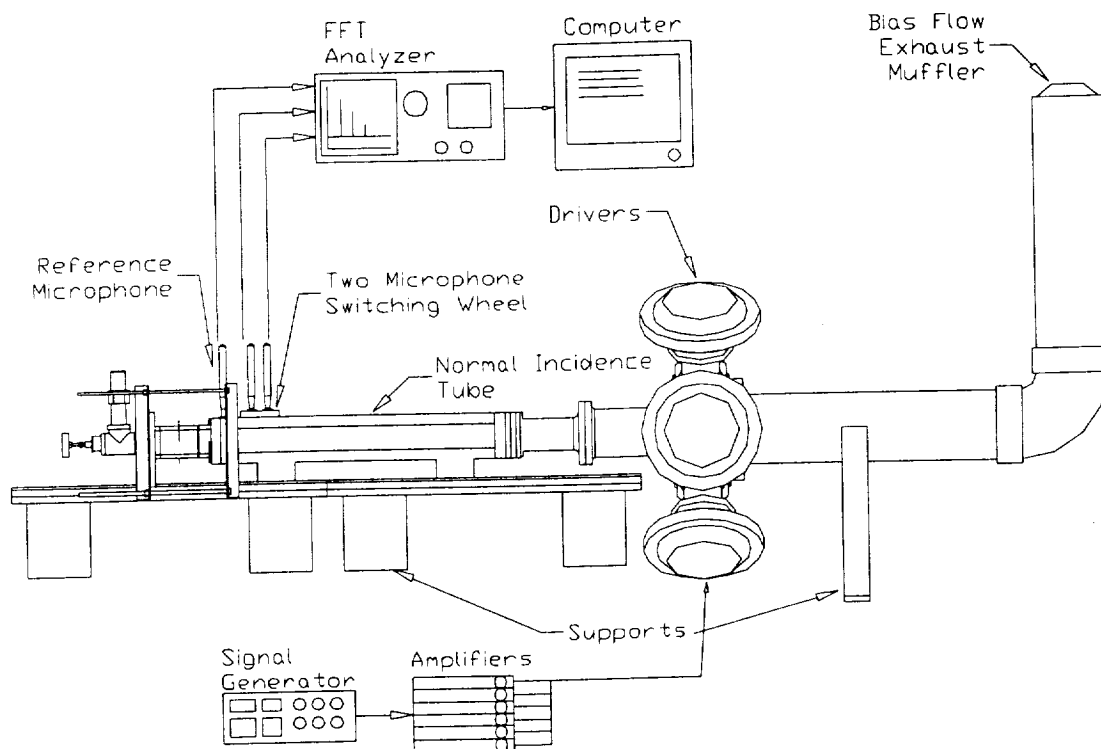
Figure 5. Schematic description of NASA Normal Incidence Tube with modifications to allow for bias flow. One-degree-of-freedom liner installed at left end (see Figure 6).

The signals from the microphones are sampled and averaged using an FFT analyzer and the data is stored on the computer hard disk. The signal generator was used to create discrete frequency tones and its signal output was amplified to the acoustic drivers.

The flow is introduced through the 2.54-cm i.d. inlet tee, shown in Figure 6, into a 5.08x5.08-cm^2 plenum chamber, which then continues through a high resistance fibermetal sheet into the cavity section and through the perforate sample. The flow is exhausted through the large muffler shown in Figure 5. A reference sample was tested in the NIT before and

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after the muffler was installed. Results showed the muffler had no impact on the measured impedance.
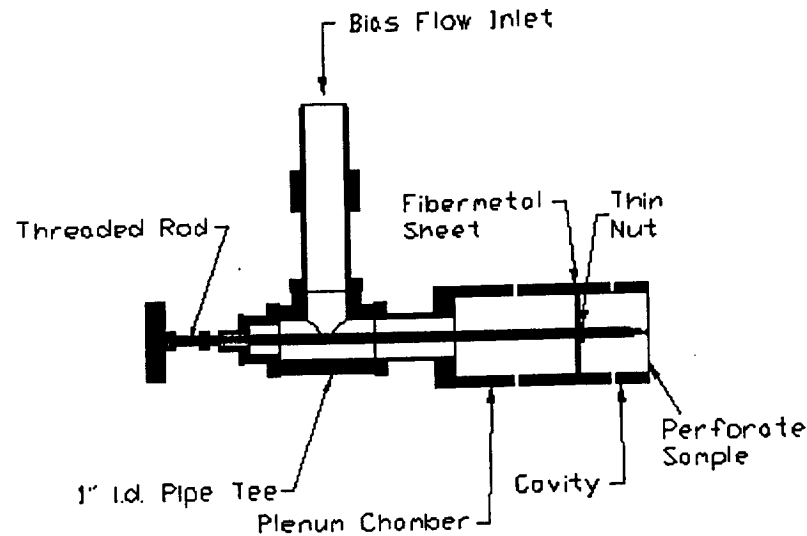
Figure 6. Schematics of hardware to supply mechanical support and bias flow to perforate sample.

Several perforate liner samples were tested in the NIT. The perforate geometries tested varied in percent open area from 1 to 15, the diameter from 0.25 to 1.40 mm, and the thickness from 0.64 to 1.02 mm. The sound pressure level was varied from 120 to 140 dB and the frequency from 1000 to 3000 Hz. The bias flow was varied from −25 to 600 cm/s incident upon the perforate. The cavity depth was a constant 2.72 cm. These experimental measurements form the core of the impedance database used for evaluating the prediction accuracy of the impedance model.

2.1.2 Model Evaluation

The surface impedance predictions were obtained with the NASA Langley Zwikker-Kosten Transmission Line Code (ZKTL)[7]. This computer program is based on Zwikker and Kosten's theory for sound propagation in channels[8]. In general, the liner is modeled as a

composite of continuous arrays of multi-degree-of-freedom liner elements. Matrix techniques are employed to compute the composite impedance due to the liner elements[9]. For a nonlinear liner, an iteration scheme determines the impedance based on a given incident sound pressure level (SPL). A liner is said to be non-linear if its impedance is dependent upon the sound pressure level. For this investigation, a finite impedance boundary condition was developed to simulate a porous back plate that was used to introduce the bias flow.

A new bias flow model was developed for perforated plates. The experimental database was used to evaluate the prediction accuracy of this model. Comparisons between experimental and numerical results shows that this model performs better for higher (15%) rather than lower (5%) percent open area (POA) samples. With this model, the ultimate goal is the design of double-degree-of freedom (DDOF) liners representing optimum passive and bias flow liner configurations.

2.2 Phase II – NIT Optimal Bias Flow Liner Design

The second phase of the research program is to design, build and test liners using the impedance models. These liners will be designed for testing in the NASA Langley Normal Incidence Tube (NIT). The clear goal of liner design is the production of a liner that gives the best sound absorption over a broad range of frequencies and sound pressure levels. The optimum impedance of liners in the NIT configuration is determined from the absorption coefficient.

This phase will concentrate on the production of two test liners. One liner will be the current aircraft engine liner configuration, a two-layer passive liner that is "tuned" to two frequencies. The second liner will be a two-layer bias flow liner, which will also be "tuned" to two frequencies. However, the bias flow liner is expected to increase absorption signifi-

cantly outside of these two frequencies and also be independent of the sound pressure level. These last two points are the focus of phase II. The direct comparison of the passive and bias flow liners is expected to conclusively show that overall, the bias flow liner is significantly better in terms of sound absorption for these two reasons stated.

An optimization study will be performed that will determine the liner parameters that provide the best overall absorption. The liner parameters are the cavity length, POA, thickness, and hole diameter of both layers of the bias flow liner, and the bias flow velocity. The overall absorption is the average absorption over the design frequency and sound pressure level ranges.

2.2.1 Optimization of Two-Layer Liner Parameters

Utilizing the impedance models, two liners will be designed that give their respective best overall absorption. Through the use of specific optimization routines coupled with the ZKTL impedance prediction code, the liner parameters will be varied until an optimum value of the overall absorption is reached. Once these parameters are determined the liners will be fabricated and tested in the NIT and compared to predictions.

The models have been programmed into the ZKTL FORTRAN code that has been ported to MATLAB. By accessing ZKTL through MATLAB, it is a much simpler matter to run the optimization routines and quickly plot the results.

With the final goal of maximizing liner absorption over a range of frequencies and sound pressure levels, the optimization will focus on mean absorption. The most significant factor affecting liner absorption is the sound frequency. The impedance non-linearity at high sound pressure levels will also have a marginally significant effect. The optimization routine will integrate over frequency and SPL.

$$\alpha = \frac{4\theta}{(1+\theta)^2 + \chi^2} \tag{1}$$

$$\overline{\alpha} = \frac{\int_{f_{min}}^{f_{max}} \int_{SPL_{min}}^{SPL_{max}} \alpha(f, SPL) dSPL df}{(f_{max} - f_{min})(SPL_{max} - SPL_{min})} \tag{2}$$

where α is the absorption coefficient, θ and χ are the normalized resistance and reactance, respectively, which are calculated using the ZKTL code, and $\overline{\alpha}$ is the mean absorption. α is integrated over the minimum and maximum frequency and sound pressure level. The optimum impedance for the normal incidence absorption (equation 1) is $\theta = 1$ and $\chi = 0$.

The optimization routine selected was a constraint type minimization. Since the absorption coefficient maximum value is 1.0, the minimization routine could be used by scanning for the liner parameters that best approached an average absorption of −1.0. For the implementation of the constraint minimization, the parameters needed to be limited to values within the valid range of the impedance models. These constraint values were selected based on the experimental impedance database of the perforate samples.

Specifically, a Sequential Quadratic Programming (SQP) method of constraint minimization will be used. The SQP method is a form of the Quasi-Newton method that includes constraints. Simply put, it computes the values and gradients of the function to estimate where the minimum should be and iterates until it is reached. The minimization problem is given as,

$$\min\{-f(x_i)\} \tag{3}$$
$$x_{i,min} \le x_i \le x_{i,max}$$

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where $f(x_i)$ is the overall absorption given in equation 2 and the minus sign indicates inversion of the function, x_i is the vector of liner parameters, and is constrained between a minimum and maximum vector.

Using ZKTL and the MATLAB SQP optimization routine, two sets of liner parameters were calculated. One optimum passive liner and one optimum bias flow liner. These liners were then fabricated and tested in the NIT.

2.2.2 Experimental Verification of Optimal Two-Layer Liner Impedance

In order to verify the results of the optimization study, the two liners were tested in the NIT. They were tested in the same manner as the liners in the experimental database.

Figures 7 and 8 show the liner setup for the passive and bias flow configuration, respectively. Again, a porous fibermetal high resistance sheet is used in the bias flow configuration to simulate the acoustic hard wall while allowing flow through. The impedance and absorption are computed and the results will be compared to the results of the optimization study.
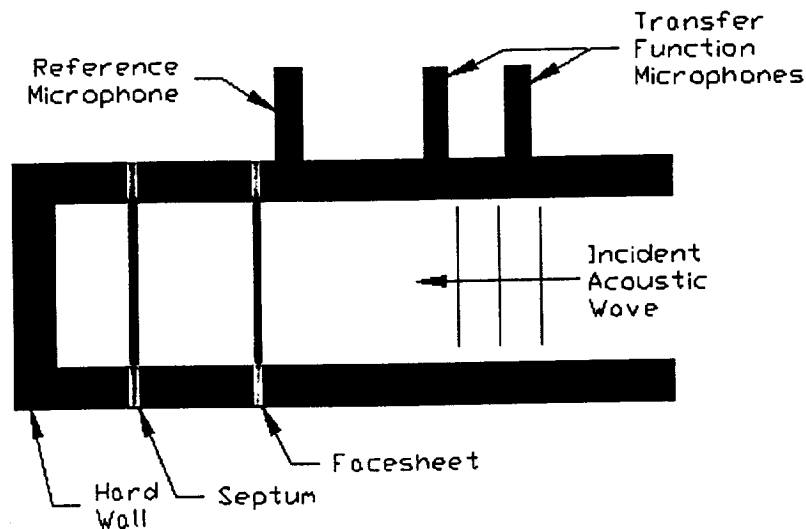

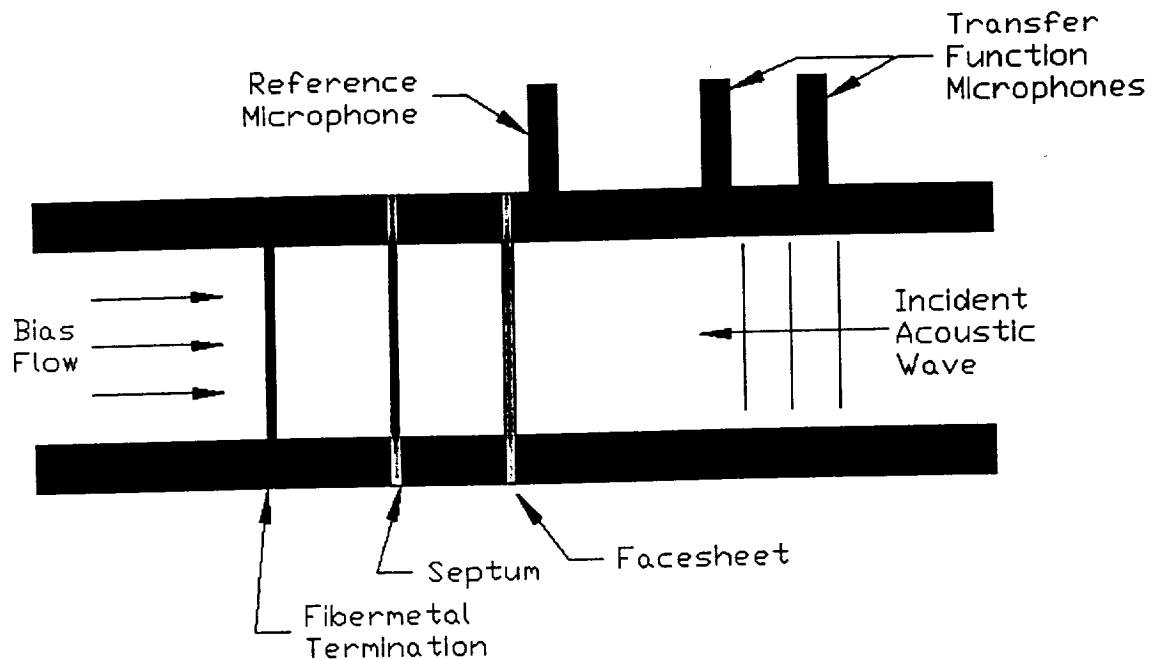Figure 7. NIT experimental setup for the optimum passive liner.

Figure 8. NIT experimental setup for the optimum bias flow liner.

With the successful optimization of the bias flow liners in the normal incidence acoustic tests, the next and final phase of the research program is the application to grazing flow conditions.

2.3 Phase III – FIT Optimal Bias Flow Liner Design

The NASA Langley Flow Impedance Tube (FIT) is a measurement apparatus used to measure liners in a more realistic engine-operating environment. Acoustic liners are installed on the walls of the duct. As a result, the grazing flow and the acoustic pressure waves pass parallel to the liner face. Figure 9 illustrates this configuration. The design and testing of a viable bias flow liner in the FIT is the ultimate goal of this research program.
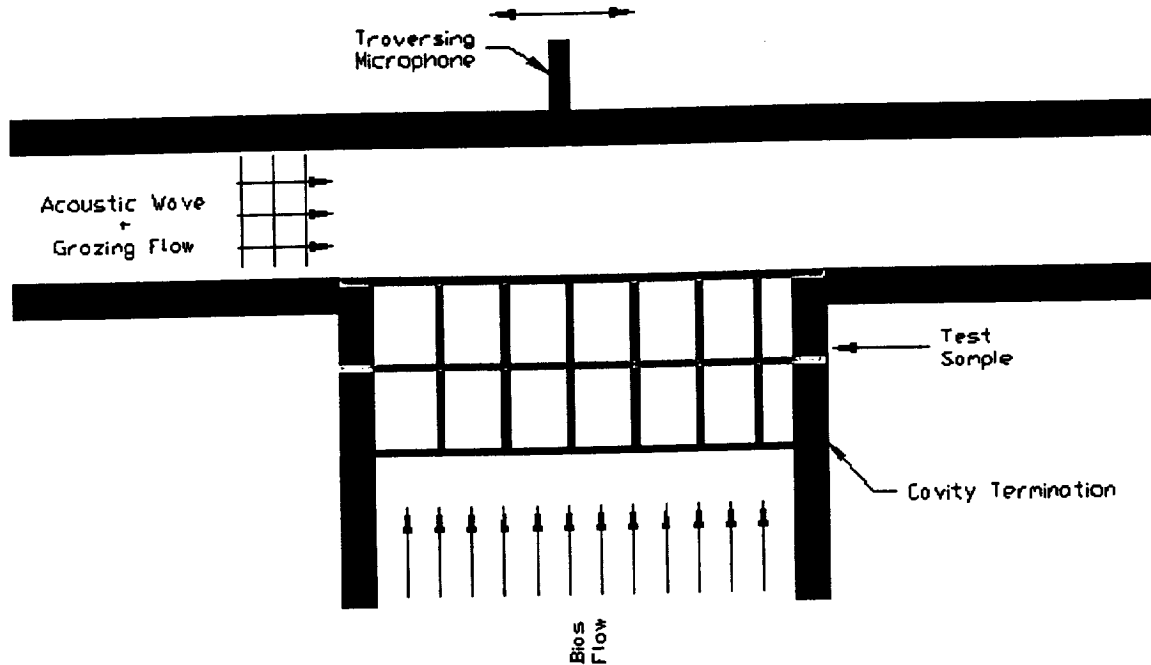
Figure 9. FIT experimental setup for the optimum bias flow liner.

2.3.1 Development of Grazing Flow Impedance Model and Verification

For an optimization to be applied to the design of the grazing flow/bias flow liners, a grazing flow/bias flow impedance model will need to be implemented. The ZKTL code is already capable of calculating liner impedance and insertion loss for acoustic waves at an oblique angle to the liner in the presence of grazing flow. However, the prediction of impedance with bias flow or for acoustic waves travelling parallel to the liner has not been investigated with great certainty. A preliminary model will be developed that will encompass both of these current shortcomings. The model results will be compared to existing grazing flow/bias flow liner data and potentially improved if necessary.

2.3.2 Optimization of 2-DOF Liner Parameters

The optimization will be handled in the same manner as before, except that for the grazing flow liners, the optimization parameter is not the normal incidence absorption. The performance of a grazing flow in-situ liner is based on its insertion loss, which is a measure

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of the slope of the sound pressure level decrease as a function of liner length. Figure 10 illustrates the results of a sample insertion loss measurement. The steeper the slope, the more sound pressure is absorbed over the length of the liner. This is an important distinction from the normal incidence absorption since the optimal impedance of the liner is no longer a constant, but a function of grazing flow velocity, frequency and duct geometry.
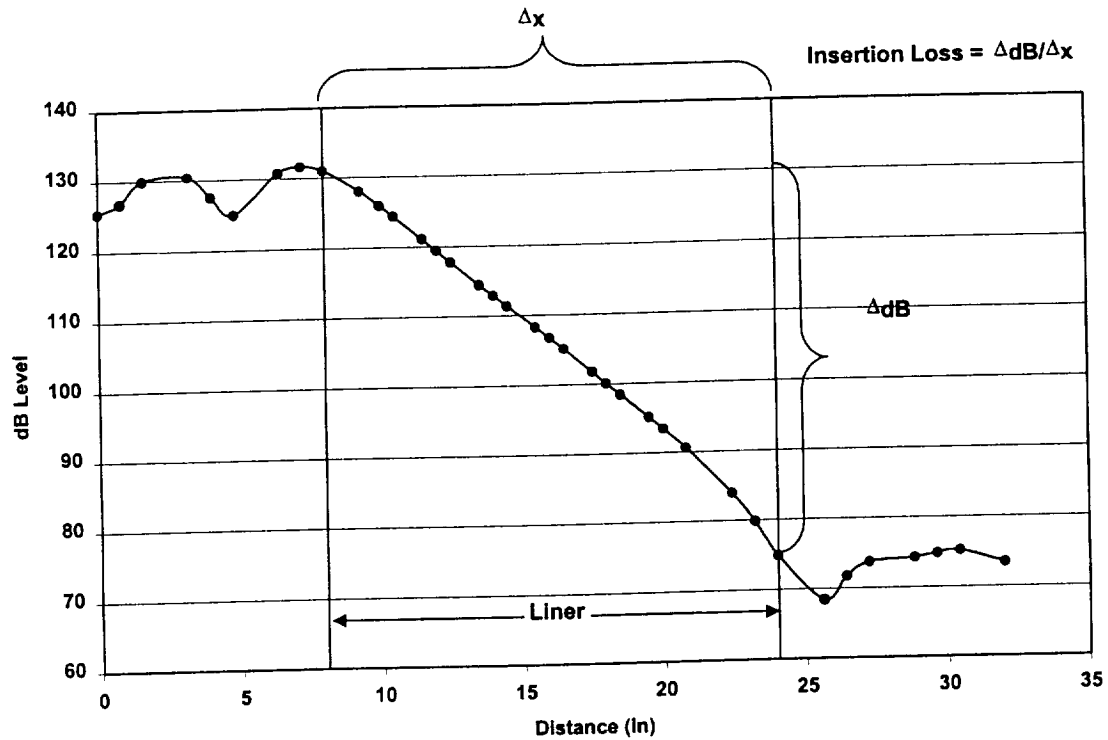

Figure 10. Sample data plot of insertion loss measurements.

Cremer[10] first described the optimum impedance of a liner parallel to the acoustic wave and then Testor[11] extended the model to include grazing flow effects. The optimum impedance is described in equation 4.

$$Z_{opt} = \frac{1}{(1+M)^2}(0.92 - 0.77i)H\frac{f}{c} \qquad (4)$$

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where Z_{opt} is the optimum impedance, M is the grazing flow Mach number, H is the duct height, f is the acoustic frequency, and c is the speed of sound.

The optimization of the liner parameters can now no longer be based on the absorption. In order to utilize the same optimization methods used previously, the optimization function can find the average minimum of the impedance relative to the optimum impedance.

$$\phi(M,f,SPL) = Z_{opt} - Z \tag{5}$$

$$\overline{\phi} = \frac{\int_{M_{min}}^{M_{max}} \int_{f_{min}}^{f_{max}} \int_{SPL_{min}}^{SPL_{max}} \phi(M,f,SPL) \, dSPL \, df \, dM}{(M_{max} - M_{min})(f_{max} - f_{min})(SPL_{max} - SPL_{min})} \tag{6}$$

where $\phi(M,f,SPL)$ is the minimization function, and Z is the calculated impedance of the liner. Minimizing equation 6 will give the maximum insertion loss possible with the given fixed liner geometry. Here again, the liner geometry and bias flow rate are varied using optimization routines to achieve the minimum $\overline{\phi}$.

The main difficulty in the optimum liner investigation is using the bias flow rate as a control variable in targeting the optimum impedance of varying grazing flow Mach number and frequency. Specifically, when the engine operating conditions change (i.e. Mach number or frequency changes), the bias flow can be increased or decreased to change the liner impedance to better match the new optimum impedance based on equation 4. The minimization function in equation 6 can be described,

$$\overline{\phi}(V_b(M,f),t1,d1,...,POA2,L2) \tag{7}$$

where the bias flow velocity V_b is a function of both grazing flow Mach number and frequency while the liner geometry (t1, d1,etc.) are fixed for the function V_b. So, not only will

the liner geometry have to be optimized but also it will have to be optimized for a range of bias flow rates that best match the optimum impedance based on equation 6.

Again, two grazing flow/bias flow liners will be fabricated for testing in the FIT and compared to validate the results of the optimization and to determine if that bias flow improves liner performance.

2.3.3 Experimental Verification of Optimal 2-DOF Liner Impedance

The two liner designs from the optimization study will be fabricated and tested in the FIT. These results are expected to both validate the prediction of the optimization study and verify that a bias flow liner can outperform current passive liners.

The NASA Langley Flow Impedance Tube (FIT) is similar to the Normal Incidence Tube except for some key differences in liner placement and measurement technique. The FIT operates with four acoustic drivers that are capable of achieving 140 dB at the liner start position. Grazing flow speeds of Mach 0.5 are achieved through a large pressure gradient supplied by a high-pressure bottle source and a large vacuum pump. A 2"x16" liner is installed on the side of the tube. A series of microphones are installed on the opposite side of the tube. The microphones are traversed along the length of the tube and measure the pressure magnitude. The impedance of the liner can then be calculated using the techniques described in Armstrong, Beckemeyer, and Olsen[12].

The flow will be introduced through the liner in a similar fashion to the NIT liners with the main difference being the size of the liner. The impedance calculation requires a sufficient length to determine the insertion loss of the liner. Too short a liner will not produce a significant enough insertion loss. The full capability of the facility (i.e. $0 \leq M \leq 0.5$, $120 \leq SPL \leq 140$, etc.) will be used for the evaluation of the liners within the design ranges.

Since this will only be a preliminary investigation of using the grazing flow/bias flow impedance model, qualitative analysis of the comparison between prediction and data will not be stressed. However, further investigation into improving the model will be discussed. Most of the importance of this analysis will be utilizing the optimization techniques to design these grazing flow/bias flow liners, in particular the handling of the function optimization of the bias flow rate to target the different operating conditions of the aircraft engine.

3 Summary

This research involves the utilization of bias flow to improve liner absorption over a broad frequency range and the ability to tune the liner to match optimum impedance at varying grazing flow velocities. To apply this concept, a sufficiently accurate numerical model of the impedance of a perforate liner needs to be produced. Once this model is complete, optimization tools will be used to design "optimum" liners with and without bias flow for both the normal incidence and parallel (grazing) flow liner configurations.

Summarizing the approach of this research,

1. Produce a database of impedance values of several perforate liners with and without bias flow.
2. Use the database to validate and improve the normal incidence impedance model with bias flow.
3. Use the impedance model and optimization tools to design "optimum" liners with and without bias flow.
4. Test "optimum" liners and compare the passive and bias flow liners.
5. Develop a preliminary grazing flow/bias flow impedance model.
6. Use models and optimization tools to design "optimum" grazing flow liners with and without bias flow.
7. Test "optimum" grazing flow liners and compare the passive and bias flow liners.

With the growing need for quieter aircraft, further development of noise suppression techniques is a requirement for the aircraft industry. Bias flow liners offer great potential for improved sound absorption in aircraft engines. This study is expected to show the benefits of bias flow liners over traditional passive liners. It will also illustrate the use of optimization tools for improving preliminary liner design methodology. There is significant potential for further research in bias flow liner design. Offered in this research is only a preliminary study of bias flow as an impedance control mechanism. The importance of accurate design of the liners lies within the predictions of the impedance model. Only recently has work been done to derive impedance models for grazing flow liners with bias flow and more research is required to fully understand the mechanisms involved.

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