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West Lafayette, Indiana 47907

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A STUDY OF METHODS TO PREDICT AND MEASURE THE TRANSMISSION OF SOUND THROUGH THE WALLS OF LIGHT AIRCRAFT

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This is a semi-annual status report for NASA Grant NAG1-58 for the period October 1, 1985 through May 15, 1986.

RESEARCH PROGRESS

Research investigations either fully or partially supported by NASA for the semi-annual reporting period progressed toward the following objectives:

1. Development of a numerical/empirical noise source identification procedure using boundary element techniques.
2. Identification of structure-borne noise paths using structural intensity and finite element methods.
3. Development of a design optimization numerical procedure to be used to study active noise control in three-dimensional geometries.
4. Measurement of dynamic properties of acoustical foams and incorporation of these properties in models governing three-dimensional wave propagation in foams.
5. Structure-borne sound path identification by use of the Wigner distribution.

Numerical/Empirical Noise Source Identification Procedure (Bryce Gardner)

The final verification of the direct boundary element method (DBEM) program was completed and interior point source capabilities were added. A paper was written for the AIAA Aeroacoustics Conference describing the applicability of boundary element methods to acoustic cavities and discussing the merits of IBEM and DBEM methods.

The DBEM program was then rewritten to solve the noise path identification problem. This reformulation involves calculating a new matrix equation to solve the boundary solution from the pressures measured in the cavity interior. Thus, two matrix equations exist. The matrix equation for the boundary solution with only impedance conditions is singular. The matrix equation for interior pressures is most likely incomplete. Together these equations overdetermine the problem and thus the boundary solution can be solved with a least squares technique.

The first step required for the noise path identification technique is a discretized model of the geometry of the boundary of the cavity. As a next step, the locally reacting surface impedance is measured over the entire surface of the real cavity at points that correspond to the centers of the elements in the discretized model. Next, the pressure (magnitude and phase) is measured at a few locations inside the cavity during operation. The pressures and impedance values are input to the DBEM identification program which solves for the pressure and velocity conditions of the cavity boundary. With these pressures and velocities the power or intensity distribution may be calculated over the surface of the cavity, thus allowing identification of the noise paths. After the identification procedure is completed, the DBEM program can be used as a design tool to analyze proposed design changes.

Much analytical verification has been done on the identifica tion technique and program in this reporting period. The investigations used the spherical cavity in most cases. This model has been used for earlier verification of the DBEM and is well understood. As a measure of the accuracy of the method the percent error on each element was averaged over the entire model as a standard of comparison. For the cases studied the average error was found to be representative of the error for each individual element.

Investigations were conducted for problems of varying complexity. Complex problems were solved equally as well as the simple ones. The effect of weighting the relative importance or confidence of the measured input data was also investigated. This did have an effect on the results and could be used advantageously. Many cases of different numbers and locations of interior pressure measurements were analyzed. The placement of these pressure measurements made little difference in the accuracy of the results. The number of interior pressure measurements necessary for accurate results was relatively few. Even as few interior measurements as ten percent of the number of elements gives consistently good results. Usually a lot less than ten percent is sufficient.

As an example, the identification procedure was used over a range of frequencies for a problem with fairly complex boundary conditions. The results are shown in Figure 1. The results were good except near the natural frequencies of the model where the technique was not expected to work. The sensitivity of the program to errors in the impedance measurement data and the interior pressure measurement data was also tested. The program showed little sensitivity to input error as shown in Figure 2. In fact, usually the solution has less error then the input data. It is hypothesized that because an integral technique is used,

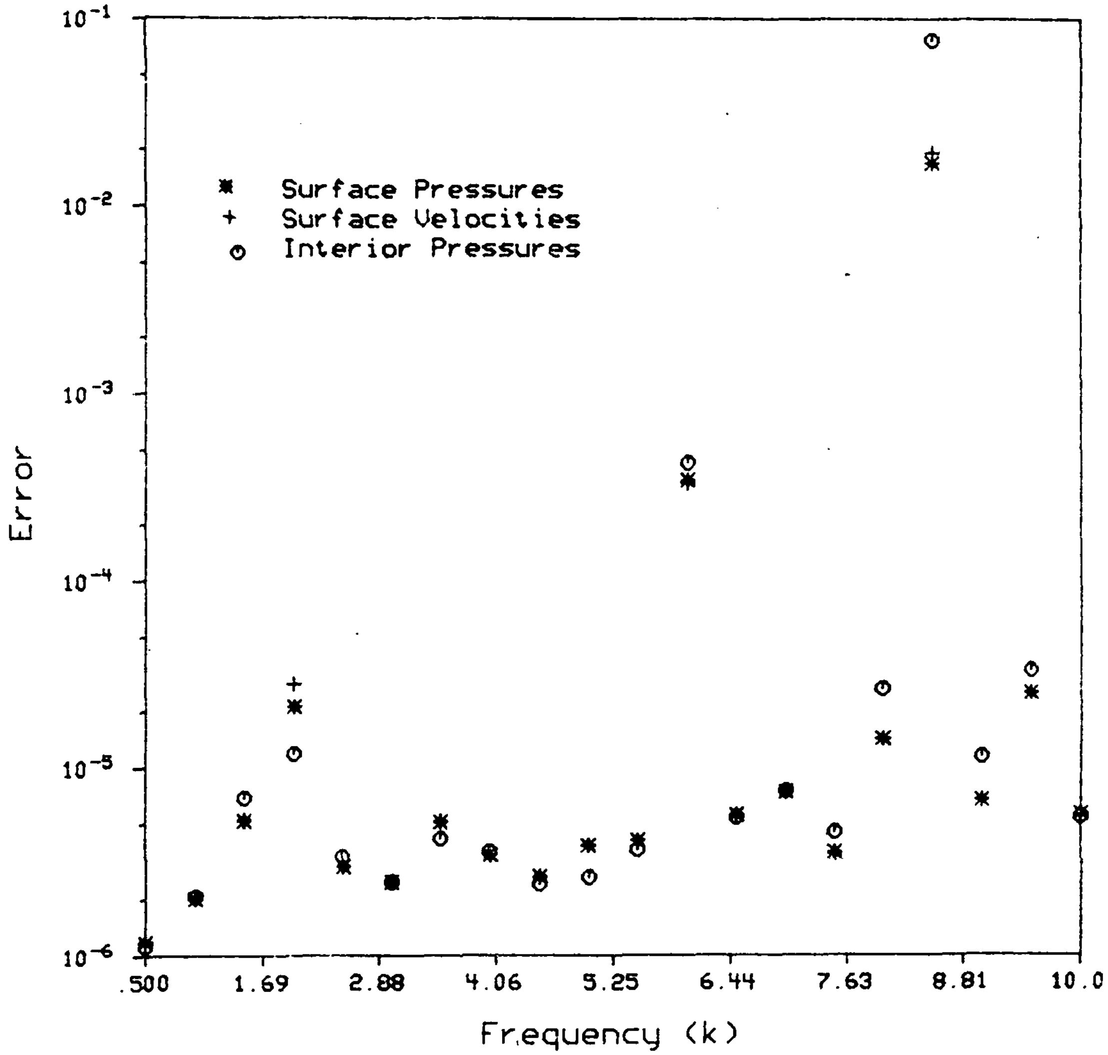


Figure 1. Accuracy of the identification process using boundary impedance information and 5 internal microphone measurements.

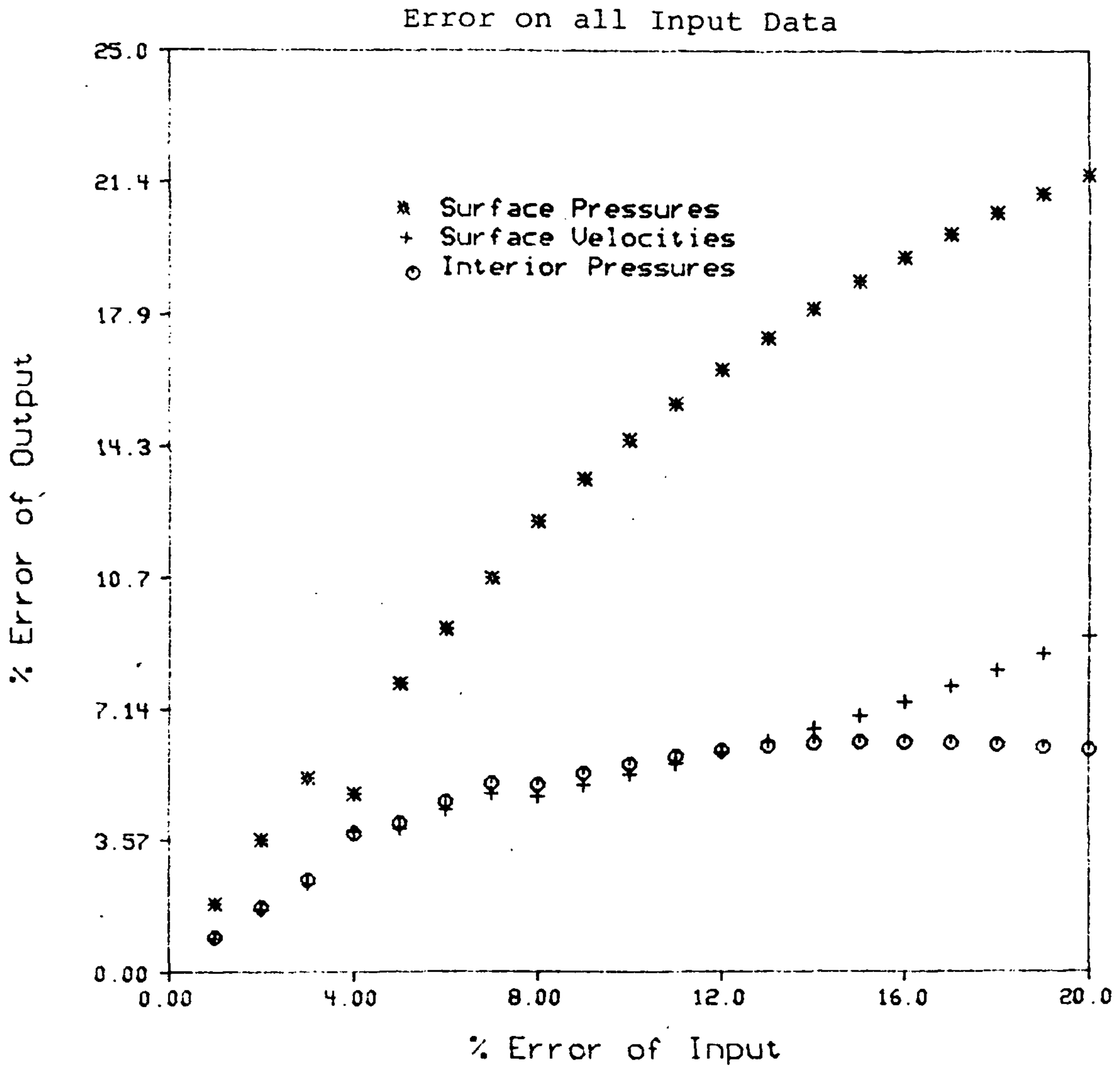


Figure 2. Sensitivity of the identification technique to error in the data input.

the program is not extremely sensitive to measurement error. More problems are being worked as the verification is continuing.

Structure-borne Noise (John Mickol)

The structure-borne noise investigation has continued the study of structural energy transmission in finite, lightly damped plates. The investigations of the measurement of structural intensity using two accelerometers has been the primary focus of the work. The measurement technique is now completely contained on a microprocessor based data acquisition system. An undergraduate student, Dave McFarren, did a special project during the Spring 1986 semester collecting structural intensity and power flow data on a beam. The beam was excited at the center and terminated at either end in sand. The energy absorption of these terminations was small. The excitation used for the studies was sinusoidal. A typical result is shown in Figure 3. The general trend of the result is good but there still remains a difference between power measured using the force transducer and accelerometer and that measured using the structural intensity device. We are continuing this study using a more heavily damped beam.

We resolved one source of error in previous measurements. In earlier investigations an impedance measuring device had been used to measure power flow into the structure. We were advised by the manufacturer that the impedance measurement device was not well designed for this purpose. Thus, we checked the impedance measurements against separate force and acceleration measurements and found substantial differences. Subsequently, input power measurements are taken with a force transducers and accelerometer.

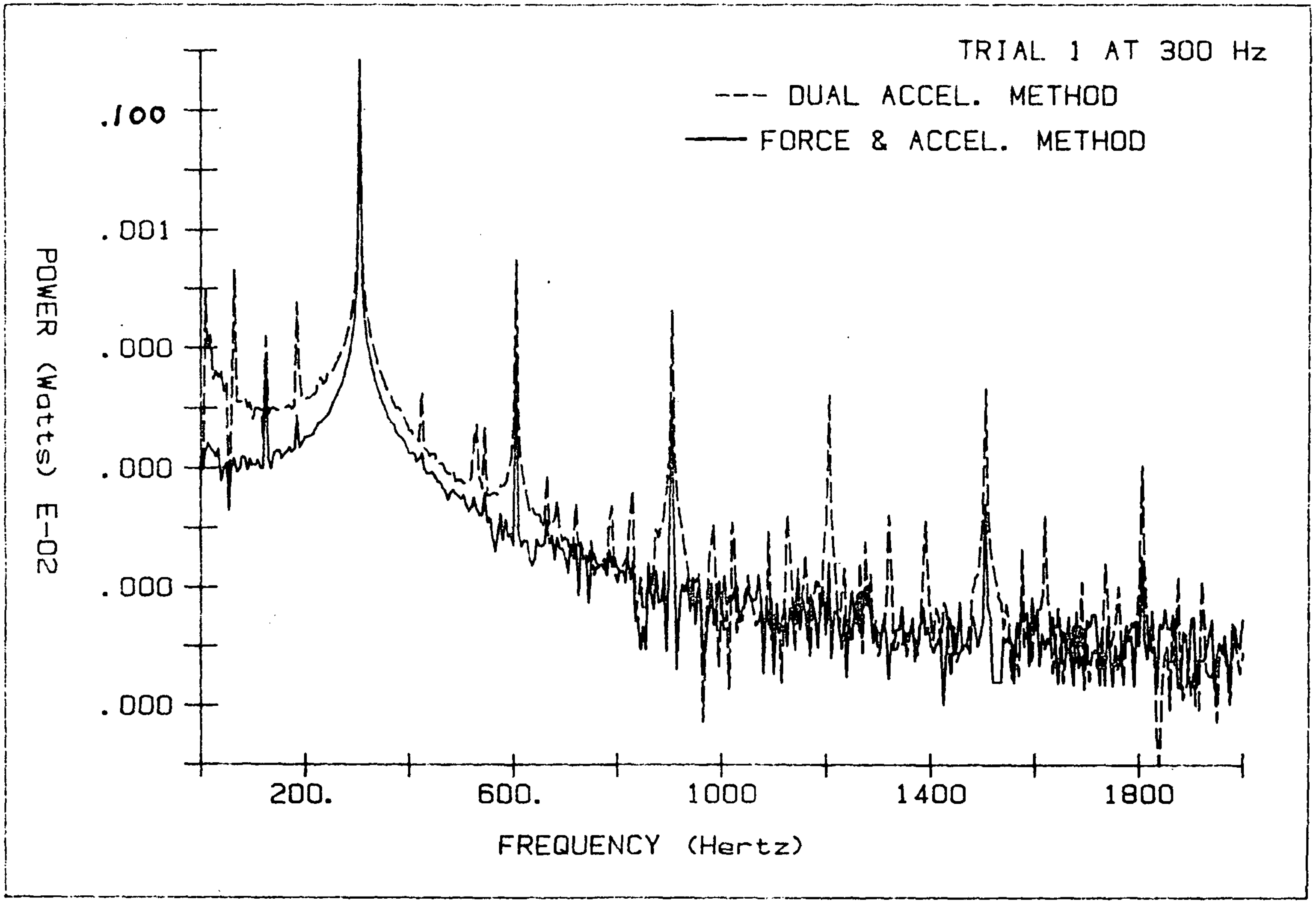


Figure 3. Comparison of power input and integrated intensity for vibration of a lightly damped beam excited at 300 Hz.

To study the effect of damping and the error introduced by the approximations made in developing the structural intensity technique, we have developed several models of damped beams and plates. An analytical model of a finite beam has been used to verify the two-accelerometer approach on a beam and is being used to evaluate the resolution requirements of the measurement system under a variety of damping conditions. An ANSYS finite element model is also being utilized to study behavior in plates. The initial studies are to determine the suitability of the ANSYS finite element program for structural intensity prediction. If successful, we can use this model to evaluate the 4-accelerometer structural intensity approximations and evaluate the performance requirements of the measurement system. Furthermore, such a model could be utilized to study energy transmission in built-up structures of plates and beams.

Design Optimization of Active Noise Controllers (Chris Mollo)

An indirect boundary element (IBEM) program was written and verified by solving for the acoustical pressure fields of both the interior and exterior of a pulsating sphere. These results are part of the AIAA Aeroacoustics Conference paper. Next, the capability to model acoustical point sources within the domain was added to the IBEM program. Again, the program results were verified. For this verification, a single source was placed at the center of the sphere and the boundary of the sphere was given either pressure, velocity, or impedance boundary conditions.

After the IBEM program was verified, the program was rewritten such that the new program could calculate an optimal active source strength. The sound sources arise from either the motion of the boundary of the cavity or other independent (uncontrollable) point sources within the cavity called primary sources. The controllable sources are point sources and are called secondary sources. The secondary source(s) is found which minimizes the weighted mean square pressure at user specified locations. This new formulation was implemented in a program called OPCON. This program has the capability to handle multiple secondary and primary sources.

OPCON was used to study five different noise control problems. The domain for all cases was the interior of a sphere. The sphere was modeled using 48 triangular elements. The three most interesting cases are discussed below.

1. Case 1: The sphere boundary is given a uniform velocity. A single secondary source is located at the sphere center. Nine observation points located in a radial line with equal weighting are used. The attenuation (insertion loss) is shown in Figure 4. The optimal secondary source strength is shown in Figure 5.
2. Case 2: The sphere boundary is given a uniform velocity. A single secondary source is located at the sphere center. Forty-eight observation points are used with an r^3 weighting where r is the distance from the sphere center to the observation point. The maximum attenuation (insertion loss) attainable is shown in Figure 6. The optimal secondary source strength is shown in Figure 7.

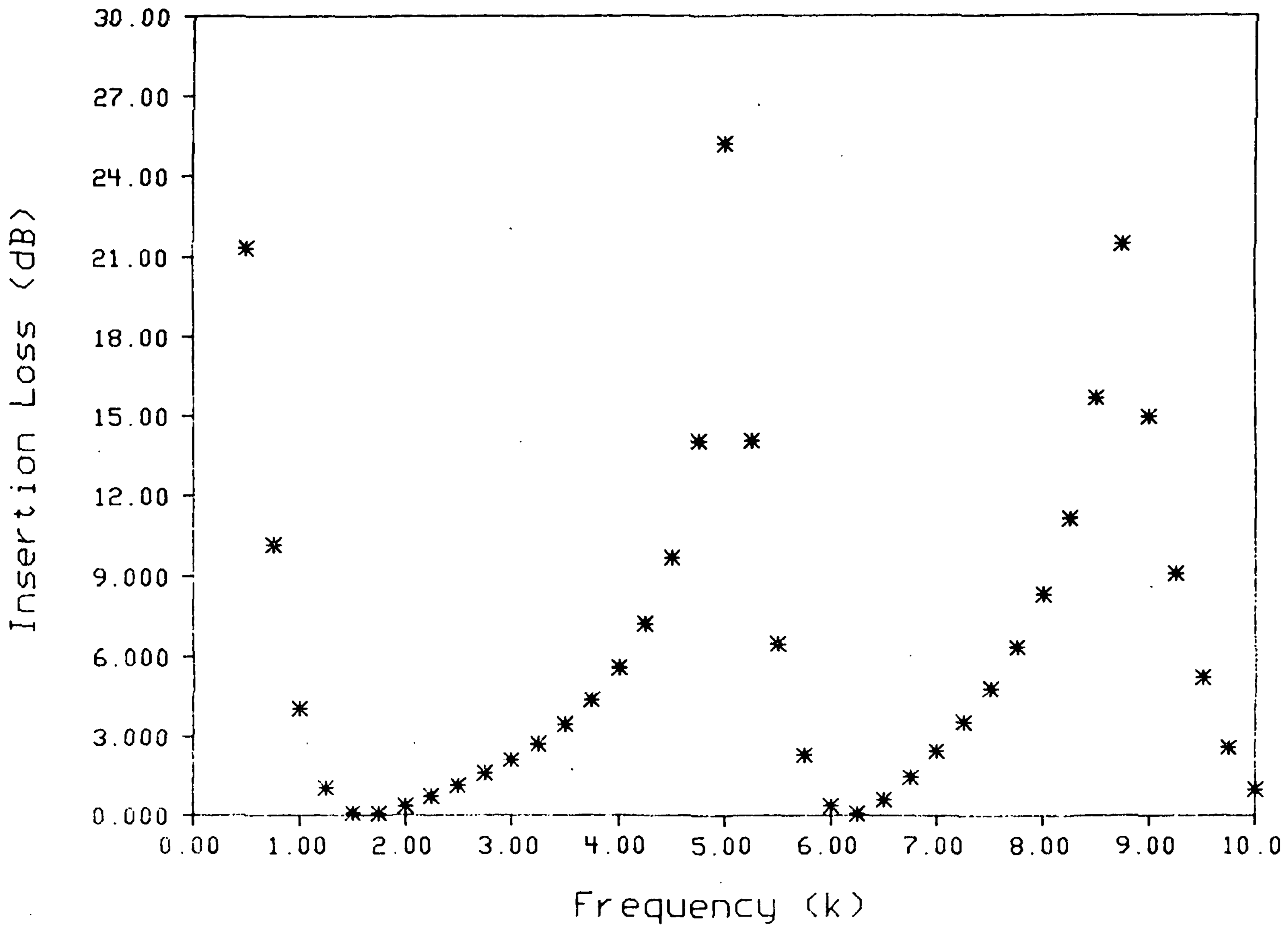


Figure 4. Optimal attenuation of the cavity of a pulsating sphere with secondary source at the centroid with 9 observation points.

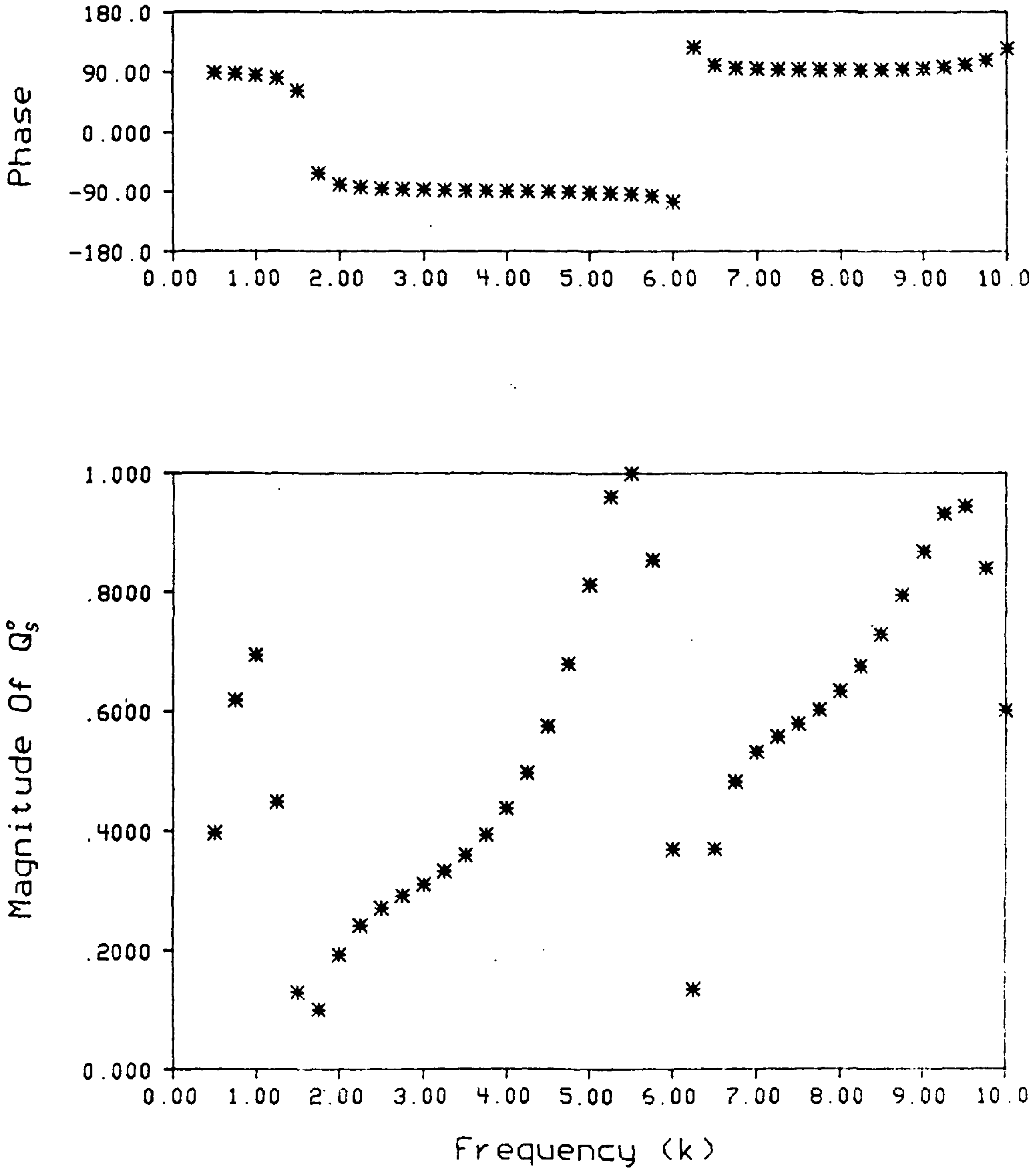


Figure 5. Secondary source strength for the optimal solution of a pulsating sphere with secondary source at the centroid with 9 observation points.

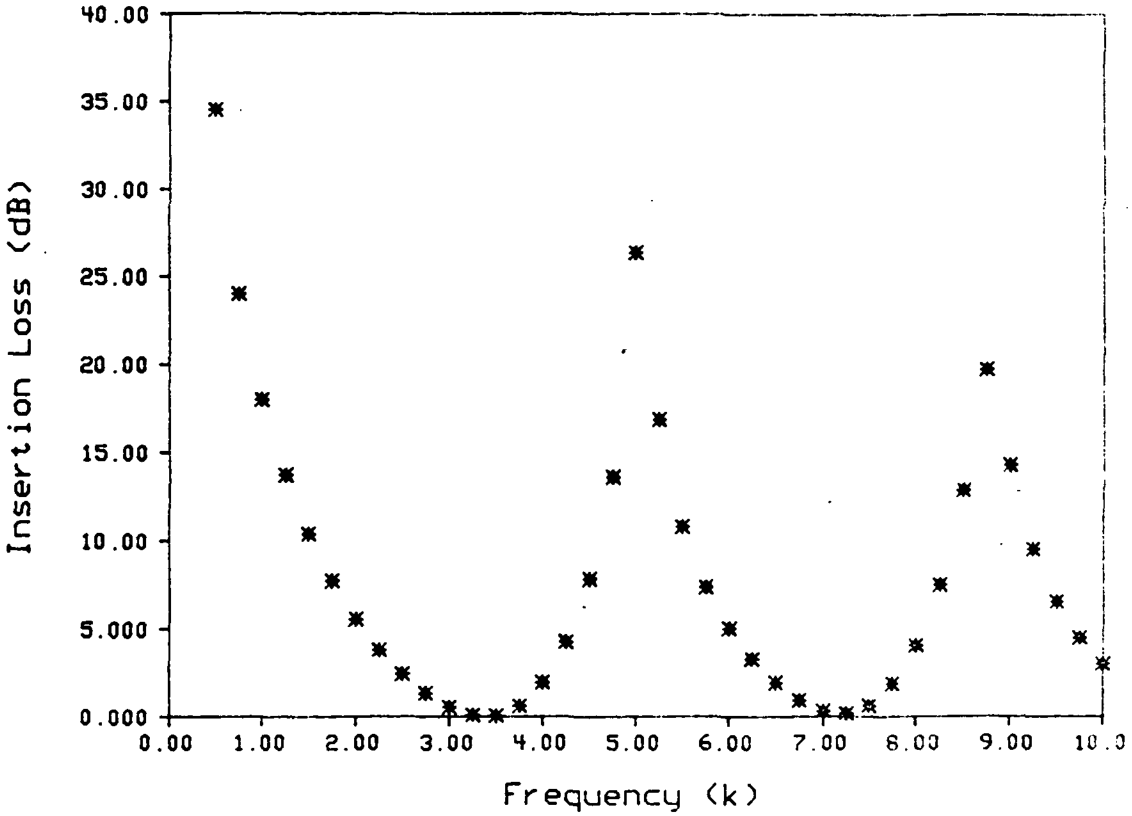


Figure 6. Optimal attenuation of the cavity of a pulsating sphere with secondary source at the centroid with 48 distributed observation points.

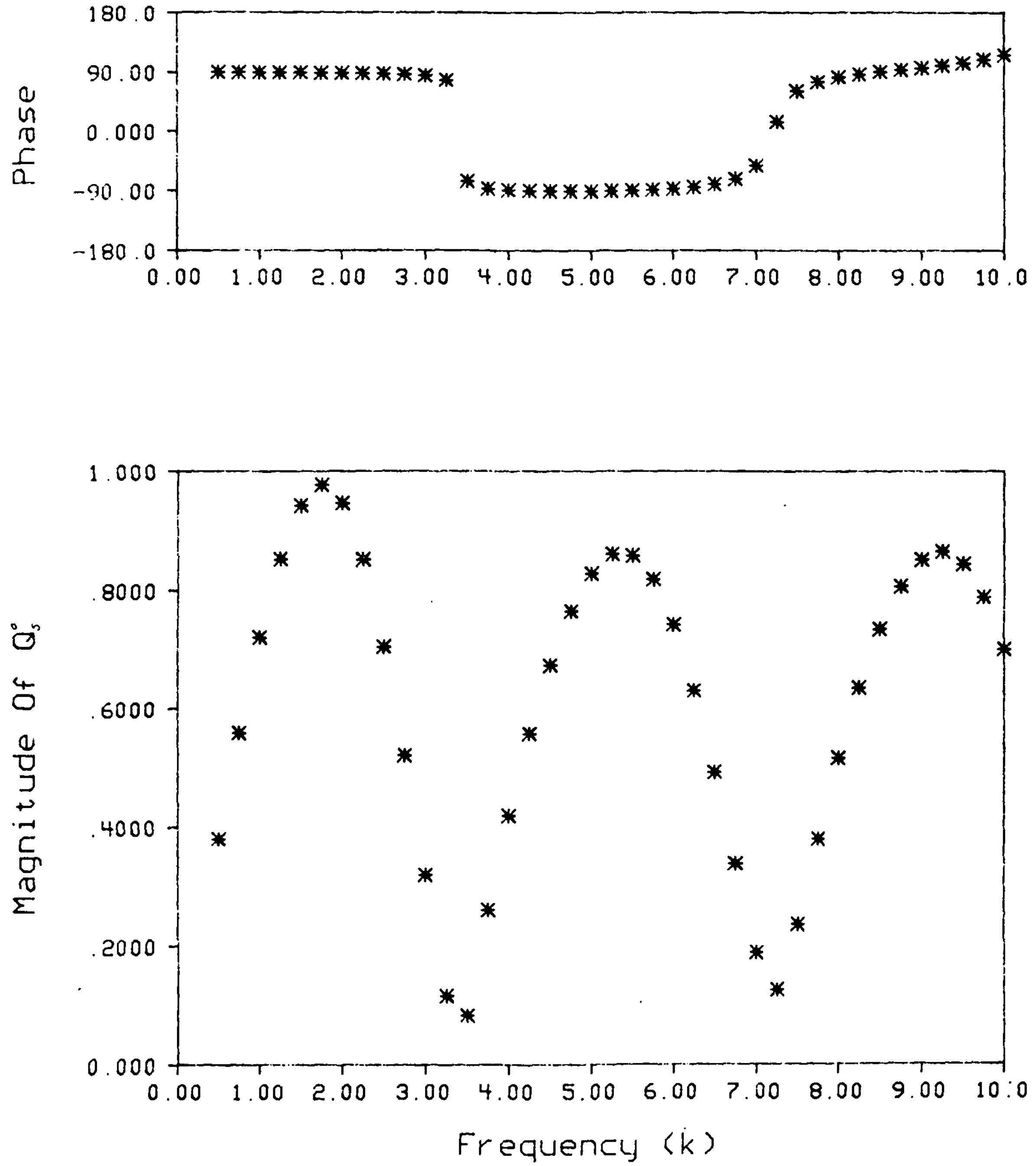


Figure 7. Secondary source strength for the optimal solution of a pulsating sphere with 48 distributed observation points.

Note that the optimal secondary source is different for Case 2 than Case 1.

3. Case 3: The sphere boundary was given a uniform velocity. A single secondary source located at half the sphere radius is used. Forty-eight observation points with a r^3 weighting are used. The maximum attenuation and corresponding optimal source strengths are shown in Figures 8 and 9.

From these different cases several conclusions can be made. First, there are frequencies at which maximum and minimum (zero) insertion loss occur. Insertion loss is a measure of the effect of the secondary source. Thus, at certain frequencies the secondary source is unable to reduce the sound pressure while at other frequencies the secondary source greatly reduces the sound energy. Secondly, the solution of the optimal secondary source strength and the values of insertion loss depends on the placement and weighting of the observation points. Thirdly, the effectiveness of the secondary source is dependent on its position. And lastly, maximum attenuation occurs at the natural frequencies of the cavity. These results have been presented at the Spring meeting of the Acoustical Society of America (paper H5, JASA Supp No. 1, Vol. 79, 1986).

Measurement of the Dynamical Properties of Acoustical Materials

(Christina Bruer)

Porous materials are used to line aircraft fuselages in order to reduce heat loss and to increase the fuselage sound transmission loss. Fiberglass is most often used as the lining material.

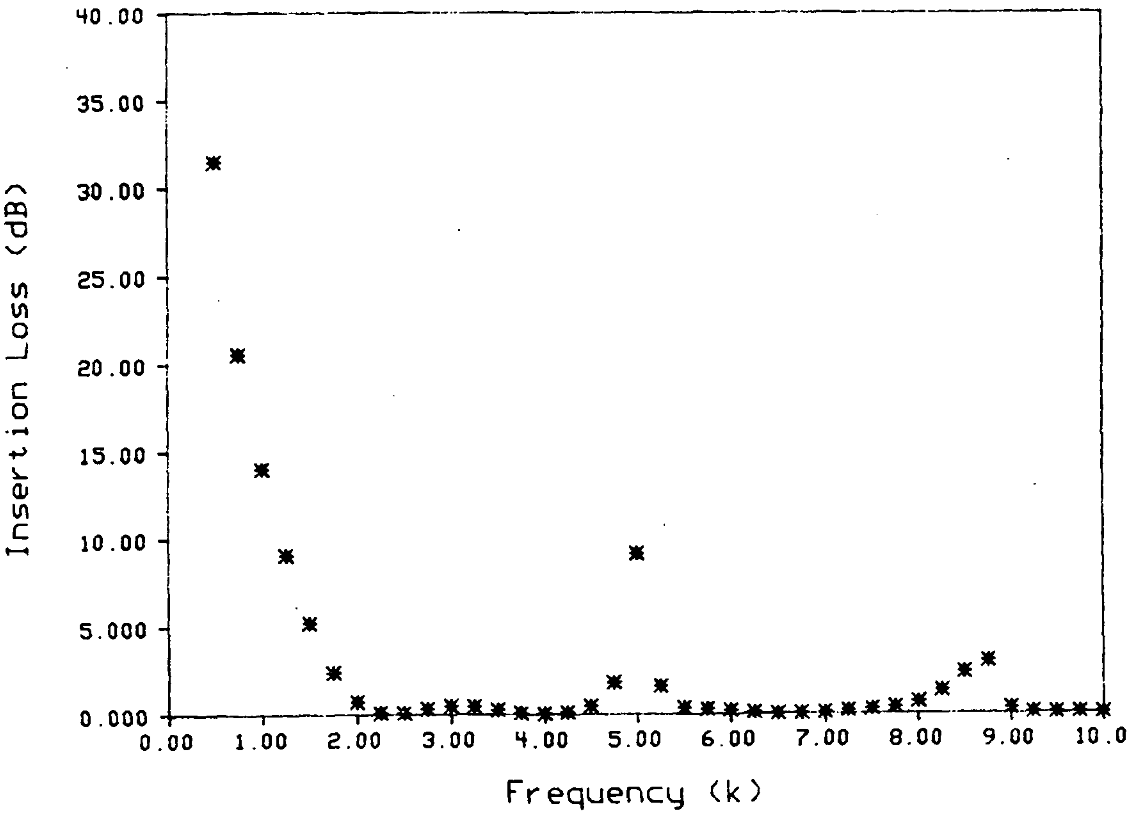


Figure 8. Optimal attenuation of the cavity of a pulsating sphere with secondary source offset to 1/2 r_o with 48 distributed observation points.

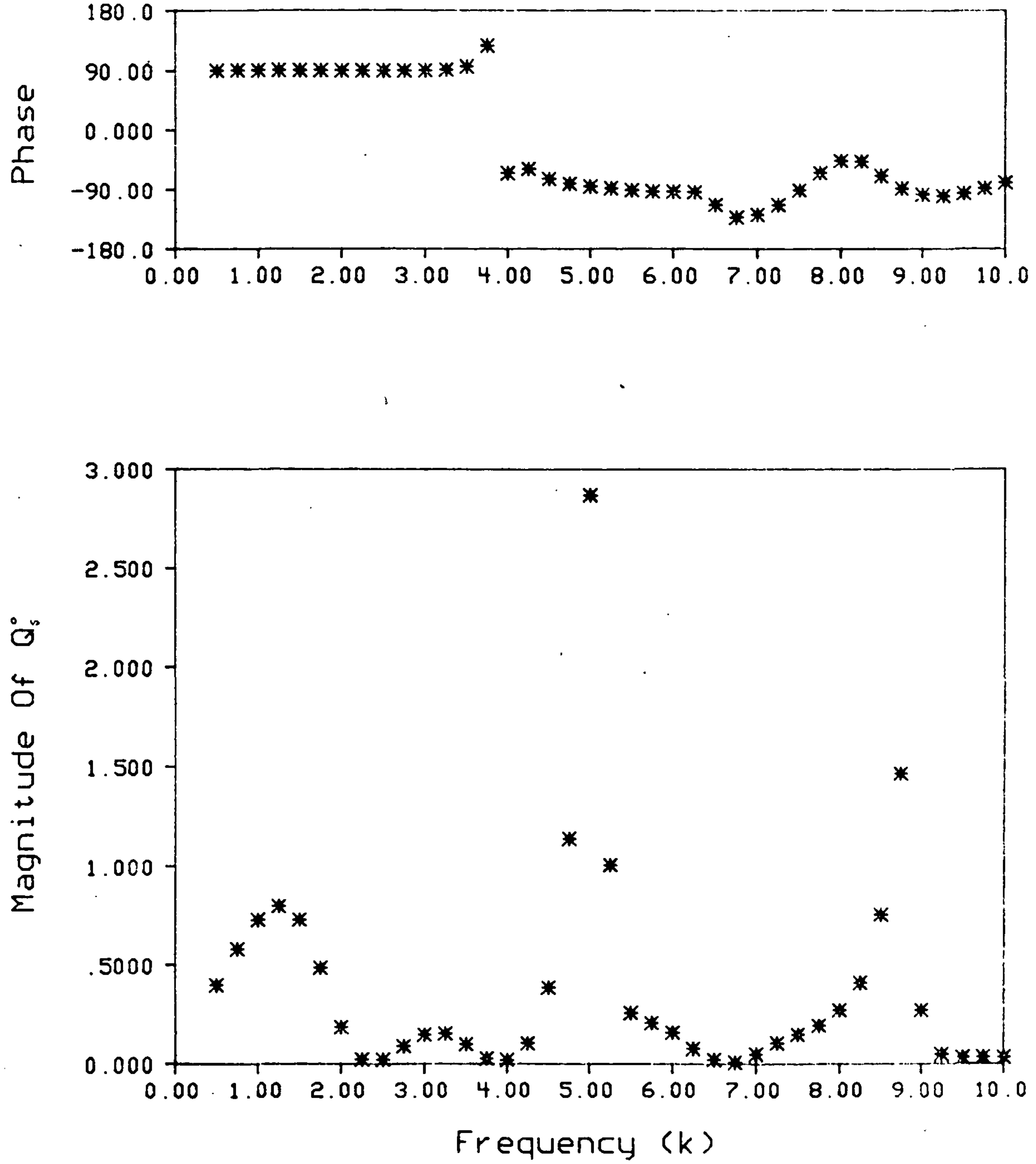


Figure 9. Secondary source strength for the optimal solution of a pulsating sphere with secondary source offset to 1/2 r_o with 48 distributed observation points.

Experimental and theoretical work by Stuart Bolton and Ed Green (see section entitled, "Related Work of Possible Interest to NASA") has indicated that foam linings may improve the transmission loss at low frequencies. It is desirable from the design point of view to be able to predict theoretically the behavior of foam-lined double panel systems. Theory governing one-dimensional wave propagation in elastic porous materials such as foam are relatively well developed. However, at present the physical model parameters, in particular, the bulk modulus of elasticity of the foam and its loss factor, must be determined by acoustical testing and model fitting. These parameters are particularly important since they control the behavior of typical noise control foams. The project work conducted by Christina Bruer is directed towards non-acoustic methods of measuring the bulk mechanical properties of foam. The properties will be estimated from the influence of an attached foam layer on the vibration properties of a structure such as a beam. This type of approach is referred to as Oberst's method. In this way it is also possible to measure the bulk shear modulus of elasticity of foam; this parameter is necessary to extend theoretical treatments to three-dimensional wave propagation. This extension will allow prediction of oblique incidence sound transmission.

During the first period of the project the following tasks were accomplished:

1. A measurement set-up was built according to ASTM E 756-83 which prescribes the standard method for measuring vibration-damping properties of materials by Oberst's method.

2. Computer programs were written to predict the vibrational behavior of the structure (a beam) and to compute its forced response to different kinds of excitation. Both wave and modal models have been developed. Results are expressed in terms of acceleration/force transfer functions or impulse responses.
3. First tests were run and the measured results compared to the computer model.

The apparatus for the ASTM E 756-83 measurement consists of a beam which is hung using thin threads in order to simulate free-free boundary conditions. One end of the beam is driven electromagnetically by a transverse force while at the other end a transducer measures the acceleration response. The input signals used in the present tests are either random white noise or a band limited periodic signal whose Fourier coefficients are constant over a certain range of analysis frequencies (the so-called Schroeder phase signal). The result of the measurements is the acceleration/ force transfer function versus frequency.

A comparison of the theoretical and measured results have suggested the following:

- When the white noise generator is used to provide the input signal the beam mode shapes occasionally appear distorted and the natural frequencies differ from the computed ones. These effects are related to non-linear response of the beam/transducer assembly.
- By using the Schroeder phased periodic wave form as the input signal the measured peaks of the transfer function

can be made to correspond well with the predicted ones; with this signal type it is straightforward to establish the proper input level to avoid non-linear distortion.

Next, it is intended to repeat the measurements with an impulse input and to develop programs to determine the complex natural frequencies of the beam from the measured data. The real and imaginary parts of the natural frequency may be used to infer the beam's damping factor and hence, the structural properties of the materials comprising the beam.

For the future it is planned to perform these tests in a vacuum chamber and replace the bar by sandwiched specimens covered by foam. The vacuum chamber is used to reduce the influence of the air in the foam cells and so allow measurement of the loss factor, Young's modulus and shear modulus of the solid part of the foam. These in vacuo material properties are required to predict the three-dimensional transmission and absorption properties of foam layers.

Application of the Wigner Distribution to Structural-Acoustic Path Identification (J.S. Bolton)

The Wigner Distribution is a function which can be used to indicate the time-frequency distribution of a signal's energy. Although originally developed in quantum physics, it has recently found application in a number of different fields: e.g., speech processing, de-dopplerization of aircraft fly-over noise data and detection of multi-path effects in underwater acoustics. The present intention is to use it to analyze the impulse response between an excitation point on a structure and a response point either on the structure or in an adjacent medium (e.g., wing vibration to passenger cabin sound pressure). It is expected that when the impulse response is analyzed using the Wigner Distribution, the dispersion relations of the waves carrying energy between source and receiver will be revealed. In particular, it should be possible to discriminate between airborne paths (phase speed independent of frequency) and structure-borne paths (phase speed generally increasing with frequency, except for longitudinal waves which may be distinguished from airborne waves by their much higher phase speed).

A literature search has been conducted to identify significant papers on this topic. Initial research suggests that the use of the Wigner Distribution as originally defined will lead to confusing results in the case of multi-path propagation. This effect is the consequence of the interaction of positive and negative frequency components. However, it has been demonstrated that these effects may be minimized by using the analytic equivalent of the impulse response (i.e., a complex function consisting of the original impulse response plus its Hilbert transform as the imaginary part) as the input to the Wigner Distribution calculation. In the coming period it is intended to implement this procedure numerically and conduct simulations to investigate its capabilities. When this has been accomplished, it is intended to analyze beam data (generated as part of Christina Bruer's work) to confirm the ability to visualize dispersion relations. The work will then be extended to two-dimensional structures.

Related Work of Possible Interest to NASA

There is significant interaction between the NASA sponsored work and other investigations at Purdue. This section will briefly summarize some of that work.

Through an NSF grant on active noise control, Purdue has recently been assigned two Handley Page 137 Jetstream III Aircraft (one of the Jetstream III's is shown in Figure 10). The aircraft are no longer airworthy and consequently can only be used for ground-based testing. It is our plan to keep one of the aircraft in operational condition for realistic ground-based studies. The operational aircraft will be stored and tested at the Purdue airport. The second aircraft will be used for parts and will not be operational. The structure of the second aircraft will be kept intact so that structural/acoustic testing can be done. This aircraft will be located at the Herrick Laboratories. The two aircraft should make ideal test facilities for active noise control and structure-borne noise studies as well as other structural/acoustic studies.

The active noise control investigations supported by NASA are complemented by three other investigations sponsored by NSF and Purdue University. One of these investigation is concerned with the modeling of the transient behavior of active noise control systems. The other investigations utilize experimental techniques similar to those discussed by Richard Silcox (see paper No. H3 JASA Supp. 1, Vol. 79, 1986) with application to three-dimensional geometries. Both analog and digital control schemes are being studied to evaluate the speed, adaptability and feasibility of each procedure.

Figure 10. The operational Handley Page 137 Jetstream III.

We have recently negotiated a research contract with an automotive company to develop a structural/acoustic design methodology. The contract involves significant experimental investigation to identify structural/acoustic energy paths. In addition, we are implementing a numerical design procedure whereby relatively mature modeling procedures (i.e., finite element methods for structures and boundary element methods for acoustics) are reformulated such that design sensitivity information is calculated along with the solution. Thus, the designer is able to compute the sensitivity of the solution to given design variables and possibly to develop formal procedures to optimize the design. Such procedures should also be applicable to interior cavity acoustics and structure-borne noise problems as models for the methodology mature.

During the reporting period work funded by the Herrick Laboratories has continued on sound transmission through foam-lined double panel systems. Experiments were conducted to determine the transmission impulse response of unfaced foam layers. This data was used to determine the appropriate structural and acoustical parameters of a model governing wave propagation in elastic porous media. Having determined these parameters, the theoretical model was used to predict the behavior of double panel systems lined with foam. In particular, the significance of the method by which the foam is attached to the panels (i.e., whether it was continuously bonded or was separated from the panels by thin air spaces) was investigated. As was the case with sound absorption, it has been found that sound transmission through these structures is highly dependent on the foam/panel boundary conditions. The major result of the work to-date is the identification of an optimum mounting arrangement. When the foam is bonded to one panel but separated from the other panel by an air gap the mass-air-mass resonance is essentially eliminated. Below 500 Hz (for a three inch depth of foam faced by 0.040 in. aluminum panels) this hybrid configuration gives approximately 10 dB better transmission loss than configuration in which the foam is either bonded to both panels or is separated from both by an airgap. It has also been possible to show that foam-lined double panels give better performance than fiberglass-lined double panels. This work was recently presented at the Cleveland meeting of the Acoustical Society of America (by J.S. Bolton and E.R. Green) and will be presented in expanded form at the AIAA Aeroacoustics Conference in Seattle (9-11 July 1986). It is anticipated that this work may be applicable to the design of high performance fuselage treatments. Several calculated results comparing the performance of foam-lined (in several configurations) and fiberglass-lined double panels (three inch treatment depth, 0.040 in. aluminum panels) are shown in Figures 11, 12, and 13.

TRAVEL

Funds from the grant were used to fund one domestic trip during the grant period. The trip was taken by the principal investigator to the ASME Winter Annual Meeting in November 1985. Activities included presentation of a paper on Carl Kipp's results at an ASME forum on Numerical Techniques in Acoustics.

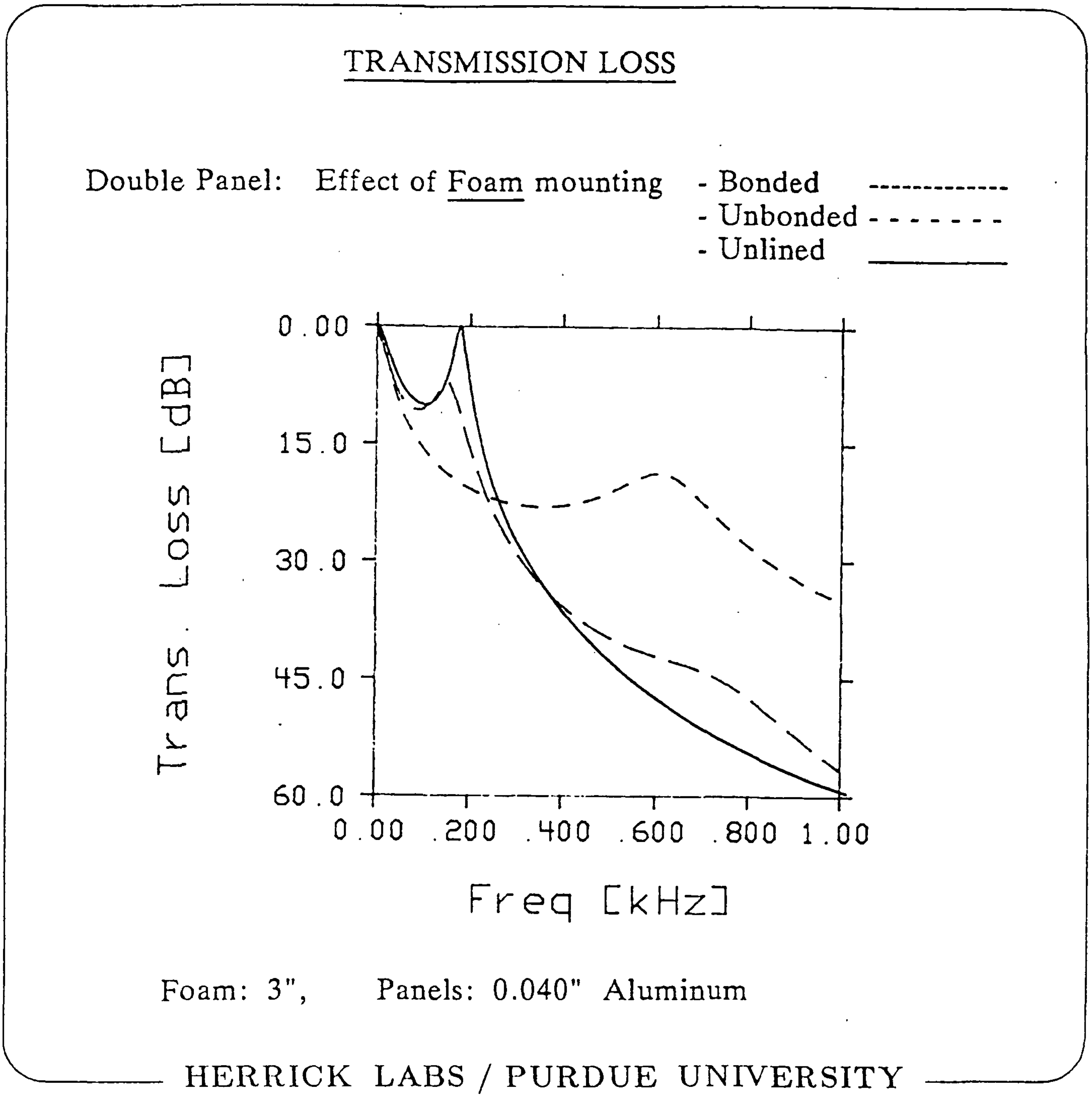


Figure 11. Transmission loss of foam-lined double panel in two configurations: i.e., lining either bonded directly to both panels ("bonded") or separated from both by a 1 mm air gap ("unbonded").

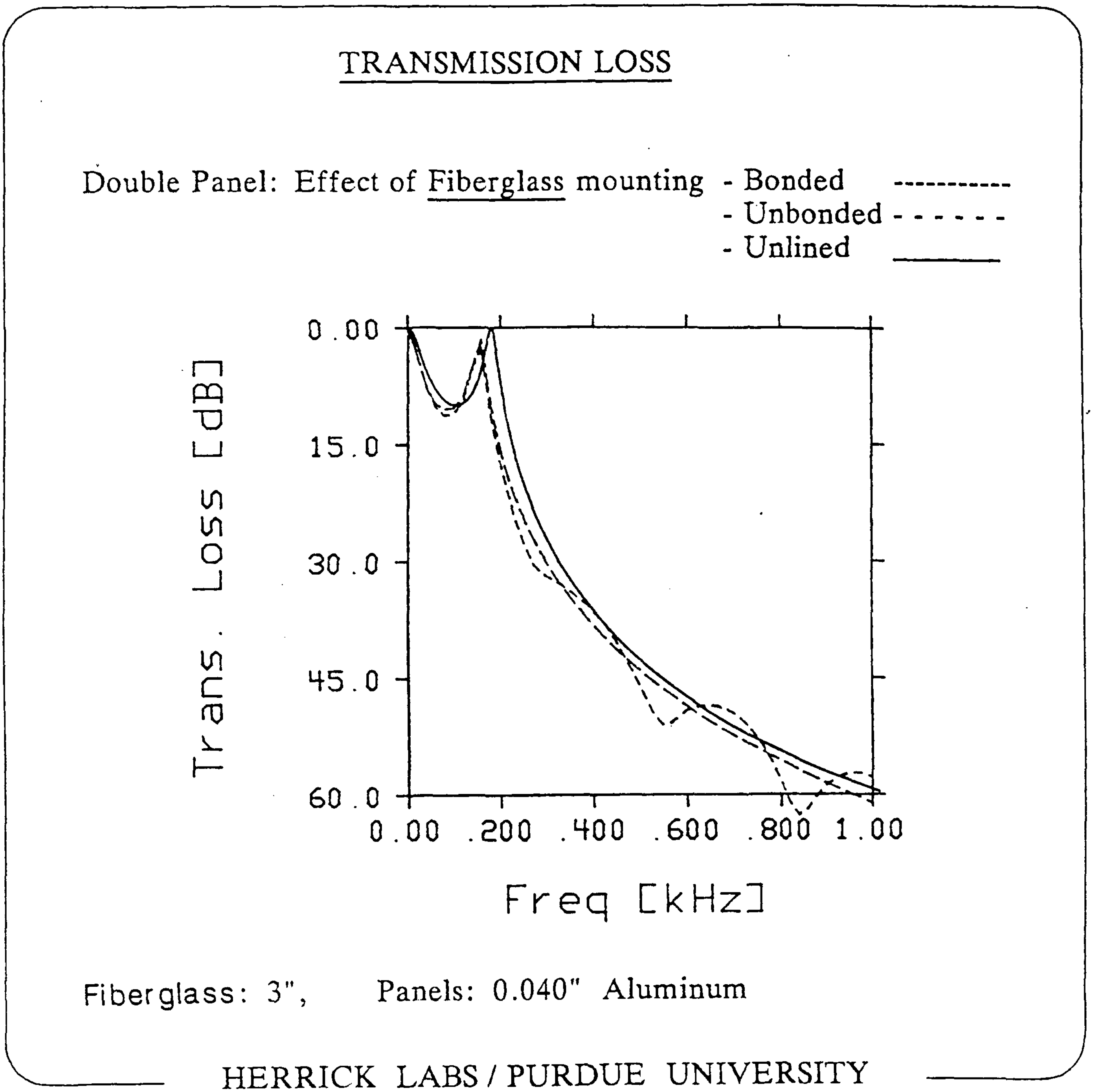
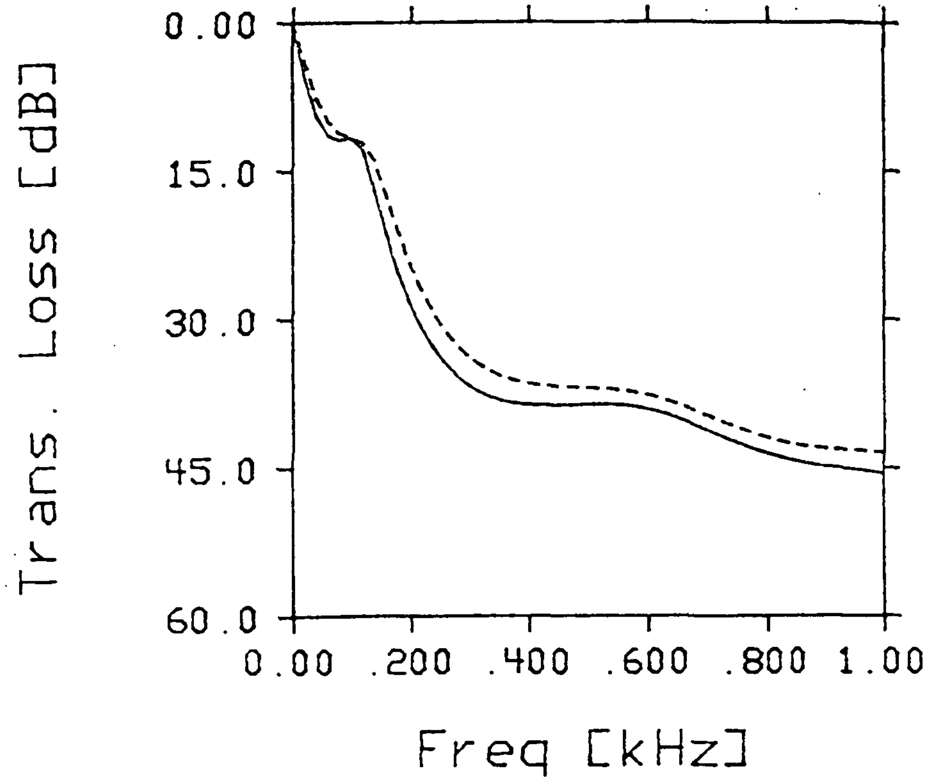


Figure 12. Transmission loss of fiberglass-lined double panel in two configurations (as in Figure 10). Note that in vicinity of "mass-air-mass" resonance, fiberglass lining does not compare favorably with unbonded foam.

TRANSMISSION LOSS

Double Panel: Effect of Foam mounting - Bonded/unbonded ———
- Unbonded/bonded - - - - - -



Foam: 3", Panels: 0.040" Aluminum

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Figure 13. Transmission loss of foam-lined double panel in two configurations: i.e., foam bonded to incident side panel and separated from the other by 1 mm air gap ("bonded/unbonded") and vice versa ("unbonded/bonded").

PUBLICATIONS

Complete bibliographic citations of articles published during the grant period is included at the end of this report. In addition, available abstracts are included in Appendix A. Copies of various papers are being sent to NASA under separate cover.

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2. R.J. Bernhard and C.G. Mollo, "Predictioon of Optimal Active Noise Controllers Using Boundary Element Methods", Paper H5, 111th Meeting of the Acoustical Society of America, Cleveland, OH, May 1986.

3. J.S. Bolton, "Normal Incidence Absorption Properties of Single Layers of Elastic Porous Materials," presented at the 110th Meeting of the Acoustical Society of America, Nashville, TN, November 1986.

4. J.S. Bolton and E.R. Green, "Sound Transmission Through Foam-Lined Double Panel Constructions," presented at the 111th Meeting of the Acoustical Society of America, Cleveland, OH, May 1986.

5. B. Forssen and M.J. Crocker, "Determination of Transmission Loss of Double Walled Panel Structures, Including Cavity Absorption and Stiffness, by Use of the Sound Intensity Technique," Proceedings of Internoise '85, pp 1147-1150, 1985.

6. M.S. Atwal and M.J. Crocker, "The Effect of the Transmission Loss of a Double Wall Panel of Perforating the Second Panel," Proceedings of Internoise 85, pp 389-392, 1985.

7. M.S. Atwal and M.J. Crocker, "Measurement of the Absorption Coefficient of Acoustical Materials Using the Sound Intensity Method," Proceeding of the Second International Congress on Acoustic Intensity, pp 485-490.

APPENDIX A

ABSTRACTS OF PUBLICATION

S60 J. Acoust. Soc. Am. Suppl. 1, Vol. 78, Fall 1985 110th Meeting: Acoustical Society of America

10:30

DD4. Normal incidence absorption properties of single layers of elastic porous materials. J. S. Bolton (Ray W. Herrick Laboratories, Purdue University, West Lafayette, IN 47907)

Recently, a theory has been developed which describes wave propagation in relatively stiff, partially reticulated polyurethane foams, the type most commonly used in noise control applications [J. S. Bolton and E. Gold, J. Acoust. Soc. Am. Suppl. 1 77, S59 (1985)]. A high impedance wave associated with the bulk mechanical properties of the foam matrix is usually significantly excited in these materials. As a consequence, the acoustical performance of finite depth layers of foam of this type is very sensitive to the boundary conditions which apply at the front and rear layer surfaces. Specifically, it will be shown in this paper that the action of a film facing is dependent on how it is attached to the foam layer. In addition it will be demonstrated that a small gap, e.g., 1 mm, separating a foam layer from a hard backing can increase the low-frequency absorption dramatically. A similar effect occurs when a film facing is not bonded directly to the surface of a foam layer but is separated from it by a thin air gap. This work has suggested an arrangement for enhancing the low-frequency absorption of thin foam layers.

4:30

H5. Prediction of optimal active noise controllers using boundary element methods. Robert J. Bernhard and Chris G. Mollo (Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907)

Boundary element methods have been used as numerical approximations of boundary integral equations to predict the sound fields in complicated three-dimensional interior and exterior spaces. In this investigation the methods have been investigated for their capability to find and evaluate the optimal active noise controller for complex acoustic geometries. The boundary element methods are utilized to enforce the specified boundary conditions while solving for the optimal secondary source distribution necessary to minimize a given performance equation. For the current work the performance equation is a weighted sum of mean-square pressures at specified points. Thus the method can predict the optimal controller required to achieve local control using a single point, or to achieve a space averaged reduction by using a distribution of points. The formulation allows multiple secondary sources and either pressure, velocity, or normal specific acoustic impedance boundary conditions. The optimal secondary source's strengths and the insertion loss performance of several active controller configurations are illustrated.

10:00

O6. Sound transmission through foam-lined double panel constructions.

J. Stuart Bolton and Edward R. Green (Ray W. Herrick Laboratories, Purdue University, West Lafayette, IN 47907)

This paper describes the sound transmission performance of foam-lined double panel constructions, in particular, the acoustical effect of two foam mounting arrangements. The foam considered is relatively stiff and partially reticulated, the type most often used in noise control. A recent theory is used to model the foam [J. S. Bolton and E. Gold, J. Acoust. Soc. Am. Suppl. 1 77, S59 (1985)]; the theory allows for both a frame wave and an airborne wave. The applicability of the theory is demonstrated by comparing theoretical and measured transmission coefficients and impulse responses for freely suspended foam layers. The extension of the theory to allow for bonded or unbonded facing panels is then described. It is shown that when the foam lining is bonded directly to the facing panels sound transmission through the foam occurs largely via the high impedance frame wave. As a consequence, the transmission loss of foam-lined double panels is improved, particularly at low frequencies, when the lining and panels are separated by a small air gap; in this case a larger fraction of the energy is carried by the more heavily damped airborne wave.