STUDIES OF NOISE TRANSMISSION IN ADVANCED COMPOSITE MATERIAL STRUCTURES

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CONCERNS AND POTENTIAL PROBLEMS RELATED TO NOISE TRANSMISSION IN COMPOSITE FUSELAGES

The noise transmission characteristics of advanced composite material structures must be taken into account early in the design phases of composite fuselages so that the weight-saving advantage of composite construction will not be compromised by high noise transmission and heavy add-on acoustic treatments. Some of the noise transmission concerns and potential problems related to advanced composite material fuselages are indicated in figure 1. Noise from a variety of noise sources can enter an aircraft fuselage through a number of paths or mechanisms. Noise from these sources is frequently classified as being either airborne or structureborne. In many instances the airborne and structureborne noises are highly correlated and indistinguishable once inside the aircraft. The airborne noise transmission characteristics of a fuselage can be either favorably or adversely affected by the use of advanced composites materials depending on the frequency of the incident noise. At low frequencies, a composite fuselage may transmit less noise because of increased stiffness. In the region where structural resonances and damping control noise transmission, a composite fuselage may transmit either more or less noise depending on the damping characteristics of the materials. At mid frequencies a composite fuselage should transmit more noise for an equivalent stiffness design. Noise frequencies for which the lengths of acoustic and structural waves coincide should be lower for composite constructions and therefore could allow more overall noise transmission for most aircraft noise sources (upper mid frequency range). The effects of composite construction on structureborne noise in the low and mid frequencies are hard to generalize although noise problems may be found in the upper mid frequency range because radiation efficiency is very high in the coincidence region.

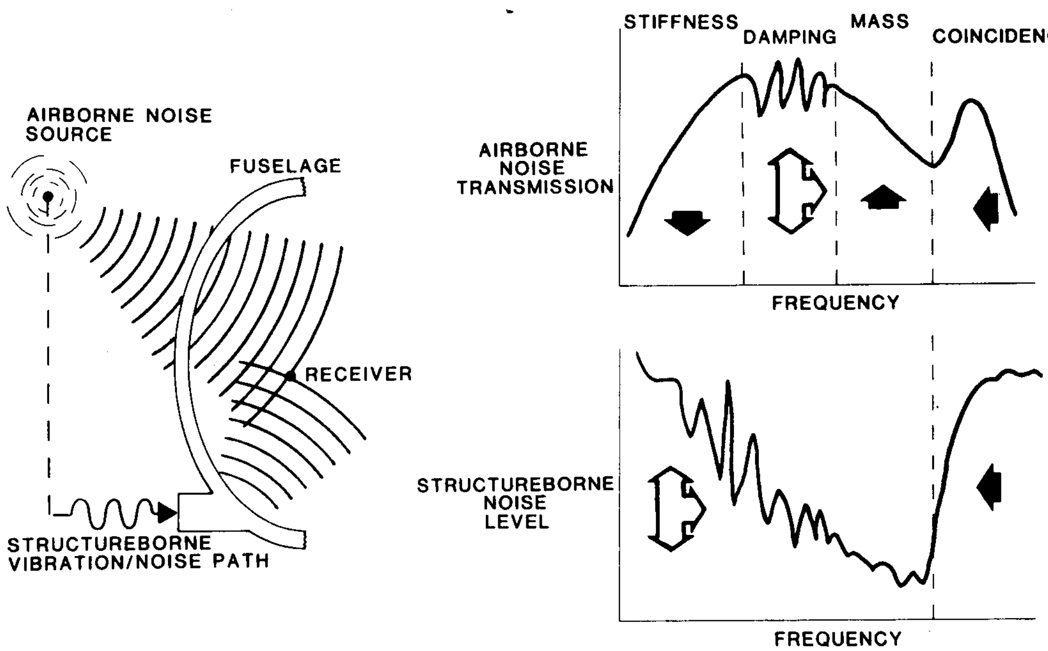

Figure 1

RESEARCH PROGRAM

The Structural Acoustics Branch at the NASA Langley Research Center has begun a research program in noise transmission of advanced composite material structures with the ultimate goal of providing optimum design from the standpoint of aircraft interior noise. Figure 2 outlines the elements and overall strategy for the research program and the topics which are addressed in this report. The initial emphasis is to develop models for the noise characteristics of simple structural panels of composite materials. Elements included in the model are: 1) transmission loss in infinite anisotropic panels, 2) transmission loss in finite panels with consideration of their modal behavior, 3) effects of different advanced composite materials, and 4) radiation characteristics of both airborne and structureborne noise of composite panels. The future emphasis of the program will be to develop models for the more complicated structures representative of aircraft fuselages. The research elements in these models include (1) a finite element representation of the structure and acoustical processes, (2) effects of stiffeners and other non-panel elements, (3) effects of add-on acoustical treatments, (4) consideration of cylindrical and other curved structural configurations, and (5) use of optimized structural configurations to enhance noise transmission characteristics. In addition to the model development, the research program includes noise transmission testing and verification of the various elements in the models. This report will concentrate on the progress and plans of the elements of the simple panel models and finite element representations and on noise transmission loss tests which have been conducted or are in progress.

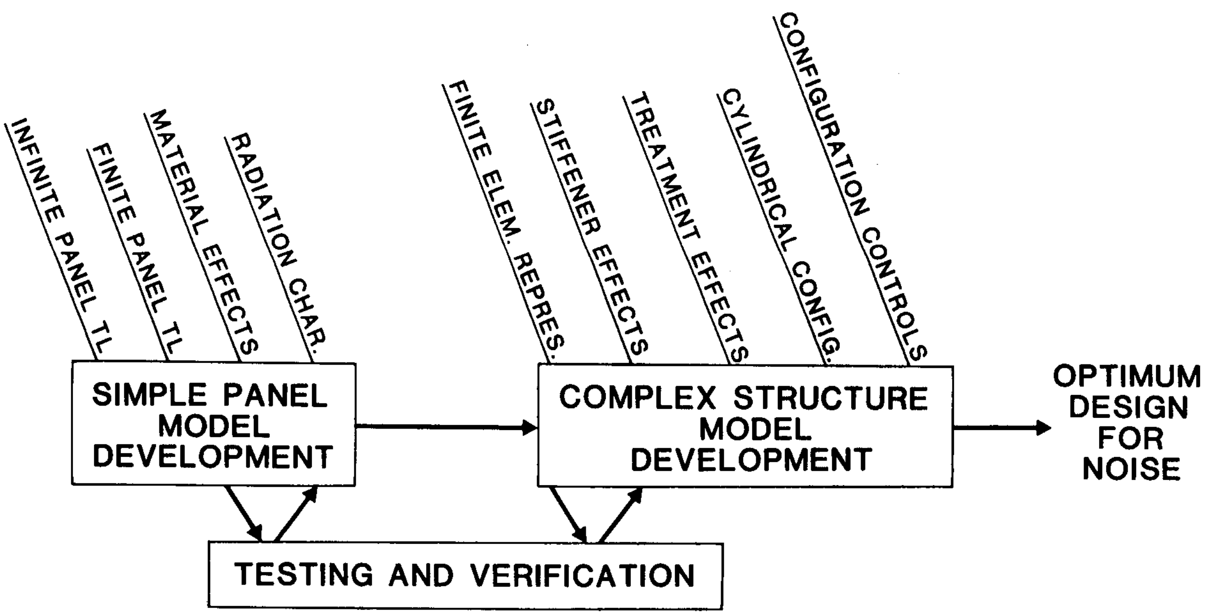

Figure 2

INFINITE PANEL THEORY TRANSMISSION LOSS MODEL

In infinite panel theory the panel is modelled as a thin plate with infinite area. For oblique incidence transmission loss, the incident sound is modelled as a single plane wave that impinges on the panel at an arbitrary angle. Because the panel is infinite, the reflected and transmitted pressures are also plane waves. The geometry of the transmission is shown in figure 3. Since the intensity of a plane wave is linearly proportional to the mean square pressure, the oblique incidence transmission loss, which is calculated from the ratio of incident to transmitted intensities, reduces to the simple relationship between incident and transmitted pressures shown in the figure. The ratio of incident to transmitted pressure is calculated from the differential equation of motion of the plate: the general form of the equation is given in the figure. The frequency at which the term in brackets is a minimum is called the coincidence frequency and corresponds to a wavelength resonance condition at which the trace wavelength of the incident noise is equal to the free bending wavelength in the infinite plate. At frequencies below the coincidence frequency, the first term within the brackets, the so-called "mass law" term, governs the transmission. Above coincidence the curve rises sharply and is a function mainly of the damping, which is represented by the loss factor in the equation in the figure. In summary, the infinite panel theory transmission loss model is applicable only in the mass controlled and coincidence frequency regions of transmission loss.

$$\text{T. L.} = 10 \log \left| \frac{p_i}{p_t} \right|^2$$

$$\frac{p_i}{p_t} = 1 + j \left[\frac{\overline{m} \pi f \cos \theta_i}{\rho c} - g\left(D_{ij}, f, \eta, \theta_i, \Phi_i\right) \right]$$

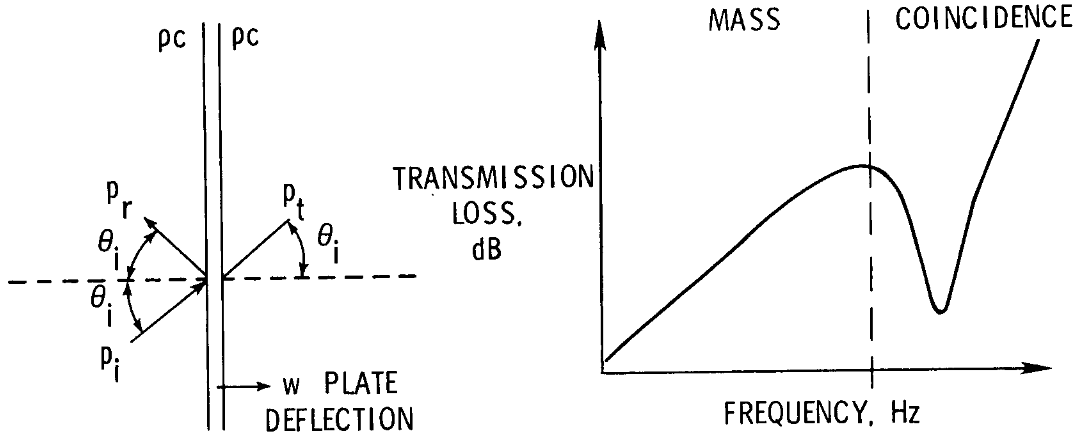

Figure 3

TRANSMISSION LOSS TESTS OF LARGE PANELS

Facility and Method

To validate the infinite panel theory and experimentally establish the noise transmission loss characteristics of large composite test panels, the panels were mounted in the ANRD Transmission Loss Apparatus as partitions between two adjacent rooms which are designated the source room and the receiving room. Top and side views of the apparatus are shown in figure 4. In the source room a diffuse field is established by two reference sound power sources. Sound is transmitted from the source room into the receiving room only by way of the test panel, which has a sound exposed vibrating area of 0.85 m by 1.46 m (2.8 ft by 4.8 ft). The test specimen is mounted in a steel frame which is designed for minimum structural flanking. The receiving room is acoustically and structurally isolated from the rest of the building. A space and time average of the sound pressure levels is taken in each of the rooms by a microphone mounted at the end of a rotating boom. The microphones measure the panel's noise reduction, which is defined as the difference between the measured average sound pressure levels in the source and receiving rooms. Noise reduction includes characteristics of the test specimen as well as room characteristics. Transmission loss, which is a function of the properties of the test specimen only, is calculated from noise reduction by correcting for the absorption in the receiving room as well as for the non-diffusivity of both rooms.

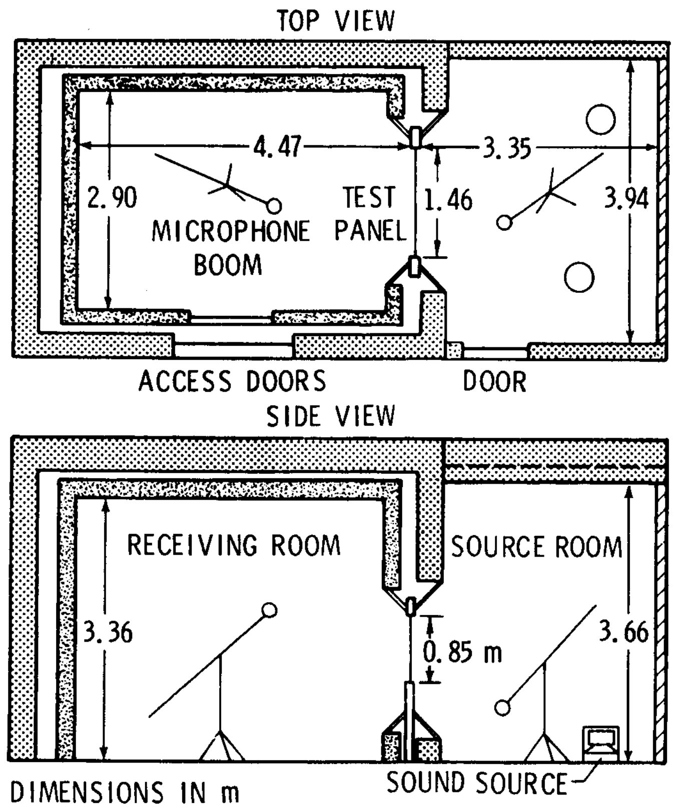

Figure 4

TRANSMISSION LOSS TESTS OF LARGE PANELS

Panel Configurations

A total of 28 fiber-reinforced composite panels were tested. Twelve of these panels were of tape construction, fourteen were of fabric construction, and two were of sandwich construction with fabric composite skins and syntactic (microballoon-filled epoxy) cores. The tape panels were made by bonding together several plies of unidirectional fibers. Each ply has a "ply angle" which refers to the angle at which the fibers are laid up in relation to the longer boundary of the panel. Thus, a 0° or 90° ply has its fibers parallel to one of the boundaries. The panels with fabric construction were similarly made by bonding several plies together. Since a fabric ply consists of two sets of fibers woven perpendicular to each other, two ply angles are associated with each ply. Also, in one fiber direction called the fill direction, the fibers are straight, while in the opposite warp direction, the fibers bend up and down as they weave around the straight fibers. For a 0°/90° ply, the warp of the fabric was oriented in the direction of the longer boundary of the panels, i.e., in the 0° direction. Descriptions of ply material, ply angle lay-up, thickness, and number and type of plies for each panel are given in figure 5. As can be seen in the figure, three ply materials were tested (graphite-epoxy, Kevlar*-epoxy, and fiberglass-epoxy) for both tape and fabric construction, for two thicknesses, and for various ply angle lay-ups.

*Kevlar aramid fibers, manufactured by E. I. du Pont de Nemours & Co., Inc.

TAPE PLY ANGLE CONFIGURATIONS

G/E, K/E, AND F/E

8 PLIES (0.10 CM) ... ±45, 0/90

16 PLIES (0.20 CM) ... ±45, 0/90

FABRIC PLY ANGLE CONFIGURATIONS

G/E, K/E, AND F/E

4 PLIES (0.10 CM) ... ±45, 0/90

8 PLIES (0.20 CM) ... ±45, 0/90/±45

OTHER G/E (0/90) FABRIC CONFIGURATIONS

3 PLIES (0.10 CM)

6 PLIES (0.20 CM)

6 PLIES w/0.10 CM SYNTACTIC CORE

6 PLIES w/0.20 CM SYNTACTIC CORE

Figure 5

TRANSMISSION LOSS TESTS OF LARGE PANELS

Typical Results

In figure 6 the measured field incidence transmission loss of two graphite-epoxy panels is compared with infinite panel theory. Infinite panel theory is seen to be in good agreement (within 1 dB) with the data over the entire mass controlled frequency region. In the coincidence frequency region, the agreement is again quite good. The theory follows the slope of the coincidence dip for both panels and is within 1 to 3 dB of the measured levels. The agreement between theory and measured data in this figure is typical of the agreement that occurred for all 28 panels.

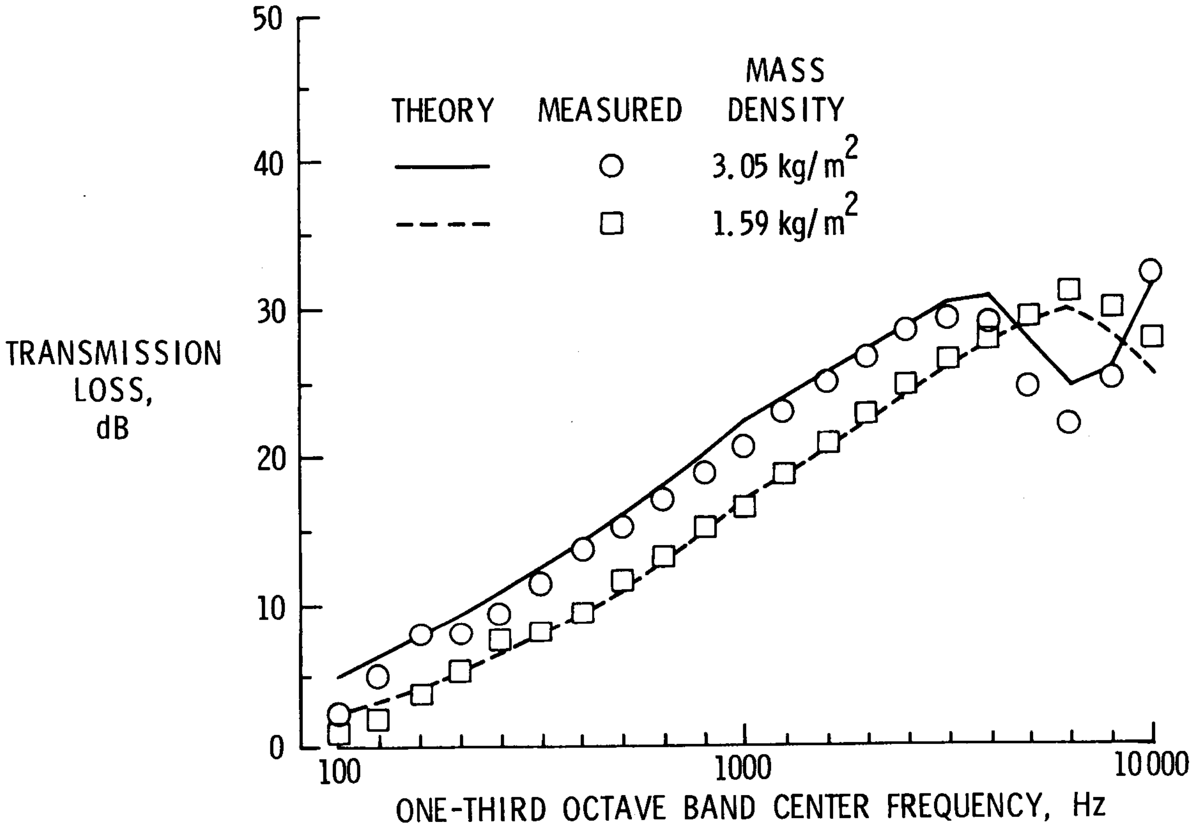

Figure 6

TRANSMISSION LOSS TESTS OF LARGE PANELS

Overall Prediction Ability

The noise transmission loss prediction ability of infinite panel theory for the large composite panels is indicated in figure 7. The prediction error, the difference between predicted and measured transmission loss, is plotted for 14 of the 28 composite panels. The frequency scale on the abscissa has been normalized by dividing by the critical frequency, the lowest frequency for which coincidence occurs. The prediction error in the mass controlled region (f/f-critical < 1) is seen to be generally less than ±3 dB. In the coincidence region, the error is somewhat greater (generally within ±6 dB). This is because the stiffness and damping properties used in the infinite panel theory model were only rough estimates and these properties govern the transmission loss in the coincidence region.

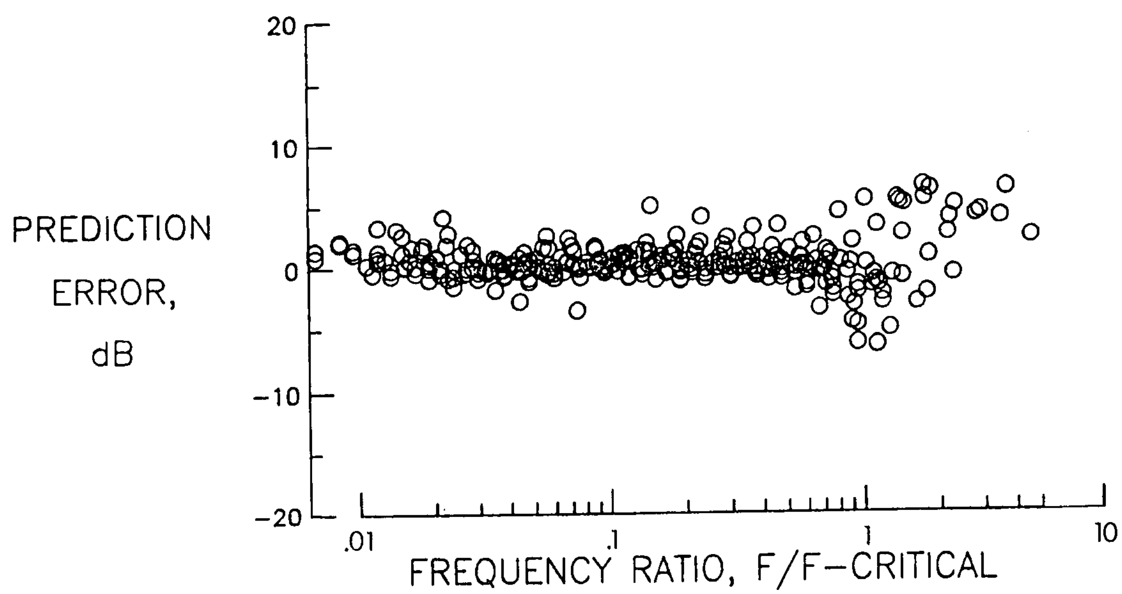

Figure 7

FINITE PANEL THEORY DEVELOPMENT

For low frequency noise, the dimensions of the transmitting panel are comparable to or smaller than the sound wavelengths so that boundary effects are important. Therefore, for this case, a new finite panel noise transmission theory, as indicated in figure 8, has been developed. In this theory the panel is modelled as a rectangular plate simply supported in an infinite rigid baffle. The incident acoustic pressure is modelled as a plane wave impinging on the plate at an arbitrary angle of incidence. The incident, reflected, and transmitted pressures are approximated by the blocked pressure which is assumed to be much greater than the reradiated pressure. This assumption allows the plate vibrations to be calculated by a normal-mode approach. The Rayleigh Integral is used to link the plate vibrations to the transmitted acoustic pressure. The incident and transmitted acoustic powers are calculated by integrating the incident and transmitted intensities over their appropriate areas, and transmission loss is calculated from the ratio of incident to transmitted acoustic power.

- RECTANGULAR PLATE SIMPLY SUPPORTED IN INFINITE BAFFLE
- BLOCKED PRESSURE ASSUMPTION
  $$p_i + p_r - p_t \approx 2p_i$$
- MODAL SOLUTION FOR PANEL VIBRATIONS
- RAYLEIGH INTEGRAL WITH FAR-FIELD APPROXIMATIONS
- INTEGRATION OF INTENSITIES FOR INCIDENT AND TRANSMITTED ACOUSTIC POWERS
- $\text{T. L.} = 10 \log \left(\dfrac{\text{INCIDENT ACOUSTIC POWER}}{\text{TRANSMITTED ACOUSTIC POWER}} \right)$

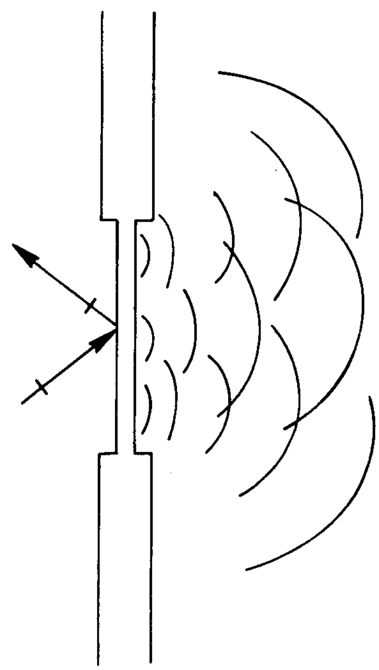

Figure 8

FINITE PANEL THEORY DEVELOPMENT

Radiation Directivity Results

An example of the use of the model for calculating radiation directivity is shown in figure 9. Plotted here is the variation of transmitted intensity in the far field of a 36-cm by 20-cm by 0.01-cm graphite-epoxy panel for a plane wave incident on it at a polar angle of 45° and an azimuthal angle of 0° (parallel to the 36-cm side of the plate). The ply angle lay-up of the panel consisted of 8 alternating +45° and -45° plies laid up symmetrically about the midplane. Transmitted intensity was calculated for two frequencies, 500 Hz and 3000 Hz. The sample results show that as frequency increases, more of the transmitted sound becomes concentrated at a transmitted angle equal to the incident angle. The results showing the variation of transmitted intensity with azimuthal angle display an example of symmetry which helps reduce integration time. With an incident azimuthal angle of $\phi_i = 0°$, symmetry occurs about $\phi = 0°$. Though not shown, for an incident azimuthal angle of $\phi_i = 90°$, symmetry occurs about $\phi = 90°$. And, for an incident polar angle of $\theta_i = 0°$, symmetry occurs about both $\phi = 0°$ and $\phi = 90°$. Studying these transmitted intensity radiation patterns is thus seen to aid in both the understanding of the physics of the problem and the understanding of the numerics involved in calculating transmission loss.

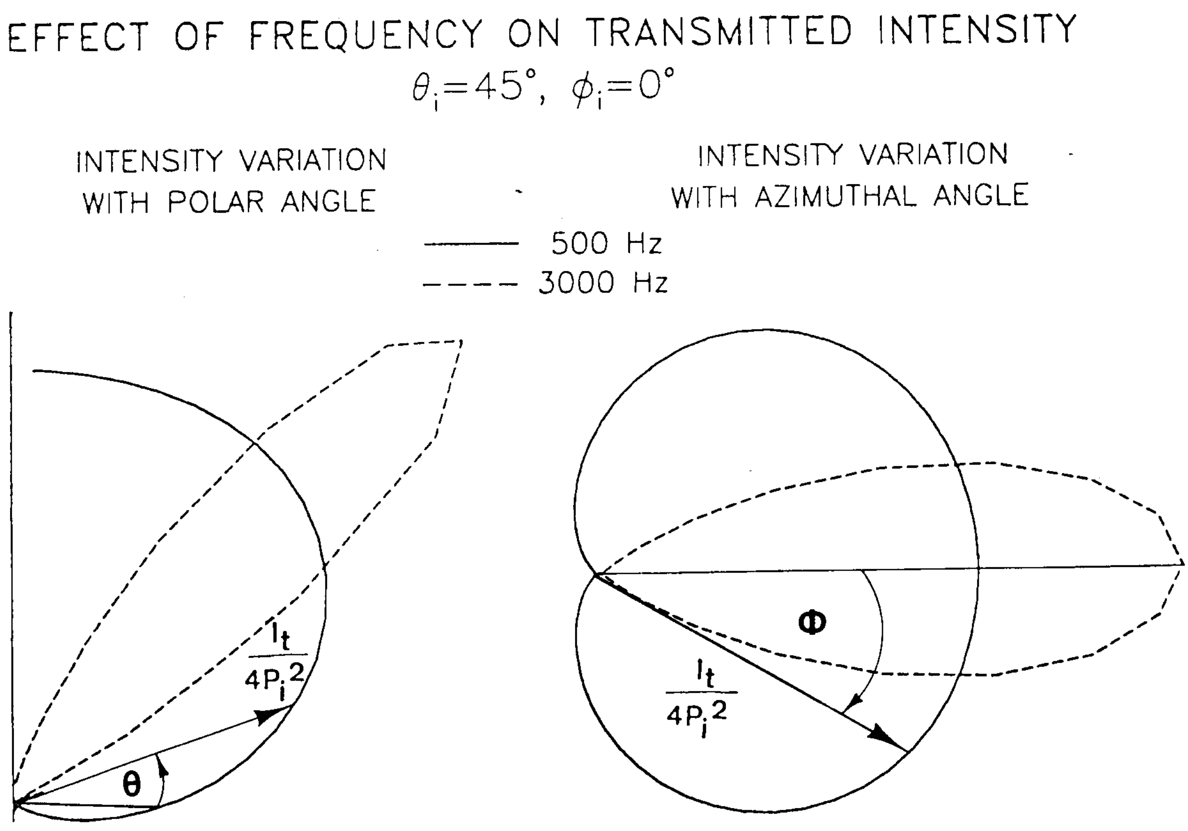

Figure 9

FINITE PANEL THEORY DEVELOPMENT

Prediction of Effect of Ply Angle and Incidence Angle on Transmission Loss

In a composite panel the flexural rigidity moduli will be different in different directions depending on ply angle lay-up. Therefore, panels with different ply angle lay-ups or with different orientations with respect to the incident noise could have markedly different low frequency noise transmission characteristics. The effects of ply angle and incidence angle on transmission loss have been calculated for a 36-cm by 20-cm by 0.10-cm graphite-epoxy panel and the results are shown in figure 10. The curves showing ply angle effect, which were calculated for the case of normal incidence, indicate that a panel made of +45°/-45° plies has significantly higher (6 to 14 dB) transmission loss in the stiffness controlled low frequency region than a panel made of 0°/90° plies. In the frequency range immediately following the fundamental resonance of the +45°/-45° panel, the 0°/90° panel has 2 to 9 dB more transmission loss. Since the panels weigh the same, the transmission loss curves merge together in the high frequency mass controlled region. In comparing the transmission loss for the +45°/-45° panel for two different angles of incidence, very little difference (less than 2 dB) is found in the stiffness and resonance controlled regions, while in the mass controlled region the normal incidence curve rises up to a maximum of 3 dB above the 45° incidence case. These predictions indicate that the ability to tailor the ply angle lay-up of a composite panel can significantly affect the low frequency noise transmission characteristics, and the effect of varying the angle of incidence is not as important an effect at low frequency. Further study is needed to fully understand the ply angle effect and to determine the effect of varying the azimuthal incident angle.

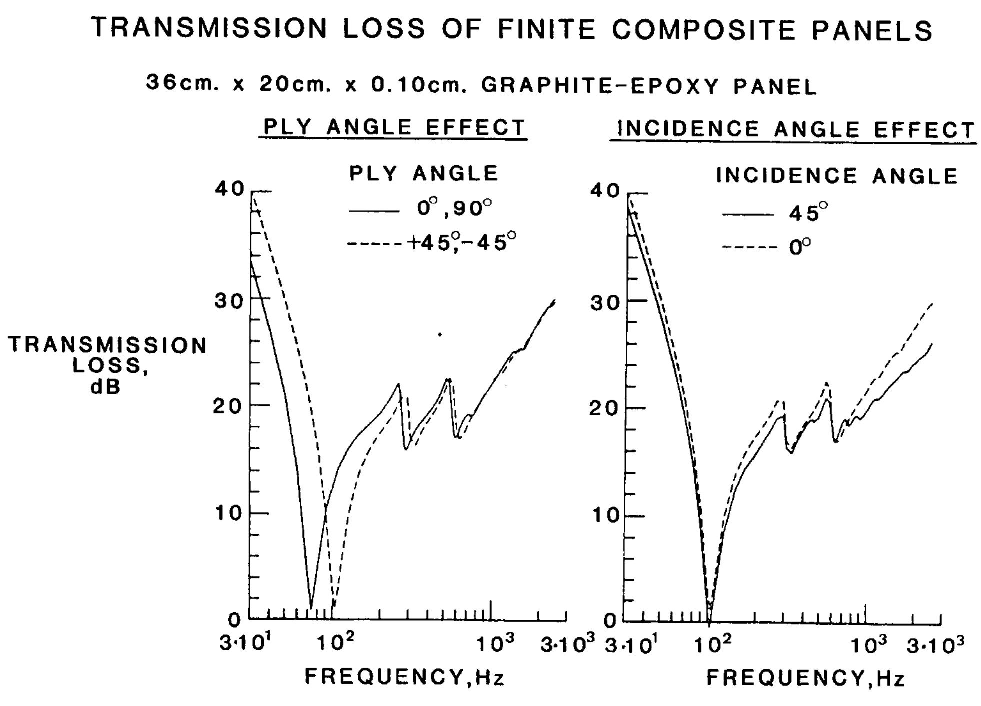

Figure 10

FINITE PANEL THEORY DEVELOPMENT

Design Comparison

The analytical model has been used to investigate the effect on noise transmission of replacing a typical general-aviation type aluminum skin with either graphite-epoxy or Kevlar-epoxy skins. The design comparison presented here is based on equal critical shear load for the composite and aluminum panels. The panels were assumed to be approximately 36 cm by 20 cm with simply supported boundary conditions. The composite panels were assumed to be of tape construction with each ply being 0.013 cm thick. The critical shear load was first calculated for the aluminum panel which was assumed to be 0.10 cm thick. Each composite panel was then designed for the minimum thickness necessary for its critical shear load to be greater than or equal to that of the aluminum panel. The incidence sound is assumed to impinge at an angle of 60°. In figure 11, it can be seen that because of their higher fundamental frequencies, the graphite-epoxy and Kevlar-epoxy panels have over 12 dB more transmission loss at the aluminum panel's resonance (79 Hz). The increase in transmission loss over the aluminum panel is about 4 dB at the lowest frequencies plotted. In the high frequency mass controlled region, the graphite-epoxy and Kevlar-epoxy panels have about 3 to 4 dB less transmission loss because they would be about 34 percent lighter than the aluminum panel. Such transmission loss characteristics indicate that composites may be beneficial for low frequency noise transmission problems at or below the resonance of conventional aluminum panels.

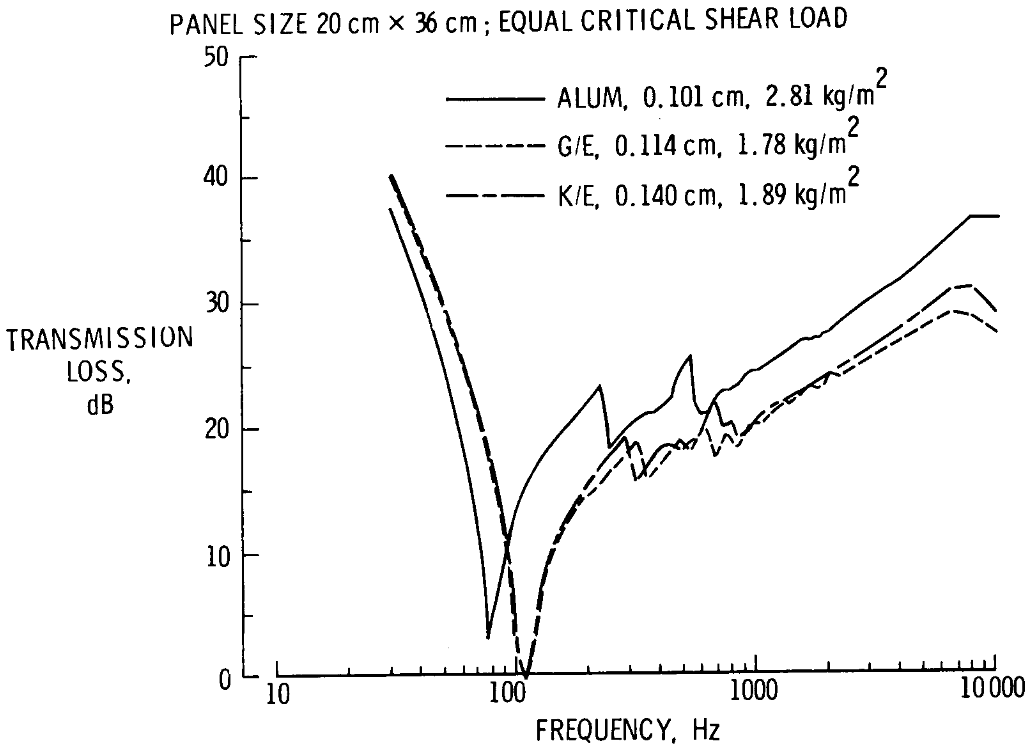

Figure 11

TEST PLAN FOR FINITE PANELS

To investigate the effects of high-strength/lightweight composites in the low frequency regions of transmission loss, experimental studies are planned for small panels (40 cm by 24 cm) whose fundamental frequencies will typically be 150 Hz or more. The small panels will be cut from 10 of the 28 large panels that had been tested earlier. The calculated simply supported and clamped fundamental frequencies for the panels to be tested are shown in figure 12. The actual fundamental frequencies will be measured and are expected to fall somewhere in between these extremes. The percent critical damping will also be measured. Ply angle lay-up and damping will be investigated especially for their effects on noise transmission in the stiffness and resonance controlled regions of transmission loss.

TRANSMISSION LOSS TESTS OF SMALL PANELS

PANEL CONFIGURATIONS

PLY MATERIAL	NUMBER OF PLIES	PLY ANGLES	TOTAL THICKNESS, CM	SURFACE DENSITY, KG/M^2	NATURAL FREQUENCY, Hz	
					SIMPLY SUPPORTED	CLAMPED
G/E TAPE	16	+45/-45/0/90	0.21	3.36	127	252
G/E TAPE	16	+45/-45	0.19	3.05	130	218
G/E FABRIC	8	(+45/-45)/(0/90)	0.23	3.58	168	324
G/E FABRIC	8	(+45/-45)	0.23	3.56	165	320
K/E TAPE	16	+45/-45/0/90	0.20	2.79	100	198
K/E TAPE	16	+45/-45	0.20	2.79	115	193
K/E FABRIC	8	(+45/-45)/(0/90)	0.15	2.10	80	155
K/E FABRIC	8	(+45/-45)	0.15	2.09	82	156
G/E FABRIC	6	(0/90)	0.21	3.31	154	299
G/E FABRIC W/SYNTACTIC CORE	6	(0/90)	0.32	4.16	251	458

Figure 12

FINITE ELEMENT MODEL DEVELOPMENT

In order to model more complicated structural configurations, a finite element model for the plate vibrations is being incorporated into the finite panel theory. Using finite elements, as indicated in figure 13, will allow more realistic modelling of the anisotropic behavior of composites, the modelling of stiffened plates and plates with windows, and the modelling of more realistic boundary conditions. Though the use of finite elements can become overly costly, it will be feasible in the current research because the concern here is at low frequency where only a few elements are needed to model the few modes that are being excited. Since the ultimate goal is to predict the interior noise levels in an aircraft cabin, the effect of cabin acoustics needs to be included in the model. As a step in this direction, finite elements are also being used to link the plate transmission problem with a receiving acoustic space. This problem is commonly referred to as noise transmission into an enclosure. These advancements in the structural and acoustical aspects of the problem are currently under development and the research is being conducted for NASA by Professor Leslie R. Koval of the University of Missouri at Rolla, Missouri.

OBJECTIVES: TO ACCOUNT FOR

- o COMPLEX STRUCTURAL CONFIGURATIONS
- o NON-IDEALISTIC BOUNDARY CONDITIONS
- o ANISOTROPIC STIFFNESS PROPERTIES
- o COUPLING TO CABIN ACOUSTICS

PRINCIPAL INVESTIGATOR:

- o DR. LESLIE R. KOVAL
  UNIVERSITY OF MISSOURI-ROLLA

Figure 13

STRUCTUREBORNE NOISE RADIATED BY COMPOSITE PANELS

Until recently, both the analytical and experimental research programs on the noise radiative properties of composite materials have been devoted almost exclusively to the study of airborne sound transmission through composite structures. Present and future research in this area includes a comprehensive study of the structureborne noise radiative properties of these materials. Evidence of the extreme differences in these two sound generating mechanisms (airborne vs. structureborne) can be predicted analytically and measured experimentally in terms of the acoustic source directivity, the acoustic radiation efficiency, and the complexity of the acoustic near field. Figure 14 shows the large difference in the acoustic radiation efficiency for the airborne and structureborne sound radiated by a rectangular sheet of plexiglass. Similar differences in the airborne and structureborne noise radiative properties of panels constructed with composite materials are expected.

CHARACTERISTICS OF STRUCTUREBORNE SOUND RADIATION IN TERMS OF THE ACOUSTIC RADIATION EFFICIENCY σ :

$$\sigma = \frac{\Pi}{\rho c \, \langle v^2 \rangle_{r,t} \bullet \text{Area}}$$

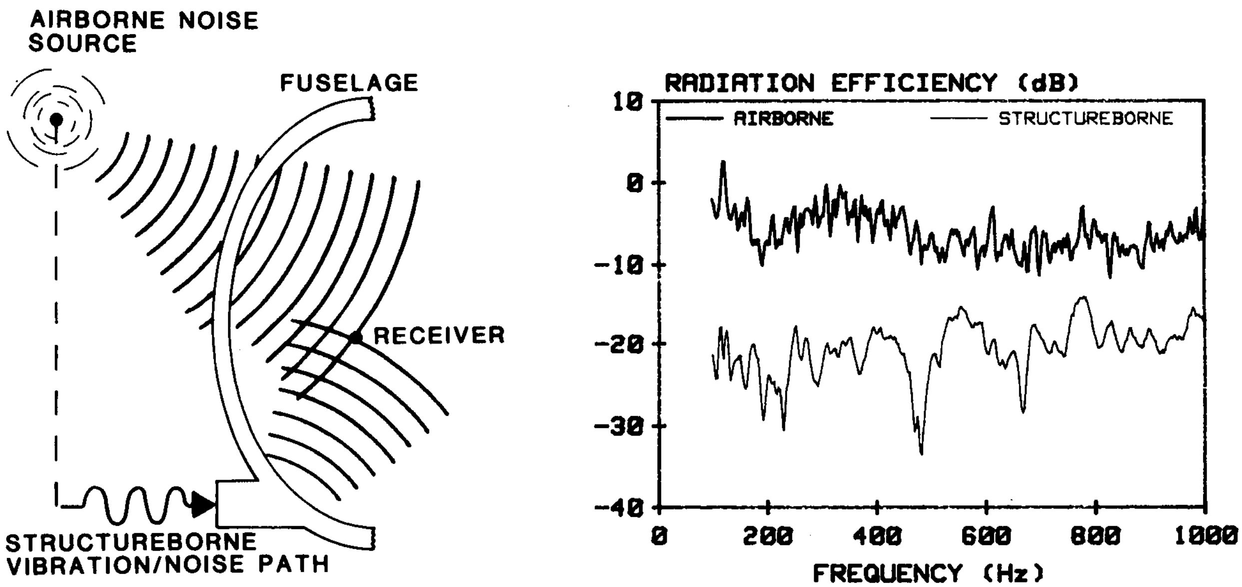

Figure 14

METHOD FOR SEPARATING AIRBORNE AND STRUCTUREBORNE NOISE IN COMPOSITE PANELS

Figure 15 illustrates a new measurement method for separating airborne and structureborne noise radiated by aircraft-type panels which is under development. The method is an extension of the two-microphone cross-spectral acoustic intensity measurement method combined with conventional methods for measuring the space-averaged mean square surface velocity of the structure. Both analytical and experimental studies are planned, with the aim of developing a comprehensive set of user guidelines for this method. The measurement method will be applied to panels constructed of both conventional aircraft materials and advanced composites. Parameters which will be studied include the frequency range of excitation, relative magnitude and phases of the combined airborne and structureborne inputs, and the effects of added structural damping.

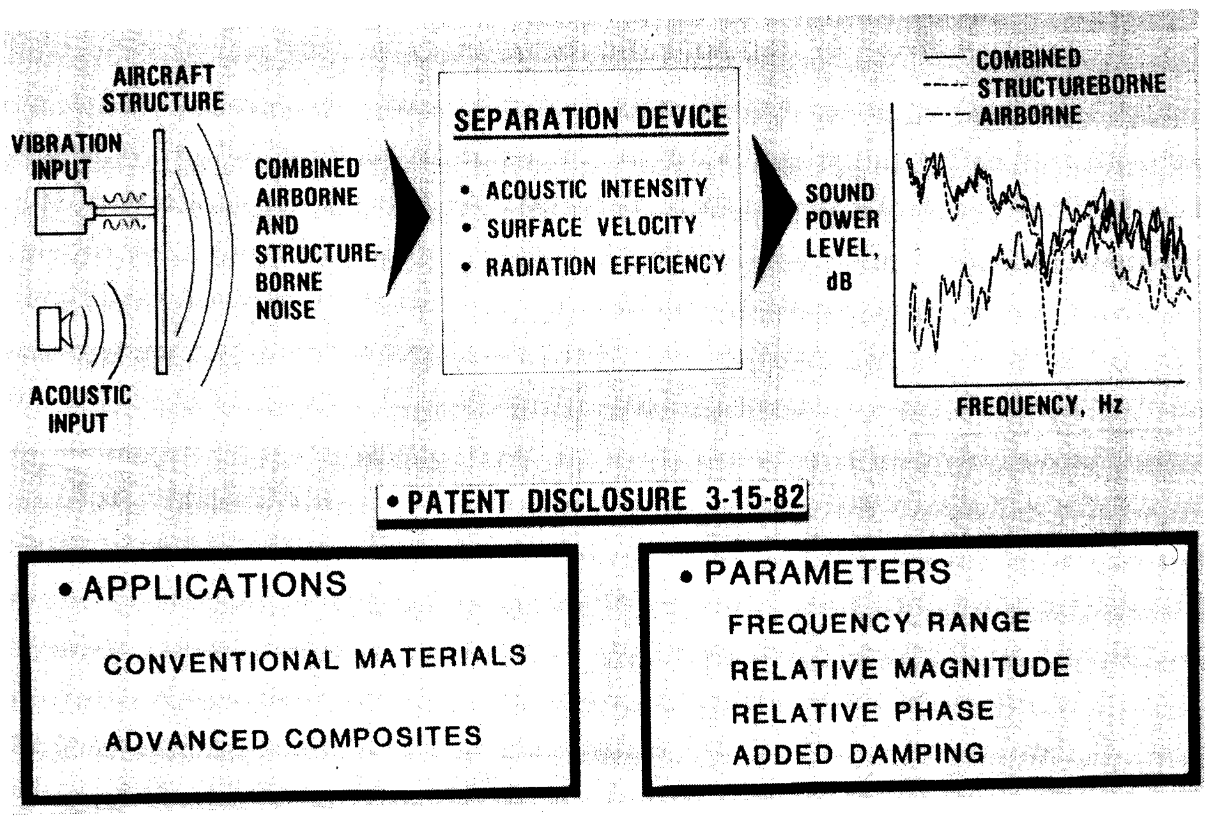

Figure 15

NOISE TRANSMISSION IN STIFFENED COMPOSITE STRUCTURES

Future research will also include studies of more complicated composite structures. It is expected that both analytical and experimental studies of the noise radiative properties of built-up composite panels, such as the panel shown in figure 16, will be undertaken. Presently, the analytical study of noise transmission through composite cylinders is being updated by Professor Koval to include the effects of frames and stringers. Parameters which will be studied include the geometry of the stiffeners (e.g. shape, size and spacing) and the methods of attaching the stiffeners to the panels (e.g. fabricated, adhesive bonded, riveted).

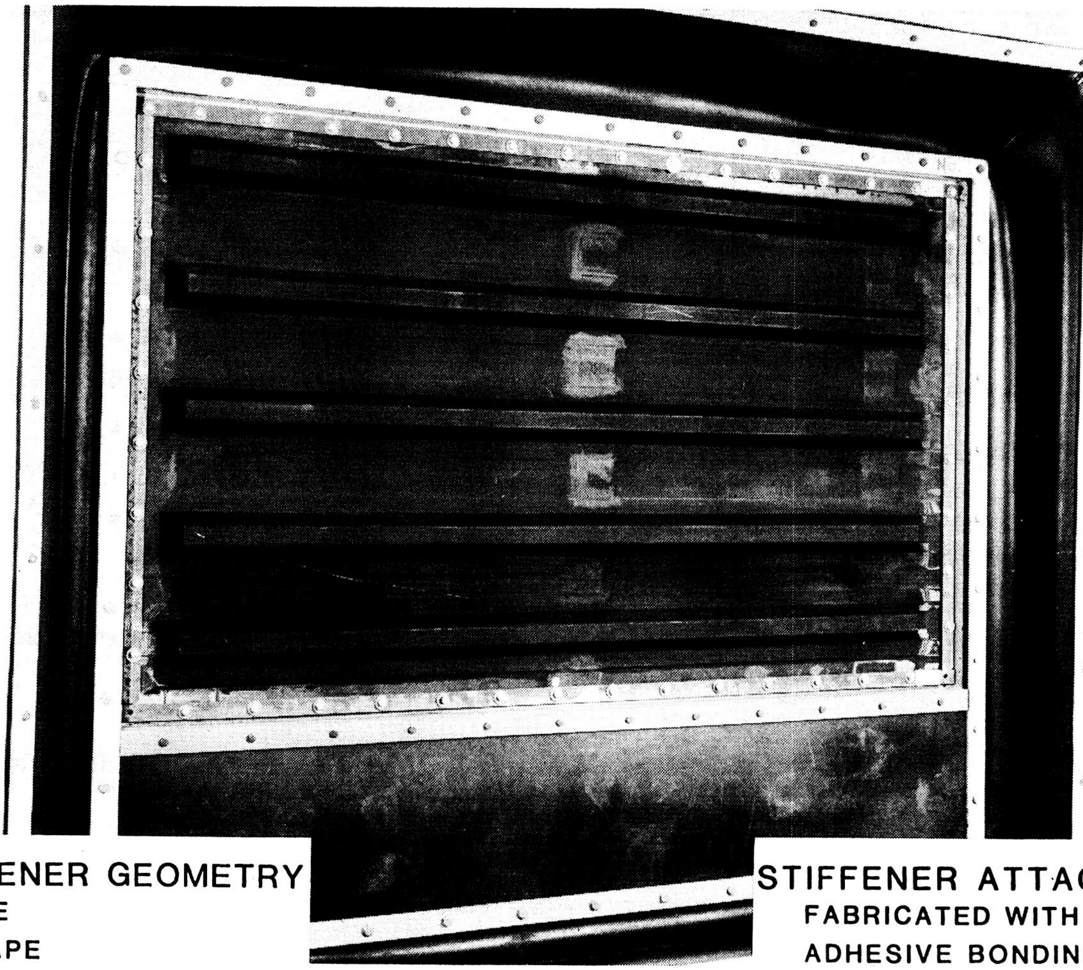

Figure 16

SUMMARY/PROGRAM STATUS

Significant progress has been made in the program to determine noise characteristics of advanced composite material structures. Theory has been developed and verified for noise transmission loss of infinite panels which can have anisotropic stiffness characteristics. Similarly, theory has been developed and is being experimentally verified for orthotropic finite panels. An oblique incidence model of that theory is currently operational and a random incidence model is being programmed. Progress is also being made under a grant with Prof. Koval at the University of Missouri-Rolla to develop finite element models to account for added stiffness and coupling to acoustic volumes. A study is under way to determine radiation characteristics for airborne and structureborne noise and to separate those components in mixed situations. Finally, test plans to determine transmission loss characteristics of stiffened composite panels are being made with the cooperation of the Army Structures Laboratory at Langley Research Center. The successful completion of this program should make it possible to design composite structures with noise attenuation characteristics as good as current aluminum structures and which still provide the weight savings anticipated for equal stiffness designs. (See fig. 17.)

- ANISOTROPIC INFINITE PANEL THEORY DEVELOPED AND VERIFIED.
- ORTHOTHROPIC FINITE PANEL THEORY DEVELOPED, OBLIQUE INCIDENCE MODEL OPERATIONAL, RANDOM INCIDENCE MODEL BEING PROGRAMMED, VERIFICATION IN PROGRESS.
- FINITE ELEMENT MODEL DEVELOPED FOR SIMPLE PANELS, STIFFENED PANEL MODEL BEING DEVELOPED AT U. MISSOURI-ROLLA.
- PROGRAM TO DETERMINE RADIATION CHARACTERISTICS FOR AIRBORNE AND STRUCTUREBORNE NOISE INITIATED.
- TRANSMISSION LOSS OF STIFFENED PANELS TO BE INVESTIGATED.

Figure 17