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Master Plan for Prediction of Vehicle Interior Noise

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Earl H. Dowell
Princeton University, Princeton, N. J.

I. Introduction

THERE are two principal parts to this survey paper: one is bibliographical, and the other editorial. For the former, the literature on the subject (Refs. 1-171) has been organized as follows. The older literature, defined somewhat arbitrarily as pre-1974, is listed in an alphabetical General Bibliography which is further subdivided into two parts: 1) Books and Background Articles and 2) Articles. Much of this literature retains its value, but in most cases has been superceded by later work, often by the same authors. The more recent contributions to the literature (as well as a few items from pre-1974) are contained in the Topical Bibliography and are further subdivided by associated subject matter. This subdivision should be useful for its own sake and also prepares the reader for the editorial state-of-the-art discussion which follows.

It is suggested that the reader first examine the entire Bibliography, which is partially annotated, before proceeding further. (See Sec. VIII.) Then, after reading the state-of-the-art editorial review which follows below, readers are encouraged to examine the original sources themselves and form their assessment of the state-of-the-art. To the extent that this occurs and the present paper facilitates that process, the author will consider his efforts successful. The state-of-the-art discussion is inevitably subjective. However, the major points that are made should be widely accepted. These are that:

1) An improved and improving capability is available for noise transmission analysis.

2) To use it effectively requires a substantial manpower investment comparable to that used in structural dynamics analysis.

3) The question then becomes whether, in a given application, the improved results are worth the additional effort required.

Moreover, the key to advancing the state-of-the-art further is a systematic program of theory and experiments which are mutually reinforcing. This is the Master Plan referred to in the paper title and it is discussed in more detail in the text.

II. Elements of the Interior Noise Problem

Interior cabin sound levels have become a problem of increasing importance for a variety of aircraft as well as railway and automotive vehicles. Much attention has been given to conventional subsonic and, more recently, supersonic aircraft. However, helicopter, short-take-off-and-landing (STOL), and general aviation aircraft also have important and somewhat unique interior noise problems. Indeed their sound levels are typically well above those of conventional aircraft. Moreover the frequency content of these noise levels has significant low frequency content near the structural resonances of the cabin walls. This appears to be true of some other types of transportation vehicles as well.

There are three significant needs which must be met in order to decrease interior noise levels. There is a need to 1) improve noise control techniques, 2) develop better structural noise transmission prediction methods, and 3) establish acceptable levels for safety and comfort. The basic assumptions, ingredients, and an overall assessment of the problem are given here.

Assumptions

1) The principal area of concern is in the low frequency region for general aviation, helicopter, and STOL aircraft where individual internal cavity acoustic resonances and/or structural wall resonances may be dominant. The high frequency regime, which is of more interest for CTOL aircraft, is unlikely to demand new methods, although improved methods, once available, may well be used there also.

2) It is desired to provide an analytical framework which may fully utilize the evolving state-of-the-art in terms of noise source definition, structural wall modeling, and internal acoustic field modeling. The analytical model should be sufficiently flexible so that modifications may be made a) to simplify the analysis, if desired for reasons of economy, or b) to accept new, as yet undeveloped, improvements in structural and acoustic technology as they become available.

3) The major elements of the analysis should be capable of systematic validation by experiment. The four major elements (which may be further subdivided) are described below.

Noise Sources[79-85]

External:
- A-A Propellers[84]
- E-A Jet Exhausts[85]
- E-A Boundary-Layer Noise[3]

Internal:
- P-P Gear Boxes[11]
- A-P Vibration of Engine Housing[16]
- A-P Air Conditioning Units and Other Auxiliary Devices[11]

Dr. Earl H. Dowell is a Professor of Mechanical and Aerospace Engineering at Princeton University. His research interests include unsteady aerodynamics, acoustics, structural dynamics and aeroelasticity. He is Chairman of the AIAA TC on Structural Dynamics, a member of the AIAA Publications Committee, and a member of the ASME, ASA, AHS and the American Academy of Mechanics.

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Index categories: Noise; Structural Dynamics; Aeroacoustics.

Noise Effects on People and Payloads[86-90]

A-A Loss of Hearing[13]
A-A Speech Interference[14,16]
P-P Task Interference[14,16]

Noise Reduction Concepts[91-93]

Mass, stiffness, and damping of structure
Inertia, compliance and absorption of acoustic cavity
Frequency matching (tuning) among structural and acoustic components

Noise Transmission Analysis[94-142]

Structural Walls:
E-A Mass
E-A Stiffness
A-A Damping

Interior Acoustic Cavities

E-A Mass
E-A Stiffness
A-A Damping (absorptive wall impedance)

See following Section III for further discussion and references on this topic.

In the above the following code has been used to assess the state-of-the-art: E = excellent; A = acceptable; and P = poor. A distinction has been made between physical understanding and computational efficiency. Thus E-P would mean that excellent physical understanding exists, but poor computational efficiency with available techniques. Obviously, these characterizations are subjective, are most meaningful in a relative sense within a specific component, and are constantly changing. For example, recent research has substantially improved our understanding of interior acoustic cavities. No characterization of noise reduction concepts is made since as given above they are quite general and to be more specific would involve discussion of particular applications. The cited references are representative of the best state-of-the-art review papers available.

The noise transmission analysis element is reviewed in greater detail in the next section of the paper. It is the common element which relates any noise source to the receiver of the noise effects. It also allows one to assess, and perhaps even suggests, noise reduction concepts. As such, it plays the central role in establishing a noise predictive capability. This is not to underestimate the importance of the other elements. Indeed, to the extent that some aspects of noise sources, effects, and reduction concepts are not being pursued with sufficient emphasis in the context of external acoustics, additional work should be undertaken. In particular, uniquely internal noise sources and receiver sensitivity to task interference may require some further commitment of resources.

In what follows we shall focus on generic noise transmission analysis and consider primarily *external* noise sources (at least external to the acoustic cavity of interest, e.g., pilot in cabin with noise source outside the cabin). For a discussion of applications to specific vehicle types the reader is referred to the appropriate entries in the Bibliography (Refs. 143-171).

In Fig. 1 (provided by the Noise Effects Branch, NASA Langley Research Center), a schematic of some of the detailed elements of the interior noise problem is presented.

III. State-of-the-Art of Noise Transmission Analysis

There are many similarities with respect to sound transmission for all types of transportation vehicles. Improved acoustic-structural (acoustoelastic) analytical models should be generally useful and practitioners in one industry should benefit from advances in another. It is interesting to note that

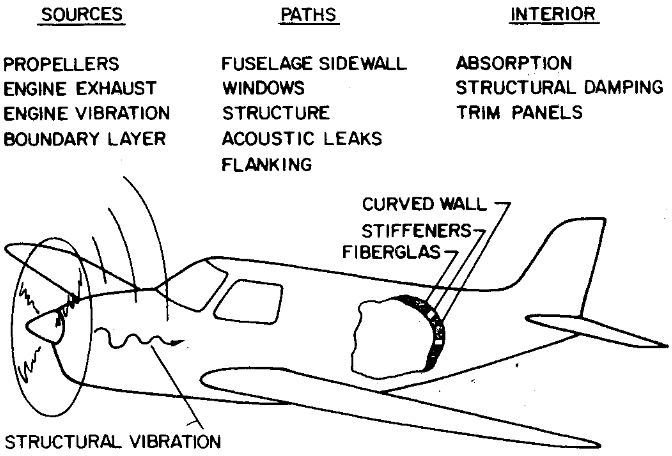


Fig. 1 Considerations for prediction of light aircraft interior noise.

the automobile industry has pioneered the use of modal methods of analysis, including the use of finite element techniques.[120-123,143,144] Readable and relatively brief accounts of sound transmission prediction techniques used in design practice today in the aerospace industry are available by Wilby et al. in Chaps. 22 and 23 of Ref. 20 and by Lyon in Chap. 11 of Ref. 16.

We now consider, in turn, four methods of analysis: modal analysis, which the author feels is the brightest hope for the future; classical noise transmission analysis, which is used most frequently in practice today; statistical energy analysis; and acoustoelastic experimental scale models.

Modal Methods

For both the (internal) acoustic and structural parts of the physical model, we are concerned with mass, stiffness, and damping. It is natural then to think in terms of structural natural modes and acoustic natural modes, or even coupled acoustic-structural modes, to describe the sound transmission from the external to internal regions. The coupled modes include the mutual interaction of the acoustic and structural fields. Because these latter are more difficult to determine, and the coupling between the acoustic and structural motion is not large (i.e., the structural modes do not change significantly due to the internal acoustic pressures), the uncoupled acoustic and structural modes are normally employed. Even using these, it has been thought until recently that the summation of individual modes to obtain the internal acoustic field resulting from structural motion was not practical. See for example, Ref. 12. However, for highly resonant internal cavities whose sound field is dominated by a relative handful of modes, the modal approach clearly becomes an attractive technique. Indeed, even if a large number of modes are present, the natural mode approach is still attractive conceptually as a technique for decomposing the total sound field. *It is the determination of the natural modes themselves which is the principal difficulty.* More will be said of this later.

One modal result which was conspicuous by its absence in the sound transmission literature until recently, is the analog to Miles' one mode simplified analysis[60] for structural vibration response to a random pressure loading. Two alternatives must be considered, one in which a structural resonance is dominant and another where an acoustic cavity resonance is dominant. The special case of near structural and acoustic resonances also requires attention. Dowell et al. have now developed the required results.[115]

Classical Noise Transmission Analysis

The most widely used method in current practice is what is sometimes referred to as "architectural acoustics," which relies heavily on the concepts of a locally reacting structural wall of infinite extent and its high frequency limit, the mass law, combined with extensive experimental determination of absorption characteristics of insulation materials. Clear discussions of this approach are given in one article by Wilby and Jones and another by Wilby in Ref. 20 and by Lyon in Ref. 16. A good discussion of the basic theory underlying the mass law and the classical theory of sound transmission is given by Mead in Ref. 20.

Himelblau et al.[12] have developed scaling methods for structural vibration response which use experimental data on a similar structure as a base. The mass law is then used to scale the previous experimental data to the new situation. These approaches may also be used for internal acoustic field determination. The accuracy of such approaches is highly dependent on a good data base and good judgment.

Recently Koval[129-135] in a series of papers has made a number of improvements to this method. One of his most recent contributions[135] tends toward the modal method by including explicitly the acoustic resonances of the interior cavity. To quote, "The principal result of this study is Fig. [2] and it shows the effect on noise reduction of interior cavity resonances.... The upper solid curve is noise reduction... where a totally absorbing interior has been assumed. The rapidly varying curve is ... with the effects of cavity resonances included.... The sharp dips in this curve represent the effects of the cylinder's structural resonances and interior cavity resonances.... A modest amount of absorption (corresponding to $\alpha = 1/4$) seems to significantly diminish the fluctuations due to interior cavity resonances."

Koval's result brings out two important points. For cavity interiors with low absorption, the acoustic modes must be modeled. By adding absorption the details of the acoustic modes become less important and, of course, the interior sound levels at frequencies near acoustic resonances are much reduced. The structural resonant modes, however, may still require more detailed modeling.

Statistical Energy Analysis

In recent years statistical energy analysis (SEA)[69,77,78,136-139] has been proposed as a possible alternative. It bypasses the difficulties associated with detailed structural and acoustic models by using averages of large numbers of acoustic and/or structural modes. In this respect it avoids rather than solves the basic problem of the classical modal structural and acoustic response theories, which is the determination of the natural modes themselves. *The classical theory is relatively concise and tractable too, once the natural modes are determined or prescribed as is done in SEA.* SEA does, however, offer an alternative conceptual framework which may be useful in interpreting the results of experiment or even those of classical modal analysis! Lyon gives a readable account of SEA in Refs. 15 and 77. Pope, Wilby et al. have applied SEA to the Space Shuttle interior noise question noise question recently[167] as well as made contributions to the underlying methodology.[139]

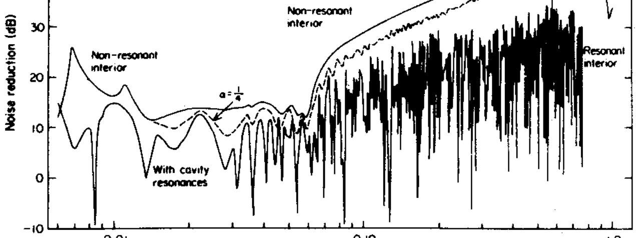


Fig. 2 Noise reduction as a function of frequency.

Recent Advances in Modal Methods

There have been a number of recent advances which are relevant to the present discussion.

1) First of all, finite element methods of structural analysis (and acoustic mode analysis) continue to advance. While these are paced in large part by computer technology, continued improvement can be expected. Coupled structural-acoustic finite element analysis have been carried out as well (see Refs. 118-126). However, one may expect that for acoustic-structural analysis (as for aeroelastic analysis[7]) the use of uncoupled modes (which themselves may have been determined from finite element calculations) in a Rayleigh-Ritz procedure to consider the combined acoustic-structural problem will be most efficient.[115]

2) In a series of papers, Gladwell[8-10] has discussed the basic variational and energy principles underlying coupled acoustic-structural problems. Taborrak has recently further advanced this approach.[127] Using the uncoupled structural and acoustic modes in a Rayleigh-Ritz procedure with these variational principles leads to a system of spring-mass-damper equations for the structural and acoustic modal generalized coordinates. The coupling between the equations is entirely due to the effect of the interior acoustic field pressure on the structural motion. This may frequently be neglected. When the latter is important, there is considerable theoretical and experimental evidence that the acoustic field may be represented by a Helmholtz resonator for the purpose of determining the structural motion (see Refs. 32, 38, 39, 61, 62, and 115). The full acoustic modal representation, with structural motion now determined, may then be solved for the acoustic field. These equations are now uncoupled, of course, due to the use of acoustic natural modes, and this considerably simplifies matters.

An alternative derivation of the model equations may be obtained from Lagrange's equations for the structure and Green's Theorem for the internal acoustic field.[115] This leads to the same results as from the combined acoustic-structural variational statement. Both methods are powerful and efficient for their purpose.

3) In structural vibration analysis the method of component modes has proved to be advantageous. The essence of this approach is the decomposition of a complex structure into many simpler components. The modes of these components are often already known or, at least, more readily determined. The component modes method then provides an efficient algorithm for determining the modes of the original structure in terms of the component modes. Hurty[49] appears to have originated this technique. Recently Dowell[40] has suggested an alternative algorithm using Lagrange multipliers which has proven very effective for some problems. Reference 115 discusses this approach inter alia in the context of acoustoelastic analysis. Interestingly, several years ago Covert[29] suggested an approach for pure acoustics problems which is similar in spirit though rather different in technique to the component mode approach for structures. A clear discussion of this approach is available in Ref. 18, p. 679.

Periodic structure theory may be broadly conceived as a form of component mode synthesis.[107]

Comparison of Theory and Experiment for Combined Acoustic-Structural (Acoustoelastic Modes)

A few significant experimental studies have been undertaken which consider the interesting question of acoustic-structural mode coupling (see Refs. 38, 39, 44, 45, 61, 62, and 64). The agreement with theory (using modal analysis) on changes in natural mode frequency with acoustic cavity size, structural characteristics, etc., is good. Also there is good agreement on internal sound levels due to simple external forces. Hence, there is a high level of confidence in the ability of the basic physical theory to model coupled structural and acoustic mass and stiffness. Also considerable insight has been obtained into when acoustic-structural coupling is important.

As is often the case for resonant systems, the principal uncertainties in noise transmission analysis revolve around damping. Some success was achieved in Refs. 44 and 45 by measuring the uncoupled damping coefficient in the structural modes and modifying these on a simple frequency basis due to acoustic-structural coupling. For highly absorbent walls, the wall impedance will have to be determined experimentally (using porous media theory[18,100] as a basic framework) and incorporated into any noise transmission theory on that basis.

Constrained layer damping[111-114] for the structure or radiation damping[101-103] to the external field may be treated theoretically when they are important. There is some experimental confirmation for the existing theoretical models. A sampling of representative results from model analysis is given in Sec. V and compared, where possible, to available experimental data.

Acoustoelastic Experiment Scale Models

These have been infrequently used although the underlying theory is known.[140-142] One may expect (hope?) for their greater use in the future.

Summary of Analytical Methods for Noise Transmission

Any acceptable model must provide for the mass, stiffness, and damping of the structural wall(s), the internal acoustic cavity(ies), and their possible interaction. Existing and/or proposed analytical methods do this in various ways. Finite element methods, which are increasingly dominant in all forms of structural modeling, are becoming prevalent in acoustic (fluid mechanic) modeling and even in structural-acoustic interaction modeling. Such methods, of course, directly model mass, stiffness, and damping of each element. However, for complicated physical systems, even with present day and projected computer technology, the requisite number of finite elements may saturate available computer storage. Hence, *component mode synthesis* has become an effective technique for overcoming this problem by first analyzing physical components of the overall system *separately* and then *combining* them to consider the total system behavior. This technique has the following advantages:

1) By judicious selection of components, the appropriate component modeling may already be known without further analysis or, at least, much easier to determine than that of the overall system.

2) In the synthesis when components are combined, only the essential aspects (modes) of each component need be retained. Hence, the representation of the component in the total system may be much simpler than its original representation when treated separately.

As the name implies, in component mode synthesis each component is most efficiently represented in terms of its own (natural) modes. In the present context, an obvious division is into structural (wall) and acoustic (cavity) components. Where multiple walls or cavities exist, a further subdivision into additional components may be desirable. Component mode synthesis has been developed largely in the context of structural modeling; however, its extension to internal cavity acoustics is straightforward.

Statistical energy analysis may be thought of as a primitive (or perhaps its advocates would say, sophisticated) version of component mode synthesis in which averages of component modes are considered. It is intended for applications where there is a large number of modes per unit frequency.

Perhaps Cockburn and Jolly[3] were the first to formulate a noise transmission analytical framework along the lines discussed here. They considered structural and acoustic modes of a stiffened cylindrical shell and an enclosed cavity. However, certain unnecessary (and, indeed for some applications, inaccurate) assumptions were made in their work. Most notably these were:

1) Restriction to cylindrical shell and acoustic cavity geometry.

2) Special end conditions on the cylindrical cavity (zero pressure) and boundary conditions on the structural wall (pinned) were assumed so that a single wall mode would be coupled only to a single radial family of cavity modes. The cavity end condition of zero pressure is unrealistic for some applications. It turns out that, at most, only a single cavity mode (the Helmholtz resonator mode) will be significant for modifying the resonant frequency of most structural wall modes. However, this is not included in the zero pressure cavity modes!

3) Damping (acoustic absorption) in the cavity modes is handled in an ad hoc manner as a correction to the basic undamped cavity mode transmission analysis. It would clearly be preferable to include the acoustic damping as an integral part of the cavity modes.

The division by Cockburn and Jolly[3] of the structural model into separate low, intermediate, and high-frequency ranges is clearly an effective and sensible approach. Qualitatively it anticipates the more systematic ideas of component mode synthesis. For example, in the low-frequency range they use one structural component, the entire structural shell. In the high-frequency range, they consider many individual (uncoupled) components, namely panels whose edges are essentially fixed at the bounding rings and stringers. In the intermediate range, the coupling of these individual panels (components) across stringers is considered. It is worth emphasizing that if the coupling of these individual panels (components) across both stringers *and* rings were considered, then (retaining only the lowest modes) one would have the overall structural modes of a complete stiffened cylindrical shell, cf. Refs. 108 and 109. Hence, the use of component mode synthesis is the natural extension of the low, intermediate, and high-frequency classification of Cockburn and Jolly. By using structural and/or acoustic subcomponents, one can remove the somewhat arbitrary distinction between airborne and structure borne (flanking) noise. In particular, multiply connected cavities and/or walls may be considered.

In the Appendix the essentials of a new proposed mathematical model for noise transmission developed by Dowell,[115] Vaicaitis,[116,117] Craggs,[118,119] Wolf,[120-123] Petyt,[126] and others are given. The model is based on a knowledge of the (uncoupled) in vacuum structural modes and rigid wall acoustic modes of the structural and acoustic components, respectively. Once these are known, the model allows for full coupling between the structural wall and acoustic cavity. It is a logical extension of and improvement upon the method of Cockburn and Jolly.

To summarize the relationships among the various methods of noise transmission analysis as the author sees them, consider the following. Conceptually, modal analysis is the most accurate and complete. The *practical* difficulty with this method has been determining the modes themselves. Finite element procedures combined with the ideas of component mode synthesis are advancing rapidly and the determination of the modes per se is becoming increasingly tractable. The *principal* practical advantage of SEA is that it assumes that the modes of the actual structure may be replaced by those of a related simple structure which are already known analytically. Clearly this premise may be used in conjunction with modal analysis too and a corresponding advantage obtained. To the extent that SEA develops criteria as to when this premise is accurate, it provides a basis for *simplifying* modal analysis without loss of accuracy. Periodic structure theory takes advantage, where appropriate, of repetitive patterns in a structure. If each unit cell of that structure is thought of as a component, the periodic structure theory may be conceived broadly as a form of component mode synthesis.

Hence it is the author's contention that modal analysis combined with component mode synthesis provides a general conceptual framework within which other methods logically fit.

IV. Noise Reduction Concepts

While an improved predictive capability using noise transmission analysis is to be desired for its own merits, it is important to exploit this capability to assess and further enhance effective noise reduction techniques. Among those reduction devices which can be studied with the predictive methods under development are:

1) Geometrical sizing of multiple interior cavities for optimum sound distribution (sound absorber concept).[18,115]

2) Acoustic liners or absorptive wall treatments[93]: a) perforated plate with honeycomb cells, b) resistive resonators, and c) bulk-reacting materials. Unlike jet engine duct applications, nonlinearity of liner impedance should not be an issue and, of course, the thermal and flow environments should be much less severe.

3) Selection of mass, stiffness, and damping of structural walls to reduce interior noise levels. This general category includes the interesting ideas of Sen Gupta[91,92] on tuned structures as well as the possibility of tuning or mistuning structural and acoustic resonances to achieve noise reduction.[171] See the annotated literature in the Bibliography.[91,92]

Key Questions

Among the questions which can be answered by improved noise transmission are the following:

1) In order to reduce aircraft interior (cavity) noise should one change a) structural wall (mass, stiffness, or damping), b) cavity wall (absorption)? or, c) structural wall geometry, e.g., multiwall construction?

2) If structural wall, which part and how, i.e., mass, stiffness, or damping?

3) If cavity wall, what absorption material should be used? In particular, what frequency characteristic or impedance of the material is desirable?

4) If geometry is to be changed, what shapes are most advantageous?

5) In analyzing (mathematically or experimentally) interior cavity sound levels, when must one account for effect of interior sound levels on structural wall motion?

6) Can one develop a simple estimate for interior noise levels, employing structural and acoustic natural modes, analogous to that of Miles[60] for structural response to random loads?

Answers to Key Questions

Based upon advances described in the literature,[94-142] the best available answers to these questions are as follows:

1) a) Yes, structural wall characteristics are important. b) Cavity absorption is not usually important for structural resonances below acoustic resonances. c) The importance of multiwall construction is still undetermined quantitatively, though it is known to be qualitatively important.

2) Stiffness and damping of structural walls are more important parameters than mass for response in the range of the lower structural resonant frequencies when the external pressure field leads to resonant structural response. For external pure tones at off-resonant structural wall conditions, mass may be more important.

3) Absorption on cavity walls is not very important for structural resonances below acoustic resonances; however, it may become significant if external excitation frequencies are near cavity acoustic resonances.

4) Preliminary work has begun on the effect of cavity geometry, but the answer is still undetermined.

5a) If the fundamental wall resonant frequency is well below the fundamental acoustic resonant frequency (in the direction perpendicular to the wall), the Helmholtz mode of the cavity will provide a spring stiffness which may raise substantially the panel wall mode frequency above its in vacuum value. b) If a structural wall mode and an acoustic cavity resonant frequency are in close proximity, then again, a fully coupled wall-cavity analysis may be required. But then only the two closely coupled modes need be examined. However, both panel structural and cavity acoustic absorption damping will be important if they are of comparable magnitude.

6) One may develop simple estimates for interior noise levels analogous to those of Miles[60] for structural response to random loads. However, various cases must be considered depending primarily upon whether a fundamental wall or cavity resonance is considered and which of the two is dominant (normally the lower of the two). Moreover, separate consideration must be given to the special, but occasionally important, case where a cavity acoustic resonant frequency and a wall structural resonance are in close proximity. If the exterior noise is itself dominated by pure tones at off-resonant frequencies, simple single mode estimates are less reliable. However, the basic theoretical model will be more accurate as modal damping, whose value is often uncertain, will be less important.

Future Tasks

Based upon the above, the work most needed is:

1) Application of new analytical developments to the understanding and improvement of an existing aircraft (e.g., the Aerocommander).

2) Application of new analytical developments to the understanding and improvement of a new aircraft (e.g., the fuel efficient propfan).

3) Improved fundamental understanding of absorption materials and their analytical modeling to obtain better estimates of interior acoustic damping.

4) Systematic study of double wall geometries and their behavior.

5) Systematic validation of analytical models by experiment. This work is further described in Sec. V.

V. Validation of Theoretical Predictive Capability by Experimental Data—The Master Plan

It is essential to compare the results of the analytical model with an appropriate set of experimental data. There are three basic components in any prediction method, i.e., noise source, structural wall, and internal acoustic cavity. The key idea is to keep the other two simple when performing experimental studies to evaluate the third. For example, the following sequence of experiments might be used. Where a cited reference is given, substantial work has been completed. Needed additional work is indicated.

Evaluation of Various Noise Sources

Actual propeller, jet exhaust, transmission gear box and/or boundary-layer noise sources exciting a simple rectangular acoustic cavity with a flat, isotropic plate structural wall. No work of this type has been done apparently.

Evaluation of Structural Wall Modeling

Simple loudspeaker source, simple rectangular acoustic cavity, with various structural wall models.

1) Flat, isotropic plate[115] (work completed).

A representative experimental arrangement is shown in Fig. 3. A simple rectangular box with one flexible wall is the acoustoelastic model. A loudspeaker is the noise source and microphones are inserted into the cavity to measure interior noise levels. For a sinusoidal loudspeaker excitation the cavity

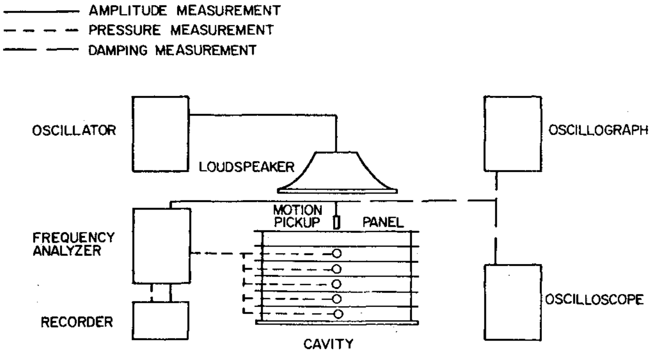


Fig. 3 Experimental arrangement for interior noise studies.

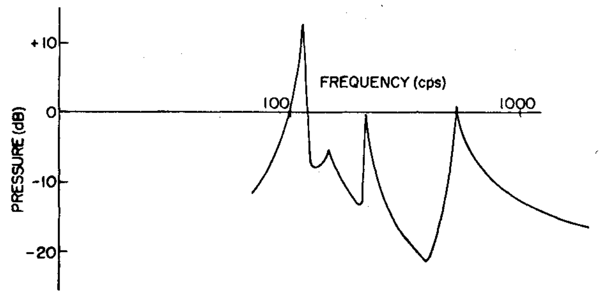


Fig. 4 Interior (sound) pressure (level) as a function of frequency.

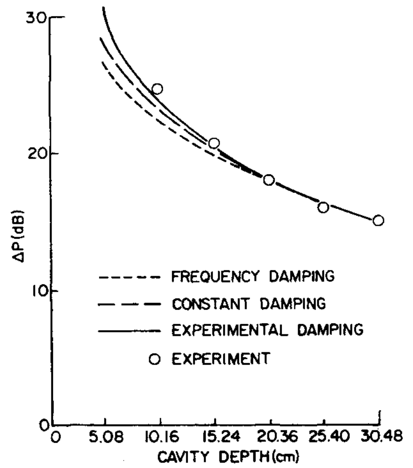


Fig. 5 Interior (cavity) pressure as a function of cavity depth.

response might appear as in Fig. 4. The ratio of internal to external noise level is shown in dB vs excitation frequency. The peaks occur at structural wall or acoustic cavity resonant frequencies. In this example the structural wall fundamental resonant frequency, 113 Hz, falls below that of the cavity, 518 Hz, and excitation at its resonant frequency leads to the highest interior noise levels. In Fig. 5 the noise level at the fundamental structural resonant frequency is shown as a function of acoustic cavity depth from both modal theory and experiment. As may be seen, the noise level increases with decreasing cavity depth and the agreement between theory and experiment is good.

Another interesting feature of Fig. 4 is that at the fundamental cavity resonant frequency the panel is essentially motionless and the interior and exterior sound levels are the same. At its own resonance the cavity acts as a vibration absorber for the panel. This is also predicted by theory. Adding absorption material to the cavity will lower the interior sound levels under these conditions. A special, but important, case is when an acoustic and a structural resonant frequency coincide. This has been studied theoretically,[115] but

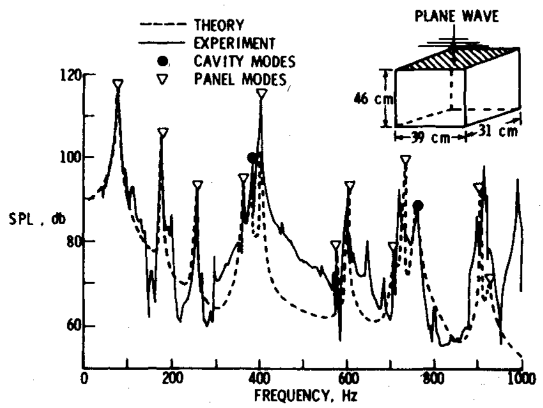


Fig. 6 Interior (sound) pressure (level) as a function of frequency.

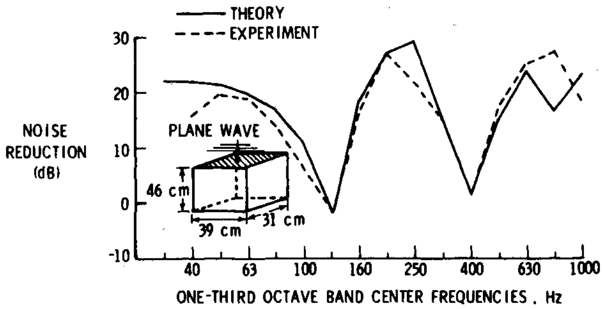


Fig. 7 Noise reduction as a function of frequency.

a definitive experiment result is lacking. Good agreement between theory and experiment has also been obtained for random excitation.[45]

2) Flat, stiffened plate (work completed *except* for measurement of structural damping).[128,142,149,150]

Similar experiments and calculations have been made for unstiffened and stiffened plates.[149,150] Figures 6 and 7 are representative of these results for unstiffened plates. Again the agreement between theory and experiment is good. However, the structural damping used in the noise transmission had to be estimated since it was not measured. Similar results have been obtained for stiffened plates.[128]

3) Curved, isotropic plate[150] (measurement of wall resonant frequencies and damping required).

4) Curved, stiffened plate (future work needed).

5) Isotropic, circular cylinder[126] (work under way†).

6) Stiffened, circular cylinder[109] (future work needed).

There is an extensive literature on plate and shell resonant frequency measurements and calculations. This is admirably summarized by Leissa.[75,76] Also see Sen Gupta.[70] Among the more impressive achievements is the work of Hu et al.[109] Figure 8 is drawn from their work and displays how the resonant frequencies of a ring-stiffened cylindrical shell vary with circumferential mode number. These authors discuss how the pattern shown may be qualitatively anticipated from a knowledge of the 1) ring-alone resonant frequencies, 2) the shell-alone resonant frequencies, and 3) the frequencies calculated by assuming the rings are rigid. It seems plausible that a similar result can be obtained for stringer stiffened shells. Work has recently begun by Petyt, Lim[126] and Mayes† on measuring interior sound levels for cylindrical shells and cavities, but no definitive comparisons have yet been made between theory and experiment for interior noise levels.

7) Full-scale vehicle wall, with internal cavity stripped[148,150] (work under way).

†W. H. Mayes, NASA Langley Research Center, private communication.

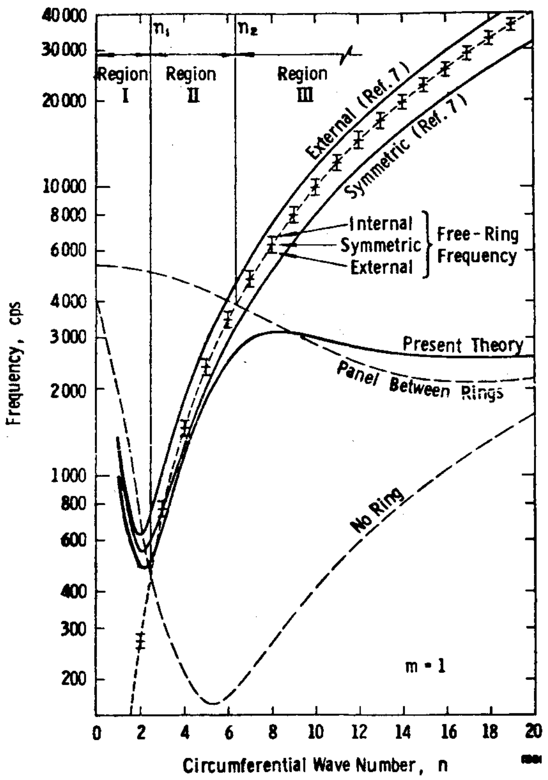


Fig. 8 Construction of natural frequency curve as a function of circumferential wave number for a ring-stiffened shell.

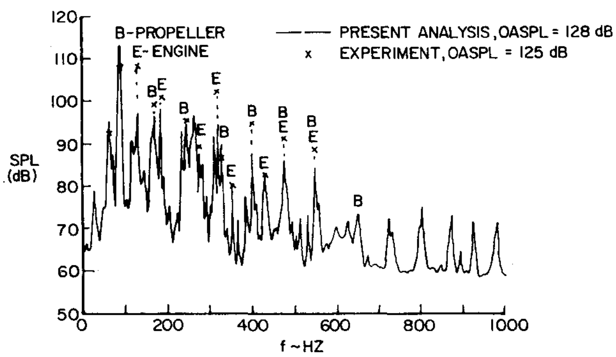


Fig. 9 Interior (sound) pressure (level) as a function of frequency—engine at 2600 rpm.

Vaicaitis and McDonald have pioneered in using modal methods to predict interior sound levels of full scale vehicles. In Fig. 9 a representative comparison between theory and experiment is shown for an Aerocommander aircraft. In view of the uncertainty in some of the vehicle parameters and the modeling of the actual cavity geometry by a rectangular parallelepiped, the agreement is most encouraging. This work can usefully be extended in several ways and efforts are being directed toward that end.

Evaluation of Internal Acoustic Cavity Model

Simple loudspeaker source with flat, isotropic plate structural wall and various internal acoustic cavity geometries and wall treatments.

1) Hard wall vs absorptive material[142] (additional work needed).

2) Multiple cavity and geometrical effects[95-97,115,120,122,123,128,144] (work completed). Prediction of acoustic natural frequencies for arbitrary cavity geometries is well in hand and several convincing correlations between theory and experiment are available. Figure 10 shows a two cavity

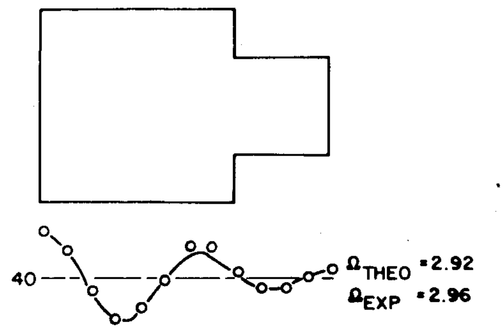
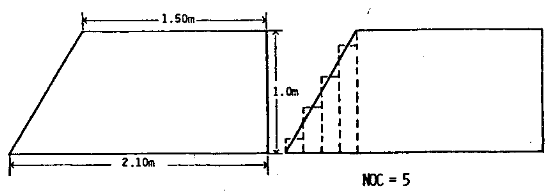


Fig. 10 Natural acoustic mode frequency and pressure distribution—comparison of theory and experiment.

IRREGULARLY SHAPED CAVITY: TRAPEZOIDAL CAVITY (FROM REF. 128)



NUMERICAL RESULTS OF PRESENT ANALYSIS (NOC=5, NXA=5)

FREQ. / MODE	NYA=2 MYMR=2	NYA=3 MYMR=3	NYA=4 MYMR=4	NYA=5 MYMR=5
1st MODE	93.64 Hz	93.52 Hz	93.50 Hz	93.49 Hz
2nd MODE	164.02 Hz	163.00 Hz	162.94 Hz	162.94 Hz
3rd MODE	180.93 Hz	180.85 Hz	180.85 Hz	180.83 Hz

RESULTS OF OTHER DIFFERENT METHODS

FREQ. / MODE	F.E.M.	F.D.M. 1 (FINE)	F.D.M. 2 (COARSE)	EXP.
1st MODE	92.5 Hz	92.7 Hz	93.3 Hz	93.0 Hz
2nd MODE	162.5 Hz	162.8 Hz	163.7 Hz	164.0 Hz
3rd MODE	179.1 Hz	176.8 Hz	176.7 Hz	182.0 Hz

NUMERICAL RESULTS OF PRESENT ANALYSIS (NOC=5, NXA=5)

FREQ. / MODE	NYA=2 MYMR=2	NYA=3 MYMR=3	NYA=4 MYMR=4	NYA=5 MYMR=5
1st MODE	93.64 Hz	93.52 Hz	93.50 Hz	93.49 Hz
2nd MODE	164.02 Hz	163.00 Hz	162.94 Hz	162.94 Hz
3rd MODE	180.93 Hz	180.85 Hz	180.85 Hz	180.83 Hz

RESULTS OF OTHER DIFFERENT METHODS

FREQ. / MODE	F.E.M.	F.D.M. 1 (FINE)	F.D.M. 2 (COARSE)	EXP.
1st MODE	92.5 Hz	92.7 Hz	93.3 Hz	93.0 Hz
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3rd MODE	179.1 Hz	176.8 Hz	176.7 Hz	182.0 Hz

Fig. 11 Natural acoustic mode frequencies for an irregularly shaped cavity—comparison of various theoretical methods and experiment.

geometry with values of calculated and measured resonant mode frequencies and the modal pressure distribution along the centerline of the two cavities. A number of modes were studied of which the one shown is representative.[115] A well-studied geometry is shown in Fig. 11. Shuku[96,97] has used both finite element and finite difference techniques. Chao[128] has used component mode synthesis after Ref. 115. Figure 12 shows the result of a finite element calculation for an automobile acoustic cavity. Wolf[123] and Chao[128] have carried

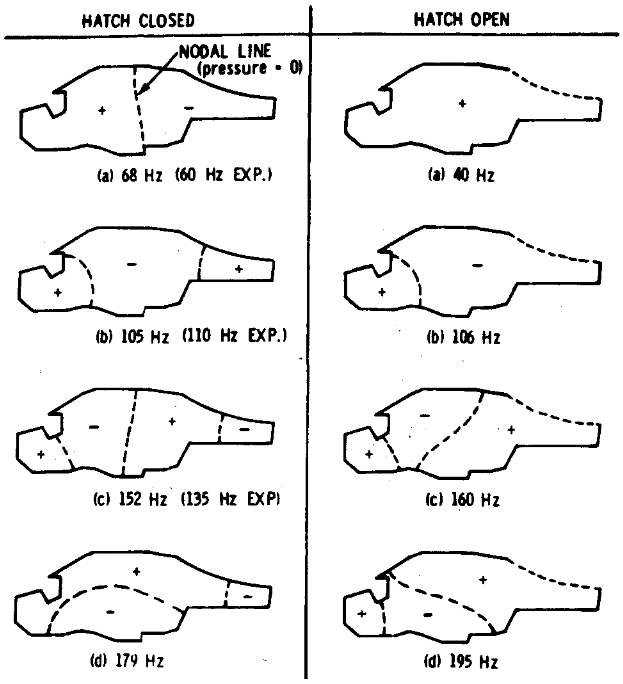

Fig. 12 Acoustic natural modes and frequencies of passenger compartment enclosure (experimental frequencies are shown in parentheses).

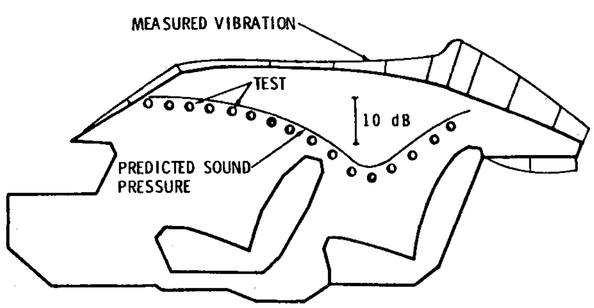

Fig. 13 Measured noise vs computer simulation results for 40 Hz structural excitation.

out three-dimensional as well as two-dimensional acoustic cavity calculations.

The General Motors group[120] has also measured and predicted interior sound levels for automobiles from a known wall motion. A representative and impressive result is shown in Fig. 13.

3) Effect of double wall construction[119,121,171] (additional work needed on double walls). Craggs[119] has studied theoretically and experimentally two acoustic cavities with a common flexible wall and demonstrated the basic soundness of the modal approach. Also see Wolf.[121] More effort is required for parameters representative of transportation vehicle applications including the effects of absorptive materials. In this respect some exploratory theoretical work is reported in Ref. 171.

Reassessment of the State-of-the-Art

Obviously there is work yet to be done. Concerning each of the above, one of the following statements can and should be made at any stage of completion of the Master Plan.

1) Basic physical mechanism not understood (e.g., gear box noise source).

2) Theory incomplete, but simple experiment is adequate for understanding [e.g., characterization of acoustic wall damping (absorptive impedance)].

3) Qualitatively accurate, theoretical models available (e.g., parameter trends predictable).

4) Quantitatively accurate, theoretical models available.

Summary of Experimental-Theoretical Correlations

The basic physical model of a simple loudspeaker noise source; a flat, rectangular, isotropic, structural wall; and a rectangular, untreated acoustic cavity has already been evaluated with good agreement having been obtained between theory and experiment.[115,149,150] Moreover, a substantial computational capability already exists for determining structural[1,107-109] and acoustic[94-97,115,120-123,128,144] natural modes. Interesting work has been done on flat rectangular, stiffened structural wall, but due to a lack of information on structural damping the comparison of theory and experiment is not entirely conclusive.[128,142,149,150] Some preliminary work on curved, isotropic plates is available, but more definitive measurements are required.[150] Very interesting comparisons have been made for an actual vehicle wall and this work is continuing.[148,150] The effects of absorptive material inside the cavity are receiving attention experimentally and theoretically.[98-100] Although geometrical cavity effects have been intensively studied as described above, double wall experiments are not yet available.

VI. Concluding Remarks

1) A general theory of noise transmission analysis is now available which includes the (modal) mass (inertia), stiffness (compliance), and damping (absorption) of structural walls and acoustic cavities.

2) Efficient and accurate numerical procedures have been developed for computing acoustic natural modes and interior noise levels due to prescribed wall motion for acoustic cavities of arbitrary geometry. The results have been verified by comparison with experiment.

3) Good agreement between theory and experiment for the total acoustoelastic problem has been obtained for *simple* geometries. That is, from prescribed exterior sound levels, structural wall motion and interior sound levels have been calculated which are in good agreement with experiment.

4) Current efforts are being directed toward the acoustoelastic problem for more *complicated* geometries including the effects of *double walls.*

5) The most fundamental problem in noise transmission and analysis which remains appears to be the uncertainty with respect to structural and/or acoustic damping.

6) Overall, there is good reason for optimism with respect to improved methods for noise transmission analysis and their use in identifying effective combinations of noise reduction techniques.

Appendix—Modal Noise Transmission Mathematical Model

Here the essentials of the mathematical noise transmission model will be summarized including the input and output data. No mathematical derivations are included, however. The basic analysis is contained, for example, in Ref. 115. A modal representation of the structural wall(s) and acoustic cavity(ies) is used.

For the structural wall

$$w(x,y,t) = \Sigma_m q_m(t)\psi_m(x,y) \tag{A1}$$

where w is the physical wall deflection, q_m the modal coordinate, and ψ_m the natural mode shape (in vacuum). Associated with the ψ_m are natural mode frequencies ω_m, damping coefficients ζ_m, and generalized masses M_m, where

$$M_m \equiv \iint m(x,y)\psi_m^2 \mathrm{d}x\mathrm{d}y \tag{A2}$$

and m is the structural mass per unit area.

For the acoustic cavity

$$p(x,y,z,t) = \rho c^2 \Sigma (P_n(t)/M_n^A)\, F_n(x,y,z) \tag{A3}$$

where p is the physical acoustic pressure, ρ the air density, c the air speed of sound, P_n the acoustic model coordinate, and F_n the acoustic natural mode (for rigid walls).

Associated with the F_n are acoustic natural frequencies ω_n^A, and generalized masses

$$M_n^A \equiv \iiint (F_n^2/V)\,\mathrm{d}x\mathrm{d}y\mathrm{d}z \tag{A4}$$

where $V \equiv$ total cavity volume, $A_A \equiv$ area of absorption material, and $Z_A \equiv$ impedance of absorption material.

The external pressure field, p_E, is represented in terms of its generalized forces

$$Q_m^E \equiv -\iint p_E(x,y,t)\,\psi_m(x,y)\,\mathrm{d}x\mathrm{d}y \tag{A5}$$

where $A_{EW} \equiv$ (external) structural wall area. The minus sign arises from the sign convention that w is positive outward and p_E is positive inward with respect to the cavity. See Fig. A1.

The input data are: p_E for the external sound field; m, ψ_m, ω_m, ζ_m for the structural wall; M_m is determined from Eq. (A2); Q_m is determined from Eq. (A5); ρ, c, F_n, ω_n^A, V, A_A, Z_A for the cavity(ies); and M_n^A is determined from Eq. (A4). q_m, P_n are then determined from the modal equations of motion

$$M_m[\ddot q_m + 2\zeta_m \omega_m q_m + \omega_m^2 q_m] - \rho c^2 A_{EW} \frac{\Sigma P_n L_{mn}}{M_n^A} = Q_m^E \tag{A6}$$

$$\ddot P_n + \frac{A_A}{V}\rho c^2 \Sigma_r \dot P_r \frac{C_{nr}}{M_r^A} + \omega_n^{A^2} P_n = -\frac{A_{EW}}{V}\Sigma_m \ddot q_m L_{mn} \tag{A7}$$

where ζ_m is the structural modal damping coefficient and

$$L_{mm} \equiv \iint \frac{F_n \psi_m \mathrm{d}x\mathrm{d}y}{A_{EW}} \text{ over } A_{EW}$$

$$C_{nr} \equiv \iint \frac{F_n F_r \mathrm{d}A}{Z_A A_A} \text{ over } A_A$$

There are two coupled systems of spring-mass oscillators with structural and acoustic damping. Hence, they are familiar and computationally efficient descriptions of the dynamics of an acoustic-structural system.

Moreover, multiple walls or cavities may be readily included in a similar fashion. In particular, if one has two connected cavities (see Fig. A2), the common wall between the two cavities may be treated as a (common) structural wall and in an obvious notation (where we have cavities a and b) Eqs. (A6) and (A7) are replaced by

$$M_m[\ddot q_m + 2\zeta_m \omega_m \dot q_m + \omega_m^2 q_m] - \rho c^2 A_{CW} \Sigma \frac{P_n^a L_{mn}^a}{M_n^{Aa}}$$

$$+ \rho c^2 A_{CW} \Sigma \frac{P_n^b L_{mn}^b}{M_n^{Ab}} = 0 \tag{A8}$$

$$\ddot P_n^a + \omega_n^{Aa^2} P_n^a = -\frac{A_{CW}}{V_a}\Sigma_m \ddot q_m L_{mn}^a \tag{A9}$$

$$\ddot P_n^b + \omega_n^{Ab^2} P_n^b = \frac{A_{CW}}{V_b}\Sigma_m \ddot q_m L_{mn}^b \tag{A10}$$

where

$$L_{mn}^a \equiv \iint \frac{F_n^a \psi_m}{A_{CW}} \mathrm{d}x\mathrm{d}y, \text{ etc.}$$

Acoustic damping is omitted for the sake of brevity in Eqs. (A9) and (A10). The subscript CW denotes common wall. For simplicity we have considered the external walls rigid. However, clearly Eqs. (A6)-(A10) can be combined to allow for both external and (internal) common wall motion with multiple cavities. See Fig. A3.

Finally, once q_m and P_n are determined, the physical deflection w and sound pressure p are known from Eqs.(A1) and (A3). The flexibility in the model is associated with treating ω_m, ψ_m, and ω_n^A, F_n as inputs. For simple shapes, these are already known analytically. In some cases it will be possible to approximate the structural wall and cavity by a simple shape or several component simple shapes. In other cases it will be necessary to determine the natural modes by numerical methods (finite element analysis and/or component mode synthesis) or experiment (scale models). *For the higher frequency modes, one may invoke one of the premises of statistical energy analysis and approximate these modes for an arbitrary geometry by those from a simpler geometry, e.g., rectangular or cylindrical.*

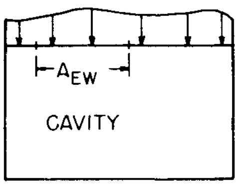

Fig. A1 Acoustic cavity—structural wall geometry.

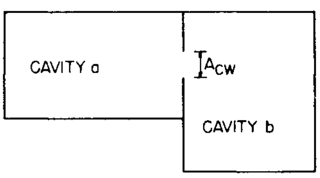

Fig. A2 Acoustic cavity—structural wall geometry.

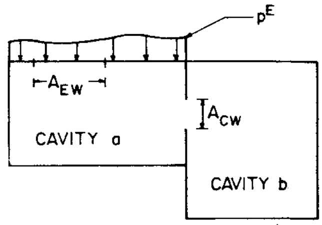

Fig. A3 Acoustic cavity—structural wall geometry.

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Topical Bibliography—Recent Literature

Review Papers and Proceedings

[69]Rennison, D.C. and Wilby, J.F., "A Review of Analytical Models for Sound Transmission Through Fuselage Side Walls with Application to General Aviation Aircraft," Bolt, Beranek, and Newman Rept. No. 3851, 1978. Emphasis is on locally-reacting models and statistical energy analysis.

[70]Gupta, G. Sen, "Current Developments in Interior Noise and Sonic Fatigue Research," *The Shock and Vibration Digest,* Vol. 7, 1975, pp. 3-20. A nice discussion of structural modeling considerations and noise reduction by tuning of structural components.

[71]Murphy, G., "Scaling and Modeling for Experiment," *The Shock and Vibration Digest,* Vol. 10, No. 1, 1978, pp. 5-13. A broad discussion of fluid-structural modeling including acoustic and structural models.

[72]Broner, N., "The Effects of Low Frequency Noise on People—A Review," *Journal of Sound and Vibration,* Vol. 58, 1978, pp. 483-500.

[73]Bettiess, P., *Special Issue on Fluid Structure Interaction. International Journal of Numerical Methods in Engineering,* Vol. 13, 1978, pp. 1-201. A broad-ranging collection of thirteen articles. The two by Petyt and Lim, and Taborrok are particularly noteworthy and are listed separately elsewhere in this bibliography.

[74]*Helicopter Acoustics,* NASA Conference Pub. 2052, Parts I and II, 1978. An authoritative compendium on the subject. The papers by Sternfeld and Doyle, Hubbard, Maglieri and Stephens, Schmitz, Schlegel and all those in the session on interior noise will be of interest.

[75]Leissa, A.W., "Vibration of Plates," NASA SP-160, 1969.

[76]Leissa, A.W., "Vibration of Shells," NASA SP-288, 1973.

The above two references are authoritative and readable summaries of the literature on vibration of plates and shells.

[77]Lyon, R.H., *Statistical Energy Analysis of Dynamical Systems,* MIT Press, Cambridge, Mass., 1975. Perhaps the best place to begin a study of this method.

[78]Lyon, R.H., "Recent Developments in Statistical Energy Analysis," *The Shock and Vibration Digest,* Vol. 10, No. 2, 1978, pp. 3-7. The latest word from one of the founders of SEA.

Noise Sources

Most of the literature on jet noise and boundary-layer noise sources predates 1974. There is a revival of interest in an older aeronautical noise source, however, the propeller.

[79]Piersol, A.G., Wilby, E.G., and Wilby, J.F., "Evaluation of Aero Commander Propeller Acoustic Data," Bolt, Beranek, and Newman Rept. No. 3706, 1978. The authors are rather pessimistic about a simple representation of the propeller noise field, see p. 49.

[80]Woan, C.J., and Gregorek, G.M., "The Exact Numerical Calculation of Propeller Noise," AIAA Paper 78-1122, 1978.

[81]Korkan, K.D., Woan, C.J., and Gregorek, G.M., "Effect of Airfoil Sections on Acoustic Performance of Propellers," NASA Conference on Advanced Technology Airfoil Research, Langley Research Center, 1978.

[82]Korkan, K.D., Woan, C.J., and Gregorek, G.M., "An Aeroacoustic Investigation of Scaled Propellers," 50th Semi-annual Meeting of the Supersonic Wind Tunnel Assoc., Urbana, Ill., 1978.

[83]Korkan, K.D., Woan, C.J., and Gregorek, G.M., "Aeroacoustic Considerations for General Aviation Propellers," 5th Annual General Aviation Technologyfest, Wichita, Kansas, 1978.

The final four references describe very recent work and work-in-progress. The authors may be contacted at the Dept. of Aeronautical and Astronautical Engineering, Ohio State University, Columbus, Ohio.

[84]Lowson, M.V., "Rotorcraft and Propeller Noise," AGARD Lecture Series No. 77, 1975. A good overview.

[85]Tyler, J.M., "Jet Engine Noise and Its Control," AGARD Lecture Series No. 77, 1975. A good entrée to the literature on this noise source.

Noise Effects on People and Payloads

[86]Clevenson, S.A., Dempsey, T.K., and Letherwood, J.D., "Effect of Vibration Duration on Human Discomfort," 95th Meeting, Acoustical Society of America, 1978.

[87]Clevenson, S.A., "Subjective Response to Combined Noise and Vibration During Flight of a Large Twin-Jet Airplane," NASA TM X-3406, 1976.

[88]Letherwood, J.D., Dempsey, T.K., and Clevenson, S.A., "Ride Quality Criteria for Multifactor Environments," Ann. Mtg. Trans. Res. Board, 1978.

[89]Dempsey, T.K., Letherwood, J.D., and Clevenson, S.A., "Noise and Vibration Ride Comfort Criteria," NASA TM X-73975, 1976.

[90]Broner, N., "The Effects of Low Frequency Noise on People—A Review," *Journal of Sound and Vibration,* Vol. 58, 1978, pp. 483-500.

The above collection forms a readable introduction to this important aspect of the overall problem.

Noise Reduction Concepts

Most such concepts are very old and it is the province of new analytical techniques, both theoretical and experimental, to help assess what combination of mass (inertia), stiffness (compliance), and damping (absorption) will provide the needed noise reduction for minimum weight added. A new concept, at least in part, is that of tuning of structural components to reduce structural response and, hence, interior noise. The following two references provide an introduction to this idea. Also see Ref. 70 under Review Papers.

[91]Gupta, G. Sen, "Reduction of Cabin Noise and Vibration by Intrinsic Structural Tuning," *AIAA Journal,* Vol. 16, June 1978, pp. 545-546.

[92]Gupta, G. Sen, "Low Frequency Cabin Noise Reduction Based on the Intrinsic Structural Tuning Concept," NASA CR-145262, 1978.

In addition to tuning (or mistuning) structural component natural frequencies to maximize noise reduction, one can also think of doing so for structural and acoustic natural frequencies. Particularly for double wall construction, there are several options available. See, e.g., Ref. 171. Many of the references under Applications are concerned with noise reduction concepts, of course.

A related reference written in a somewhat different context is:

[93] Lowson, M.V., "Duct Acoustics and Mufflers," AGARD Lecture Series No. 77, 1975.

Generic Noise Transmission Analysis—Experimental and Theoretical Acoustic

[94] Petyt, M., Lea, J., and Koopman, G.H., "A Finite Element Method for Determining the Acoustic Modes of Irregular Shaped Cavities," *Journal of Sound and Vibration*, Vol. 45, 1976, pp. 495-502.

[95] Petyt, M., Koopman, G.H., and Pinnington, R.J., "The Acoustic Modes of a Rectangular Cavity Containing a Rigid, Incomplete Partition," *Journal of Sound and Vibration*, Vol. 53, 1977, pp. 71-82.

[96] Shuku, T., "Finite Difference Analysis of the Acoustic Field in Irregular Rooms," *Journal of the Acoustical Society of Japan*, Vol. 28, 1972, pp. 5-12.

[97] Shuku, T. and Isihara, K., "The Analysis of the Acoustic Field in Irregularly Shaped Rooms by the Finite Element Method," *Journal of Sound and Vibration*, Vol. 29, 1973, pp. 67-76.

The above four references are representative of the state-of-the-art for computing acoustic resonant modes for cavities of arbitrary shape. Craggs,[118,119] the General Motors group,[120-123] and the Princeton group[115-128] have developed broadly similar capabilities in the context of *Acoustoelastic* analysis.

The next three references deal with how one may include the effects of absorption materials on the cavity walls.

[98] Kagawa, Y., Yamabuchi, T., and Mori, A., "Finite Element Simulation of an Axisymmetric Acoustic Transmission System with a Sound Absorbing Wall," *Journal of Sound and Vibration*, Vol. 53, 1977, pp. 357-374. State-of-the-art for using finite element methods for acoustical cavities including the effects of absorbing walls.

[99] Dowell, E.H., "Reverberation Time, Absorption and Impedance," *Journal of the Acoustical Society of America*, Vol. 64, 1978, pp. 181-191. A demonstration of how modal methods and modern computing power can be used to solve an old problem.

[100] Bliss, D.B., "A Study of Bulk Reacting Porous Sound Absorbers and a New Boundary Condition for Thin Porous Layers," submitted to *Journal of the Acoustical Society of America*, 1979. A basic study on an improved theoretical modeling of absorption materials which can be used with any state-of-the-art numerical algorithm.

There is an interesting literature which studies how external acoustic radiation damping is provided to the structural wall. However, to date, it has been largely unused in the context of interior noise. The following three articles are representative. Also, see the work of Koval[129-135] in the next section who discusses this topic inter alia under "flight effects."

[101] Mixson, J.S. and Koval, L.R., "On the Interaction of a Vibrating Plate with an Acoustic Medium," 87th Meeting of the Acoustical Society of America, 1974.

[102] Yen, D., Maestrello, L., and Padula, S., "An Integro-Differential Equation Model for the Study of the Response of an Acoustically Coupled Panel," AIAA Paper 75-508, 1975.

[103] Dowell, E.H., "Aerodynamic Boundary Layer Effects on Flutter and Damping of Plates," *Journal of Aircraft*, Vol. 10, Dec. 1973, pp. 734-738.

Structural

[104] Roskam, J., vanDam, C., and Grosveld, F., "Some Noise Transmission Loss Characteristics of Typical General Aviation Structural Materials," AIAA Paper 78-1480, AIAA Aircraft Systems and Technology Conference, 1978. An experimental study which demonstrates the importance of structural mass, damping, and stiffness due to elastic bending and also pressurization.

[105] Getline, G.L., "Low Frequency Noise Reduction of Lightweight Airframe Structures," NASA CR-145104, 1976. An experimental-theoretical study of a family of airframe structures.

[106] Jacobs, L.D., Lagerquist, D.R., and Gloyna, F.L., "Response of Complex Structures to Turbulent Boundary Layers," *Journal of Aircraft*, Vol. 7, 1970, pp. 210-219. Still a convincing demonstration of what can be done using classical methods of structural modal analysis in conjunction with the finite element method. Also, shows the effect of pressurization.

[107] Gupta, G. Sen, "Natural Frequencies of Periodic Skin-Stringer Structures Using a Wave Approach," *Journal of Sound and Vibration*, Vol. 16, 1971, pp. 567-580. Representative of the work of Lin, Mead and others on how one can reduce the analysis of a period structure to that of a single component. As such it is related broadly to the component mode synthesis approach.

[108] Resnick, B.S. and Dugundji, J., "Effects of Orthotropicity, Boundary Conditions, and Eccentricity on the Vibrations of Cylindrical Shells," AFOSR Report 66-2821, 1966.

[109] Hu, W.C.L., Gormley, J.F., and Lindholm, U.S., "An Analytical and Experimental Study of Vibrations of Ring-Stiffened Cylindrical Shells," Southwest Research Institute of Technology Report No. 9, 1967.

These last two references are representative of a rich literature on shell dynamics which may find new value for interior noise studies. See also the review papers by Leissa[75,76] for an authoritative summary of this literature.

[110] Dowell, E.H. and Vaicaitis, R., "A Primer for Structural Response to Random Pressure Fluctuations," Princeton University AME Report 1220, 1975. As the title says.

The entire literature on structural damping is, of course, relevant to the subject of interior noise. Often one must accept whatever damping is available in the structure; however, in recent years the concept of constrained layer damping has been developed extensively. As an introduction to this literature the reader may wish to examine the following four references and the literature cited therein.

[111] Ross, D., Ungar, E.E., and Kerwin, E.M., Jr., "Damping of Plate Flexural Vibrations by Means of Viscoelastic Laminae," ASME Colloquium on Structural Damping, 1959, pp. 50-87.

[112] Mead, D.J. and Markus, S., "The Forced Vibration of a Three-Layer, Damped Sandwich Beam with Arbitrary Boundary Conditions," *Journal of Sound and Vibration*, Vol. 10, 1969, pp. 163-175.

[113] Yan, M.-J. and Dowell, E.H., "High Damping Measurements and a Preliminary Evaluation of an Equation for Constrained Layer Damping," *AIAA Journal*, Vol. 11, March 1973, pp. 388-390.

[114] Jones, D.I.G., "Constrained Layer Treatments for Noise Control in a Helicopter," U.S. Air Force Material Laboratory TR-73-305, 1974. The literature on this topic is expanding rapidly and the interested reader must necessarily track the recent journal literature.

Acoustoelastic

Modal Analysis

[115] Dowell, E.H., Gorman, G.F., and Smith, D.A., "Acoustoelasticity: General Theory, Acoustic Natural Modes and Forced Response to Sinusoidal Excitation, Including Comparisons with Experiment," *Journal of Sound and Vibration*, Vol. 52, 1977, pp. 519-542. An introduction and outline of the basic modal approach including analytical and numerical results and comparison with measurements for simple structures and acoustic cavity geometries.

[116] McDonald, W., Vaicaitis, R., and Myers, M.K., "Noise Transmission Through Plates into an Enclosure," NASA TP 1173, 1978.

[117] Vaicaitis, R., "Noise Transmission by Viscoelastic Sandwich Panels," NASA TN D-8516, 1977.

These last two reports are extensions and improvements of Ref. 115.

[118] Craggs, A., "An Acoustic Finite Element Approach for Studying Boundary Flexibility and Sound Transmission Between Irregular Enclosures," *Journal of Sound and Vibration*, Vol. 30, 1973, pp. 343-357.

[119] Craggs, A., "Sound Transmission Between Enclosures—A Study Using Plate and Acoustic Finite Elements," *Acustica*, Vol. 35, 1976, pp. 89-98. An independent development of the basic modal approach using finite elements.

[120] Wolf, J.A., Jr., and Nefske, D.J., "Vibration Analysis of Structural-Acoustic Systems Using Finite Elements," General Motors Research Lab. GMR-2281R, 1976.

[121] Wolf, J.A., Jr., "Modal Synthesis for Combined Structural-Acoustic Systems," General Motors Res. Lab. GMR-2205R, 1976. Also, *AIAA Journal*, Vol. 15, 1977, pp. 743-745.

[122] Wolf, J.A., Jr., and Nefske, D.J., "NASTRAN Modeling and Analysis of Rigid and Flexible Walled Acoustic Cavities," General Motors Research Lab. GMR 1921R, 1977.

[123] Wolf, J.A., Jr., "Three-Dimensional Acoustic Natural Modes and Frequencies," General Motors Research Lab., Research Memo 15-86, 1976.

[124] Wolf, J.A., Jr., Nefske, D.A., and Howell, L.J., "Structural-Acoustic Finite Element Analysis of the Automobile Passenger Compartment," General Motors Research Lab. GMR-2029R, 1975.

In addition to being in the forefront of applications, GM Research Laboratories have made substantial contributions to the generic state-of-the-art as the above five reports demonstrate. Comparisons with experiments for acoustic and acoustoelastic experiments are included.

[125]Koopman, G.H. and Pollard, H.F., "A Joint Acceptance Function for Structural-Acoustic Coupling Problems," *Journal of Sound and Vibration,* Vol. 46, 1976, pp. 302-305. A measure for assessing the extent of coupling between acoustic modes of a cavity and the structural modes of its walls is suggested.

[126]Petyt, M. and Lim, S.P., "Finite Element Analysis of the Noise Inside a Mechanically Excited Cylinder," *International Journal of Numerical Methods in Engineering,* Vol. 13, 1978, pp. 109-122. A finite element-modal analysis of the cylindrical shell-cavity geometry including comparisons with experiments.

[127]Tabarrok, B., "Dual Formulations for Acousto-structural Vibrations," *International Journal of Numerical Methods in Engineering,* Vol. 13, 1978, pp. 197-201. A contribution to the basic variational theory underlying modal methods.

[128]Dowell, E.H. and Chao, C.-F., "Sound Transmission Analysis for Determining Interior Sound Levels," Quarterly Progress Reports, 1978. A continuing series reporting on modal methods research.

Classical Noise Transmission Analysis

There is a substantial literature in acoustics on structural models of infinite extent (locally reacting) being excited by plane waves. In the context of interior noise the work of Koval is among the most recent and complete.

[129]Koval, L.R., "Effect of Airflow, Panel Curvature, and Internal Pressurization on Field-Incidence Transmission Loss," *Journal of the Acoustical Society of America,* Vol. 59, 1976, pp. 1379-1385. The classical analysis for an infinite, flat panel is extended to include the effects mentioned in the paper title.

[130]Koval, L.R., "On Sound Transmission into a Thin Cylindrical Shell Under 'Flight Conditions,'" *Journal of Sound and Vibration,* Vol. 48, 1976, pp. 265-275. As in the previous paper, but with a cylindrical shell structural model.

[131]Koval, L.R., "Effect of Stiffening on Sound Transmission in a Cylindrical Shell in Flight," *AIAA Journal,* Vol. 15, 1977, pp. 899-900. The effects of stiffening by rings and stringers is approximated by a "smeared," orthotropic shell model.

[132]Koval, L.R., "Effect of Longitudinal Stringers on Sound Transmission into a Thin Cylindrical Shell," *Journal of Aircraft,* Vol. 15, 1978, pp. 816-821. As in the above paper, but now stringers are modeled as discrete structural elements.

[133]Koval, L.R., "On Sound Transmission into an Orthotropic Shell," *Journal of Sound and Vibration,* to be published. A more general study of the effects of orthotropy as might be obtained using composite materials.

[134]Koval, L.R.,"On Sound Transmission into a Heavily-Damped Cylinder-Aircraft Noise in Fuselage," *Journal of Sound and Vibration,* Vol. 57, 1978, pp. 155-156. The effects of large structural damping are studied.

[135]Koval, L.R., "Effects of Cavity Resonances on Sound Transmission into a Thin Cylindrical Shell," *Journal of Sound and Vibration,* Vol. 59, 1978, pp. 23-33. In previous work, Koval had assumed a completely absorbing cavity. Here the cavity acoustic modes are considered explicitly and the analysis becomes closely aligned with modal methods, except that the cylinder length remains infinite.

Statistical Energy Analysis

Statistical energy analysis has been widely discussed and used for vibration and acoustic analyses. The following are representative of the interior noise SEA literature.

[136]Price, A.J. and Crocker, M.J., "Sound Transmission Through Double Panels Using Statistical Energy Analysis," *Journal of the Acoustical Society of America,* Vol. 47, 1970, pp. 683-693. One of the first studies of its kind.

[137]Wilby, J.F. and Scharton, T.D., "Acoustic Transmission Through a Fuselage Sidewall," NASA CR-132602, 1974. Another early study. Interesting reading, particularly for those relatively unfamiliar with SEA.

[138]Wilby, J.F., "An Approach to the Prediction of Airplane Interior Noise," AIAA Paper 76-548, AIAA 3rd Aeroacoustics Conference, 1976. Focus is on jet and boundary layer noise sources. Using SEA, the author concludes that nonresonant response of the structure dominates.

[139]Pope, L.D. and Wilby, J.F., "Band-Limited Power Flow into Enclosures," *Journal of the Acoustical Society of America,* Vol. 62, 1977, pp. 906-911. A basic study of SEA in the context of interior noise.

Acoustoelastic Scale Models

Acoustoelastic scale experimental models have not been used to the extent that they probably should. The following references are indicative of what might be done.

[140]Dowell, E.H., "Acoustoelastic Scaling Laws," Princeton University MAE Report No. 1420, 1970. A basic study of the underlying theory.

[141]Murphy, G., "Scaling and Modeling for Experiment," *The Shock and Vibration Digest,* Vol. 10, No. 1, 1978, pp. 5-13. A broad discussion of fluid-structural modeling including acoustic and structural models.

[142]Barton, C.K., "Experimental Investigation on Sound Transmission Through Cavity Backed Panels," NASA TM X-73939, 1977. A systematic study of several stiffened and unstiffened structural walls with a simple, rectangular, cavity geometry. Vaicaitis[149,150] and Dowell[128] have shown good agreement with these experimental data using modal theory (subject to the uncertainty in the structural damping which had to be estimated since it was not measured). Earlier experimental data for unstiffened walls obtained by Gorman[44,45] were also in good agreement with modal theory.[115]

Applications

The distinction between application papers and generic papers is obviously subjective to some degree. The only claim made here is that at least the present author has found the distinction useful and, hopefully, some readers will also.

Automobiles

[143]Wolf, J.A., Jr., Nefske, D.A., and Howell, L.J., "Structural-Acoustic Finite Element Analysis of the Automobile Passenger Compartment," General Motors Research Lab. GMR-2029R, 1975.

[144]Nefske, D.J. and Howell, L.J., "Automobile Interior Noise Reduction Using Finite Element Methods," General Motors Research Lab. GMR-2592R, 1978. Also, SAE Paper 780365.

Conventional Take-Off-Landing (CTOL)

Most, if not all, of the significant literature predates 1974.

General Aviation

[145]Roskam, J., vanDam, C., and Grosveld, F., "Some Noise Transmission Loss Characteristics of Typical General Aviation Structural Materials," AIAA Paper 78-1480, AIAA Aircraft Systems and Technology Conference, 1978.

[146]Howlett, J.T. and Morales, D.A., "Prediction of Light Aircraft Interior Noise," NASA TM X-72838, 1976.

[147]Jha, S.K. and Catherines, J.J., "Interior Noise Studies for General Aviation Types of Aircraft, Part I: Field Studies. Part II: Laboratory Studies," *Journal of Sound and Vibration,* Vol. 58, 1978, pp. 375-406.

[148]Vaicaitis, R. and McDonald, W., "Noise Transmission into a Light Aircraft," AIAA Paper 78-197, AIAA 16th Aerospace Sciences Meeting, 1978.

[149]Mixson, J.S., Barton, C.K., and Vaicaitis, R., "Interior Noise Analysis and Control for Light Aircraft," SAE Paper 770445, 1977.

[150]Mixson, J.S., Barton, C.K., and Vaicaitis, R., "Investigation of Interior Noise in a Twin-Engine Light Aircraft," *Journal of Aircraft,* Vol. 15, 1978, pp. 227-233.

[151]Catherines, J.J. and Mayes, W.H., "Interior Noise Levels of Two Propeller-Driven Light Aircraft," NASA TM X-72716, 1975.

[152]Howlett, J.T., Williams, L.H., Catherines, J.J., and Jha, S.K., "Measurement, Analysis, and Prediction of Aircraft Interior Noise," AIAA Paper 76-551, AIAA 3rd Aeroacoustics Conference, 1976.

Helicopters

[153]Wilby, J.F. and Smullin, J.J., "Interior Acoustic Environment of STOL Vehicles and Helicopters," Noise-Con Langley Research Center, 1977, pp. 165-178.

[154]Sternfeld, H., Schairer, J., and Spencer, R. "An Investigation of Helicopter Transmission Noise Reduction by Vibration Absorbers and Damping," USAAMRDL Tech. Report 72-34, 1972.

[155]Levine, L.S. and DeFelice, J.J., "Civil Helicopter Research Aircraft Interior Noise Reduction," NASA CR-14546, 1977.

[156] Howlett, J.T., Clevenson, S.A., Rupf, J. A., and Snyder, W.J., "Interior Noise Reduction in a Large Helicopter," NASA TN D-8477, 1977.

[157] Anon., "Helicopter Acoustics," 1978 NASA Conference Publication 2052, Parts I and II. See especially articles on pp. 493, 583-695, 781, 797, and 839.

[158] Pollard, J.S. and Leverton, J.W., "Cabin Noise Reduction—Use of Isolated Inner Cabins," Paper No. 19, Second European Rotorcraft and Powered Lift Aircraft Forum, 1976.

[159] Howlett, J.T., Williams, L.H., Catherines, J.J., and Jha, S.K., "Measurement, Analysis and Prediction of Aircraft Interior Noise," AIAA Paper 76-551, AIAA 3rd Aeroacoustics Conference, 1976.

[160] Sciarra, J.J., Howells, R.W., Lensku, J.W., Jr., Drago, R.J., and Schaffer, E.G., "Helicopter Transmission Vibration and Noise Reduction Program: Vol. I, Technical Report, Vol. II, User's Manual," USARTL-TR-78-2A, 1978.

Railway Vehicles

[161] Eade, P.W. and Hardy A.E.J., "Railway Vehicle Internal Noise," *Journal of Sound and Vibration,* Vol. 51, 1977, pp. 403-415.

[162] Grootenhuis, P., "Rapporteur's Report, Session 5: Noise Inside Vehicles, Noise Control; Acceptability Criteria," *Journal of Sound and Vibration,* Vol. 51, 1977, pp. 417-418.

Short Take-Off-Landing (STOL)

[163] Wilby, J.F. and Smullin, J.I., "Interior Acoustic Environment of STOL Vehicles and Helicopters," Noise-Con Langley Research Center, 1977, pp. 165-178.

[164] Barton, C.K., "Interior Noise Considerations for Powered-Lift STOL Aircraft," NASA TM X-72675, 1975.

[165] Butzel, L.M., Jacobs, L.D., O'Keefe, J.V., and Sussman, M.B., "Cabin Noise Behavior of a USB STOL Transport," AIAA Paper 77-1365, AIAA 4th Aeroacoustics Conference, 1977.

Space Shuttle

[166] Piersol, A.G. and Rentz, P.E., "Experimental Studies of the Space Shuttle Payload Acoustic Environment," SAE Paper 770973, 1977.

[167] Piersol, A.G., Rentz, P.E., Wilby, J.F., and Pope, L.D., "Space Shuttle Payload Bay Acoustics Prediction Study," Bolt, Beranek, Newman Rept. No. 3286, Vols. I-V, 1977.

[168] Cho, A.C., "Space Shuttle Payload Bay Noise," 96th Meeting, Acoustical Society of America, 1978.

Turboprop

[169] Conlon, J.A. and Bowles, J.V., "Application of Advanced High Speed Turboprop Technology for Future Civil Short-Haul Transport Aircraft Design," AIAA Paper 78-1487, AIAA Aircraft Systems and Technology Conference, 1978.

[170] Dugan, J.F., Miller, B.A., and Sagerser, D.A., "Status of Advanced Turboprop Technology," in NASA CP 2036 CTOL Transport Technology—1978, pp. 139-166.

[171] Dowell, E.H., "Turboprop Interior Noise Studies," AIAA Paper 79-0647, AIAA 5th Aeroacoustics Conference, 1979.