Review of Recent Research on Interior Noise of Propeller Aircraft

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Introduction

CONTROL of interior noise is required as one element in providing a comfortable environment for aircraft passengers. Recent efforts to increase aircraft performance and to reduce weight and fuel consumption have presented new challenges for noise control technology. To meet these challenges, substantial research and development have been carried out. In this paper the technical areas involved in aircraft noise control are identified, and examples of recent research accomplishments are presented to illustrate the state-of-the-art. The bibliography has been made as complete as possible to acknowledge the many contributors and to provide a starting point for those interested in more extensive information.

An overall perspective on aircraft cabin noise can be obtained from previous noise control efforts[1-19] and from the general noise control literature.[20-24] The contributors to cabin noise and the principles for noise control have been recognized for a long time.[1,3,20-24] Even so, substantial effort is usually required to provide satisfactory noise levels in new generation aircraft.[7-11,17-19] Cabin noise *sources* include propellers, exhaust from reciprocating or turbofan engines, turbomachinery, turbulent airflow over the aircraft structure, and engine vibrations. Noise from internal sources, such as air-conditioning systems, may also be important. Noise is transmitted to the cabin along *airborne paths* through the fuselage sidewall and along *structureborne paths* (from sources such as engine vibrations) through engine mounts or the wing structure. Noise control measures are constrained to minimize added weight, space required, and impact on aircraft performance. Consequently, efficient measures usually include not only reduction at the source and in the transmission path (including cabin noise absorption), but also careful consideration of cabin noise characteristics required for *passenger comfort*. Efficiency also requires that noise control treatment be applied only at locations where it is necessary, therefore, there is need for *source/path identification* methods that can quantify the various contributions. Thus, cabin noise control requires information in each of the technical areas indicated previously by the italicized type.

Review of the literature indicates that there is active research under way in each of these technical areas. Moreover, the number and variety of publications are so great that a review of all of the technical areas would be impractical for this paper. Therefore, only the areas of sources, airborne transmission, and passenger comfort are reviewed herein. With regard to structureborne noise and path identification in aircraft, a brief examination of the literature suggests that the state-of-the-art is not as well developed and that improved capability will probably be required for future applications. The emphasis herein is on definition and prediction of the characteristics of propeller source noise, fuselage noise transmission, and passenger comfort response. Comparison between theory and test results is relied upon to illustrate progress, however, the description of the theoretical methods is left to the references. The comparisons show that substantial progress has been made in understanding, in the development of methods, and in achieving agreement between theory and test. For the three technical areas covered, application of the technology to cabin noise control and possible future research needs are discussed.

Aircraft Interior Noise Sources

The principal sources of airplane interior noise include propellers, fuselage boundary layers, and the exhaust from turbojet or turbofan engines. Other sources that may be important in some situations include turbomachinery noise, structureborne noise, environmental control systems, and separated aerodynamic flow.

Recent noise research has focused on propellers because of important new applications such as commuter and high-speed turboprop aircraft. This paper will emphasize the significant advances made in understanding and predicting propeller noise, as illustrated in Refs. 25-62. Boundary-layer noise and jet exhaust noise have also been studied extensively, however, the research emphasis took place some time ago. Therefore, only a few publications[63-69] are included as a guide to the literature. For example, prediction methods are well established for boundary-layer[64] and jet exhaust[68] noise. Noise of impinging jets in powered-lift configurations has been deter-

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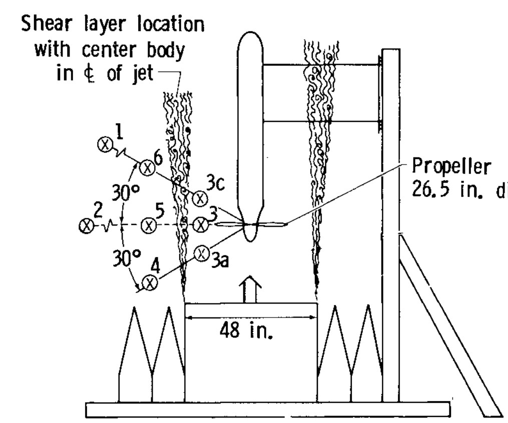
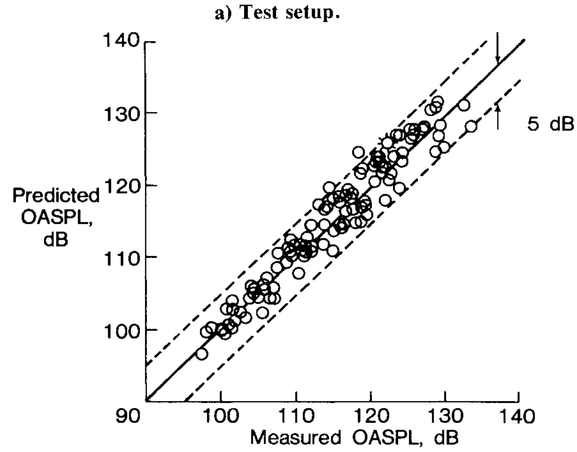


a) Test setup.



b) Results for 119 test conditions.

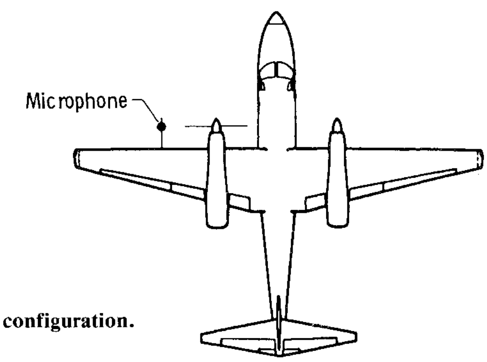
Fig. 1 Prediction of low-speed propeller noise for laboratory conditions.[56]

mined,[65,67,69] and is of continuing interest for new V/STOL and STOL configurations.[63,66]

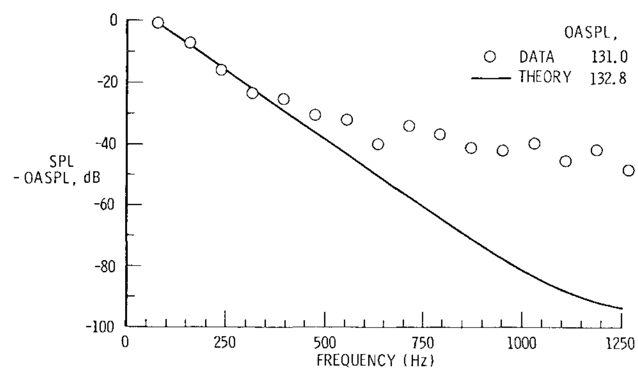
Propeller Noise Prediction

For interior noise studies, the source information needed includes the level, spectrum, and point-to-point correlation at all points on the fuselage for flight conditions. New theoretical methods have been developed for the prediction of this information.[40-42,45-47,56,62] Experimental studies have been carried out for comparison with theoretical predictions, for empirical determination of propeller noise characteristics, and for evaluation of new propeller concepts.

Comparison of measured and predicted propeller noise is illustrated in Fig. 1 for low-speed propellers.[56] The tests were carried out using two different 0.25-scale models of commuter-class aircraft propellers in an anechoic chamber test facility having a specially designed low-turbulence airflow. Each propeller was operated at tip speeds up to Mach = 0.82, thrust loadings from about 40 to 100 lb, and a simulated forward speed of 120 ft/s. Noise measurements were taken at eight positions, including both near and far fields, for a total of 119 data points shown in Fig. 1. The figure shows that predicted and measured overall sound pressure level (OASPL) values agree to within ± 5 dB for all but two data points. More detailed analysis shows that the OASPL is overpredicted by an average of 0.9 dB with a standard deviation of 2.2 dB. It is known that the predicted noise depends strongly on the aerodynamic pressures on the blade, and the theory used for Fig. 1 predicts these aerodynamic pressures as part of the noise prediction. When differences between measured and predicted aerodynamic loads are accounted for, much improved prediction accuracy is possible.[62] It can be concluded that the noise of low-speed propellers can be predicted within 1-2 dB under laboratory conditions.



a) Test configuration.



b) Noise spectrum: rpm = 1584, $M_\infty = 0.23$, $M_T = 0.65$.

Fig. 2 Prediction of low-speed propeller noise in flight.[56,62]

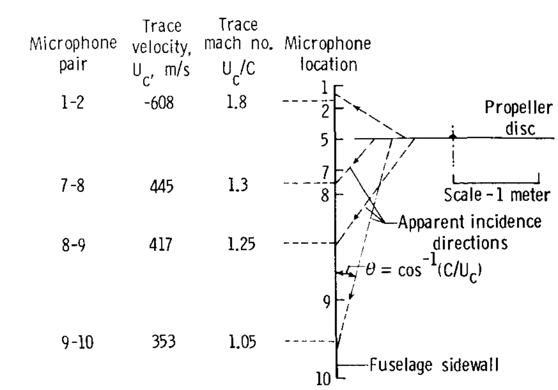
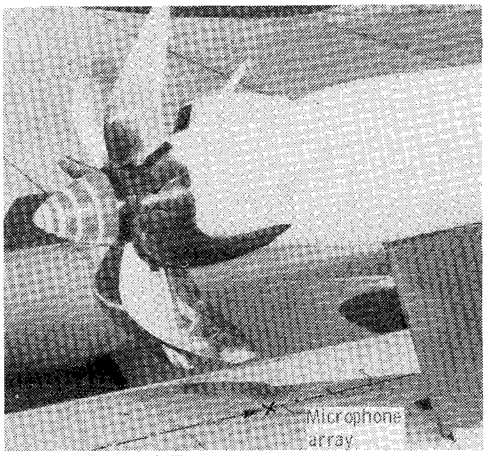
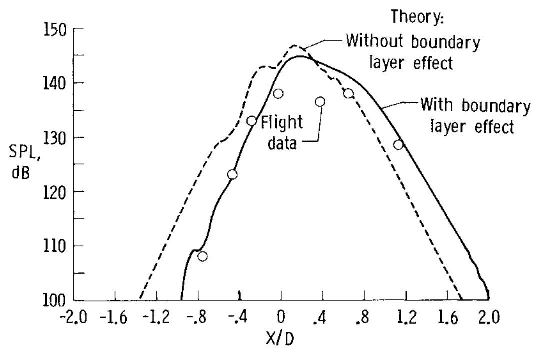


Fig. 3 Noise impingement geometry for a low-speed propeller in static test.[55]

Predicted and measured propeller noise is shown in Fig. 2 for flight conditions. A microphone boom was used to measure near-field noise on the outboard side of the propeller. The effects of the fuselage are expected to be small for this microphone position. The spectrum shown was measured at a flight speed of Mach = 0.23 and a propeller tip speed of $\text{Mach}_T = 0.65$. Measured noise data were ensemble-averaged over 50 propeller revolutions to separate the random and periodic parts of the signal. The noise was predicted using the ANOPP propeller noise prediction system[62] with an effective propeller blade pitch angle that was adjusted so that the predicted power coefficient matched the measured value. This procedure was used because the pitch angle was not measured in flight; but it also avoided the difficulties associated with the aerodynamic predictions mentioned previously. Figure 2 shows excellent agreement between data and theory for the overall noise and for the first five harmonics of the spectrum. At frequencies above about 600 Hz, the measured spectrum values are much larger than those predicted. These measured values are thought to be influenced by recording instrumenta-



a) Test arrangement.



b) Noise level distribution.

Fig. 4 Prediction of noise level for a high-speed propeller in flight.[62]

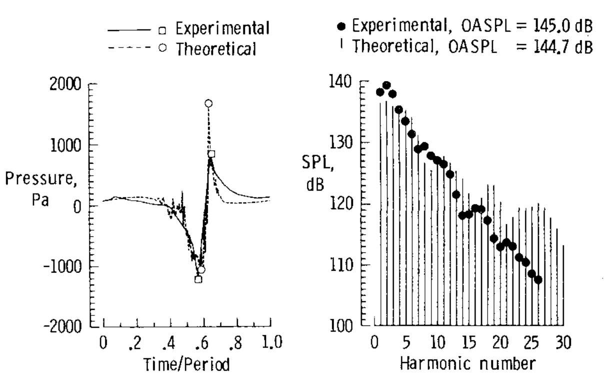


Fig. 5 Noise signature of a high-speed propeller in a quiet wind tunnel.[29]

tion dynamic range limitations. Interior noise studies indicate that the first few harmonics are the most significant in establishing A-weighted cabin noise level, and that the propeller tones tend to disappear into the broadband level in many cases at frequencies above the fifth harmonic. While Fig. 2 shows data for only one test condition, it does suggest that theoretical methods can predict propeller noise levels in flight for reasonably clean flow conditions, i.e., a tractor propeller in smooth flight at locations away from the fuselage.

Only a few measurements of low-speed propeller noise on an aircraft sidewall, including static and taxi tests[31] and flight tests,[60] have been published. Reasonable agreement was obtained between taxi test spectra and predictions of an early version of the theory of Farassat.[41] Recently, theoretical procedures to account for the effects of acoustic scattering around a cylindrical fuselage and acoustic refraction through a fuselage boundary layer have been developed.[46,47,62] Work is now under way to evaluate these effects.

The distribution of phase angle, or point-to-point correlation, over the fuselage surface is required for a complete description of the propeller noise field. Some phase information has been obtained using an array of ten microphones flush-mounted on the fuselage of a twin-engine aircraft in static tests.[31,55] Examination of phase angle data for pairs of microphones led to the impingement geometry model illustrated in Fig. 3. According to this model the measured phase data could be interpreted in terms of a plane wave incident on the sidewall at angle θ, Fig. 3. The incidence angles determined for that test are shown in Fig. 3 for positions along the fuselage length. In the circumferential direction, the measured phase indicated a noise field turning in the direction of propeller rotation at a speed closely related to propeller tip speed. While the data are limited, these results seem intuitively reasonable and have been used to formulate a propeller noise model for use in interior noise studies.[115] Recently, the analytical capability of the ANOPP program was used to predict the complex acoustic pressure (amplitude and phase for each propeller harmonic) at 160 grid points distributed over a cylindrical fuselage.[56]

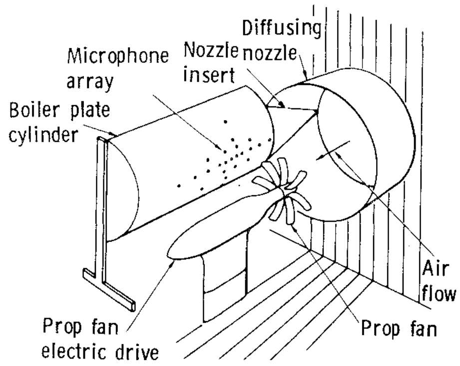
From the examples shown in Figs. 1-3 and from the references it appears that understanding and prediction of low-speed propeller noise is well developed, and that methods are available for interaction with interior noise prediction and control studies.

Some of the theoretical methods of Refs. 40-42 and 45-47 apply to high-speed propellers. The computation methods are somewhat different than for low-speed propellers because the high-speed propellers have supersonic helical tip speeds that cause a singularity in the solution of the governing equations.

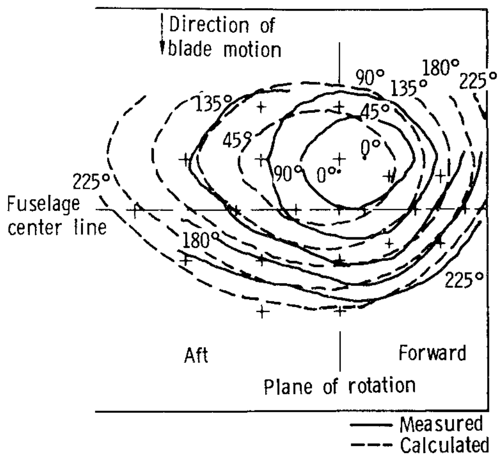
Predicted and measured noise levels are shown in Fig. 4 for a 2-ft-diam model of a high-speed propeller tested at Mach = 0.8 flight conditions. The model propeller was attached to the top of an aircraft fuselage and microphones were flush-mounted in the fuselage, as shown in Fig. 4. Reasonably good agreement is obtained between data and theory when the boundary-layer effect is included, except for the region just aft of the propeller plane, near $X/D = 0.4$ (D = propeller diameter). Reasons for this difference are under investigation.[62] The model propeller shown in Fig. 4 was also tested in an anechoic wind tunnel.[51] The propeller was operated with four blades instead of eight because of a limit of the propeller drive power in the tunnel, and the rpm were increased above the design value to obtain the correct helical tip Mach number at the lower air speed limit of the tunnel. A noise signature from these tests is shown in Fig. 5. Comparison of test data with predictions from an early version of the method of Farassat shows that in general the agreement is good for the lower harmonics.

Phase angle distribution over the surface of a boiler-plate cylinder (representing an aircraft fuselage) was also determined for the wind tunnel conditions,[51] Fig. 6. The cylinder was sized relative to the propeller, which was located with a tip clearance appropriate for aircraft application. The cylinder was located in the airflow, which was carefully checked to be sure that the cylinder did not cause noise-producing flow disturbances. Propeller noise was measured using an array of 21 microphones flush-mounted in the cylinder. The theoretical methods of Hanson[45,47] and Hanson and Magliozzi[46] were used to predict phase distributions (as well as spectra). Comparison of the predicted and measured phase contours, Fig. 6, shows that the overall character and distribution of phase are predicted reasonably well, however, differences in magnitude appear.

The results shown in Figs. 4-6 and in the references indicate that methods are available for prediction of the noise of high-speed propellers with reasonable accuracy. The accuracy of these methods, however, depends upon estimates of

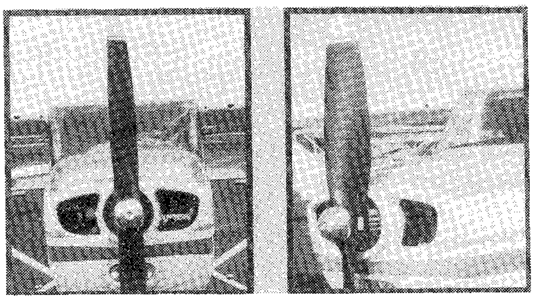


a) Test arrangement.



b) Phase angle contours.

Fig. 6 Fuselage noise phase angle for a high-speed propeller in laboratory conditions.[51]



a) Production. b) Quiet.

Fig. 7 Low-speed propeller design for 5-dB reduction of flyover noise.[28]

aerodynamic pressure loading on the blade surface. Accurate estimates of aerodynamic pressure may not be available.

Propeller Noise Control

Approaches to the reduction of propeller noise have been studied for both low- and high-speed propellers.

For low-speed propellers, theoretical methods have been used to examine variations of noise and performance with propeller parameters.[50,59] Such studies led to the testing of several new propellers,[44] including the one shown in Fig. 7. As described in the references, reduction of noise is obtained by the use of new airfoil sections, wider chord and larger angles of attack at inboard stations, and reduced tip speed. A reduction of about 5 dB of flyover noise was obtained with very little change in aircraft performance.

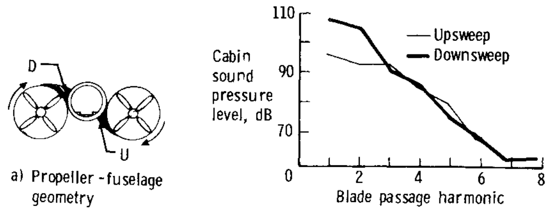
For high-speed propellers, the need to avoid compressibility losses as well as high noise at the target flight speed of Mach = 0.8 led to radical new designs, such as shown in Fig. 4. Noise reduction features include the highly swept blades and the larger number of blades, as well as the reduced tip speed, wide inboard sections, and advanced airfoils used also for the low-speed propellers. The resulting noise reductions were projected to be 10 dB at blade passage frequency[53] and were measured at 4-8 dB depending on harmonic.[34]

Some other approaches to cabin noise reduction have examined the interaction of a propeller with the fuselage (upsweep-downsweep effect) and the interaction of several propellers with each other and with the fuselage (synchrophasing). An example of the upsweep-downsweep effect is shown in Fig. 8. These test results were obtained using a twin-engine commuter-class aircraft in flight at 12,000 ft with the cabin pressurized. Running each engine at a slightly different rpm allowed the identification of each contribution to the cabin noise. Rpm values were interchanged in separate test runs to eliminate frequency as a variable. The levels presented in Fig. 8 were obtained by averaging two microphones at left- and right-hand seat positions just aft of the propeller plane. The results show that the upward-sweeping propeller has lower cabin noise levels at the first two harmonics. Similar results have been observed in other test situations. This effect is thought to be associated with nonsymmetries of the fuselage structure and the propeller noise field with respect to the fuselage upper and lower halves. Nonuniform inflow and installation effects may also be contributing factors. The upsweeping blade is thought to exert its highest noise pressures on the lower part of the fuselage where its noise transmission is lower, and conversely for the downsweeping blade. Reductions such as shown in Fig. 8 are significant and warrant further study of this noise reduction approach.

Synchrophasing refers to the control of the angular position of one or more propellers relative to a reference propeller. Flight studies have been carried out to determine the relation of cabin noise to propeller angular position.[48,49,52] An example of the test results is shown in Fig. 9. Interior noise levels were measured at 12 cabin positions for a flight where the four propellers were controlled only by a mechanical governor, which allowed angular drift of the relative propeller positions (run A). Detailed analyses of the cabin noise levels for various propeller positions were then performed on a computer using data measured on run A. These analyses predicted the noise levels that should be obtained if the relative propeller positions could be locked on, i.e., synchrophased. Figure 9 indicates that substantial reductions could be obtained for the minimum average synchrophased conditions compared to the baseline run A. Potential reductions have been reported by other researchers as well. A synchrophasing device is standard equipment on many aircraft. To realize the full potential noise reduction requires new electromechanical systems that can hold relative propeller positions within a few degrees. The acoustic-structural interactions that lead to the observed cabin noise behavior in synchrophasing are not fully understood, but appear to be more than simple acoustic interference of the propeller noise fields. Recently initiated theoretical studies are exploring these interactions.[43]

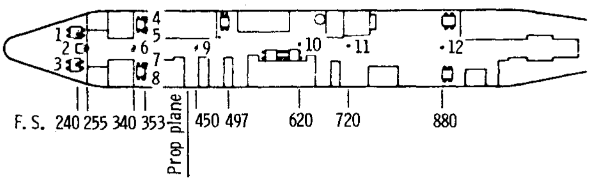
Outlook for Future Propeller Noise Research

Propeller noise prediction methods of reasonable accuracy and capability recently have become available for cabin noise studies for tractor configuration propellers. Recently initiated studies have coupled these propeller prediction methods to interior noise transmission analyses. Exercise of such programs should provide new insights into cabin noise control through the variation of propeller conditions, propeller positions, and relative frequencies of propeller tones and structural modes. The results may indicate whether new propeller prediction work is needed. For preliminary design, prediction methods that are very quick and easy are of interest. Empirical methods

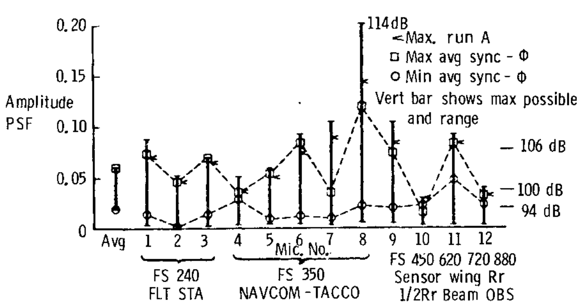


b) Effect of rotation direction

Fig. 8 Effect of propeller rotation direction on cabin noise level in flight.



a) Measurement locations.



b) Effect on 68-Hz propeller tone.

Fig. 9 Cabin noise reduction using propeller synchrophasing.[48]

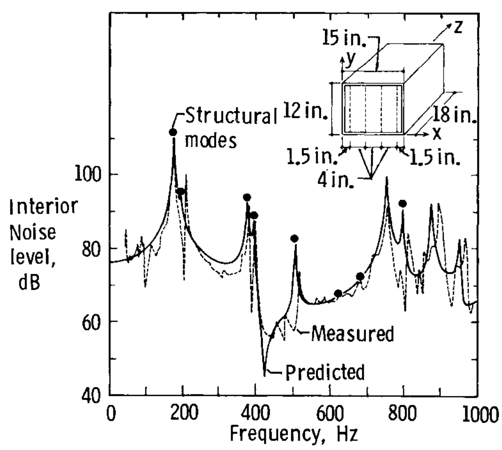


Fig. 10 Noise transmission of a stiffened panel to a hard-walled enclosure.[90]

have been developed for this purpose,[30] however, the new analytical methods might be able to provide more reliable and detailed predictions with comparable speed and ease. Some new aircraft designs feature counterrotating[58] and pusher-propeller configurations that require study of their acoustic behavior. Exploratory investigation of a low-speed propeller operating in the wake of an airfoil, simulating a pusher configuration, indicates that substantial increases of noise occur.[32]

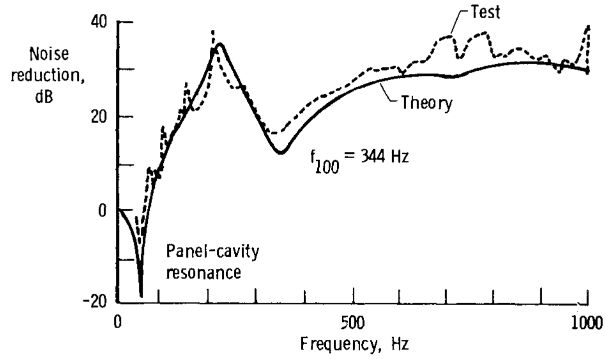


Fig. 11 Noise transmission of an unstiffened panel into a fiberglass-lined enclosure.[74]

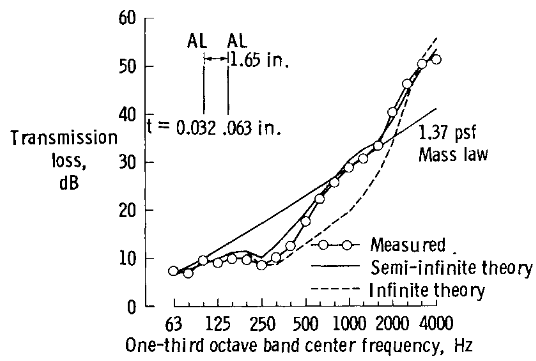


Fig. 12 Transmission loss of a double-wall panel.[80]

Airborne Noise Transmission

Noise from external sources, such as propellers and boundary layers, transmitted through the fuselage sidewall is a major contributor to cabin noise in virtually all aircraft. In the past, noise control by fuselage sidewall treatment has relied heavily on empirical methods and results derived from architectural studies. Recent research has emphasized theoretical prediction methods with the objectives of optimizing the treatment for existing aircraft and defining treatment for future aircraft. Progress in prediction of interior noise has been reviewed in a comprehensive paper covering the period up to 1979,[70] and in papers covering more recent work.[71-73] The following discussion intends to describe progress since 1979.

Flat Sidewall-Rectangular Cabin

Part of the recent cabin noise research has focused on the class of aircraft having a rectangular fuselage cross section, nearly flat sidewalls, and twin propellers located such that the propeller plane intersects the passenger cabin. Papers related to this research are listed as Refs. 74-97.

By 1979, predictions had been shown to agree with tests for simple panels attached to a hard-wall rectangular enclosure and subjected to a normally incident uniform sound field.[70] Since then, the development of prediction capability has continued,[74,76,80,82,88-93] and comparisons have been made with increasingly complex laboratory configurations, and recently with aircraft in flight. Example results illustrating progress in both prediction and noise control are presented in Figs. 10-20.

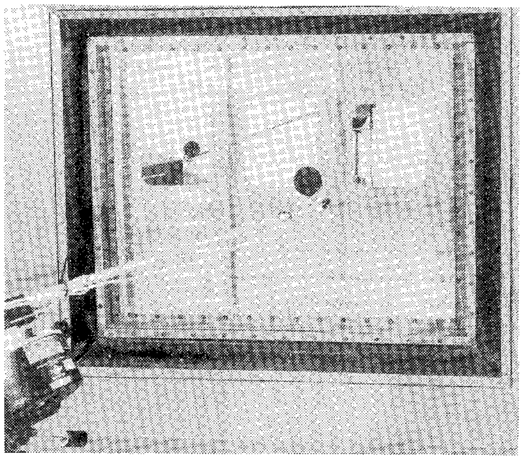
Figure 10 illustrates the noise transmission through a stringer-stiffened panel into a small hard-wall enclosure. The general agreement between predicted and measured results is good, and the frequencies of most structural modes are predicted closely.[90] The magnitude of sound pressure levels (SPL) at the modes may not be accurate because of the lack of measured modal damping values for use in the prediction. When the enclosure is lined with fiberglass the resonances are strongly damped, Fig. 11, and the smoother curve of noise reduction can be predicted using a simplified theory that accounts for only a few system modes.[74]

Noise transmission of double-wall panel systems has been studied for application to aircraft sidewalls where the fuselage structure and trim panel form the double wall.[80] Transmission loss (TL) of 4 × 5-ft unstiffened double panels is shown in Fig. 12. The measured results show reduced TL below mass law at frequencies near 250 Hz, where the double-wall resonance occurs. This reduction often does not occur in architectural structures, however, for (flat) aircraft structures some reduction usually occurs. Infinite panel theory, often used for architectural studies, is shown to underpredict the TL between 500 and 2000 Hz. The new theory for semi-infinite panels provides much better agreement with the test results.[80] Finite panel theory has not been incorporated in general interior noise prediction programs, and may be needed along with a finite model of the airspace between panels[85] to obtain agreement at frequencies near the double-wall resonance.

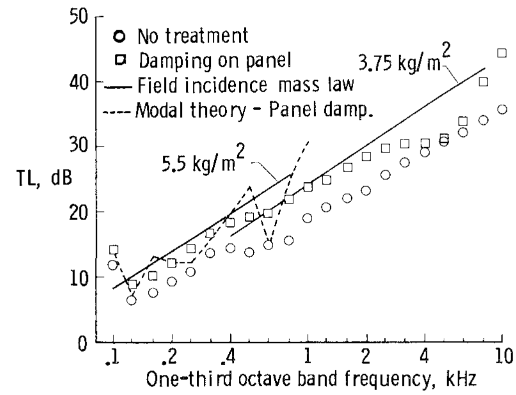
Laboratory results for a realistic aircraft panel and treatments are shown in Fig. 13. The test panel is 4 × 5 ft in area and has structural details close to those of an unpressurized 19-passenger commuter-class aircraft. The test results were obtained without windows, but with the same skin-stringer structure over the whole panel area. Figure 13b shows that the panel with only a damping layer for treatment has TL values that follow mass law curves in two frequency ranges. This behavior is characteristic of some stiffened panels and has been referred to as "double mass law" behavior.[20] The detailed modal theory is shown to predict the overall trend of the data, but there are differences, especially at the higher frequencies (400-1000 Hz), where the panel has many complex modes that must be calculated and summed. Figure 13c shows the effect of adding a fiberglass layer and a trim panel. The increase of TL is shown to be well predicted, except for underprediction in the region near 160 Hz, where a double-wall resonance occurs. Similar underprediction is reported for 8 × 8-ft treated panels.[117] The theory used to predict the treatment effect was derived for infinite panels, and the results shown here suggest that improvements are desirable. Possible improvements include the use of finite panels[80] or a finite airspace.[85] For the overall TL of the structure-fiberglass-trim system, Fig. 13c, the theory predicts the overall trend, but has some differences with data associated with the characteristics described previously.

Studies of complete aircraft fuselages in a laboratory have been carried out in order to obtain better realism than for single-panel and small-box tests. Fuselage tests allow the panel or structure under study to interact with the adjacent structure and with the cabin acoustics in a more realistic manner, and laboratory tests allow greater control of noise sources and greater flexibility in test procedures and treatment materials compared to flight tests. However, analysis is much more complicated for the complete fuselage. Figure 14 illustrates the results[95] for a general-aviation fuselage of a twin-engine aircraft weighing about 7000 lb takeoff gross weight. In one test, noise sources were enclosed by an acoustic guide to limit the sound to a particular panel area, and in another test a more distributed sound was used to expose the whole fuselage sidewall. The theoretical procedure calculates the sound transmission through a localized panel area, so the acoustic guide setup is appropriate for comparision with this element of the theory. The result, Fig. 14b, shows that the overall trend is reasonably well predicted, however, differences occur at higher frequencies. The theory then combines the cabin sound levels from the various panel areas, so the data for the diffuse input are appropriate for comparison. Figure 14c shows similar overall agreement in trend. Comparisons such as these[96] suggest that some improvements of theory are desirable, but that the theory is sufficiently accurate for trend studies.

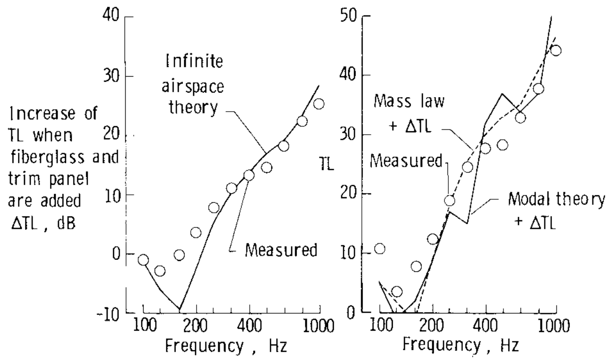
The fuselage test setup was also used to study noise transmission of windows.[93,95] The noise source was directed



a) Panel installation in the TL facility, viewed from the receiving room.



b) Transmission loss of the panel without treatment and the panel with damping layer.



c) Noise transmission of the test panel with fiberglass and trim panel treatments.

Fig. 13 Noise transmission of an aircraft panel for reverberant source noise.[85]

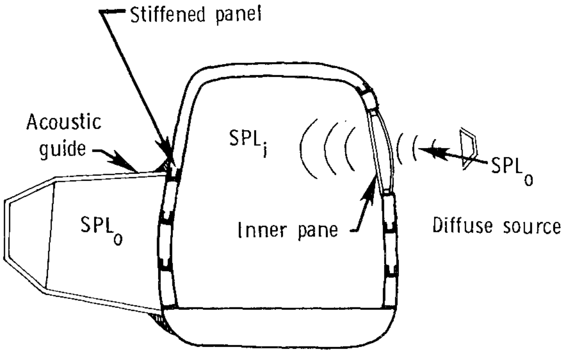
only onto the window using the acoustic guide, Fig. 15. Agreement of prediction and data is excellent. The theory has been used to optimize multiple-pane window configurations for a particular aircraft structure and acoustic treatment.[93]

A comparison of measured and predicted interior noise for flight conditions is shown in Fig. 16. The aircraft is a twin-engine general-aviation aircraft of about 11,000 lb gross weight. The tests were run for cabin noise test purposes using experimental sidewall acoustic treatments, therefore, the interior noise levels are not representative of operational conditions. However, the aircraft structural configuration and flight conditions were representative of normal operational aircraft. As shown in Fig. 16, the overall trend of the data is reasonably well predicted considering such practical factors as inexact definition of some flight conditions (such as propeller noise distribution on the fuselage exterior and structureborne noise), large variations in the effects of treatment with cabin microphone position,[86] and approximations made so the analysis would be manageable.

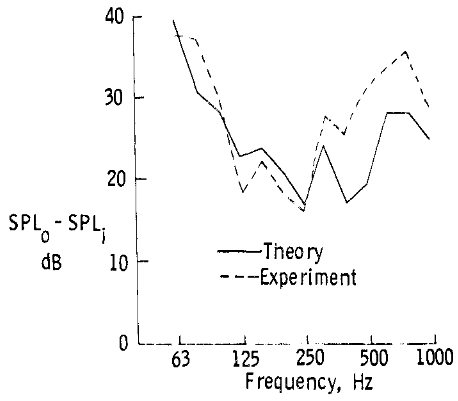
Flight tests were carried out with several different configurations of sidewall acoustic treatment. Flight conditions were repeated, within the accuracy allowed by pilot capability and weather conditions, to aid direct comparison of the treatments. Results for one treatment[86] are shown in Fig. 17. The treatment consisted of damping, fiberglass, and septum/barrier materials, and the combination of these materials varied at different areas of the sidewall, Fig. 17a. In a parallel program, similar treatments were tested in a laboratory setup using a 4-×5-ft test panel modeled after the aircraft sidewall.[79] Transmission loss (TL) data measured in the lab, shown in Fig. 17b, were used together with measured values of treatment absorption to predict insertion loss (IL) for comparison with the flight results. In flight, the effect of the treatment is characterized by its insertion loss, defined as the reduction of SPL at a cabin location that occurs when the treatment is added to a bare aircraft interior. The variations with cabin position of insertion loss at the propeller tones was quite large.[86] (This variation has also been studied in the laboratory.[83]) Figure 17c shows IL for only the broadband part of the spectrum for some of the positions shown in Fig. 16a. The agreement shown is reasonable in the midfrequency range, and suggests that further work should be done so that treatment design studies can be carried out in the less expensive lab environment with assurance that the results will apply to flight conditions.

Theoretical studies have examined variations of structure and treatment for improved noise reduction configurations,[92] Fig. 18. The interior noise level is calculated for a complete fuselage with propeller noise on the exterior. The baseline is the calculated level for the untreated sidewall. The figure shows the noise level and added weight for several combinations of honeycomb stiffening, damping tape, and mass added to the fuselage skin between the stiffening frames. The treatment labeled "optimized" includes also fiberglass, a vinyl septum, and a trim panel, and reduces the noise level to a reasonably comfortable 85 dBA for an added weight about equal to the sidewall structure weight. A similar optimization study has been done[94] for the aircraft used to obtain the results shown in Figs. 16 and 17, and the resulting treatments are being evaluation in the laboratory[81,83] for possible future testing in flight.

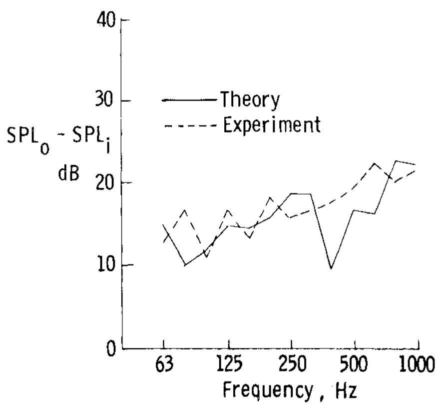
Stiffened sidewall configurations using honeycomb[75,95] and a new structure called Isogrid[84] have been evaluated for noise control. Figure 19 shows results from a laboratory test of a light-aircraft fuselage using a horn to simulate propeller noise. The results indicate that the stiffness treatment provides more



a) Test setup.

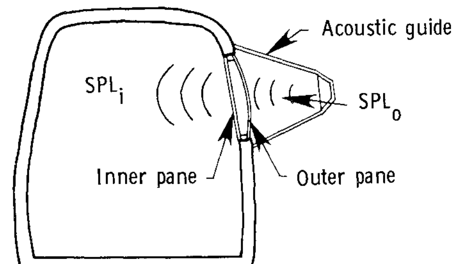


b) Acoustic guide source.

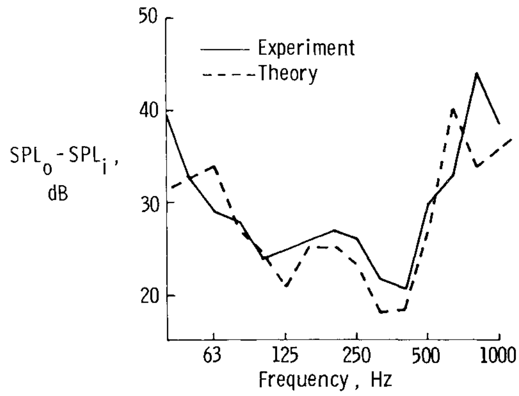


c) Diffuse source.

Fig. 14 Noise reduction of a complete aircraft fuselage in a laboratory.[95]

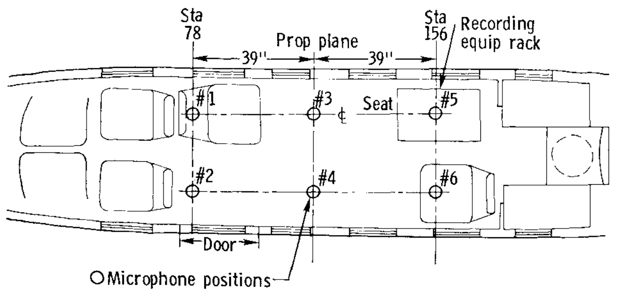


a) Test setup.

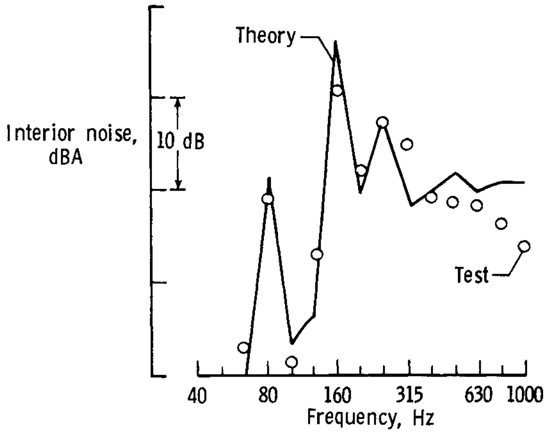


b) Noise reduction.

Fig. 15 Noise transmission of double-pane windows in a laboratory aircraft test.[93]

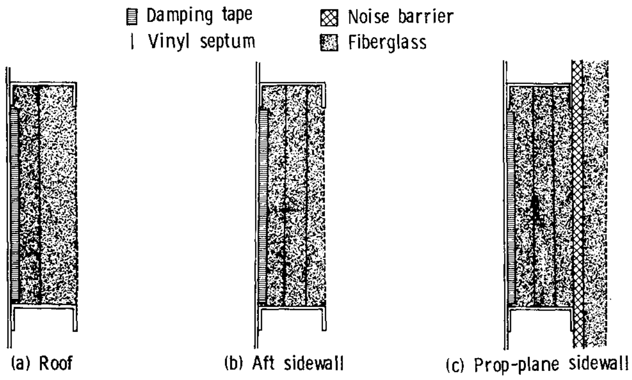


a) Test arrangement.

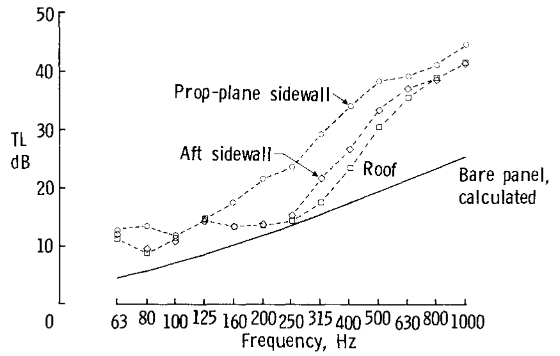


b) Interior noise at microphone 3.

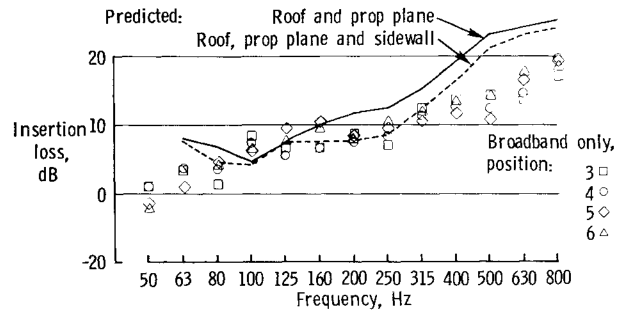
Fig. 16 Cabin noise levels in flight.[86,94]



a) Treatments.



b) Lab test results.



c) Flight.

Fig. 17 Prediction of treatment effects in flight.[86]

noise reduction than an equal weight of mass treatment in the frequency range of importance for the aircraft studied. The Isogrid structure shown in Fig. 20 was tested in a random incidence transmission loss setup. The test results indicate that the Isogrid has higher TL than predicted by mass law for a panel of equal weight. These results suggest that honeycomb or other stiffening means has good potential for noise control, and that future development should be continued, even though some partially successful applications suggest caution.[81]

Cylindrical Fuselage

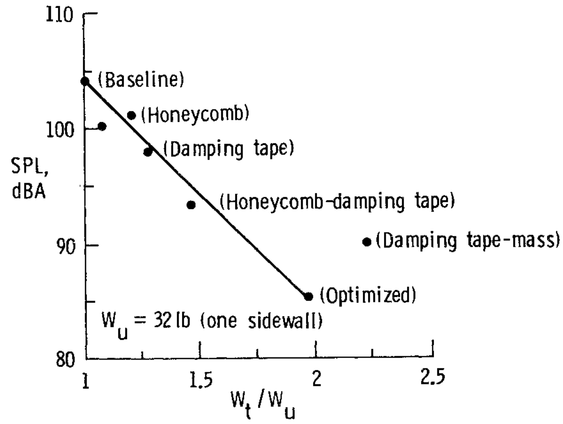
Substantial recent research has focused on the class of aircraft having cylindrically shaped (or nearly cylindrical) fuselages. The work has included basic studies of simple cylinders, application to advanced high-speed turboprop aircraft, and developments directed toward commuter-class aircraft. The related publications are listed as Refs. 98-126.

A number of theoretical methods have been developed and applied to cylindrical shells. The general theory of acoustic-structural modal analysis[76] has been applied to a cylindrical aircraft configuration[103] to show the relation between interior noise levels and mismatching of the forcing and structural-acoustic natural frequencies. This general theory has also been used to derive asymptotic results that link modal analysis methods with Statistical Energy Analyses (SEA) methods.[104] The analytical methods used for flat sidewall structures[92] have been applied to curved panels and cylindrical sidewall structures.[100,101,121,122] These results illustrate 1) the use of transfer matrix and finite element strip methods for calculation of the resonances of curved stiffened panels accounting for the details of discrete stiffeners, and 2) the use of such modes for interior noise calculations. For additional capability for efficient handling of great structural detail for periodic structures, matrix difference equation analysis may be useful.[102] Extensive programs of interior noise analysis and experiments have been carried out by two research teams, as described next.

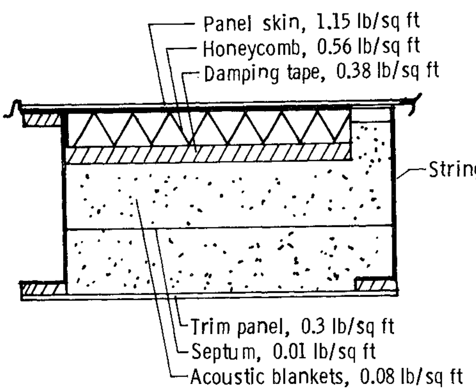
Research Based on Koval Theory

The theoretical methods of Koval, referenced in Refs. 70, 105, and 106, form the theoretical basis of one research program. These methods have been supplemented with panel and treatment analyses and incorporated into an extensive computer program at the Lockheed-California Company.[98,113,114,117-120] Some results from these theoretical methods and comparisons with test results are illustrated in Figs. 21-26.

Measured and predicted noise transmission for cylinders under reverberant laboratory conditions is illustrated in Figs. 21-24.[98,106] Results shown in Fig. 21 for 0.032-in.-thick unstiffened skin indicate excellent agreement between theory and test. The shell is unstiffened and, therefore, is represented in the analysis with minimum approximations. The analysis assumes an infinitely long cylinder, whereas the test cylinder is 78 in. long supported by heavy end plates that are also required to prevent sound transmission through the cylinder ends. Tests of a similar cylindrical shell in an anechoic chamber with simulated oblique plane wave incident sound indicate some differences between theory and test that depend on the angle of incidence. The agreement shown in Fig. 21 sug-



a) Noise-weight tradeoff.



b) Optimized treatment.

Fig. 18 Theoretical study of sidewall treatment for a twin-engine light aircraft.[92]

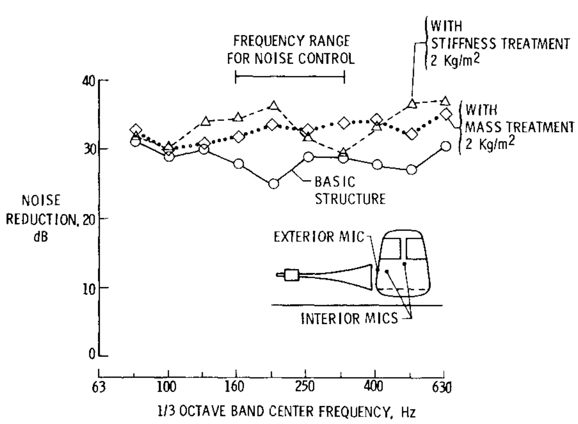
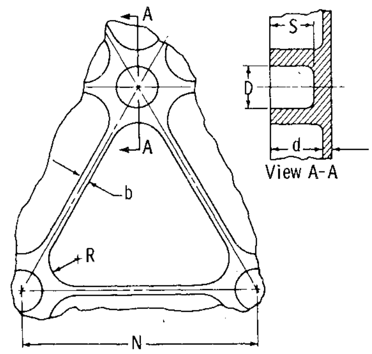


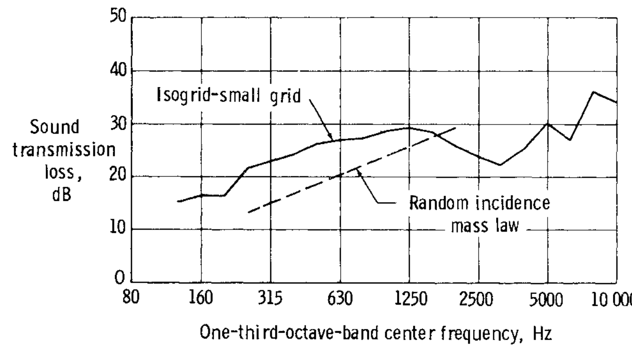
Fig. 19 Laboratory study of sidewall treatment for an aircraft fuselage.[75]



Dimensions (Inches)

	Large Grid	Small Grid
t	0.069	0.046
d	0.44	0.46
D	0.75	0.75
S	0.37	0.46
R	0.50	0.38
N	4.60	3.5
b	0.075	0.04

a) Panel dimensions.



b) Transmission loss.

Fig. 20 Transmission loss of Isogrid concept for noise control.[84]

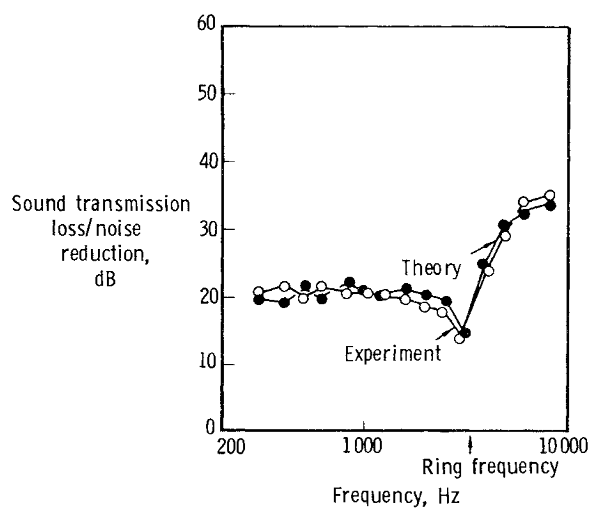


Fig. 21 Transmission of reverberant sound into an unstiffened cylindrical shell.[98] Diameter = 20 in., length = 78 in., skin $t = 0.032$ in.

gests that any differences average out for the reverberant field having many angles of incidence.

Transmission into a double-wall cylinder with unstiffened walls is shown in Fig. 22. Theoretical results are shown for two values of the acoustic loss factor. For an acoustic loss factor of zero the theory underpredicts test results over most of the frequency range. Similar underprediction has been shown, especially near the double-wall resonance (labeled "D.W." in Fig. 22), for flat panels in laboratory transmission loss tests, Fig. 13. Further research on double-wall configurations is suggested. The acoustic loss factor was introduced as a means to allow for energy dissipation in the air gap between the double walls, and the value of 2 was determined to give the best agreement with test data. Some possible mechanisms for this energy dissipation are described.[98]

Results for a double-wall, ring- and stringer-stiffened cylindrical shell are shown in Fig. 23.[98] Overall, the agreement between test and theory is reasonably good. The acoustic loss factor value of 1.0 provides improved agreement with experiment at lower frequencies. Differences at higher frequencies are thought to result from the use of a smeared stiffener analytical model which averages the stiffener properties into a monocoque representation for skin and stiffeners. The results shown in these figures are encouraging and provide valuable insights into the acoustics of double-wall cylinders.

Theoretical methods have been developed to provide a more detailed representation of a stiffened shell. Results for an orthotropic shell[105] indicate that TL is increased as circumferential stiffness is increased compared to axial stiffness. This result suggests an approach to noise control through structural design. Results using theoretical models that treat stiffeners as discrete elements[106] are illustrated in Fig. 24. The figure shows that discrete stiffener theory predicts lower TL than smeared stiffener theory at the higher frequencies. This trend suggests that discrete stiffener theory would improve higher frequency comparisons with test results such as shown in Fig. 23.

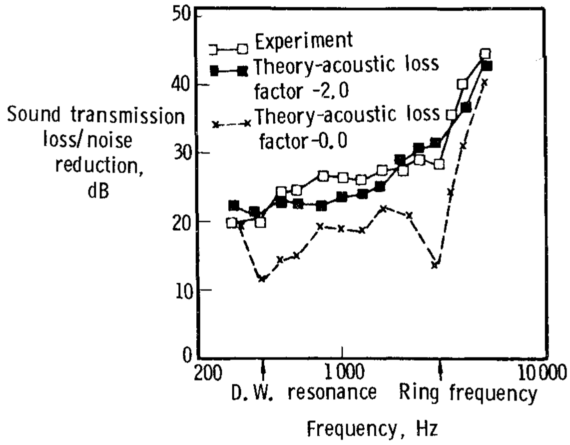


Fig. 22 Transmission of reverberant sound into an unstiffened double-wall cylinder.[98] Diameter = 20 in.

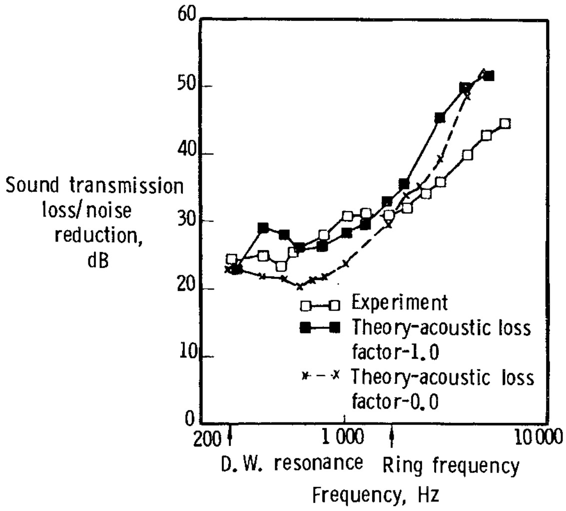


Fig. 23 Transmission of reverberant sound into a double-wall, ring- and stringer-stiffened cylindrical shell.[98] Diameter = 24 in.

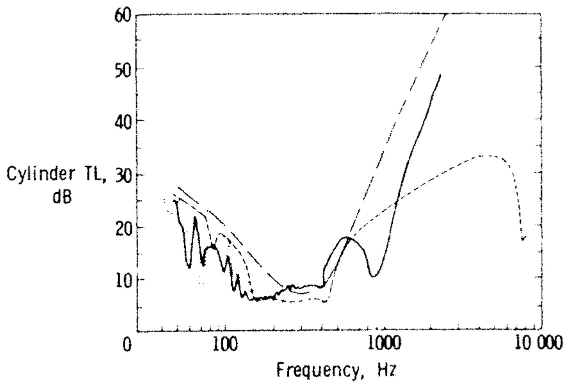
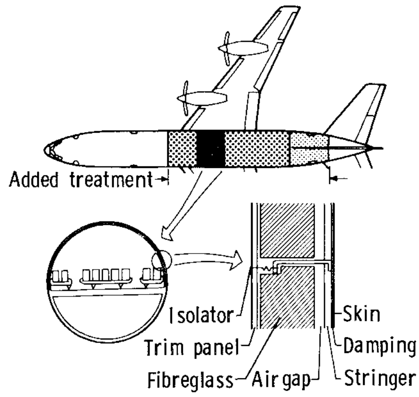
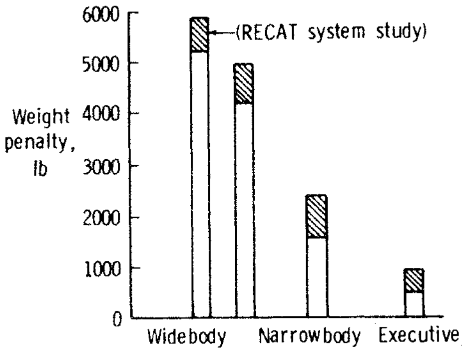


Fig. 24 Calculated transmission loss of a stiffened shell. Sound incident angle = 45 deg. ----, infinite monocoque; ····, finite monocoque; _· _, smeared stiffener model (infinite length); __, discrete stiffener theory.[106]

The theoretical methods described previously have been used to study sidewall treatment for propeller noise control on high-speed advanced turboprop aircraft.[117-120] The approach was to estimate the exterior noise generated by a high-speed propeller (such as shown in Fig. 4) and then to design a minimum-weight sidewall configuration that would provide a cabin level of 80 dBA. Extensive parametric studies varied sidewall and trim panel weights and materials.[117] Results are

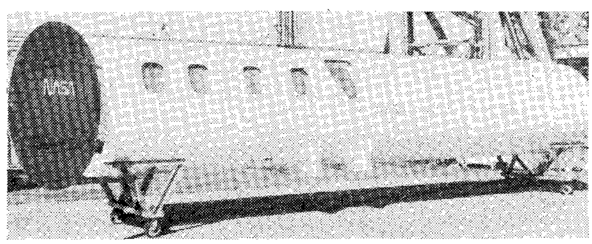


a) Treatment distribution.

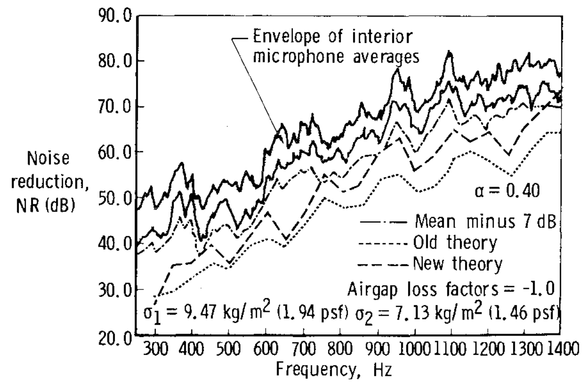


b) Additional weight required.

Fig. 25 Results of theoretical studies of sidewall treatment for high-speed turboprop aircraft.[115,117]



a) Test fuselage. Length = 30 ft, diameter = 5.5 ft.



b) Results for design-point sidewall.

Fig. 26 Noise transmission of a 43%-scale model of sidewall and heavy treatment for high-speed turboprop applications.[113]

illustrated in Fig. 25. As shown in the sketch, the treatment varied along the fuselage length and around the circumference. It was concluded that conventional treatment materials could provide the required noise reduction provided that sufficient weight was added. The weight required for three sizes of aircraft is shown in Fig. 25b. The weight value labeled "RECAT system study" was estimated as part of a feasibility study using less detailed analysis methods and indicates weight allowable for an advanced turboprop aircraft to have a fuel saving over an equivalent turbofan-powered aircraft. The detailed analysis confirms the RECAT weight estimate and provides an engineering description of the associated sidewall configuration. The shaded area at the top of the bars indicates the range of values obtained from two independent analytical studies. One analysis is described above and the second used power flow SEA methods and is discussed below.[115] The two analyses produced similar weight estimates.

An experimental program was carried out[113,114] to validate the theoretical prediction methods, to evaluate the sidewall designs developed by the analysis, and to provide experience with the very heavy sidewalls that may be required for high-speed turboprop application. The test fuselage, shown in Fig. 26, was a segment taken from an operational commuter aircraft to obtain a realistic structure. The fuselage, a specially designed floor, and the sidewall treatment were designed to be a 43%-scale model of the narrow-body aircraft design of the theoretical study. Test results are obtained for several sidewall/treatment configurations. Noise prediction is shown in Fig. 26b for only the configuration representing the design resulting from the analytical study. Results indicate that the original (old) theory predicts less noise reduction (NR) than is measured, suggesting that the weight estimates in Fig. 25 are conservative. Approaches to improving the agreement between theory and test have been explored. The "new theory," Fig. 26b, includes an improved model of the cabin acoustics and an air gap loss factor for the double wall. This theory provides somewhat better agreement with test results. A second approach takes into account the large 20-dB gradient of the external noise over the fuselage length. Averaging the external noise leads to a calculated reduction of 7 dB of the measured noise reduction for equivalence with the predictions. This adjustment also provides improved agreement between test and theory, Fig. 26b.

Figures 21-26 provide only a few samples of the results obtained in this research program. Additional information on new analytical capability and the behavior of cylindrical shells is available in the references cited previously.

Research Based on Pope-Wilby Theory

A second program of research is based on acoustic power flow and Statistical Energy Analysis (SEA) theoretical concepts and includes experiments performed at Langley Research Center. Papers related to this research include Refs. 99, 108-112, 115, 116, and 123-126. The SEA theory has been in development for a long time.[70] Recent developments have included general theory extensions,[108] application to Space Shuttle payload bay noise,[123] and application to sidewall design for cabin noise control in high-speed turboprop aircraft.[115,116,124] As noted previously, the results of the turboprop study gave weight estimates quite similar to the estimates obtained by Lockheed-California Company even though the analytical methods and design procedures were widely different. Subsequent analytical developments[109-112] have been used for comparison with laboratory[125,126] and

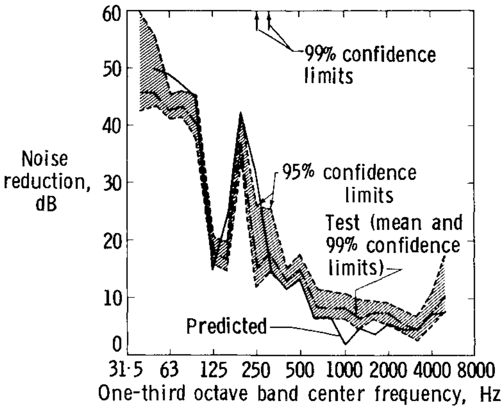
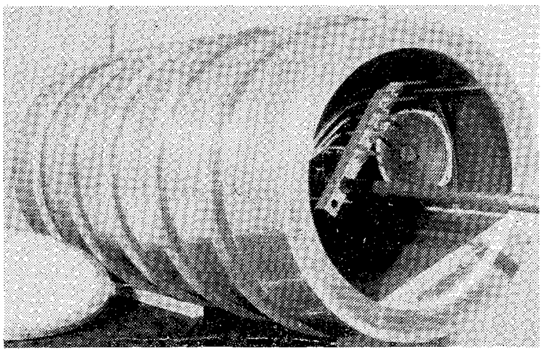
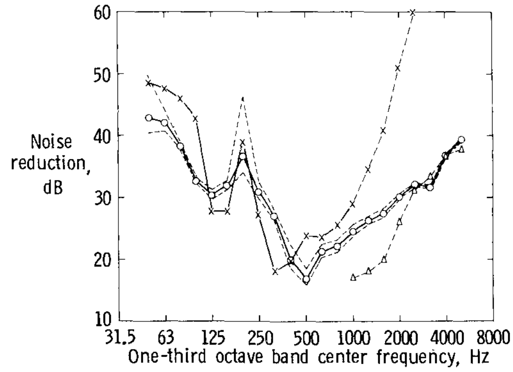


Fig. 27 Transmission of diffuse sound into an unstiffened cylindrical shell.[111] Diameter = 0.508 m, length = 1.2192 m, skin t = 1.6 mm.



a) Stiffened cylinder: interior view showing floor, microphone array, trim, and end cap insulation.



b) Noise reduction.

Fig. 28 Predicted and measured noise reduction of a stiffened cylinder with floor and trim (stringers exposed).[111] —0—, measured values; ---, 99% confidence intervals; —x—, predicted values; --x--, predicted with no stringer exposure; --Δ--, predicted with stringer exposure.

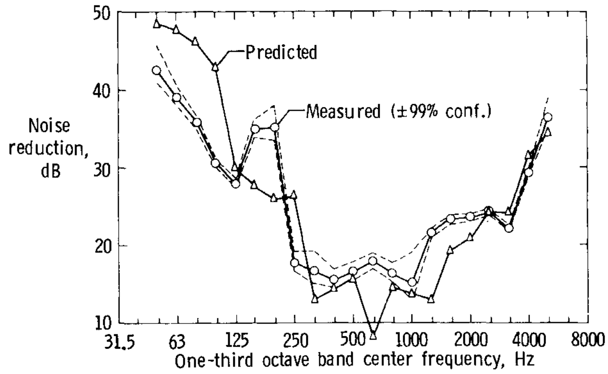


Fig. 29 Predicted and measured noise reduction of an unstiffened cylinder with floor and insulation.[111] —0—, measured values; ---, 99% confidence intervals; —Δ—, predicted using measured acoustic loss factors.

flight data.[99] Some of the comparisons are illustrated in Figs. 27-29.

Figure 27 shows noise reduction as predicted by the power flow methods and as measured on an unstiffened cylinder in a reverberant diffuse noise field. Substantial effort was expended in determining the cylinder frequency and damping characteristics, and in statistical analysis of the data to ensure that theoretical and experimental results would be directly comparable and that the theory used the correct shell dynamic properties. As shown in the figure, the overall agreement is excellent. It can be concluded from these results and the results shown in Fig. 21 that interior noise can be predicted accurately for simple shells in a reverberant noise field provided the theory uses measured properties such as damping.

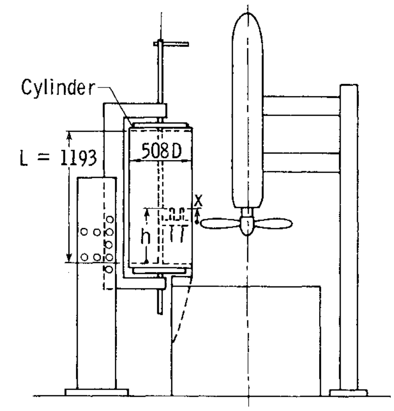
Results for a more complex shell (having stiffeners, a floor, and sidewall treatment) are shown in Fig. 28. Similar effort was expended on defining shell modes and damping characteristics. The agreement between test and theory at low frequencies is quite good, considering the complexities of the configuration. At high frequencies the internal radiation of the stringers was observed to be improtant, as predictions with stringer exposure and without exposure bracket the test results at frequencies between about 1000 and 3000 Hz. The importance of covering stringers and rings with treatment has been observed by others in laboratory tests and aircraft treatment studies. It would be useful to have quantitative methods to determine the effect of stiffener radiation for design in some weight-critical treatment installations.

Results for a cylinder model having a floor and absorption treatment but no stiffeners are shown in Fig. 29. The overall trend of the data is predicted quite well. The floor is attached to the cylindrical shell by structural connections, therefore, the structure is nonaxisymmetric. The nonsymmetry of both the structure and the interior acoustic spaces is taken into account rigorously in the analyses. This represents a significant advancement toward realistic representation of an aircraft fuselage for acoustic calculations.

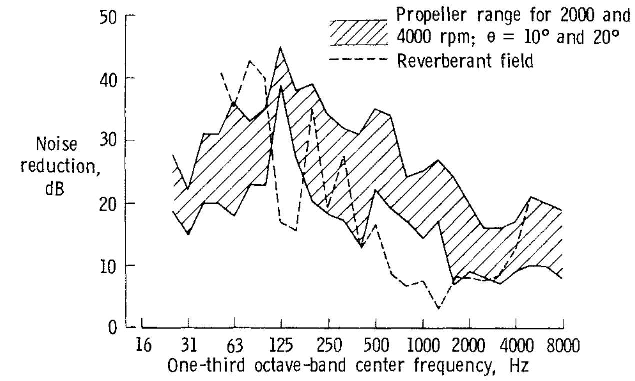
Realism of the noise source has been obtained by the use of model propellers in the laboratory noise transmission tests,[125] Fig. 30. The propeller is located in a vertical airflow to simulate aircraft forward speed. The noise pressures exerted by the propeller are determined using a (rigid) hardwood cylinder with flush-mounted microphones. Noise transmission measurements have been obtained for an unstiffened cylinder for a variety of propeller rpm and pitch angle (θ) values.[125] A summary of propeller results is shown in Fig. 30b. The results show that the noise reduction (NR) values for this cylinder are quite high at low frequencies, and that the propeller NR is substantially different from NR in a reverberant field at some frequencies, even though the NR for both sources has an overall trend of decreasing NR with increasing frequency. Ongoing work includes prediction of the propeller noise field using the methods described previously and prediction of the interior noise using the power flow/SEA methods.

A flight study of the interior noise of a twin-engine turboprop aircraft with a cylindrical fuselage has been carried out.[99] Flight tests were performed specifically for interior noise studies with a variety of rpm, power, altitude, cabin pressure, and sidewall treatment values. Comparisons with predictions of the power flow/SEA method also are under way.

Statistical energy analyses methods have been used also in a noise transmission study of a large-scale fuselage-type structure.[107] The test structure, Fig. 31a, simulates the forward section of an airplane fuselage, is 18 ft in diameter and 42 ft long, and was built for evaluation of an adhesively bonded primary structure. The noise reduction results shown in Fig. 31b were obtained using a speaker noise source. The theoretical method incorporates simplifications to provide an engineering prediction tool that does not require extensive computations. The damping value of $\eta_2 = 0.02$ is based on measurements.[107] Predictions using this value show good agreement with data ex-

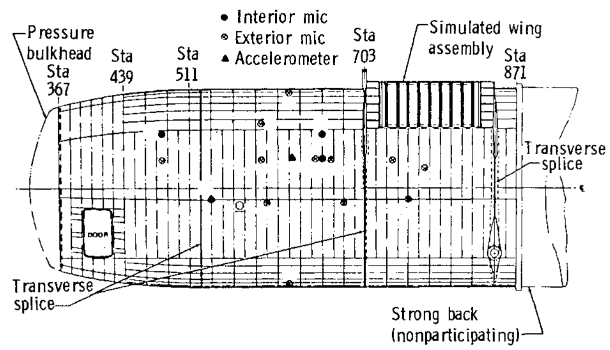


a) Test arrangement.

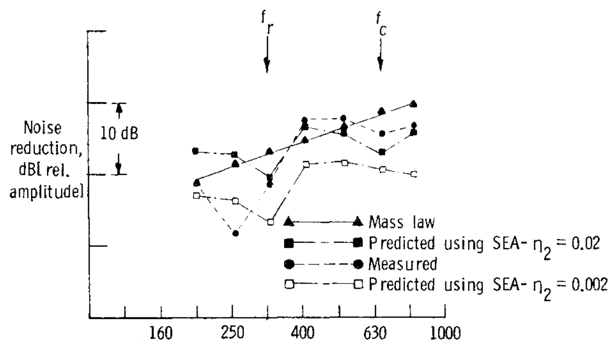


b) Noise reduction.

Fig. 30 Laboratory test of propeller noise transmission.[125] Propeller diameter = 0.381 m, cylinder diameter = 0.508 m.



a) Test structure.



b) Noise reduction.

Fig. 31 Noise transmission of a full-scale fuselage structure with diameter = 18 ft.[107]

cept at 250 Hz. Predictions using the smaller damping value $\eta = 0.002$ show that the NR is very sensitive to damping, consequently, new materials or joining techniques (such as adhesive bonding) that may reduce the damping of a structure may also require added damping for interior noise control.

Outlook for Future Airborne Noise Research

As indicated in the preceding sections, considerable progress has been made in defining and predicting interior noise levels and in the study of sidewall acoustic treatment for propeller-driven aircraft. Some areas for possible future research include improvement of the existing prediction capability, application to aircraft noise control in both preliminary design and final outfitting processes, examination of a variety of advanced concepts for cabin noise control, and preparation of analytical methods for future fuselage constructions such as advanced composite materials.

Improvements of existing theory are indicated in the areas of 1) multiple-layered sidewall treatment, and 2) increasing realism/detail of the structural acoustic model. As indicated in Figs. 12 and 13, the frequency range near the double-wall resonance is difficult to model for aircraft structures. Papers relating to multiple-layer treatments, including double walls and fiberglass absorbing materials, are listed as Refs. 127-144. Most of the existing interior noise prediction methods are based on the multiple-layer analysis of Beranek[127] and Beranek and Work[128] and use fiberglass properties measured by architectural standards.[134] Improved analysis is under development for bulk[129-132] or nonlocally[135] reacting models of the porous layers. The relation of the acoustical properties with the dimensional properties of porous materials is under study,[136-138] and manufacturers are considering the possibility of producing porous materials to acoustic specifications.[143] The benefits of tailoring a multiple-layer treatment for a particular acoustic application have been explored,[139-141] and the positive results suggest that the study be continued.

Analytical studies started with simple structural models and have followed an orderly process of increasing realism and complexity. To handle the irregularities, such as seats, overhead compartments, and bulkheads in the acoustic space, and floors and wing boxes in the structure, finite element methods may eventually be needed. Some finite element studies of interest have been conducted,[102,145-152] that may provide guidance for future applications to aircraft.

Sandwich construction may find increased use for aircraft both as a noise control measure, as previously discussed, and because of the structural advantages of high stiffness and low weight. Recent papers describing the continuing research on noise transmission through sandwich panels are listed as Refs. 153-167. Analysis of noise transmission through a sandwich panel is complicated by multiple modes of vibration involving flexural and dilatational motions and by sensitivity to core shear stiffness. Further complications may be introduced if the face plate or core material is nonisotropic. This complexity, however, provides more parameters that can be varied in a search for optimum acoustic designs.[160,164] The positive results obtained in these investigations suggest that further study should be useful.

The search for lighter-weight approaches to cabin noise control has included study of tuned structural elements[168-172] and active noise control.[173-175] Tuned element studies work either with the existing skin-stringer frame structure or with added spring-mass components to develop resonances that act as vibration absorbers. Promising results have been obtained for both approaches in particular applications.[19,169] Additional theoretical study appears to be required (and worthwhile) in order that reliable design procedures for general use can be developed.

Advanced composite materials, such as graphite or Kevlar fibers in an epoxy matrix, are being used increasingly for

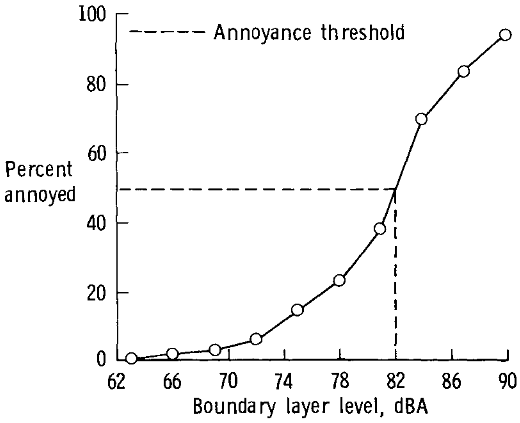


Fig. 32 Cumulative distribution of subjective annoyance response to broadband noise.[29]

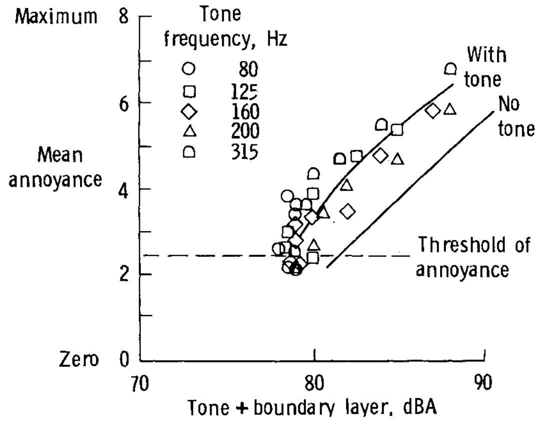


Fig. 33 Subjective response to combined noise signatures. Broadband level for tone tests = 78 dBA.[29]

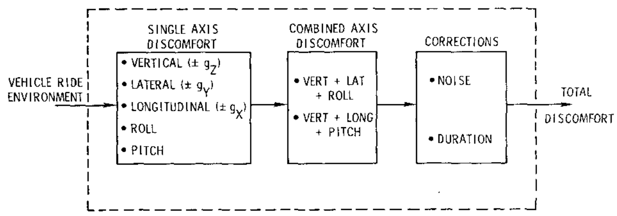


Fig. 34 NASA Langley Ride Quality Model.[28]

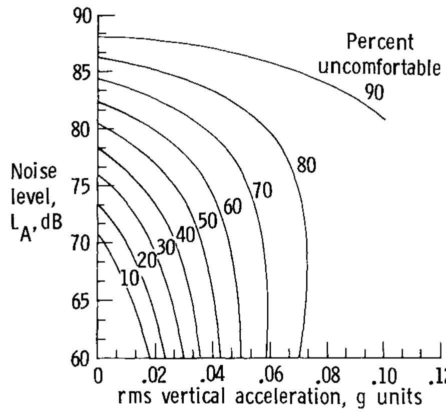


Fig. 35 Contours of A-weighted noise level and rms vertical acceleration that produce constant values of discomfort.[185]

fuselage structures. Prototype general-aviation aircraft have been constructed[176] and studies are under way for application to larger aircraft. The composites have weight and stiffness advantages for structural design; however, very little information is available on the noise transmission properties. Some studies indicate advantages at low frequencies where noise transmission may be stiffness controlled,[177,178] but the higher stiffness-mass ratio may bring the coincidence frequency into a frequency range where the added noise transmission is a disadvantage. Theoretical and experimental studies have been initiated[179-182] recently to begin study of noise transmission in composite structures.

Passenger Response

Research investigations related to passenger response to noise have included laboratory studies of particular aircraft noise signatures,[28,29,185,187] studies aimed at development of a generalized ride quality prediction model including both noise and vibration,[28,184,186] and flight studies of passenger satisfaction, including such factors as seat width and cabin temperature, as well as noise and vibration.[183]

Laboratory studies of the effects of propeller tones in aircraft interior noise have been carried out in an anechoic chamber and in the Passenger Ride Quality Apparatus (PRQA) at Langley Research Center. The anechoic chamber measures 7.3-ft high × 8.1-ft wide × 12.25-ft long at the inner edge of the wedges. Tests were carried out with two subjects at a time seated facing the speaker, which was located at about eye level at the other end of the chamber. Results obtained in the chamber are presented in Figs. 32 and 33. In the first of two studies, the subjects were asked to rate various boundary-layer noise stimuli as either annoying or not annoying. The stimuli had identical spectral characteristics and differed only in terms of A-weighted sound pressure level. A total of 28 subjects experienced each of the boundary-layer noise levels, which were randomized and counterbalanced before presentation.

In the second study, 120 noise stimuli were formed from factorial combinations of five tone frequencies (80, 125, 160, 200, and 315 Hz), three boundary-layer levels (78, 82, and 86 dBA), and eight tone levels (70-98 dB). Subjective responses were obtained using both a dichotomous (annoying/not annoying) scale and a unipolar eight-point category scale anchored by the adjectives "not annoying" and "extremely annoying." Both studies used signal durations of about 30 s.

Annoyance threshold for the boundary-layer noise is defined as the A-weighted level at which 50% of the subjects were annoyed. This level was determined from the data of Fig. 32; which gives the proportion of subjects at each boundary-layer level that rated that level as annoying. The dashed lines indicate that annoyance threshold was approximately 82 dBA. This reflected the annoyance threshold in the absence of tones and provided the basis for selecting the noise levels used in the second study.

The effect of adding single tones at each frequency to a boundary-layer noise level of 78 dBA is shown in Fig. 33. This figure indicates that the mean annoyance ratings (averaged over subjects) increased as the A-weighted sound pressure level of the combined stimuli increased. Since boundary-layer noise level was constant, the increase in combined level was due to the presence of the tone, i.e., increasing tone-noise ratio. Included for comparison is the annoyance response curve for boundary-layer noise along with the threshold of annoyance indicated by the dashed line. These data show that, for equal A-weighted sound pressure levels, the combinations of tones and noise were evaluated as more annoying than the noise presented alone.

Results similar to those in Fig. 33 were obtained from tone studies[28] conducted in the PRQA. The PRQA provides a very realistic simulation of an aircraft cabin interior. The similarity of the results indicates that the test facility does not have a large effect on the overall nature of the test results.

A generalized model for estimating passenger ride comfort in the presence of combined noise and vibration has also been developed.[184,186] Elements of this generalized ride quality model are illustrated in Fig. 34. Input to the model is the passenger vibration and noise environment for the vehicle of interest and output of the model is the total discomfort measured along a single number discomfort scale. Development of the model has involved 1) empirical estimation of discomfort due to sinusoidal and/or random vibration in a single axis, 2) empricial estimation of the discomfort due to vibration in combined axes, and 3) application of empirically determined corrections for the effects of interior noise and duration of vibration. Much of the empirical information was obtained from tests using the PRQA, which is capable of rigid-body motions in three axes at a time at frequencies up to about 30 Hz. The development of this model is described in Ref. 184. A computer program for calculation of the discomfort value using these empirically derived relations has been incorporated into a hardware package along with instruments for measuring the vehicle vibration and noise environment. The package is portable, so the discomfort value can be obtained in real time with the package installed in a vehicle in motion.

An important part of this model development has been the inclusion of combined noise and vibration effects on passenger comfort. Tests were conducted in the PRQA wherein a variety of combined noise and vibration environments were rated for comfort by subjects who were either from the general public or were helicopter pilots. Similar results were obtained from both groups of subjects. Results obtained for helicopter pilots who rated environments typical of routine helicopter flights are shown in Fig. 35. The curves shown were obtained by applying a contour-generating computer program to a data base consisting of ratings by 35 pilots of 120 environments. The program used least-squares fitting to determine values of A-weighted noise level and rms floor acceleration that produce constant values of comfort rating. The data shown in Fig. 35 are considered preliminary because of the limited number and type of subjects and because of the use of laboratory-simulated environments. The curves show a strong interaction of noise and vibration. For example, starting at a point having 75 dBA and 0.06 acceleration, near the curve for 70% uncomfortable, the figure shows that reduction of the noise level alone would not result in much improvement, but that acceleration would also need to be reduced.

These research studies are intended to provide only parameter variation relations between environment and passenger response that can be used along with other factors, e.g., economics and vehicle mission, in the design process. The design of some vehicles may require consideration of other factors in addition to overall noise and vibration levels. For example, the cabin noise of advanced high-speed turboprop aircraft has been estimated to be dominated by the low-frequency propeller blade passage tone.[117] Cabin comfort requires not only an acceptable overall level, but also an absence of excessive low-frequency "booming" and excessive high-frequency "hissing," and a speech interference level low enough to allow conversation between neighboring seats but not so low that distant conversations intrude on privacy.[23] Therefore, spectrum shape considerations may be an important future research area for aircraft such as advanced turboprops.

Concluding Remarks

This paper has presented a review of recent research related to propeller aircraft interior noise control. The subjects covered are propeller noise, airborne noise transmission, and passenger response to cabin noise and vibration. Most of the work described has been published since about 1979. A number of accomplishments, illustrating the large number of research contributions in the 187 references, are presented and discussed in enough depth to identify the state-of-the-art. The reference list has been made as complete as possible for those readers interested in more depth and additional information. The topics of structureborne noise, source-path identification, and helicopter cabin noise are also important, and there is active research under way, but review of these topics is left for the future.

This review shows that a great deal of progress has been made on description and prediction of propeller noise, airborne noise transmission, and passenger response. A number of theoretical methods of propeller noise prediction have been developed and shown to be reasonably accurate by comparison with laboratory and flight data for single propellers operating in clean aerodynamic flow. Performance and noise parameter studies have led to noise-reducing blade configurations for both low- and high-speed propellers. Areas for future study include counterrotating and pusher configurations and further application of existing prediction methods for direct input to interior noise analytical studies. Recently initiated work on the interaction of propellers with a fuselage and cabin has shown potential for noise reduction through the "upsweep-downsweep effect" and "synchrophasing."

Theoretical methods for predicting cabin noise resulting from sidewall transmission have been developed for aircraft having rectangular- and cylindrical-type fuselage shapes. A series of comparisons with results from tests varying from simple unstiffened flat panels or cylindrical shells to aircraft in flight has shown reasonable accuracy for many test conditions, but important differences for others. Studies of noise control approaches, such as optimization of multiple-layer treatments, honeycomb stiffening of skin panels, and increased cabin absorption, have shown some potential for improved noise control. Areas for future study include improving the accuracy of the prediction methods (perhaps using an improved multiple-layer transmission model), continued use of the prediction methods for noise control applications, and development of theory for novel noise control approaches such as tuned mechanical vibration absorbers and active noise control.

Passenger response research has included laboratory studies for specific environments such as propeller or helicopter cabin noise and for a general model of passenger comfort including both noise and vibration. Propeller noise studies show that propeller noise environments are rated as less comfortable than broadband environments when the A-weighted noise levels are equal. An area for future study is the relative interaction of overall noise level, A-weighted noise level, and speech interference level in determining passenger comfort. A general model for passenger comfort has been developed and incorporated into a portable meter that can be carried on board to display a numerical comfort rating of the noise and vibration environment while the vehicle is in operation.

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