Theoretical Design of Acoustic Treatment for Noise Control in a Turboprop Aircraft

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An analytical procedure has been developed for design of acoustic treatment for cabin noise control of light aircraft. Using this approach acoustic add-on treatments capable of reducing the average noise levels in the cabin by about 17 dB from the untreated condition are developed. The added weight of the noise control package is about 2% of the total gross takeoff weight of the aircraft. The analytical model uses modal solutions wherein the structural modes of the sidewall and the acoustic modes of the receiving space are accounted for. The input noise spectral levels are selected utilizing experimental flight data. The add-on treatments include aluminum honeycomb panels, constrained layer damping tape, porous acoustic materials, noise barriers, limp trim panels, and tuned dampers. To reduce the noise transmitted through the double-wall aircraft windows to acceptable levels, changes in the design of the aircraft window are recommended.

Introduction

PROPELLER and turbulent boundary-layer noise transmitted through the sidewalls is the dominant source of interior noise for many propeller-driven aircraft. The traditional approaches of cabin noise control which rely largely on damping, mass, and porous acoustic material treatments do not seem to provide the required noise attenuation in these aircraft. Improved methods of reducing this noise to obtain a comfortable passenger environment are needed.

The aircraft considered in the present study is a twin-engine light aircraft, Fig. 1. Flight tests indicate that an acoustic treatment capable of reducing the average overall noise levels in the cabin by about 17 dB compared to the untreated cabin is desirable. Theoretical analyses of noise transmission have been developed to assist in the design of such a treatment. The basic concept of the theoretical model is that of modal analysis[1-3] and the acoustic impedance transfer.[4-6] A similar approach has been used for interior noise optimization of a small twin-engine aircraft corresponding to inputs measured at the ground conditions.[7] These methods have been extended for design of noise control treatments of the aircraft shown in Fig. 1 under flight conditions.[8] Improved analytical methods of noise transmission prediction through flexible panels[9] and double-pane windows[10] are incorporated in the present study. The analyses are compared with test data under laboratory and flight conditions.

The acoustic treatments considered herein include aluminum honeycomb panels, constrained layer damping tape, porous acoustic materials, noise barriers, limp trim panels, tuned dampers, and changes in aircraft window design. This work is focused on evaluating the advantages and disadvantages of these treatments for noise control and then designing a candidate acoustic treatment which reduces noise in the cabin to a satisfactory level.

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Analytical Models

The analytical models of noise transmission are developed for the aircraft and the NASA Langley Research Center Transmission Loss Apparatus.[11] For the latter case, a specially designed panel which closely represents a segment of the aircraft sidewall was constructed.[12] To determine the noise transmitted into these enclosures, solutions of interior sound pressure, sidewall panel vibrations, and sound propagation through multilayered treatments are needed.

Acoustic Model

The interior space of the aircraft is approximated by a rectangular enclosure.[2,7,8] It is assumed that the main contribution to the cabin noise is due to the airborne noise transmitted by the sidewalls and, that the noise transmitted through the remaining surfaces is either relatively small or can be controlled by conventional add-on treatments. Such an assumption seems justified due to the very stiff floor and ceiling construction and their greater distance from the propeller tips (Fig. 1).

The solution for the acoustic pressure p inside the cabin can be obtained by solving the acoustic wave equation for the idealized rectangular enclosure. Such an idealization of the cabin allows for simple representation of the acoustic modes. The contribution to noise losses due to interior absorption from treated ceiling, floor carpeting, seats, passengers, etc., is included as "equivalent" acoustic damping.[1,7] A point impedance model is used to include the effect of wall absorption.[4,6,7] The solutions for acoustic pressure p are obtained by first transforming the time-dependent boundary conditions into the governing acoustic equation and then using model expansions and a Galerkin-like procedure.[3,7,8] After these solutions are known, the theory of random processes is used to obtain the spectral density of sound pressure, $S_p(x,y,z,\omega)$.[13] The sound pressure levels in the cabin are then obtained from

$$\mathrm{SPL}(x,y,z,\omega)=10\log\{S_p(x,y,z,\omega)\Delta\omega/p_0^2\} \tag{1}$$

where ω is the circular frequency, $\Delta\omega$ the selected frequency bandwidth, p_0 the reference pressure ($p_0=2.9\times10^{-9}$ psi, 20 μN/m^2), and x,y,z the spatial coordinates. A quantity relating the spectral density in the cabin to the input spectral density of the exterior surface pressure $S^e(x^*,y^*,\omega)$ is the noise reduction NR, defined as

$$\mathrm{NR}(x,x^*;y,y^*;z,\omega)=10\log\{S^e(x^*,y^*,\omega)/S_p(x,y,z,\omega)\} \quad (2)$$

where x^*,y^* denote the spatial locations at which the external input is prescribed.

The interior sound pressure levels given by Eq. (1) correspond to the noise transmitted by a stiffened panel unit which might be composed of several single panels or windows located either on the port or starboard side of the aircraft (see Fig. 2). The total noise transmitted by all of the panel units composing the entire sidewall is determined by superposition of the sound pressure contributions from all of the vibrating panel units. Such a superposition is used with the assumption that the vibration of each structural unit is independent. The advantages and limitations of the structural model is discussed in the next section.

The general solution procedure of noise transmission through a stiffened panel in the transmission loss apparatus[11] is similar to that of noise transmission through the aircraft sidewall. However, the input acting on the aircraft fuselage is composed of convecting propeller and turbulent boundary-layer noise, while the input for laboratory testing is taken as a random reverberant field.[14]

Structural Model

The sidewalls of the aircraft shown in Fig. 1 are composed of 0.063-in.-thick external skin stiffened by frames and longerons and several single- and dual-pane windows. The exact dynamic analysis of such a structure is too complicated and a simplified model needs to be constructed. For the structural model of the present study, Fig. 2, the aircraft sidewall is segmented into four stiffened skin-stringer panels, two single panels, and six windows. The noise transmitted through other surfaces of the sidewall is neglected. Such a segmentation offers significant advantages for noise transmission path identification and computational simplification. However, this procedure is best applicable for the intermediate- to high-frequency ranges. The lowest modal frequencies calculated for window unit 1 and stiffened panel unit 11 are 114 and 134 Hz, respectively. Measurements tend to indicate the presence of several frame-wall modes in the frequency range 48-104 Hz. Thus, the segmented structural sidewall model does not account for the frame-wall modes below the frequency of about 110 Hz. To develop accurate solutions for low frequencies, numerical techniques such as the finite element method can be used.[15] Since the A-weighted interior noise in this aircraft is dominated by the second, third, and fourth (152, 228, and 304 Hz) propeller blade passage harmonics, the idealization of the sidewall into several independent units seems to be justified.

The solution for the sound pressure levels and noise reduction calculated from Eqs. (1) and (2) is a function of the structural response of each of the panel units shown in Fig. 2. The panel response is obtained by solving the governing equation of plate vibrations using a modal expansion method.[1-3,14] In this procedure, the cavity and radiated pressures are not included when calculating panel response. However, the effect of radiation damping is accounted for by increasing the structural damping.[6] For built-up structures such as aircraft sidewalls, acoustic radiation damping could be a significant means of vibrational energy dissipation. For relatively deep acoustic enclosures, the effect of cavity pressure on panel response is relatively small and can be neglected.[16,17] To complete solutions for panel response and subsequently for the cabin noise pressure, the natural frequencies and normal modes of the sidewall panels need to be known.

The panel units (Nos. 4 and 6) and the port-side pilot window (No. 1) are taken to be rectangular simply supported plates for which the natural frequencies and normal modes are obtained from the formulas given in Refs. 7 and 8. The effect of pressurization is included through the in-plane forces.[14] Panels 9-12 are stiffened with frames. The frames are thin-wall members of an open cross section.[8] The geometric and section properties of these stiffeners were calculated by dividing the cross section into a number of subelements and then using the general theory of thin-walled open sections.[18] The natural frequencies and normal modes of the stiffened panels were determined by the finite element-strip[19] and transfer matrix[2,7,13] methods. These results are presented in Ref. 8.

The double-wall aircraft windows (Nos. 2, 3, 5, 7, 8), Fig. 2, are composed of curved external and flat internal plexiglass panes. A simplified geometry of the window construction is used. The airspace between the two sheets is approximated by a uniformly distributed air spring of average depth. A linear spring-dashpot model is used to characterize the behavior of the air spring. Then, a simple double-wall structural model is constructured where both plexiglass plates are taken to be flat and simply supported on all four edges.[14] To account for the effect of the curvatures of the outside panel, the stiffness of the outside pane is increased accordingly. A detailed analysis on the structural dynamic characteristics and modal frequencies is given in Refs. 10 and 14. There are two real characteristic values for each set of modal indices. These values are associated with the in-phase flexural and out-of-phase dilatational vibration frequencies of the double-wall system. The dilatational modes could be the main contributors to noise transmission at some frequencies.[9,20]

The structural model for the laboratory tests is a built-up panel that closely represents a segment of the aircraft sidewall in the propeller plane as given in Fig. 2. The details of the panel construction can be found in Refs. 12 and 21. For frequencies up to about 160 Hz an orthotropic plate model where the effect of stiffeners is "smeared" into an equivalent skin is used to calculate modal frequencies.[22] For the frequency range between 160 and 1100 Hz, the structure is segmented into several individual panel units and one discretely stiffened panel. The modes and natural frequencies of the individual panels are obtained from available methods,[17] while for the discretely stiffened panel they are calculated by the finite element-strip method.[19]

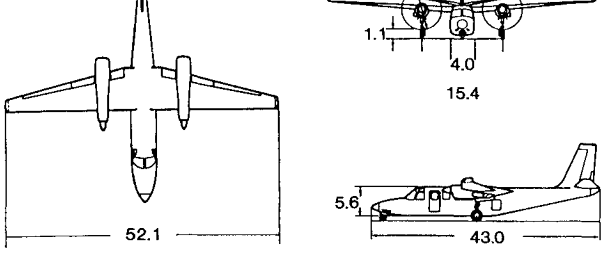

Fig. 1 Twin-engine aircraft used in noise transmission study (dimensions in feet).

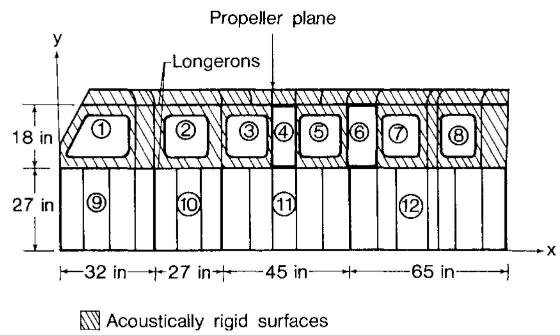

Fig. 2 Aircraft sidewall model used for noise transmission analysis.

External Pressure Field Model

The external surface pressure acting on the aircraft is propeller and turbulent boundary-layer noise. For frequencies up to about 700 Hz, propeller noise due to blade passage harmonics is the dominant noise source for this aircraft. In the present study, the input pressure field is treated as a random process with a prescribed cross spectral density function.[6-8] The sound pressure levels are taken to be distributed uniformly over each panel surface, but varying in a stepwise fashion from one panel to another. These inputs are obtained from flight data. In addition, the empirical predictions of propeller noise are utilized to distribute the sound pressure levels over the aircraft fuselage.[23] The trace velocity corresponding to the y direction was taken as the propeller rotation tip speed while sonic trace velocities were assumed for the longitudinal direction x (normal to the propeller rotation plane). The turbulent boundary-layer noise was taken to be fully correlated and distributed uniformly over each panel surface.

For the laboratory study of noise transmission, the input is taken as a random reverberant pressure field. The spatial correlation coefficients and generalized random forces are given in Ref. 14. A more detailed discussion of the sound characteristics in the source room of the transmission loss apparatus is given in Ref. 11.

Insertion Loss Model

The insertion losses due to add-on treatments which have no marked effect on the structural vibrations (porous acoustic materials, noise barriers, and trim panels) are calculated by the impedance transfer method.[4,6] In this case, the treated structure is assumed to be an infinite, stiffened, and pressurized panel. The sound impinges on the panel at an angle θ_I relative to the normal and an azimuthal angle ϕ relative to the x axis, as shown in Fig. 3. Following the procedure given in Ref. 6, the transmission coefficient τ and the insertion loss ΔTL can be obtained from

$$\tau(\omega,\theta_I,\phi)=\left|\frac{(p_I/p_2)_{\text{untreated}}}{(p_I/p_2)\cdots(p_{n-1}/p_n)_{\text{treated}}}\right|^2 \tag{3}$$

and

$$\Delta\text{TL}(\omega,\theta_I,)=-10\log\{\tau(\omega,\theta_I,\phi)\} \tag{4}$$

where p_{n-1}/p_n are the pressure ratios across the different layers of the add-on treatments. The pressure ratio p_I/p_2 is across the skin-stiffener panel requiring the information of the bare fuselage impedance. The interior of the medium is assumed to extend to infinity with an acoustic termination impedance ρc. Numerical results were obtained for treatments composed of up to eight different layers and the elastic skin-stiffener panel. These treatments include porous acoustic materials, noise barriers, and limp trim panels. The impendances for the porous acoustic materials were calculated from the relations given in Refs. 4-6. Experiments tend to indicate that for tightly packed porous materials,[12] the empirical expressions given in Refs. 4-6 might be the appropriate means to model the propagation constant corresponding to semirigid materials.

The numerical results were obtained by assuming a predominant convection field along the x axis for which the azimuthal angle $\phi=0$. The effect of field incidence transmission is considered by defining an average transmission coefficient.[4] The sound pressure levels in the cabin are calculated from

$$\text{SPL}(x,y,z,\omega)\,|_{\text{treated}}=\text{SPL}(x,y,z,\omega)\,|_{\text{untreated}}-\Delta\text{TL}_0(x,y,z,\omega)-\Delta\text{TL}(\omega) \tag{5}$$

where ΔTL_0 are the noise losses due to treatments directly attached to the aircraft skin (honeycomb panels and damping tape) and ΔTL the insertion losses due to all other treatments calculated from Eq. (4).

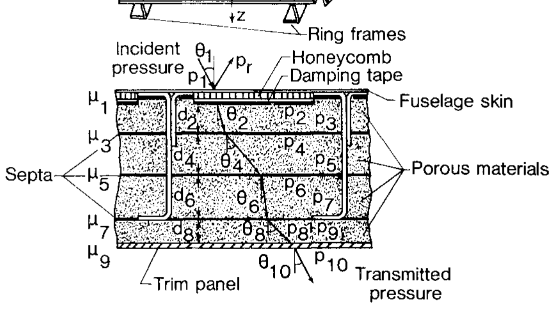

Fig. 3 Sidewall representation of multilayered add-on treatments and pressure field configuration.

Numerical Results

The numerical results presented herein include the noise reduction of a specially designed sidewall panel in the transmission loss apparatus, interior noise in the aircraft under flight conditions, parametric study of add-on treatments for noise control, and design of an acoustic treatment for interior noise optimization in a light aircraft.

Transmission Loss Apparatus

As a first step in the validation of the theory, predictions and tests were performed for a panel installed in the transmis-

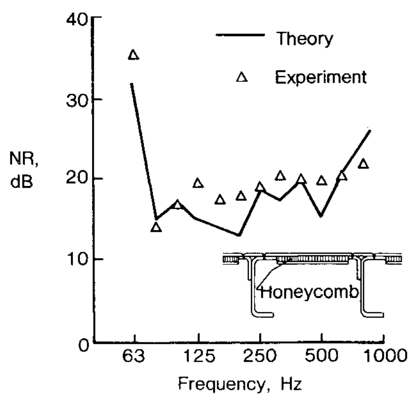

Fig. 4 Noise reduction of the panel treated with honeycomb in the transmission loss apparatus.

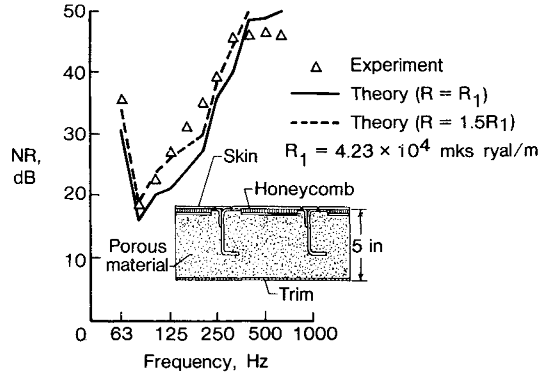

Fig. 5 Noise reduction of a sidewall panel treated with honeycomb, porous acoustic material, and trim in the transmission loss apparatus.

sion loss apparatus facility.[21] The noise inputs were measured at several positions close to the panel surface by a stationary microphone. A spatially averaged value of source pressure was selected for noise-reduction calculations and measurements. Transmitted noise was measured by a stationary microphone located at about the middle of the panel and 66 in. from the panel surface.

The analytical calculations were obtained for a constant structural modal damping ratio ζ_0 and acoustic modal damping $\alpha_{ijk} = \alpha_0(\omega^\ell/\omega_{ijk})$. ζ_0 and α_0 are the damping coefficients of the fundamental modes, ω_{ijk} the acoustic modal frequencies, ω^ℓ the lowest modal frequency in the receiving room, and i,j,k the modal indices. For the present study, it was assumed that $\zeta_0 = 0.03$ for the untreated sidewall panel and 0.05 for the case where honeycomb panels are attached to the interior surface (receiving room side) of the skin. These damping coefficients are taken to be representative of the overall damping which includes material, structural, and acoustic radiation damping.[6] The acoustic damping in the receiving room α_0 is taken to be equal to 0.005. This damping model is assumed to be a simplified representation of equivalent acoustic damping in a room with hard walls.

To investigate the effect of skin stiffening, lightweight treatments in the form of honeycomb panels were attached to the interior side of the skin. For this purpose, aluminum honeycomb sandwich construction with a core thickness of 0.25 in. and a face plate thickness of 0.032 in. was selected. The surface density of this treatment is about 0.68 psf. Figure 4 shows theoretical and experimental noise reductions of the stiffened panel treated with honeycomb. In general, the agreement between theory and experiment is good in view of the complexities involved. The bending stiffness of the honeycomb-treated panels was calculated utilizing the approximate relations given in Refs. 14 and 24. About 4-5 dB of noise attenuation is achieved in the 80-400-Hz frequency range with the honeycomb add-on treatment. However, for frequencies above 400 Hz, lower values of noise reduction were measured for treated panels. The noise reduction in this frequency range seems to be influenced by the coincidence effect at the critical frequency.[4,21] The critical frequency of a sandwich construction composed of 0.063-in. skin, a 0.25-in. honeycomb core, and a 0.032-in. face plate is about 1000 Hz. However, the presence of heavy stiffeners could reduce the critical frequency of this panel further.

To simulate a treated sidewall, porous acoustic materials and a 0.5 psf lead impregnated vinyl trim was added to the honeycomb-treated panel. These results are presented in Fig. 5. The theoretical predictions are given for two values of flow resistivity R. Data on flow resistivity of the acoustic material used for the present study do not seem to be available. However, it is assumed that these values are larger than $R = 4.23 \times 10^4$ rayl/m commonly used for AA-type acoustic blankets. From the results shown in Fig. 5, it can be seen that similar noise reduction trends are predicted by theory and experiment. However, significant differences occur at some frequencies. These differences might be attributed to the limitations of the impedance transfer method used to calculate insertion loss for finite panels and uncertainties associated with structural and acoustic damping, and material properties of acoustic materials. Addition of a limp trim panel provides a significant amount of noise attenuation for frequencies above 125 Hz. Additional results of the experimental study can be found in Ref. 21.

Noise Transmission into Aircraft

Noise transmission measurements were obtained for the aircraft shown in Fig. 1 for normal cruise at 214 knots, maximum continuous power at 96% rpm, and an altitude of 16,000 ft. This aircraft has a maximum takeoff weight of about 11,200 lb, a standard cabin layout for a pilot and seven passengers, a pressurized cabin environment, and a 35,000-ft operational ceiling. Operating at 1500 rpm during cruise, the propeller blade passage frequency is 75 Hz and the tip speed 692 ft/s. The cabin height, width, and length are 4.76, 4, and 17.5 ft, respectively. Flight-test results are reported for one acoustic treatment configuration that is similar to the standard soundproofing treatment used in this aircraft. This configuration includes a constrained layer damping tape attached to the aluminum skin, four layers of porous acoustic blankets, two layers of lead vinyl septa, and a foam-rubber-type sandwich noise barrier. The combination of the treatments and surface density varied with location in the cabin.[25] The heaviest treatment of about 2.25 psf was applied in the vicinity of the propeller rotational plane. The hard-plastic trim panels were not installed for these tests. However, the trim condition of a "limp" panel was simulated by the presence of the noise barrier located at about 2.5-3 in. from the fuselage skin.

Cabin noise measurements were obtained at six locations in the aircraft.[25] Measured exterior sound pressures were used to model the inputs for the analytical noise transmission predictions. The details of the theoretical computational procedures can be found in Refs. 8 and 10. The one-third octave A-weighted cabin noise levels are shown in Fig. 6 for the treated conditions. These results correspond to a location in the propeller plane and about 8 in. from the skin. Similar trends of interior noise are predicted by theory and experiment. The structural modal damping, $\zeta_0 = 0.02$ and 0.05, was used for sidewall panels and dual-pane windows, respectively. The equivalent acoustic modal damping of the untreated cabin was assumed to be equal to 0.03.[1,2] To account for the acoustic absorption in a treated cabin, the acoustic modal damping coefficient was increased to 0.05. The main contribution to noise attenuation of the heavy treatment occurs at frequencies above 300 Hz. The results tend to indicate that the multilayered acoustic treatments do not provide the required noise attenuation for frequencies below 300 Hz where the propeller inputs are the highest.

Parametric Evaluation of Add-on Treatments for Noise Control

A theoretical parametric study has been carried out to evaluate a variety of candidate treatments for noise transmission control.[7,8] Due to space limitations only the key results are presented here.

From the results presented in Fig. 4 and Refs. 7 and 24, it can be seen that stiffening a sidewall with honeycomb panels could provide 4-6 dB of noise atttenuation in the critical frequency range of 70-300 Hz. In order to investigate the effect of a honeycomb add-on treatment for this aircraft, calculations of noise transmission were made for several sidewall treatments. Modal frequencies were calculated assuming simply supported edges for all of the panels shown in Fig. 2. Approximate relations given in Refs. 7 and 24 were used for single panels (Nos. 4 and 6) and the finite element-strip method[19] for the skin-stringer panels (Nos. 9-12). These results are given in Ref. 8. It was found that about 6-8 dB of additional noise reduction can be achieved at the first three

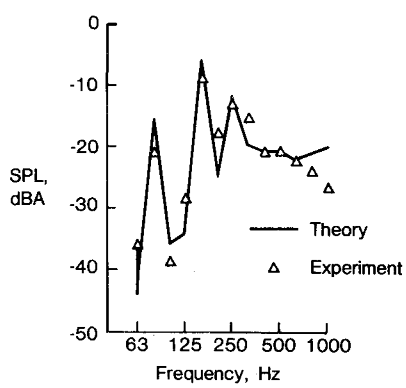

Fig. 6 Normalized interior noise levels in the aircraft treated with a heavy soundproofing package for flight conditions.

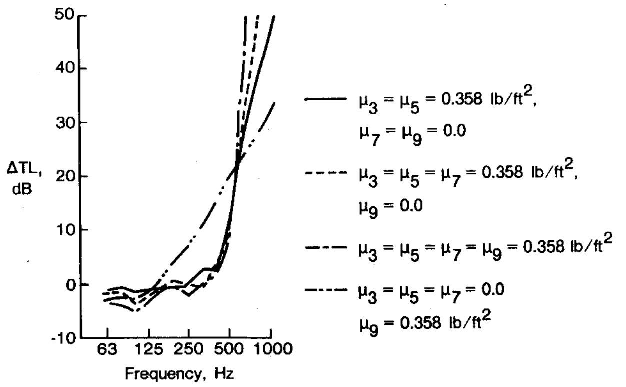

Fig. 7 Insertion loss of noise barriers and porous acoustic materials.

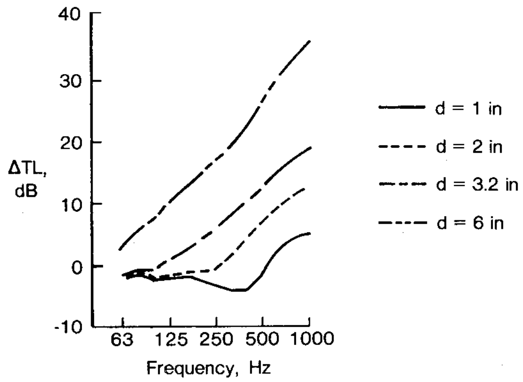

Fig. 8 Insertion loss of porous acoustic material for different cavity depths ($\mu_3 = \mu_5 = \mu_7 = 0$, $\mu_9 = 0.1$ psf).

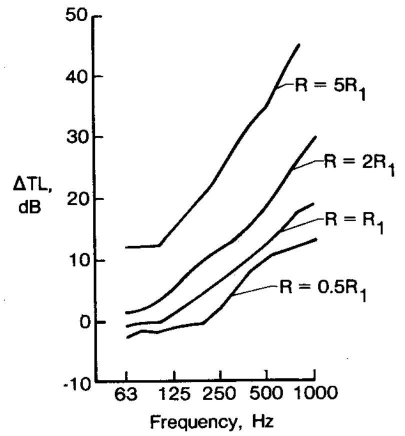

Fig. 9 Insertion loss of porous acoustic materials with different values of flow resistivity (treatment thickness = 3.2 in., $\mu_3 = \mu_5 = \mu_7 = \mu_9 = 0$, $R_1 = 4.23 \times 10^4$ mks ryal/m).

propeller blade passage harmonics by a 0.68 psf honeycomb treatment. However, the gains above 400 Hz are relatively small.

Noise transmission was also calculated for treatments composed of damping tape and nonload carrying mass. The structural modal damping coefficient was increased from 0.02 (untreated) to 0.05 for panels treated with damping tape. Approximately 6-8 dB of additional noise reduction is achieved at the second and third propeller blade passage harmonics. However, at the first blade passage harmonic, negative values of insertion loss were calculated.

Insertion losses ΔTL were calculated for a variety of multilayered treatments shown in Fig. 3. The spaces denoted d_2, d_4, d_6, and d_8 are filled with porous acoustic materials. The surface density μ_I is the total average surface density of the sidewall which includes skin, frames, longerons, straps, etc., and add-on treatments which are attached to the skin (honeycomb panels and damping tape). Numerical results were obtained for $\mu_I = 3.18$ psf. The surface densities μ_3, μ_5, and μ_7 correspond to the various noise barriers which separate the different layers of porous acoustic materials. The surface density μ_9 denotes the trim panel assumed to be isolated from the vibrations of the main aircraft structure.

The effect on ΔTL of a multilayered acoustic treatment is given in Fig. 7. Comparison of these results with the results of a single-layer treatment located at the trim panel indicates that in the frequency range of 60-500 Hz the multilayered treatment is not beneficial for noise transmission control. The insertion loss of a porous acoustic material and very light trim is shown in Fig. 8 for several cavity depths. The cavity depth is obtained from $d = d_2 + d_4 + d_6 + d_8$. These results indicate that noise attenuation increases with increasing cavity depth. The distance between the exterior skin and the trim panel of the aircraft shown in Fig. 1 ranges from about 2.2 to 3.4 in. Noise attenuation of porous acoustic materials having different flow resistivity values is given in Fig. 9. These results suggest that an increase in R is beneficial; however, the results shown should be interpreted with caution. As the flow resistivity of an acoustic material becomes large, the noise transmission characteristics of such a material would tend to approach mass law corresponding to an impervious limp septa. Thus, the analytical models used to calculate ΔTL of porous materials would not be applicable in this case.

The design of the aircraft shown in Fig. 1 includes 12 sidewall windows, a windshield, and two eyebrow windows with a total window area of about 22 ft^2. The results given in Ref. 10 suggest that windows could present a potential problem for cabin noise control. Therefore, a parametric study of noise transmission through aircraft windows was undertaken to design a window best suited for noise control in this aircraft.[10] The basic findings of this study can be summarized as follows. The addition of mass with no stiffness change to the outside (curved) pane only has a minor effect on noise reduction in the frequency range of 100-300 Hz. Since the exterior pane merely provides vibration coupling to the interior pane via the air gap, direct application of mass law to calculate noise attenuation of the dual-pane system is not valid in this case. Addition of 2-psf mass to the interior pane could provide about 4 dB of additional noise reduction at the second and third propeller blade passage harmonics. The insertion loss due to an increase in the plexiglass thickness of the exterior and interior panes could provide additional noise reduction. These results tend to indicate that increasing the thickness of the exterior pane could be very effective because of the stiffness increase for noise transmission control in the critical frequency range of 70-300 Hz. Similar trends were observed from tests of dual-pane windows.[26] The theoretical results are based on the assumption that the window supports are very stiff and can be simulated by simple support boundary conditions. The effect on noise transmission due to depressurization of the cavity between the two plexiglass panes has been calculated. A pressure differential between the cavity and the outside space induces in-plane loads and increases the stiffness of the plexiglass panes. Thus, the modal frequencies of the double-wall system increase with an increasing amount of depressurization. However, the amount of pressure differential that can be applied is limited by the allowable deflection (static) of the plexiglass sheets and cavity depth. The effect of pressure differential Δp was included in the analytical model through the in-plane loads and changes of the air spring constant. The increase in noise reduction ranges from about 1 to 3 dB for $\Delta p = 2$ psi and from 3 to 6 dB for $\Delta p = 4$ psi. Due to relatively large static deflections of the window panes for high pressure differentials and only modest gains in noise attenuation, depressurizing the dual-pane window does not seem to provide an alternative for noise transmission control.

Optimized Acoustic Treatment

The results of the parametric study were used to design a treatment suitable to provide a more comfortable cabin noise level. The design objective was to reduce the overall interior noise level of the untreated cabin by 17 dB or better at standard cruise power and rpm. To achieve this goal, substantial reduction of noise in the frequency bands of 160, 250, and 315 Hz (the propeller second, third, and fourth harmonics) is needed. A treatment which was found to meet these design objectives utilizes the combination of honeycomb panels, constrained layer damping tape, porous acoustic materials, limp-isolated trim, tuned damping, and modifications in window design. These add-on treatments, except for windows, do not require structural changes of the fuselage. Engineering judgment is exercised to limit the number of different treatments and weight configurations to design the optimized treatment. Furthermore, the function of this treatment for noise control is based on the condition that noise leakage through various flanking paths can be controlled. Installation of a barrier between the cockpit and passenger cabin is likely to be needed to reduce noise flanking from the cockpit region. A treated aft bulkhead may also be needed to reduce noise entering from the rear of the aircraft, and improve the interior absorption in the cabin.

The multilayered acoustic treatment for noise control is designed to function as a unit rather than separate individual components. The honeycomb panels are attached to the aircraft skin and cover the regions bounded by frames and longerons. Aluminum honeycomb panels with a core thickness of 0.25 in. and face plate thicknesses of 0.032 in. (region of propeller plane) and 0.016 in. (otherwise) are selected. A constrained layer of damping tape is added to all skin surfaces including the ceiling, which is not treated with honeycomb panels. A damping tape suitable for low temperatures should be used. Three layers (each layer 1 in. thick) of porous acoustic materials are added to all accessible surfaces of the cabin. The first two layers are tightly fitted in the regions between stiffeners, while the third layer covers all the frames and longerons. Space permitting, a fourth layer should be added to increase noise reduction and sound absorption capability further. In order to design a practical acoustic treatment, a trim that will contain the porous acoustic material and presents an acceptable appearance needs to be installed. The main function of the trim for noise control is to provide additional noise attenuation as the sound enters through the sidewall. A trim which has a low value of stiffness (limp panel concept) and is isolated from the vibration of the main frame structure seems to be best suited for noise control in this aircraft. Difficulties might arise installing the limp-trim panels in the aircraft. Lightweight honeycomb (paper, nomex, etc.) or a layer of another acceptable material can be attached to the limp septa to increase the stiffness so that installation requirements are satisfied.

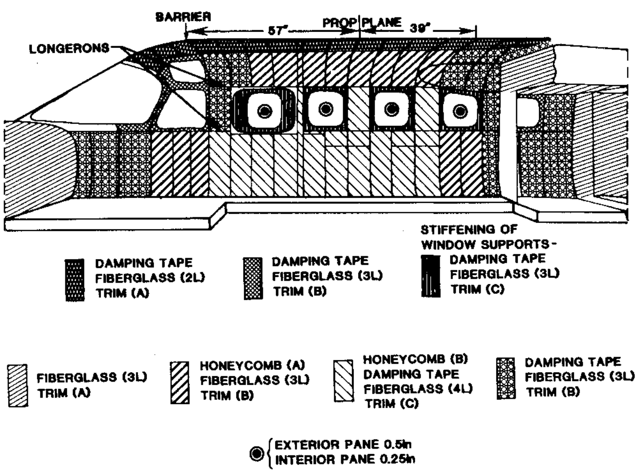

Fig. 10 Distribution of the proposed acoustic treatments for noise control in the aircraft.

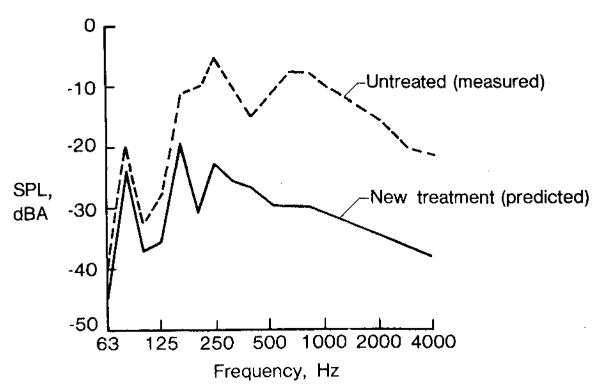

Fig. 11 Interior noise levels of untreated and treated cabin for flight conditions.

Experiments indicate that vibration of frames and longerons are relatively large at the first two propeller blade passage harmonics. These vibrations are strongly coupled to the vibrations of panels and windows. A tuned damper could provide reduction of structural motions at a selected tuned frequency. Such a reduction of structural response could subsequently lead to noise reduction at that frequency. Thus, it is recommended that vibration dampers tuned at the first and second propeller blade passage harmonics should be used to control the overall vibrations of the fuselage.

The tests and theoretical studies[8,10] indicate that noise transmitted through windows at the second, third, and fourth propeller blade passage harmonics could be a potential cause of high interior noise levels in a treated aircraft. Thus, heavy sidewall treatments might not solve the cabin noise problem if the windows are providing a weak link in noise transmission. The window supports of this aircraft are relatively flexible and the vibrations of the windows are strongly coupled to the vibrations of the supporting skin, longerons, and frames. Thus, altering the window design might not improve the noise transmission characteristics if the boundary support conditions are not changed. As the first step to improve window design for noise transmission control, the stiffness of the boundary supports should be increased significantly. The theoretical parametric study presented in Ref. 10 suggests that one of the alternatives to increase noise reduction for windows is to increase the thickness of the exterior plexiglass pane. For the present design of the proposed treatment, the thickness of the exterior window pane should be increased to 0.5 in.

Table 1 Surface densities and thicknesses of add-on treatments

Treatment	Surface density, psf	Thickness, in.
Damping tape	0.25	0.25
Fiberglass		
(2L)	0.16	1.80
(3L)	0.24	2.70
(4L)	0.32	3.60
Honeycomb		
(A)	0.40	0.27
(B)	0.68	0.28
Trim		
(A)	0.30	0.13
(B)	0.40	0.13
(C)	0.75	0.25
Increase in exterior window pane thickness	1.35	0.25

The final configuration of the proposed treatment is similar to the one shown in Fig. 3 but without any impervious septa layers. Figure 10 illustrates the treatment used in various cabin regions. The surface densities and thicknesses of these add-on treatments are given in Table 1. The total weight of this acoustic treatment is about 2% of the gross takeoff weight of the aircraft. The proposed treatment is slightly lighter than the standard acoustic-thermal treatment used for this aircraft. However, the new treatment should provide about 4-10 dB more of noise reduction than the standard treatment. Laboratory tests tend to verify these predictions.[21] A comparison of noise transmitted into the untreated cabin (measured) and the cabin with the proposed treatment (calculated) is shown in Fig. 11.

Concluding Remarks

A theoretical procedure has been used to develop an acoustic treatment for interior noise control in a twin-engine light aircraft under normal flight conditions. Relatively good agreement has been reached between theoretical predictions and experimental measurements of noise transmission through specially designed aircraft panels in the transmission loss apparatus and aircraft sidewall in flight. The average calculated overall noise levels of the untreated cabin have been reduced by about 17 dB with the new acoustic treatment.

These noise reductions have been obtained by treatments which include lightweight aluminum honeycomb panels, constrained layer damping tape, porous acoustic materials, limp trim panels, tuned dampers, and modifications in window design. Due to nonuniform distribution of the propeller noise pressure and different structural dynamic characteristics of the sidewall panels, the amount and type of treatment is varied over the aircraft fuselage.

The analytical predictions of noise transmission indicate that adding a large amount of nonload carrying mass to the aircraft skin increases noise transmission at the first propeller blade passage harmonic, but has a positive effect on noise reduction at higher frequencies. The predicted noise transmitted through aircraft windows has been reduced through design changes of window supports and increase in the exterior pane thickness.

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