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Noise Transmission and Control for a Light Twin-Engine Aircraft

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One of the dominant source-path combinations for cabin noise in light twin-engine aircraft is propeller noise being transmitted through the fuselage sidewall. This source-path was investigated and candidate sidewall add-on treatments were installed and tested using both an external sound source and the propeller in ground static engine runs. Results indicate that adding either mass or stiffness to the fuselage skin would improve sidewall attenuation and that the honeycomb stiffness treatment provided more improvement at most frequencies than an equal amount of added mass. It is proposed that double-wall construction in conjunction with skin stiffening should provide a good weight-efficient combination for the aircraft studied.

Introduction

ONE of the principal source-path combinations of cabin noise in light, twin-engine aircraft is propeller noise transmitted through the fuselage sidewall. Improved methods of controlling this cabin noise are needed to provide a comfortable passenger environment, while at the same time controlling aircraft weight and fuel consumption. Lighter weight noise control methods are needed to replace traditional approaches which have relied largely on relatively heavy damping and mass treatments.

A number of approaches have been investigated for reducing cabin noise for this type of aircraft. Flight tests indicated interior noise can be reduced about 3.5 dB(A) by a reduction of engine rpm in an aircraft with variable pitch propellers.[1] Design of propeller configurations is being investigated as a means of reducing the noise generated at the source.[2] Theoretical prediction methods for sidewall noise transmission have been developed to aid the search for noise-resistant sidewall structures. Theoretical analysis of interior noise transmission has included mechanical analogy models, rigid-stiffener/flexible-panel models, and more complex flexible-stiffener/flexible-panel models.[3-5] The analyses have been compared with laboratory test data for verification and have been used to examine a number of candidate noise control treatments including variations of skin thickness, stiffener stiffness, and structural damping, and addition of damping, mass, and honeycomb panel stiffening.

Previous work has not included evaluation of candidate noise control treatments in an experimental situation using an actual aircraft. Such studies are needed to evaluate and compare candidate treatments, and to guide further development of noise control treatments. The purpose of this paper is to describe an experimental program of evaluation of three noise control treatments. The work is focused on added stiffness in the form of honeycomb panels. Also, two mass treatments are included for comparison. The tests were carried out using a light twin-engine aircraft (Fig. 1). Candidate treatments were developed using the aircraft with a horn noise source in the laboratory. The performance of the stiffness treatment was verified using ground static runs of the aircraft engines. The laboratory portion of this investigation is described in Ref. 6.

Test Aircraft

The aircraft used for this study is shown in Fig. 1. This aircraft has a maximum takeoff weight of 3175 kg and is powered by two 6 cyl, 240 kW engines. The propellers are constant speed, have three blades, and are driven through a reduction gear of approximately 63%. The cabin dimensions are approximately 3.35 m long, 1.42 m wide, and 1.44 m high. The proptip-fuselage sidewall clearance is 12 cm which results in substantial propeller noise levels on the sidewall.[8]

The importance of the propeller as a source of cabin noise can easily be seen in Fig. 2. The data shown are an A-weighted, narrowband (3 Hz) spectrum of the cabin noise measured at the center of the fuselage during level flight. The important sources of the noise can be identified by matching the frequency of the spikes with those of the propeller and engine firing harmonics. The propeller harmonics are numbered and the other peaks are associated with the engine. The highest peaks represent the most dominant sources for the A-weighted cabin noise. As noted in the figure, the highest harmonics fall between 150 and 300 Hz. In order to reduce cabin noise levels efficiently, noise in this frequency range should be considered first.

Path Analysis

There are basically two paths by which the engine and propeller noise are transmitted to the cabin interior. One is the structural path from the engine foundation or other vibrating structure through the wing and then radiated into the interior. The second is the airborne path where noise is first radiated into the air and then transmitted through the fuselage sidewall into the cabin.

The engine and propeller noise sources and the two transmission paths result in four source-path combinations. The dominant path for the propeller noise is basically the airborne path because of the nature of the generation of propeller noise.[6] The dominant path for engine noise is not clear. Reference 6 showed that the wing spar vibration at many of the cylinder firing harmonics is the same order of magnitude (within 10 dB) as the skin, stringer, and frame vibration in the sidewall. The main purpose of the research reported herein was to investigate treatments to improve sidewall attenuation (airborne noise path), so the investigation was focused on sidewall attenuation of propeller noise.

In order to investigate the airborne path of propeller noise, two accelerometers were mounted on the sidewall. These transducers were mounted for response perpendicular to the sidewall, one on a longitudinal frame and the other on the panel closest to the propeller tip. Figure 3 shows the amplitude of vibration at these two locations at the first six blade passage harmonics for a static runup at 2600 rpm. These data

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Fig. 1 Twin-engine light aircraft used in sidewall noise control study.

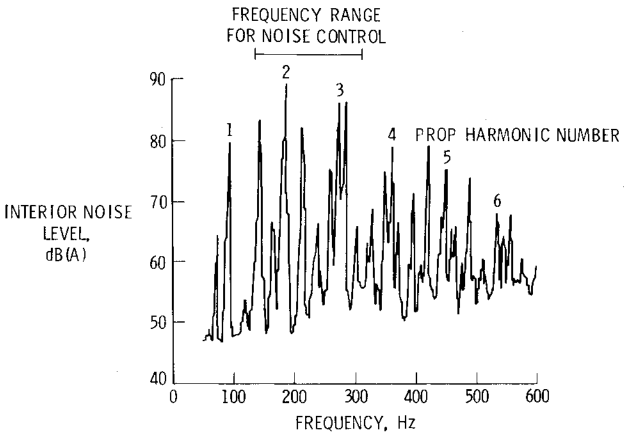


Fig. 2 Interior noise measured in flight of a twin-engine light aircraft (2750 rpm, 75% power).

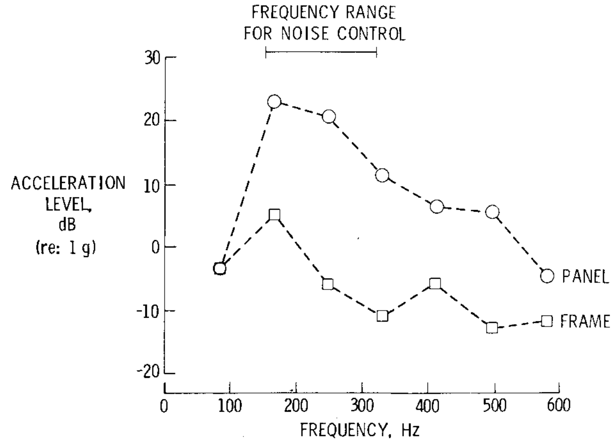


Fig. 3 Acceleration response of two fuselage structural elements, ground static test (2600 rpm).

show that the panel response is high compared to the frame, especially in the critical frequency range indicated. These and similar results for other panels suggest that adding stiffness to the panel, thereby reducing panel response to that of the frame, would improve sidewall attenuation.

The expected effects on sidewall attenuation of adding mass and stiffness to the skin is shown in Fig. 4. The solid curve (noted "basic structure" in the figure) represents the transmission loss of a structure having stringers and/or frames and can be found in several references.[7] Transmission loss is the reduction in power of an incident sound wave as it passes through a structure. This curve has two dips: the first represents the fundamental of the structure and the second represents the higher frequency subpanel fundamental. The curve is actually an oversimplification of the situation in that different subpanels will have different fundamentals as well as higher order modes. However, the curve is very useful in showing the effects of changing panel mass or stiffness. Adding mass to the skin will lower the panel fundamental frequency slightly and raise the transmission loss as shown. Increasing skin stiffness will also add mass, but the most significant effect comes from raising the panel fundamental frequency of vibration as shown. Calculations indicate that the frequency of the fundamental for most of the panels on the test aircraft fall between 100 and 200 Hz. This implies that the frequency range of greatest improvement due to skin stiffening will be from about 100 Hz to some higher frequency depending on the amount of stiffness added. As indicated in Fig. 2, this would include the critical frequency range for the test aircraft.

Design of Stiffness Treatment

The purpose of this study was to investigate stiffness and mass as noise control treatments. Although finding a suitable mass treatment simply involved purchasing a stock item from a noise control firm, a stiffness treatment was not a shelf item. A lightweight stiffness treatment was needed which could be added to an existing fuselage. Honeycomb sandwich panels have been shown to be extremely stiff and lightweight and this type of construction was selected.

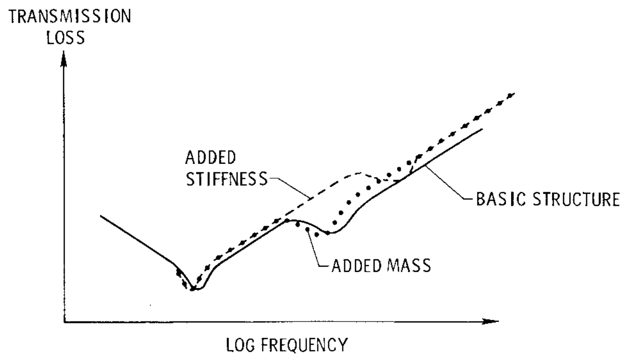


Fig. 4 Effect of stiffness and mass on transmission loss.

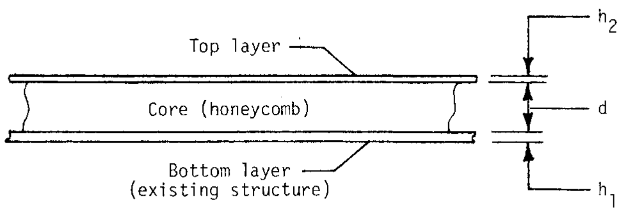


Fig. 5 Typical honeycomb construction.

In order to investigate added stiffness from a honeycomb add-on treatment, calculations were made to determine its effectiveness. One measure of panel stiffness is the frequency of the fundamental mode. Assuming simple supports, the frequency of the fundamental mode for a rectangular panel is:

$$f=\frac{\pi}{2}\left[\frac{1}{a^2}+\frac{1}{b^2}\right]\sqrt{\frac{D}{\rho_s}}$$

where a and b are the dimensions of the panel, D the flexural rigidity of the panel, ρ_s the surface mass of the panel (mass per unit area), and f the fundamental frequency (Hz). For a simple panel,

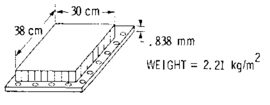
$$D=Eh^3/12(1-\nu^2)$$

where E is Young's modulus, h the thickness of the panel, and ν Poisson's ratio. For a honeycomb sandwich, the equations are the same except for the flexural rigidity D. Figure 5 shows a typical honeycomb construction. Assuming the core has no flexural rigidity, the flexural rigidity of the sandwich is:

$$D=\frac{E}{(1-\nu^2)}\left\{\frac{h_1^3}{12}+\frac{h_2^3}{12}+\frac{h_1h_2}{h_1+h_2}\left[\frac{h_1}{2}+\frac{h_2}{2}+d\right]^2\right\}$$

Table 1 Stiffness treatment test panels

Panel	Honeycomb thickness d, mm	Top layer thickness h_2, mm	Added weight kg/m^2	Fundamental frequency, Hz Calc. (simply supported)	Meas.
1	0	0	0	69[a]	69
2	3.175	0.152	1.14	178	196
3	3.175	0.406	1.74	243	246
4	6.35	0.152	1.30	317	318
5	6.35	0.406	2.02	431	398



[a] Calculated with clamped edges.

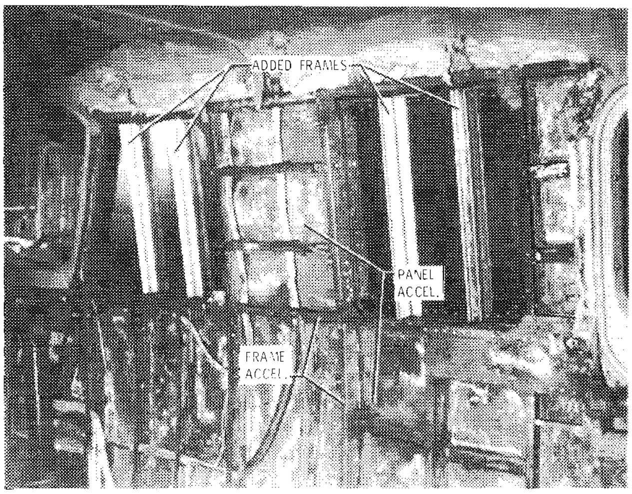


Fig. 6 Sidewall interior structure and measurement locations.

The equation assumes both top and bottom layers are the same isotropic material.

The above equations can be used to estimate the fundamental frequency of a simply supported panel which is either simple or a sandwich type. To determine the accuracy of these equations and to investigate possible problems associated with adding honeycomb sandwich construction to an existing panel, five test panels were constructed and tested. Four panels were treated with honeycomb and a top layer, which were bonded to the center area inside a rigid clamping frame to simulate adding material between frames in the aircraft. Two different honeycomb thicknesses and two top layer thicknesses were used for four different combinations. The four treated panels were bonded using a flight-qualified epoxy and techniques suitable for aircraft.

The fundamental frequencies of the panels were determined by clamping the panels in place and exciting the panels acoustically. The results are shown in Table 1 along with calculated frequencies and details of the treatment. The observed fundamental frequencies are shown at the right. The calculated frequency for the first panel was determined assuming clamped boundary condition and the others assuming simply supported edges.[9] The reason for this was that although the simple panel was clearly clamped, the stiffened panels 2-5 were treated only up to the clamped edge, so that only the original panel edge was clamped. It is evident from these data that adding a honeycomb treatment is an effective way to increase panel fundamental vibration frequency and that the frequency can be estimated using the simple equations presented.

Preparation of Aircraft

The cabin of the aircraft was prepared for testing by removing the interior trim in the area to be treated. Figure 6 is a photograph of the inside of the fuselage before testing. The two side windows were replaced with aluminum panels having the same thickness as the adjacent fuselage skin, and with frames (Fig. 6) which were formed channel sections with the same thickness and dimensions as the adjacent structural members. Thus, the transmission through stiffened-skin structure could be studied without the complicating effects of windows. During the tests, frame and panel acceleration response was measured at the locations indicated in the figure.

A sketch of the sidewall looking from inside out is shown in Fig. 7 along with some key dimensions. The lines in the figure represent frames or stringers and the accelerometer locations are again indicated.

To determine the dimensions of the honeycomb stiffness treatment to be added to the aircraft, calculations were made for the fuselage sidewall panel fundamental mode frequencies with and without such a treatment for each of the 25 panels shown in Fig. 7. These frequencies were calculated assuming simply supported edges (as recommended in Ref. 7) and are shown in Fig. 8. As shown in the figure, most of the calculated frequencies for the basic panels fall between 100 and 200 Hz, a critical frequency range for noise control. Adding the stiffness treatment (as for panel 5 in Table 1)

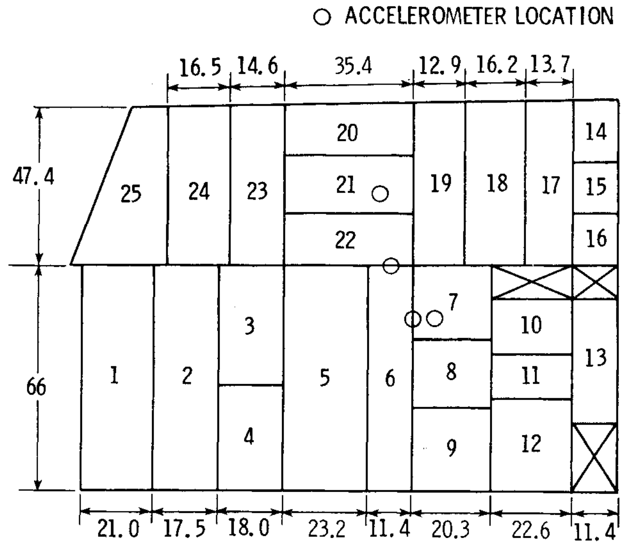


Fig. 7 Panel dimensions and measurement locations (dimensions in cm).

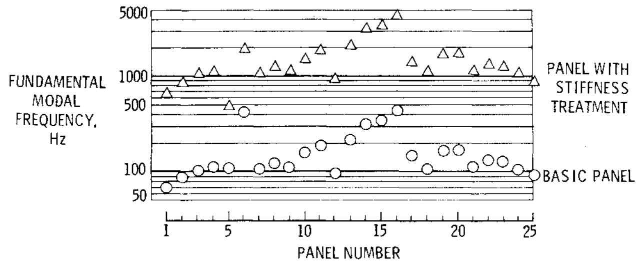


Fig. 8 Calculated effect of honeycomb stiffness treatment on panel modal frequency.

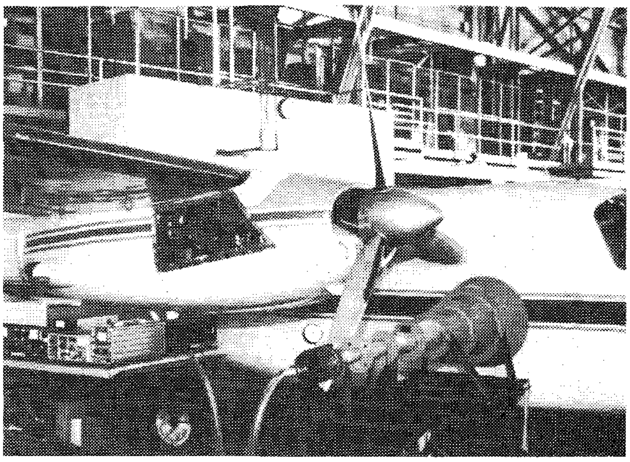


Fig. 9 Test setup for evaluation of noise control treatments.

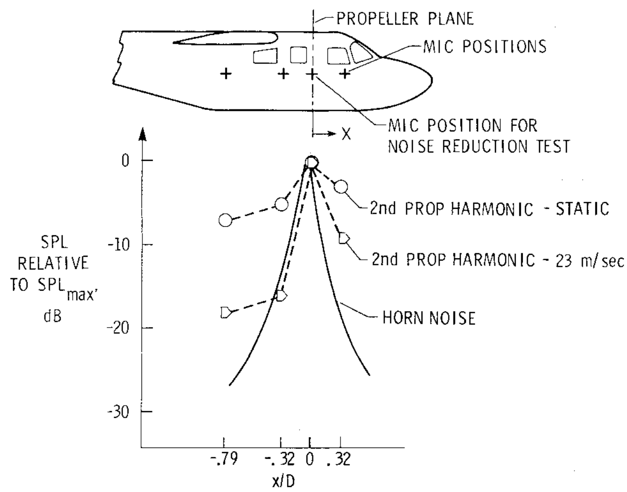


Fig. 10 Distribution of noise from horn and propeller (second harmonic) (propeller diameter $D = 2.36$ m).

increased the fundamental frequency about an order of magnitude to frequencies above the critical range for noise control indicated in Fig. 2.

The stiffness treatment selected for the aircraft was the same as that used on panel 5 of Table 1. In addition to the stiffness treatment, two mass treatments were also tested. One of these had approximately the same surface density as the stiffness (2 kg/m^2) and the other was three times that amount (6 kg/m^2).

Horn Tests

In order to investigate the effects of mass and stiffness on sidewall attenuation, laboratory tests were conducted using an external sound source as shown in Fig. 9. The horn shown in the photograph was driven by an air modulator and produced a concentrated random noise field on the fuselage.

The relative longitudinal distribution of noise produced by the horn is shown in Fig. 10. In addition, the distribution of the second blade passage harmonic is shown both in a static condition and during taxi tests at 23 m/s to determine forward speed effects.[8] These data indicate that the forward speed case has a more concentrated noise distribution than under static conditions. Similar results are found for higher blade passage harmonics. As the figure shows, the distribution of noise produced by the horn is similar to that of the propeller second harmonic at 23 m/s. This implies that the horn would produce results more like the forward speed case than would the propeller in a static run. Since taxi or flight tests were not possible after fuselage modifications, tests with the horn should provide more realistic results.

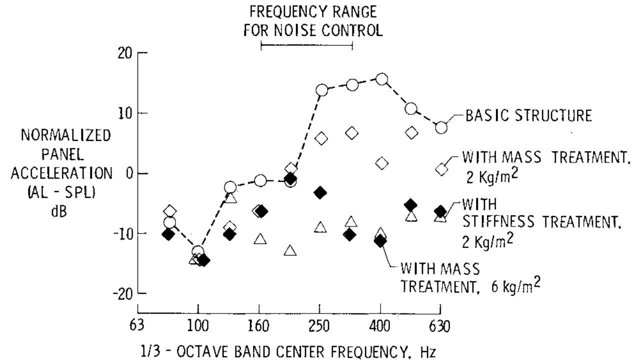
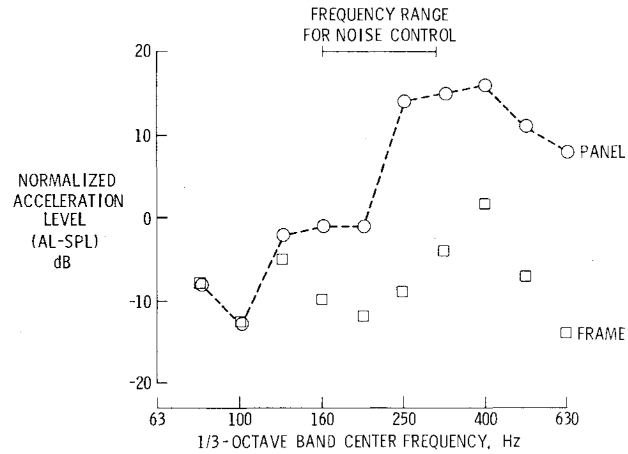
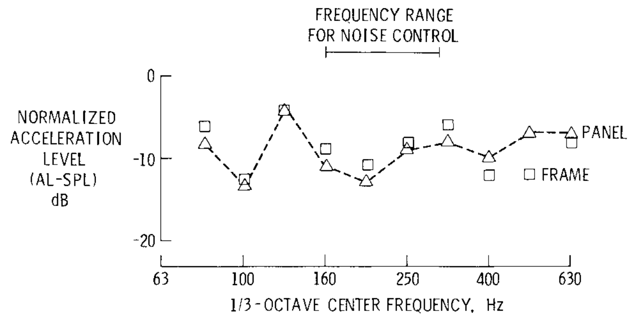


Fig. 11 Effect of noise control treatment on panel acceleration response to horn noise, panel 7.



a) Basic structure before treatment.

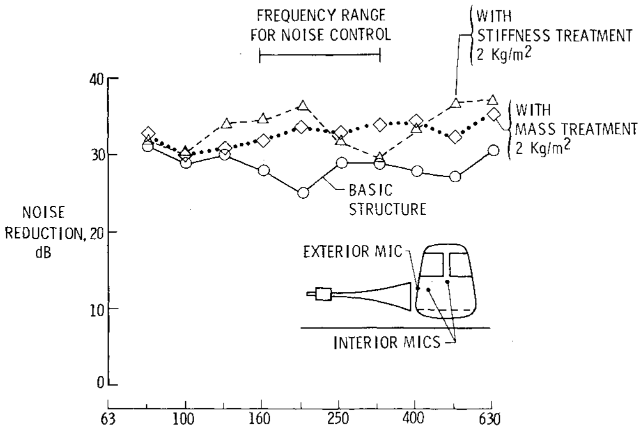


b) Structure with stiffness treatment.

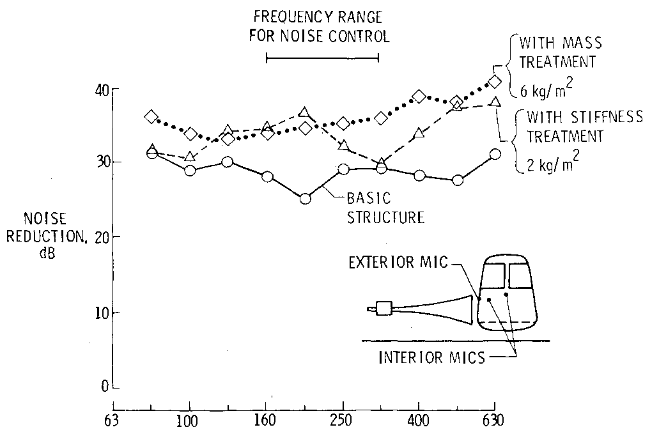
Fig. 12 Effect of stiffness treatment on panel and frame response to horn noise, panel 7.

Using the horn as a noise source, each of the three treatments was tested separately. Sound pressure inside and outside the fuselage was measured and recorded on an FM tape recorder and later analyzed in one-third octave bands. Panel and frame acceleration response was similarly recorded and analyzed.

The normalized response of panel 7 (Fig. 7) is shown in Fig. 11 for the basic untreated structure and for the same panel with each of the three treatments added. The normalized response is the acceleration level [$AL = 20 \log(a/a_{ref})$] relative to 1 μg minus the exterior sound pressure level (SPL). The data in this figure indicate that each treatment reduced panel response substantially and that the stiffness treatment provided the greatest improvement in the critical frequency range. In addition, the stiffness treatment reduced panel response at other frequencies by approximately the same amount as the heavier mass treatment weighing three times as much.



a) Lighter mass treatment.



b) Heavier mass treatment.

Fig. 13 Sidewall noise reduction for basic structure and for structure with noise control treatments.

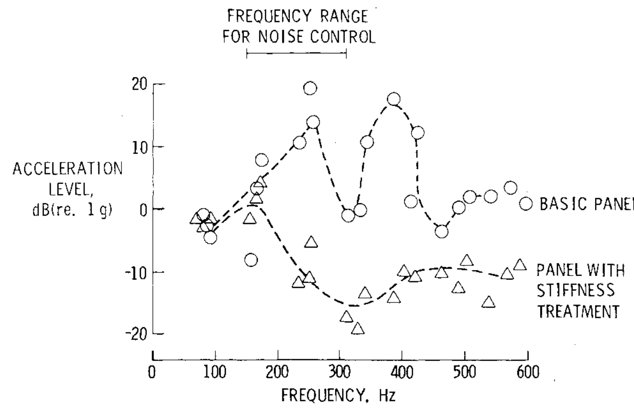


Fig. 14 Panel acceleration response at propeller harmonics (2100, 2400, and 2600 rpm; panel 7).

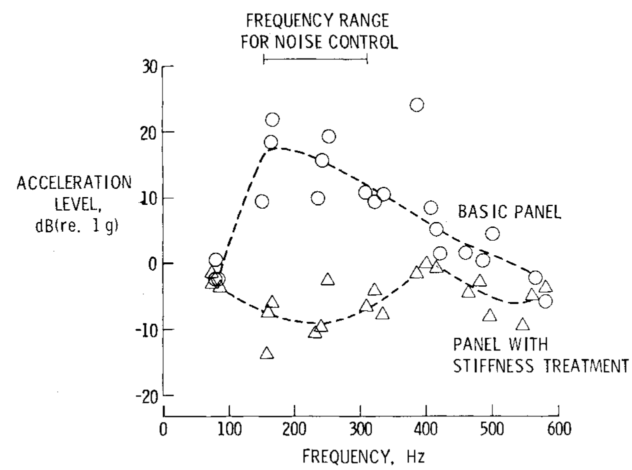


Fig. 15 Panel acceleration response at propeller harmonics (2100, 2400, and 2600 rpm; panel 21).

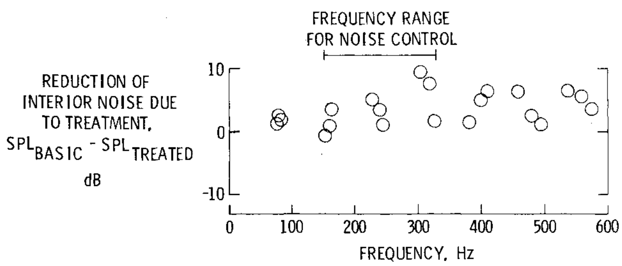


Fig. 16 Effect of honeycomb stiffness treatment on aircraft interior noise (ground static test at 2100, 2400, and 2600 rpm).

The response of panel 7 is shown again in Fig. 12 along with the response of the adjacent frame. Figure 12a shows the response of the basic structure before treatment and Fig. 12b shows the response after installation of the stiffness treatment. The effect of the stiffness treatment is to reduce panel response to that of the adjacent frame, resulting in the substantial reduction in panel response as suggested previously. This figure also shows the magnitude of the frame response, and that the stiffness treatment does not have a great effect on frame response.

Figure 13a shows the noise reduction provided by the sidewall in the basic configuration and with the stiffness or the equal weight mass treatment added. The unit of measure is noise reduction which, for the purpose of this discussion, is the difference between the outside microphone level and the average of two inside microphone levels in each one-third octave band. The exterior microphone position was in the propeller plane as shown in the sketch in Fig. 10. One interior microphone was located 25 cm inboard of the center of panel 7 (Fig. 7) and the second was located in the propeller plane 1 m up from the aircraft floor on the fuselage centerline. The data show that both treatments improved attenuation, with the stiffness treatment being especially effective at low frequencies (125, 160, and 200 Hz bands).

Figure 13b shows the noise reduction for the basic structure and with stiffness added repeated from Fig. 13a, but includes the result for the heavy mass treatment (three times heavier than the stiffness treatment). This mass treatment improves attenuation more than the stiffness treatment except in the 125-200 Hz range. Figure 13 shows that mass improves attenuation over the entire frequency range but that the stiffness treatment is better over most of the critical frequency range than either mass treatment.

Static Propeller Tests

Figure 14 shows the acceleration response of panel 7 (Fig. 7) at propeller harmonics for three different engine speeds (2400, 2500, and 2600 rpm) for the basic structure and with stiffness added. Figure 15 shows similar results for panel 21 (Fig. 7) which is the panel closest to the propeller tip. Each of these figures shows that the panel response was reduced substantially by the stiffness treatment, providing improvements on the order of 20 dB at most frequencies in the critical range. Assuming that the panels radiate most of the noise into the cabin, these data suggest that substantial reductions of interior noise might be achieved with this treatment.

Figure 16 shows the reduction of interior noise at propeller harmonics due to the stiffness treatment as compared to the basic fuselage. The improvements shown fall in the range of

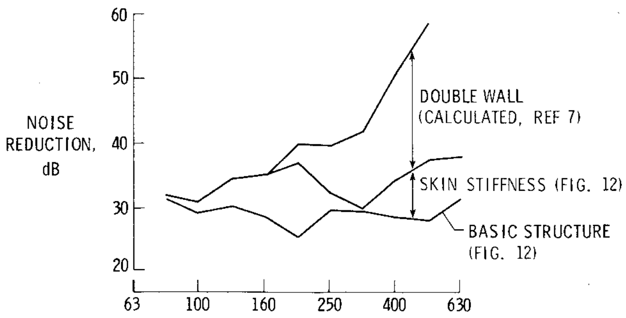


Fig. 17 Hypothetical sidewall treatment.

only 0-10 dB. The overall reduction in cabin noise averaged 4.5 dB(A) for the three engine rpm settings. However, it should be noted that the test condition was a static runup, resulting in a more evenly distributed noise field than would be found in flight. (See Fig. 10). Since only a small area of the fuselage was treated, this noise field would result in flanking through untreated areas such as the windshield and the aft portion of the fuselage. Therefore, the 4.5 dB(A) reduction should be considered only as a lower limit on cabin noise reduction.

Recommended Total Treatment

The data presented show that adding mass or stiffness to the fuselage sidewall will reduce the response of sidewall panels substantially. Also, each treatment did improve the attenuation and the skin stiffening treatment was generally the best of the three in the critical frequency range for the test aircraft.

This study was concerned with treatments to the fuselage structure or skin. Another treatment, often referred to as "double-wall construction," has been shown to be very efficient from a weight standpoint. The benefits of such a treatment have been well documented and, in fact, are used on most commercial aircraft. The shortcoming of double-wall construction is that it is effective only at mid and high frequencies. Since light aircraft noise levels are high at low frequency, such a treatment would not totally solve the problem. However, since skin stiffening does improve the low-frequency attenuation, a sidewall design utilizing skin stiffening in conjunction with double-wall construction should provide an efficient treatment throughout the frequency range. For example, Fig. 17 shows the noise reduction for the test aircraft basic structure and then with the stiffness added (from Fig. 13). The upper curve shows the combined noise reduction that would be expected if a double-wall construction were added to the stiffened structure. The effect of the double-wall construction was determined by calculation using the method of Ref. 7. The assumed double wall consisted of a 2.5 kg/m^2 trim panel separated from the sidewall by 5 cm with AA fiberglass between the two. It is not clear exactly how much such a sidewall design would reduce actual cabin noise in flight, but double-wall construction in conjunction with skin stiffening should provide a good weight-efficient combination for the aircraft studied.

Conclusion

This paper has focused on the transmission of propeller noise by the airborne path through the fuselage sidewall. This path is significant in light twin-engine aircraft and it was shown that improvements in sidewall attenuation are possible. For the particular aircraft studied, adding skin stiffness provided more noise reduction in the critical frequency range than was provided by mass treatment weighing three times as much. These treatments were customized for the particular aircraft and the results could be different for other aircraft. Therefore, when designing a soundproofing treatment for a different light aircraft, such parameters as the frequency of the sidewall subpanel fundamental modes and the frequency of the propeller harmonics should be considered. Also, consideration should be given to the windows and windshield so that they receive treatment comparable to the fuselage structure.

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