Laboratory Study of Sidewall Noise Transmission and Treatment for a Light Aircraft Fuselage

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The noise transmission through a fuselage from a twin-engine propeller aircraft was measured using a pneumatically driven horn sound source to simulate a propeller noise distribution. Sidewall noise treatments included a double-wall, production-type treatment and several combinations of fiberglass and lead-vinyl. The noise reduction through the fuselage sidewall without treatment is shown to agree in magnitude and trend with the reduction of propeller noise through an aircraft fuselage in flight, but differs substantially at low frequency from the transmission loss measured with a diffuse noise source. The effects of the horn source position and angle of incidence are shown. The treatments were evaluated using their insertion loss, defined as the reduction of the interior sound level that occurred when the treatment was installed. The fiberglass is shown to weigh less and to have insertion loss values that are often higher than those of the double-wall and lead-vinyl treatments. Variations of temperature in the test chamber are shown to result in changes of the noise spectrum within the fuselage. The changes observed may explain part of the variability of treatment insertion loss measured in the flight of a propeller aircraft.

Introduction

AN important approach to the control of aircraft interior noise is the use of sidewall acoustic treatment. The treatment is intended to reduce the noise transmitted through the sidewall structure and to provide absorption of sound within the cabin. In addition, the treatment is required to have minimum weight and occupy a limited volume. The development of treatment for an aircraft requires considerable effort and might be accomplished most efficiently by the use of laboratory ground testing. But first, ground test methods must be developed and shown to provide results that are applicable to flight conditions.

Experimental and analytical techniques have been used to study sidewall treatments. Flight testing[1,2] provides realism but may be costly, may not allow the separation of treatment effects from other factors affecting cabin noise, and may not allow adequate control of the test conditions. Flat panel testing[3] is reasonably efficient; however, complete aircraft structural motion and cabin acoustic characteristics are not represented. Analytical methods[4-7] allow great flexibility in the study of various treatments and provide valuable guidance, yet the results must still be verified by testing. The approach described in this paper, the testing of a complete fuselage in a laboratory setup, has been taken to provide a realistic structure and noise source under controlled test conditions.

This study used the same aircraft fuselage, horn sound source, and test methods used for a previous study.[8] The previous study emphasized the test methods and insertion loss of fiberglass and double-wall treatments for broadband and narrow-band propeller-type sound spectra. The present study provides new information on sidewall noise reduction, the effect of the sound source position and incidence angle relative to the fuselage, lead-vinyl treatments, and the effects of ambient temperature in the test chamber. Some of the information presented herein is reported in Ref. 9.

Experiments

The structure studied is a pressurizable, twin-engine aircraft fuselage with inside cabin dimensions of $151 \times 42 \times 50$ in. The fuselage has been placed in a hard-walled room with fiberglass baffles placed around the fuselage to reduce reflections (see Fig. 1).

Results were obtained for seven sidewall configurations using four treatments. The "baseline" configuration consists of the aluminum outer wall with a damping tape applied to the inside of the skin. For the insertion loss results presented in this paper, the sound pressure levels of the baseline configuration were used as the reference values. A double-wall production-type interior was attached to the baseline fuselage at the frames for the "double-wall" configuration. A hard plastic material covered the ceiling and sidewalls down to just below the windows. The sidewalls below the windows to the floor were covered with a masonite-hardboard backed vinyl material. A short-shag carpet covered the floor. The instrument panel was left intact. However, all instruments had been removed. The "fiberglass only configuration" added 3 in. of high-density fiberglass to the roof and sidewalls, excluding the windows. The front and rear bulkheads were covered with 1.5 in. of fiberglass. Three "fiberglass plus lead-vinyl" configurations were treated on the interior the same as for the fiberglass only configuration. For the "fiberglass plus lead-vinyl I" configuration, a sheet of lead-vinyl covered the exterior of the roof and sides (excluding the windows) from bulkhead to bulkhead. For the "fiberglass plus lead-vinyl II" configuration, a sheet of lead-vinyl covering the exterior of the tail of the fuselage was added to the fiberglass plus lead-vinyl I configuration. The "fiberglass plus lead-vinyl III" configuration consisted of the fiberglass plus lead-vinyl II configuration plus a sheet of lead-vinyl added to the exterior of the windows and 1.5 in. of fiberglass added to the interior of the windows. Removing all of the fiberglass from the interior of the fiberglass plus lead-vinyl III configuration resulted in the "lead-vinyl III" configuration. Thus, for the lead-vinyl III configuration, the top and sides from bulkhead to bulkhead and the entire tail were covered on the exterior by one layer of lead-vinyl.

Presented as Paper 86-0390 at the AIAA 24th Aerospace Sciences Conference, Reno, NV, Jan. 6–9, 1986; received June 10, 1986; revision received Feb. 27, 1987.

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The sound source for these tests was a pneumatic air-driver, with an attached exponential horn (Fig. 1). The cut-on frequency for the horn was 100 Hz. A localized sound distribution was desired in order to simulate propeller noise. A previous study using this horn[10] showed reasonable agreement with a propeller noise distribution. The different horn positions used are shown in Fig. 2. For each position, the sound power radiating from the horn was the same. Broadband white noise, filtered to obtain a flat spectrum, was supplied to the driver. Figure 2 shows the exterior SPLs that were measured at the locations 7–15. The exterior SPLs were high enough to provide adequate signal-to-noise ratios for the interior microphones.

The interior SPLs were measured using half-inch condenser microphones at the approximate head locations of each of the six passenger positions, microphones 1–6 in Fig. 2. The signals from the microphones were passed through measuring amplifiers and a switching box before reaching one channel of a two-channel fast Fourier transform (FFT) analyzer. The exterior SPL was analyzed on the second channel of the FFT analyzer. The FFT was adjusted so that the frequency range of analysis was 0–1000 Hz with 400 lines of data. This results in a bandwidth of 2.5 Hz. The data presented were calculated from 100 averages.

To assure the consistency of the noise source, the exterior SPL at microphone position 7 was measured each time a spectrum at an interior position was measured. The variation of the exterior overall sound pressure level (OASPL) was less than 1 dB for the duration of the tests. The pressures at all interior positions for a particular sidewall treatment were recorded without any adjustments made to the input instrumentation in order to reduce any variation that might result from variations of the exterior sound field.

The OASPLs measured at positions along the sidewall are shown in Fig. 3. For the near and forward source positions, the noise distribution shows a sharp peak at the center of the mouth of the horn and decreases by about 10 dB at 20 in. from the center. When the distribution of OASPLs along the sidewall for the near- and forward-source positions is overlaid, the curves have nearly the same magnitude and shape. The SPL at microphone position 7 for the far-source position is much less than for the near-source position but matches the near-source position for distances more than 20 in. from position 7.

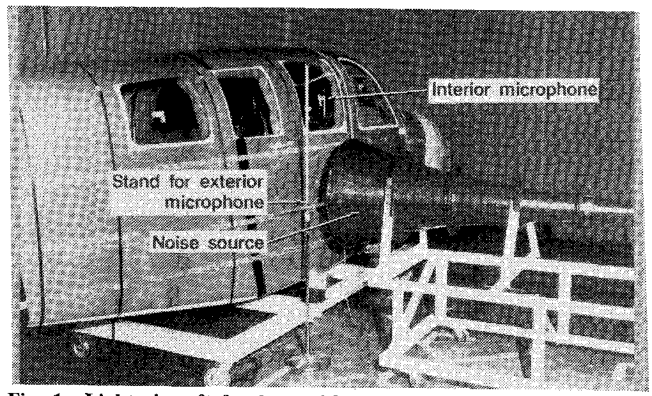


Fig. 1 Light aircraft fuselage with mass treatment in acoustic test setup.

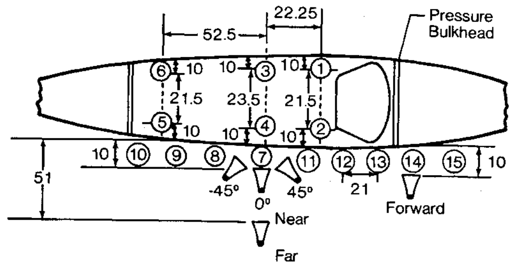


Fig. 2 Microphone and sound source positions, distances in inches.

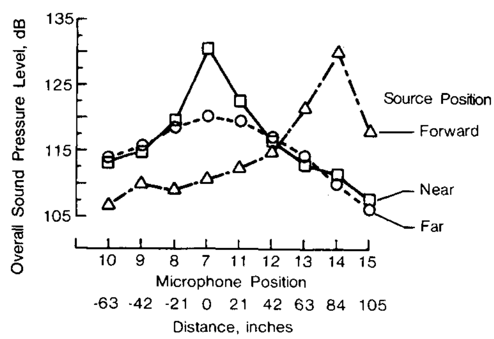


Fig. 3 Horizontal distribution of exterior OASPL.

Sidewall Noise Reduction

Effect of Source Position

Noise reduction (NR) is defined herein as the difference between the exterior and interior noise levels. For the results shown in Fig. 4, the exterior noise is measured at microphone 7 and the interior noise is averaged over the six interior positions using the equation

$$SPL_{avg} = 10 \log_{10} \frac{1}{6} \sum_{i=1}^{6} 10^{SPL i/10} \tag{1}$$

Figure 4 shows that the noise reduction for the near-source position is on the average about 10 dB greater than the NR for the far-source position and about 25 dB greater than the NR for the forward-source position. The fuselage structure and cabin furnishings were the same for all three tests; therefore the changes of noise reduction are associated with changes of the exterior noise field. As Fig. 3 shows, the exterior SPL at microphone 7 for the near-source position is about 10 dB higher than for the far-source position and about 20 dB higher than the forward position. These differences of exterior level account approximately for the differences of noise reduction shown in Fig. 4. The space-averaged interior noise levels, shown in Fig. 5, are approximately the same for all three source positions and show no systematic trend with position. These results indicate that a single point measurement may not be sufficient to characterize a source noise field for the evaluation of sidewall noise reduction, especially when comparing different noise fields having different distributions, and that source noise fields having large differences in level and distribution can result in transmitted noise levels that are not very different.

The sound distribution produced by the horn in the near position is felt to represent reasonably closely the distribution produced by a general aviation propeller located such that the propeller tip passes close to the fuselage. Comparisons of the horn and propeller distributions have shown agreement for the second propeller harmonic with the aircraft in forward motion.[10] The intense noise level localized near the propeller tip, or microphone 7 for the horn, is thought to have important effects on the interior noise. Moving the propeller to a different position is sometimes suggested as a means of reducing the noise effects. Moving the propeller outboard reduces the peak level more than the overall averaged level, similar to the change observed when the horn was moved to the far position, and moving the propeller forward reduces the level on the cabin sidewall and locates the peak levels forward of the cabin pressure bulkhead, similar to the forward source position. As shown in Fig. 3, these changes of horn position did reduce the exterior noise levels on the cabin sidewall, but Fig. 5 shows that the cabin interior noise levels were not reduced significantly.

Flight vs Laboratory Noise Reduction

Noise reduction (NR) values obtained from the present laboratory tests are compared with values measured in the flight of a twin-engine propeller aircraft[11] in Fig. 6. The comparison is intended to be qualitative because the fuselage construction and cabin furnishings are different and because the laboratory test did not include wings, engines, or empennage. For this comparison, the laboratory noise reduction is the difference between exterior microphone 7 and interior microphone 4 with the horn in the near position. In flight, the exterior noise was measured by a microphone flush-mounted in the skin and located in the propeller plane, where the propeller noise was expected to be near its maximum value. Interior noise was measured in the plane of the propellers at a position about 10 in. from the sidewall and 43 in. from the floor.

The noise reduction measured in flight is seen in Fig. 6b to have a trend of approximately constant value with frequency and a value ranging between 20 and 40 dB. These values and this trend have been observed previously in ground tests of another propeller aircraft[12] and are felt to be valid for the conditions tested. The laboratory result, Fig. 6a, is seen to have a minimum value of about 15 dB at about 150 Hz and a trend of rising noise reduction as frequency increases or decreases from that value. Many fluctuations of NR occur, with variations of up to 20 dB occurring over frequency changes of about 40 Hz. These fluctuations are thought to be associated with the structural and acoustic modes of the fuselage and do not appear in the flight data because the propeller speed is fixed, so that NR values are obtained only at the blade passage frequency of about 76 Hz and its harmonics. Within these fluctuations, the overall trends and values of NR appear to be similar in flight and in the laboratory.

These trends are significantly different from trends observed in laboratory transmission loss (TL) tests of stiffened aircraft-type panels.[3] Those tests show that panel TL follows a mass law trend and that values of TL less than 10 dB are measured in the region of 100 Hz. This large difference at a low frequency of less than 10 dB from diffuse-source TL tests compared to more than 20 dB in flight or laboratory horn tests is significant because propeller tones often occur at frequencies near 100 Hz that often dominate the cabin sound levels.

Effect of Source Angle

The effect of the source incidence angle was investigated as a possible reason why the forward horn position produced as much cabin noise as the near position even though the exterior levels at microphone 7 were lower by about 20 dB. This thought was prompted by the observation that the calculated transmission is sensitive to the incidence angle.[13,14] The maximum level was kept constant by retaining the mouth of the horn at a fixed distance from the sidewall while varying its orientation. Based on room acoustics, the directivity of the transmitted sound would be expected to have an effect on the direct and not the reverberant interior sound field. Therefore the data were acquired for the fiberglass only configuration, which is a relatively nonreverberant interior.

The effect of the source angle on the space-averaged interior SPL was found to be small.[9] The difference in SPL for the three source angles was a maximum of 3 dB and much less than 3 dB for most of the frequency bands. In addition, the SPL for a particular source angle did not dominate the SPLs of the remaining two source angles. The source angle effect might have been different if the test chamber size had allowed the horn to be moved further from the sidewall so that the incidence angles were more nearly equal over the whole length of the cabin.

A significant effect due to the source angle is shown in Fig. 7 for the individual microphone at position 6. The SPL is greatest for the +45 deg source angle and least for the −45 deg source angle in all frequency bands. The difference in SPL for the three source angles increases with increasing frequency from less than 1 dB at 125 Hz to a maximum of about 12 dB at 630 Hz. The decrease in difference near 1 kHz may be at-

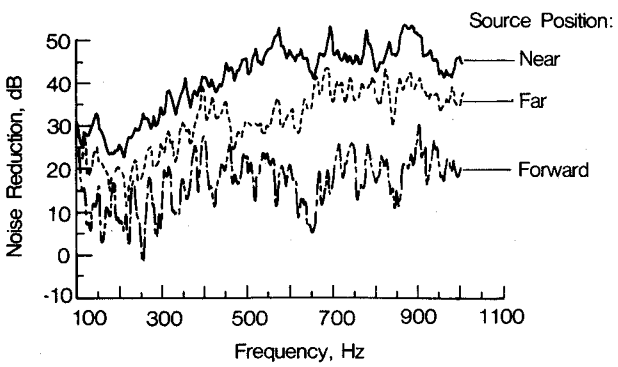


Fig. 4 Space-averaged NR for the double-wall configuration.

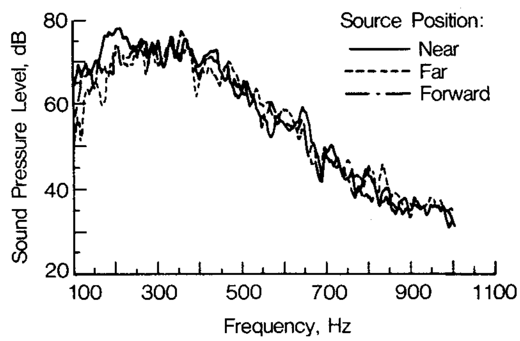
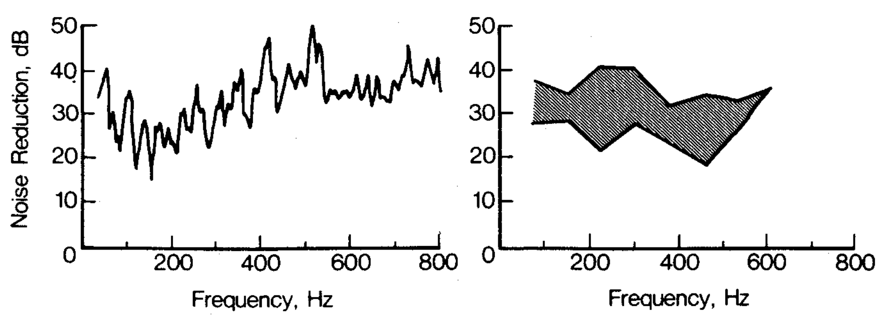


Fig. 5 Space-averaged interior SPL for the double-wall configuration.



a) Laboratory, horn source **b) Flight, propeller**

Fig. 6 Comparison of noise reduction trends from lab and flight tests. Flight results for several altitudes and cabin pressures.

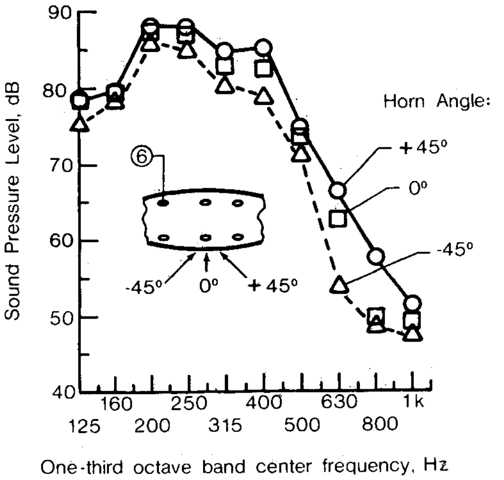


Fig. 7 Effect of sound source angle on SPL at microphone position 6.

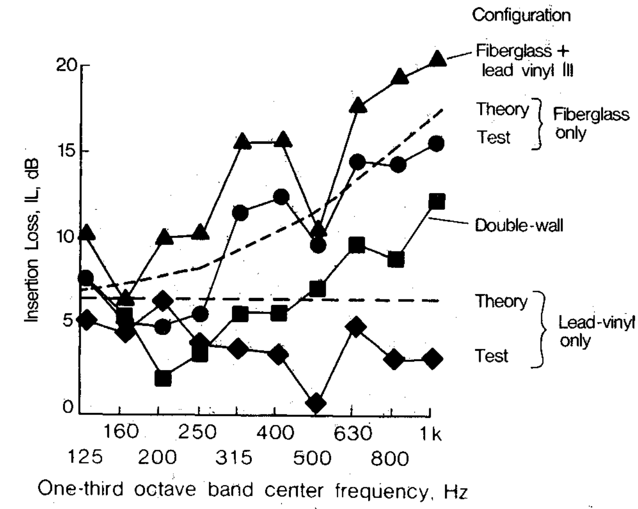
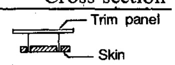
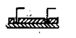


Fig. 8 IL for fiberglass and fiberglass plus lead-vinyl configurations, near source position.

Table 1 Summary of overall insertion loss (OAIL) and weight of sidewall acoustic and treatment near source position

Configuration	OAIL, dB	Weight, lb	Cross section
Double wall	4.4	108	 Trim panel, Skin
Fiberglass	7.8	75	
Fiberglass + lead-vinyl I	10.2	197	
Fiberglass + lead-vinyl II	11.0		
Fiberglass + lead-vinyl III	11.4		
Lead-vinyl III	3.6		

Damping tape, lead-vinyl, fiberglass.

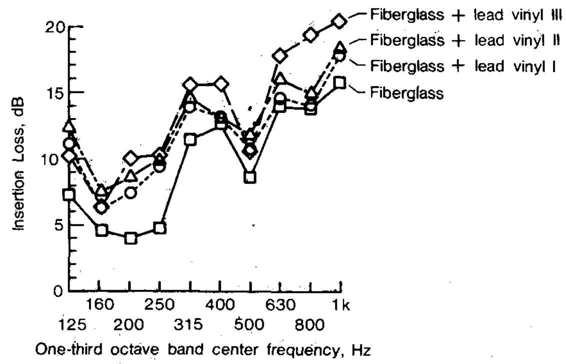


Fig. 9 Space-averaged insertion loss for four configurations of treatment, near source position.

tributed to the SPL for the 0 and −45 deg source angles nearing the noise floor.

These results agree qualitatively with a previous analytical study[14] which showed that the directivity of transmitted sound from a flat panel in a baffle is greater at higher frequencies than at lower frequencies. In addition, the major lobe of the transmitted sound is at the same angle as that of the incident sound. Thus the SPL should be largest for the source angle that directs the sound at the microphone of interest. In Fig. 7, the +45 deg source angle is directed at microphone position 6.

Treatment Insertion Loss

Overall Insertion Loss

The effects of sidewall treatment on interior noise were evaluated by examining the insertion loss (IL), defined as the change in interior sound pressure level due to a specific fuselage modification. To calculate the overall insertion loss (OAIL), the space-averaged narrow-band SPLs are first summed over frequency to obtain the overall sound pressure level (OASPL) of the configuration. The OASPL for the treated configuration was then subtracted from the OASPL of the baseline configuration to obtain the OAIL.

As shown in Table 1, the lead-vinyl III configuration provides the least OAIL while the fiberglass plus lead-vinyl III configuration has the greatest OAIL. A comparison of the fiberglass with the three fiberglass plus lead-vinyl configurations shows that as more lead-vinyl is added to the fuselage exterior, the OAIL increases. This result is to be expected and indicates the importance of different transmission paths, since the lead-vinyl II configuration blocked flanking transmission through the tail cone section and lead-vinyl III also blocked transmission through the windows. Some change of cabin sidewall dynamics may have occurred also, but the overall effects are small, as shown in Table 1.

The configurations with fiberglass show an increase in OAIL from 4 to 8 dB over the double-wall and lead-vinyl III configurations, indicating the importance of absorption in the cabin. The OAIL for the far source position is consistently 1 dB higher than the OAIL for the near source position for all but the lead-vinyl only configuration.[9] A more detailed comparison of the fiberglass only and double-wall configurations is given in Ref. 8.

Insertion Loss Spectra

Comparisons of the space-averaged insertion losses for the various configurations relative to the baseline configuration are given in Figs. 8 and 9 as a function of frequency. Space-averaged one-third-octave band insertion losses were calculated by subtracting the space-averaged one-third-octave band SPL for a configuration from the space-averaged one-third-octave band SPL of the baseline configuration.

Figure 8 shows that the IL increases at all frequencies but 160 and 500 Hz as a result of adding increasing amounts of lead-vinyl to the skin. The IL for the fiberglass plus lead-vinyl III configuration ranges from a 2 dB increase at 160 and 500 Hz to a 7 dB increase at 200 and 250 Hz above the IL for the fiberglass only configuration. This increase in IL is accompanied by a large weight increase; the fiberglass plus lead-vinyl I configuration weighs 122 lb more than the fiberglass only configuration. Similar results were found for the far source position.[9]

Comparison of the ILs for the double-wall, fiberglass only, lead-vinyl III, and fiberglass plus lead-vinyl III configurations

Table 2

Frequency, Hz	125	250	500	1000
ΔTL, dB	0.36	0.71	3.9	9.2
ΔABS, dB	6.6	7.9	7.9	7.9

is shown in Fig. 9. The ILs for the double-wall, fiberglass only, and fiberglass plus lead-vinyl III configurations have overall increasing trends with increasing frequency. However, the IL for the lead-vinyl III configuration is relatively flat across the frequency range.

This trend for lead-vinyl III may be explained by the following derivation. The insertion loss may be expressed by[8]

$$IL_{b-a} = \Delta TL + \Delta ABS = TL_a - TL_b + 10\log_{10}(\alpha_b/\alpha_a) \quad (2)$$

where TL is the transmission loss, α is the absorption coefficient, and a, b are the configuration labels. Assuming that the structure transmits sound like a limp mass, then the normal incidence transmission loss may be expressed as[13]

$$TL = 10\log_{10}\left[1 + (\rho_s\omega/2\rho_0 c)^2\right] \quad (3)$$

where ρ_s is the surface density, ω the radian frequency, and $\rho_0 c$ the characteristic impedance.

If the sidewall is sufficiently massive that $(\rho_s\omega/2\rho_0 c)^2 \gg 1$, Eq. (3) is simplified and leads to the following expression for ΔTL due to the addition of mass:

$$\Delta TL = TL_a - TL_b = 20\log_{10}(\alpha_{sa}/\alpha_{sb}) \quad (4)$$

Equation (4) is independent of frequency. The substitution of Eq. (4) into Eq. (2) yields

$$IL_{b-a} = 20\log_{10}(\rho_{sa}/\rho_{sb}) + 10\log(\alpha_b/\alpha_a) \quad (5)$$

For the lead-vinyl III configuration, the interior absorption is assumed to remain unchanged with respect to the baseline configuration so that the JL is dependent only on the change of transmission loss, which is a constant with frequency. The theoretical value of 6 dB shown in Fig. 9 was obtained for a skin thickness of 0.032 in. with attached damping tape and a lead-vinyl weight of 0.775 lb/ft^2.

For the double-wall, fiberglass only, and fiberglass plus lead-vinyl III configurations, the insertion loss is dependent on changes of transmission loss and interior absorption, which are frequency-dependent quantities. The insertion loss of the fiberglass-only configuration was estimated using Eq. (2) and the values for changes in TL and absorption in Table 2.

The values of ΔTL were obtained from tests in the Langley transmission loss apparatus. The values of α were obtained from measured data, and the untreated fuselage was assumed to have $\alpha = 0.12$.

As Fig. 9 shows, the overall trend of the insertion loss from theory and test for both the fiberglass and lead-vinyl III treatments are in agreement, but substantial differences occur at individual frequencies. The insertion loss of fiberglass measured in flight[11] shows large fluctuations with frequency, as do the IL values shown in Fig. 9.

Effect of Temperature

The insertion loss of the treatment measured in flight[15] and in laboratory fuselage tests[8] has shown very large values of scatter when the IL is measured at propeller tones in flight or individual narrow bands in the laboratory. Flight tests have been carried out to investigate some possible reasons for the scatter.[11] Insertion loss tests require two measurements separated by hours while treatments are installed. Temperature changes are one possible cause of scatter and can be studied in the controlled environment of the present tests.

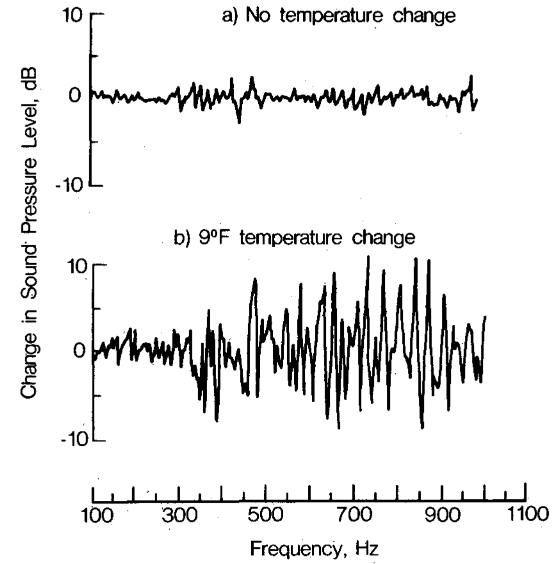


Fig. 10 Change of SPL at microphone 1 due to repeatability and 9°F temperature change.

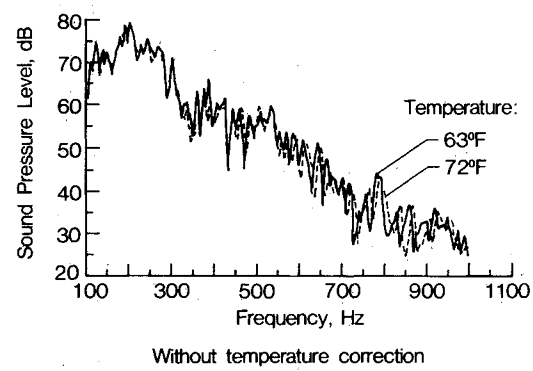


Fig. 11 SPL at microphone position 1 for ambient temperatures of 63 and 72°F.

The fuselage, fiberglass-only treatment, horn, and microphones remained unchanged during these tests. Temperature changes were allowed to stabilize over periods of about 24 h between tests.

The variation of the one-third-octave band NR with temperature for ambient temperatures of 63, 68, and 72°F was found to be less than 2 dB over the entire frequency range.[9] Figure 10 shows the change in the narrow-band SPL due to no temperature change (for repeatability) and the 9°F change in temperature for microphone position 1. In Fig. 10a, the data were acquired 15 min apart at an ambient temperature of 68°F. The peaks range from ±3 dB to about 0. A 9°F change of temperature from 63 to 72°F produced the change in SPL shown in Fig. 10b. The variation in SPL increases from ±3 dB near 100 Hz to up to ±10 dB at the higher frequencies.

The temperature-dependent behavior can be explained in principle by modeling the cabin as a rectangular box. The modal frequencies are given by[16]

$$f = c\left[(n_x/l_x)^2 + (n_y/l_y)^2 + (n_z/l_z)^2\right]^{1/2}/2 \quad (6)$$

where f is the modal frequency, c the speed of sound, l_i the length of the cabin in the ith direction, and n_i the mode number in the ith direction. In this equation, only the speed of sound changes with a change in temperature. The speed of sound is given approximately by[16]

$$c \doteq 1053 + 1.1t \quad (7)$$

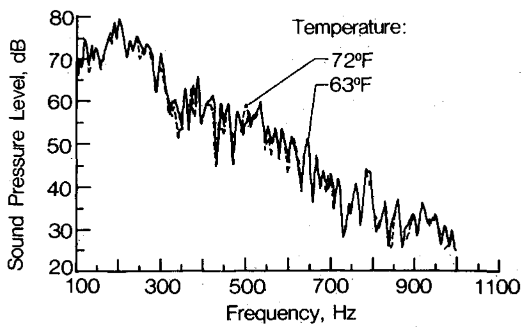


Fig. 12 SPL at microphone position 1 for ambient temperatures of 63 (unaltered) and 72°F (accounting for change in speed of sound).

where t is the temperature in °F. From Eq. (7), it follows that a temperature change from 63 to 72°F causes about a 1% increase in the speed of sound. Substituting this into Eq. (6) shows that the increase in temperature from 63 to 72°F will also cause about a 1% increase in modal frequency. Thus the effect of temperature is more apparent at higher frequencies. For example, at 100 Hz, this 9°F change in temperature will cause the modal frequency to change by about 1 Hz, while at 1000 Hz the modal frequency would change by nearly 10 Hz. Thus, as seen in Fig. 10, the effect on the SPL due to a change in temperature increases with frequency.

The temperature-dependent effects are illustrated more clearly by Figs. 11 and 12. The narrow-band SPLs at microphone position 1 for 63 and 72°F are shown in Fig. 11. These are the two spectra that were subtracted to obtain the curve in Fig. 10b. Adjusting the frequency scale of the data acquired at 72°F for the 1% change in the speed of sound and replotting it with the unaltered 63°F SPL data shows a great decrease in the variability (Fig. 12). Therefore, the large variations shown in Fig. 10 are not random but are predictable, which indicates that changes of temperature are a possible source of scatter in insertion loss measurements at narrow-band or propeller-tone frequencies.

Concluding Remarks

A laboratory study of fuselage sidewall noise transmission and add-on treatment insertion loss is described. A complete fuselage from a twin-engine propeller-driven aircraft and a pneumatically driven horn sound source were used to approximate realistic aircraft conditions.

Sidewall noise reduction is defined as the difference between the exterior noise at a single fixed microphone at the fuselage sidewall and the space-averaged interior noise (or the interior noise at a particular location). Measurements were made with the horn located at mid-cabin length and near the exterior microphone or farther away from the sidewall but at the same longitudinal position. The third location was 84 in. forward of the exterior microphone at a position near the nose of the fuselage. The space-averaged interior noise levels were approximately the same for all three horn positions, but the noise reduction values were different by 10 or 25 dB, primarily reflecting a difference of exterior noise level at the fixed microphone. The similarity of the magnitudes of the interior noise levels for the various source locations was not expected. Similar results have been shown for propeller flight tests, in which case the results were attributed to structure-borne noise. Structure-borne noise was not considered to be a path in this case. Due to a limited time period, an evaluation of the mechanisms involved in moving a noise source either further from the fuselage or forward was not possible.

The sidewall noise reduction measured in these tests is shown to agree in overall trend and magnitude with the results measured in the flight of a propeller aircraft. The effects of source incidence angle were studied, and the results showed that space-averaged interior levels did not vary significantly for source angle variations from −45 to +45 deg. However, the noise level at an individual location in the cabin was affected by variations in the source angle.

Sidewall treatment insertion loss was studied for a production-type double-wall treatment and five combinations of lead-vinyl (attached directly to the sidewall skin) and fiberglass. The fiberglass provided more insertion loss and weighed less than either the double-wall or the lead-vinyl alone. The greatest IL was provided by the fiberglass plus lead-vinyl treatment. The lead-vinyl was added in a sequence that indicated that flanking transmission through the tail section or the windows was small. Approximate theoretical methods were used to predict the IL trends of the lead-vinyl only and fiberglass only configurations. The predicted trends and magnitudes were in approximate agreement with the measured results, but the theory did not include sufficient detail to predict the sharp local fluctuations of IL that appear in the measurements.

The effect of temperature changes were studied as one possible reason for the large variations of insertion loss observed in flight and laboratory tone measurements. A temperature change of 9°F resulted in insertion loss variations of up to ±10 dB. Analysis of the data indicates that these changes result from frequency shifts of the local peaks and valleys in the sound spectrum. The magnitude of the shifts was accounted for by sound speed changes due to the temperature change.

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