Laboratory Study of Cabin Acoustic Treatments Installed in an Aircraft Fuselage

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The insertion loss of side-wall add-on acoustic treatments was measured using a light aircraft fuselage. The treatments included: no treatment (i.e., baseline fuselage), a production-type double-wall interior, and various amounts of high-density fiberglass added to the baseline fuselage. The source used to simulate propeller noise was a pneumatic-driver with attached exponential horn, supplied with a broadband signal. Data were acquired at the approximate head location for each of the six possible passenger positions. Insertion loss results for the different configurations were analyzed in space-averaged narrowband levels, one-third-octave band levels, and overall levels, and at specific frequencies representing propeller tone spectra. The propeller tone data include not only the space-averaged insertion loss but also the variation of insertion loss of these particular frequencies across the six microphone positions.

Introduction

USE of side-wall acoustic treatment is one approach to the control of aircraft cabin noise. Such treatment consists of damping or stiffening material on the fuselage structure, fiberglass and septum layers, and a trim panel. The treatment is intended to reduce noise transmitted through the side wall and may also provide absorption of the sound within the cabin. In addition to reducing cabin noise levels, the treatment is required to have minimum weight and to occupy a limited volume. Side-wall treatment is currently used on most aircraft; however, improved configurations and design methods are needed to optimize treatments for control of low-frequency propeller noise in modern high-performance aircraft.

Treatment design has been approached by trial-and-error testing of candidate treatments in-flight of the aircraft to be treated,[1] by theoretical cabin noise prediction methods,[2-5] and by testing of flat panels in a laboratory transmission loss apparatus.[6] Each approach has advantages and disadvantages. Flight testing provides realism but may be costly and may not allow separation of treatment effects from other factors affecting cabin noise. Theoretical methods allow great flexibility in variation of treatments and provide valuable guidance, but the results must still be verified by testing. Flat-panel testing is reasonably efficient, but panel motion may not represent complete aircraft structural motions, and the tests may not represent the effects of the cabin acoustic characteristics. The approach described in this paper, testing of a complete aircraft fuselage in a laboratory setup, has been taken to provide a realistic test structure and to provide control of test conditions such as exterior sound level. This test approach has been used previously to study heavy side-wall treatments for advanced turboprop application.[7] The test conditions and treatments used in the present study were chosen so that the results would complement previous related theoretical,[4] transmission loss,[6] and flight[8] studies.

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In this paper, results on the changes in interior sound pressure levels of a general-aviation aircraft fuselage are presented for various acoustic add-on treatments and sound source positions. A double-wall configuration, similar to a typical flight interior, along with various amounts of fiberglass treatments were tested. The data are presented in the form of insertion loss (IL), defined as the change of interior sound pressure level due to a specific fuselage modification. Space-averaged insertion losses are shown for several treatments, and the variations of insertion loss from microphone position to microphone position are presented for specific treatments and source positions. The space-averaged insertion loss data are also compared to predicted values.

Experimental Setup

The structure studied in the tests is a pressurizable twin-engine aircraft fuselage. The fuselage is described for use with three-bladed propellers having a blade passage frequency of 125 Hz at 100% hp. Inside dimensions of the cabin are 151 × 42 × 50 in. The fuselage was tested in a hard-walled room with absorbing fiberglass baffles placed around the fuselage to reduce reflections and ambient noise. Figure 1 is a photograph of the fuselage in the experimental setup.

Five different fuselage configurations were tested. The seats were removed for all configurations. The baseline configuration treatment, Fig. 2a, consists of the aluminum outer wall with a thin damping material applied to the inside of the skin. For most of the insertion loss curves presented in this paper, the reference sound pressure levels (SPL) were recorded for the baseline configuration. A double-wall production-type interior was added to the baseline for the double-wall configuration, Fig. 2b. This treatment was not uniform. From just below the window on the side walls up to and including the ceiling, the trim panel was a hard plastic material. The side walls below the windows to the floor were covered with a softer, cardboard-backed vinyl material. A short-shag carpeting covered the floor. For the baseline and double-wall treatments, the instrument panel was left intact; however, all instruments and gauges had been removed. The trim material was attached to the fuselage frames. The 1.5-fiberglass/windows-uncovered configuration added 1.5 in. of fiberglass treatment between the frames of the baseline configuration. The rear bulkhead was also covered with 1.5 in. of fiberglass. The floor, front bulkhead, and windows remained untreated. The 1.5-fiberglass/windows-covered configuration was similar to the 1.5-fiberglass/windows-uncovered configuration; however, the side windows were also covered with 1.5 in. of fiberglass. The 3-fiberglass configuration had an additional 1.5 in. of fiberglass covering the same areas as were covered for the 1.5-fiberglass/windows-uncovered configuration. Thus, the frames were covered with 1.5 in. of fiberglass and the remaining treated areas with 3 in. of fiberglass treatment, as shown in Fig. 2d. As with the 1.5-fiberglass/windows-uncovered configuration, the windows and floor remained uncovered. The front of the cabin (e.g., bulkhead in front of the two front passengers) was also covered with 1.5 in. of fiberglass.

The sound source for these tests was a pneumatic air-driver, with an attached exponential horn (Fig. 1). At the mouth, the horn has a diameter of 24.5 in. A previous study[9] using this same horn showed reasonable agreement with a propeller noise distribution. A concentrated sound source was desired to simulate propeller noise. The horn positions are shown in Fig. 3. Broadband white noise, filtered to obtain a flat spectrum, was supplied to the driver (Fig. 4). The exterior SPL was measured using ½-in. condenser microphones (locations 7-17 in Fig. 3). Figure 5 shows the distribution of the overall SPL (OASPL) over the fuselage sidewall for the two source positions. These exterior measurements were acquired first. Thus, before any interior SPLs were measured, the exterior sound field was known. Figure 5 shows that the sound emitted by the horn is nearly symmetric. This should be expected since the side wall at this point is relatively flat. The distribution is different for the two horn positions. For the near position it is sharply peaked much like propeller noise when propeller tip-to-side-wall clearance is small, and for the far position the distribution is smoother, as expected for large propeller clearances. A narrowband exterior SPL spectrum for microphone position 7 and the near-source position is shown in Fig. 6. The exterior SPL is shown to have high levels, over the frequency range of interest, from 100 Hz to 1000 Hz. These levels were high enough to provide adequate signal-to-noise ratio for the interior microphones.

Interior SPL was measured using ½-in. condenser microphones at the approximate head locations of each of the six possible passenger positions (microphones 1-6 in Fig. 3). As shown in Fig. 4, these pressure signals are passed through measuring amplifiers and a switching box before reaching a two-channel fast Fourier transform (FFT) analyzer. The FFT was adjusted so that the maximum reliable frequency was 1000 Hz with 400 lines of data. The resulting bandwidth was 2.5 Hz. The data stored were calculated from 100 averages.

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

In order to verify repeatability, the SPL for a specific configuration and source position was measured on two different days. Figure 7 shows the IL for microphones 5 and 6 for the double-wall configuration for two different runs for the near-source position. Between these two days, the microphones, fuselage, and sound source were moved and then replaced as closely as possible to their original positions. The primary purpose for the repeatability study was to determine the variability of IL due to repositioning. As shown in Fig. 7, the variability between the two runs is small. The ambient temperature was not measured while testing; thus, changes in SPL due to change in temperature are not accounted for.

Prediction Method

The insertion loss of the treatments is predicted using the following prediction method in an attempt to relate results obtained in the present fuselage tests with results obtained in standard transmission loss tests. The method is based on an energy analysis and predicts the space-averaged insertion loss. This model is derived from the noise reduction formula,

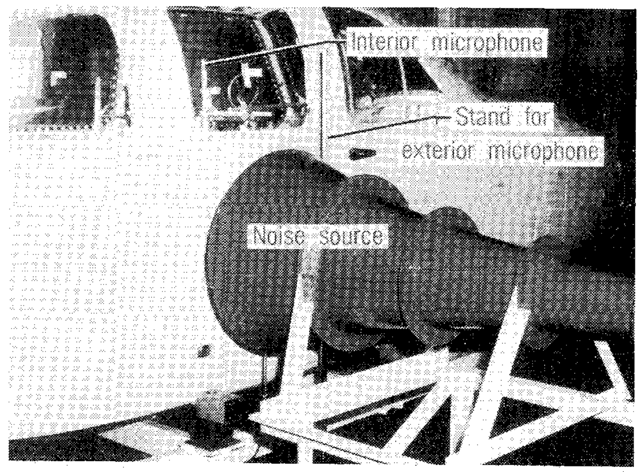


Fig. 1 Aircraft fuselage and test setup.

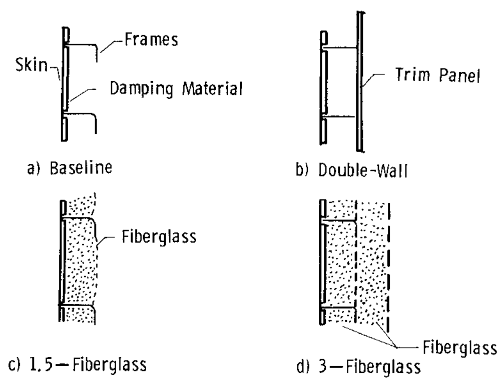


Fig. 2 Cross section of treatment configurations.

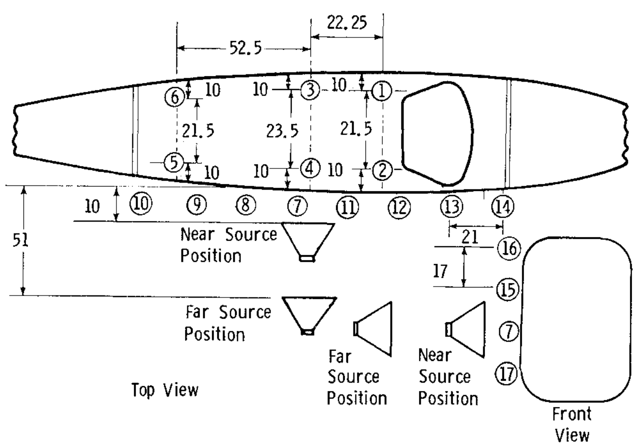


Fig. 3 Source and microphone positions; 0 = microphone positions; dimensions in in.

$$NR = TL + 10\log_{10}\alpha, \text{ dB} \tag{1}$$

where

NR = noise reduction, ≡ exterior SPL − interior SPL

TL = transmission loss

α = absorption coefficient

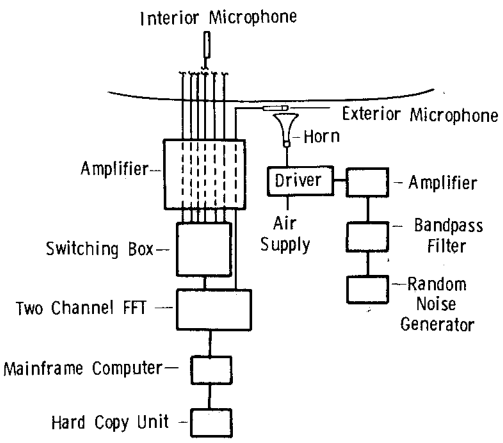
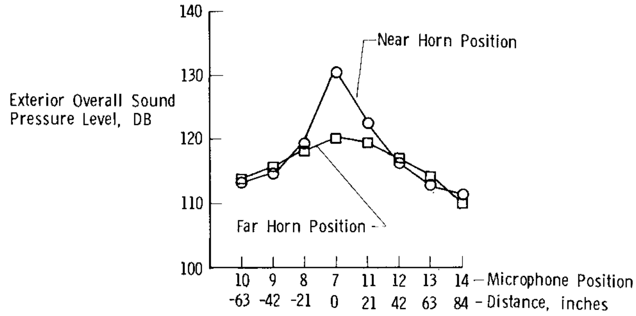
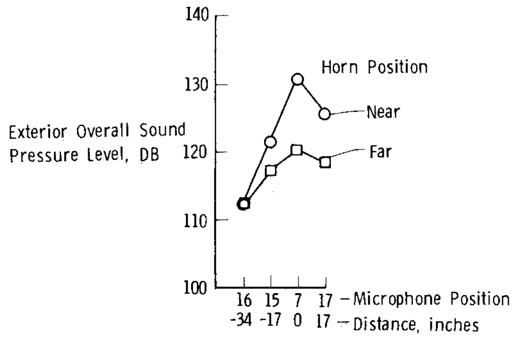


Fig. 4 Instrumentation arrangement.



a) Horizontal.



b) Vertical.

Fig. 5 Variation of exterior SPL on the fuselage side-wall.

For a constant exterior sound pressure level, the insertion loss is equal to the change in noise reduction, so that

$$\mathrm{IL}_{b-a} = \mathrm{NR}_a - \mathrm{NR}_b = \mathrm{TL}_a - \mathrm{TL}_b + 10\log_{10}\alpha_b - 10\log_{10}\alpha_a \tag{2}$$

where a and b denote two distinct fuselage configurations.

Gathering terms, this becomes

$$\mathrm{IL} = \Delta\mathrm{TL} + \Delta\mathrm{ABS} \tag{3}$$

where ΔTL and ΔABS are changes in IL due to changes in TL and absorption, respectively.

Thus, the total insertion loss is a sum of the contributions due to the increases in absorption and transmission loss. Values of TL and ΔABS were estimated using TL values obtained from unpublished laboratory tests of flat panels of similar construction and fiberglass treatment, and absorption coefficients taken from manufacturers' data sheets.

Discussion of Results

Overall Insertion Loss

Overall insertion loss (OAIL) of a treatment is determined from the measured SPL as follows. Narrowband SPLs at each frequency for a particular configuration were averaged across microphone position on an energy basis to give a space-averaged narrowband interior SPL,

$$\mathrm{SPL}_{\mathrm{avg}} = 10\log_{10}\left(\frac{1}{6}\sum_{i=1}^{6} 10^{\mathrm{SPL}/10}\right) \tag{4}$$

The averaged narrowband SPL spectrum was also summed on an energy basis to obtain the overall sound pressure level (OASPL) of the configuration. The OASPLs of two configurations were then subtracted to get the OAIL. For the results shown in Fig. 8, the OAIL was obtained by subtracting the OASPL for each treatment from the OASPL of the baseline configuration. The figure shows that the double-wall configuration has nearly the same sound attenuation (IL) as the 1.5-fiberglass/windows-uncovered configuration. The 1.5-fiberglass/windows-covered configuration has about 1 dB larger IL and the 3-fiberglass configuration has 2 to 3 dB more IL. The 3-fiberglass configuration weighs 75 lb and the double-wall weighs 107.5 lb. In addition, the OAIL for the far-source position is consistently 1 dB higher than the OAIL for the near-source position.

Comparison of Measured and Predicted Insertion Loss

The measured IL (Fig. 9) is based on averaged interior SPL data. First, the narrowband SPL of the six interior microphones were averaged on an energy basis. Then, the averaged narrowband SPL was summed on an energy basis to one-third octave bands. These one-third-octave band SPLs were then subtracted from values obtained for the baseline configuration in order to find the insertion loss.

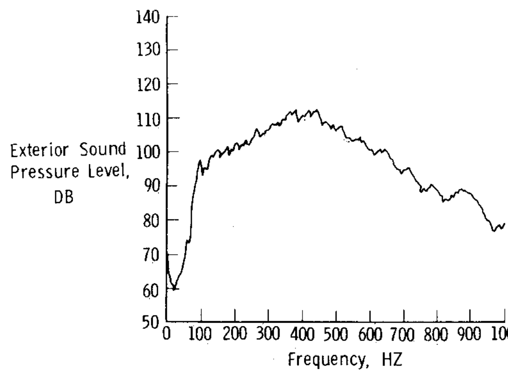
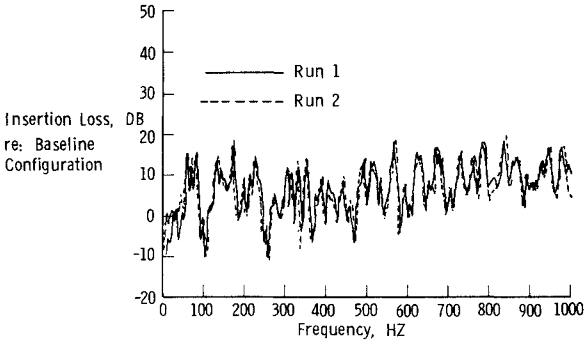
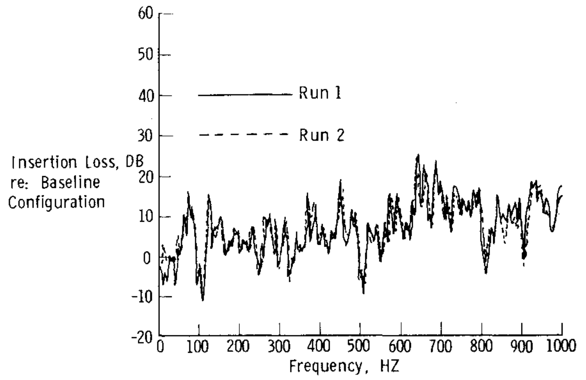


Fig. 6 Narrowband SPL spectrum for exterior microphone #7, near-source position.

Figure 9 shows that the predicted IL tends to overestimate at a majority of the frequency bands; however, both predicted and measured values show overall trends of increasing IL with frequency. The difference in IL for the two 1.5-fiberglass configurations was small in both the predicted and measured cases. On the other hand, the difference between the 1.5-fiberglass/windows-uncovered and the 3-fiberglass configurations is relatively large, 3-5 dB, for both measured and predicted IL. Thus, the model predicts overall trends and the change in IL much better than the magnitude of the IL. This is important for preliminary design studies. As will be seen later, the results for the near- and far-source positions are similar in magnitude so that either source position could be used for the measured/predicted comparison. The predicted IL values form a smooth curve, whereas the data have dips at about 250 Hz and 500 Hz. A model to predict these irregularities would



a) Microphone No. 5.



b) Microphone No. 6.

Fig. 7 Repeatability of narrowband IL for double-wall configuration, near-source position.

need to be more complex. In addition, knowledge of both structural and acoustical modes might be necessary.

Effect of Treatment

Figure 9 shows that treatments having greater amounts of fiberglass have greater IL at all frequencies except 100 Hz. For example, the 3-fiberglass configuration has the highest IL, while the 1.5-fiberglass/windows-uncovered configuration has the lowest. The increase in IL with increasing amounts of fiberglass was also true for the far-source position. This result is appropriate because the addition of fiberglass can be expected to increase both the TL of the side wall and the absorption of the interior. The IL at frequencies below 250 Hz is noteworthy since fiberglass is often thought to have little benefit at low frequencies.

For simplicity in comparison, only the lowest and highest IL of fiberglass configurations are used and the interval shaded, as shown in Figs. 10 and 11, comparing the double-wall results with fiberglass results. In Fig. 10, the IL of the double-wall treatment falls along the lower part of the shaded area for all but the 125 and 160 Hz center frequency bands. At 125 Hz the double-wall and 3-fiberglass configurations are nearly equal. At 160 Hz, the IL for the double-wall configuration exceeds the IL of the upper bound by about 1 dB. The double-wall treatment falls below the shaded areas for the 100, 200, and 400 Hz frequency bands, by less than 2 dB. Likewise, in Fig. 11, for the far-source position, the double-wall treatment falls near the bottom or below the shaded area for all but the 100-160 Hz frequency bands. From 315 to 630 Hz and at 1000 Hz, the 1.5-fiberglass/windows-uncovered configuration attenuates the sound better than the double-wall treatment by up to 3 dB. These figures show that at many frequencies the lighter fiberglass treatments perform as well as or better than the heavier double-wall treatment. Fiberglass has also been shown to provide significant IL in flight tests of a propeller aircraft.[8] These results suggest that both TL and absorption of a treatment should be considered.

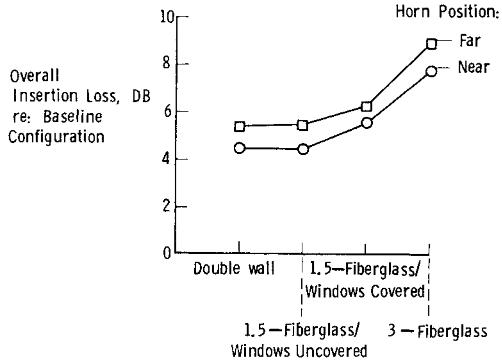


Fig. 8 OAIL as a function of configuration for two source positions.

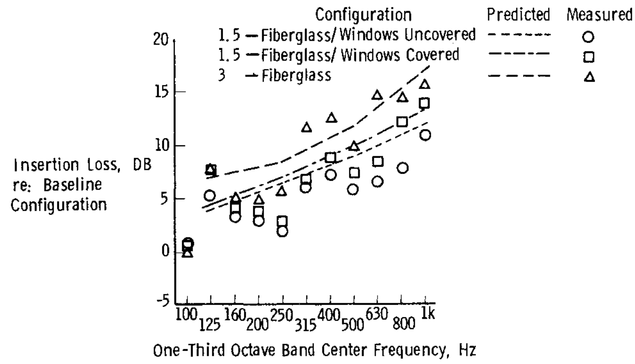


Fig. 9 Measured and predicted IL vs frequency, near-source position.

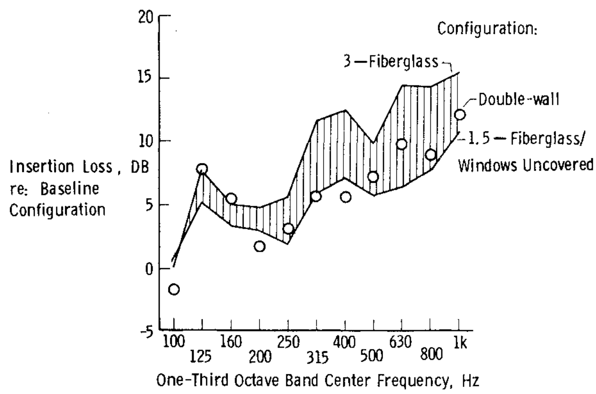


Fig. 10 IL vs frequency of the double-wall and fiberglass configurations, near-source position.

Effect of Source Position

The effect of horn position on IL is shown in Figs. 12 and 13. Examining the IL of the fiberglass treatment shown in Fig. 12 indicates that the overall effect of source position is small. However, the IL at the 125 Hz one-third-octave band is 3 dB greater at the near-source position than at the far position. The effect of source position on the IL of the other two fiberglass treatments is similar to that shown in Fig. 12.

The effect of source position for the double-wall treatment is shown in Fig. 13. A comparison of the two curves in this figure shows that they both have an overall tendency to increase IL with increasing frequency but that differences of up to 5 dB occur in some frequency bands. In the low-frequency region, the IL for the far-source position is greater than that for the near-source position. From 250 to 400 Hz, the IL is nearly the same for the two source conditions. Between 400

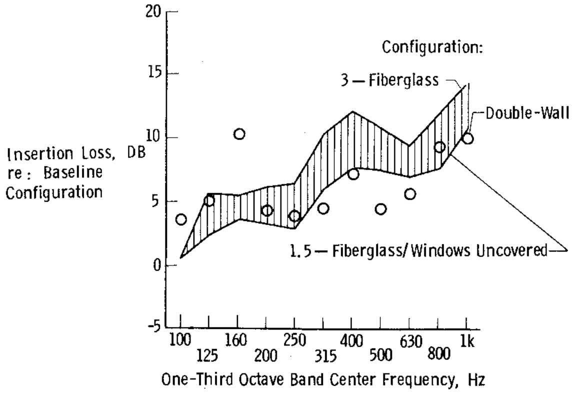


Fig. 11 IL vs frequency of the double-wall and fiberglass configurations, far-source position.

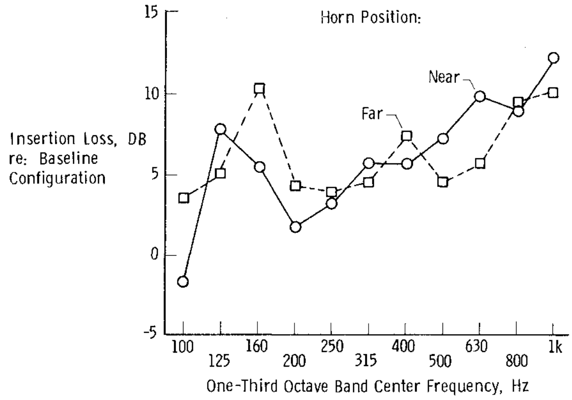


Fig. 13 IL vs frequency of the two source positions for double-wall configuration.

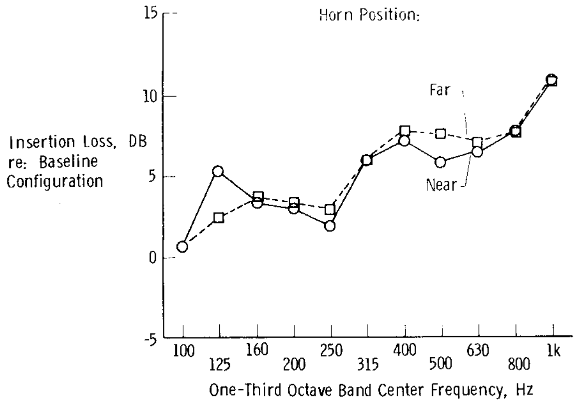


Fig. 12 IL vs frequency of the two source positions for 1.5-fiberglass/windows-uncovered configuration.

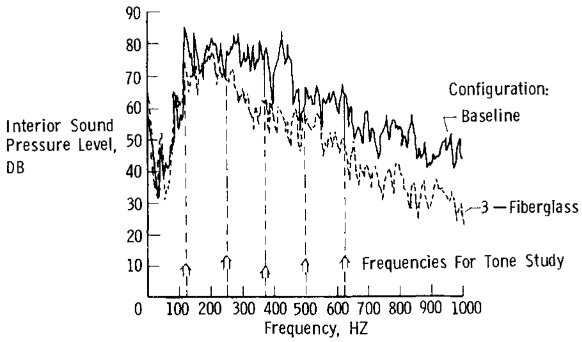


Fig. 14 Example SPLs used to calculate narrowband IL, microphone No. 1.

and 800 Hz, the insertion loss is higher for the near-source locations.

Figures 12 and 13 show that the insertion loss, and therefore the cabin noise reduction, may depend on the distribution of the exterior sound pressure level for side-wall treatments such as double walls.

Tone Study

The sound field of a propeller aircraft is characterized by high-level tones at the blade passage frequency and at its harmonics. The performance of acoustic treatments in a tonal sound field is of interest in addition to broadband results such as those shown in Figs. 8-13. Insertion loss of fiberglass and multilayer treatments has been studied in flight tests of a propeller-driven aircraft.[8] These studies showed that the treatment IL varied substantially for different locations in the cabin, and that for some tone frequencies and locations the IL was negative, i.e., the addition of the treatment increased the cabin noise level. Possible reasons for these variations were thought to be associated with acoustic or structural vibration modes or lack of repeatability of test conditions from flight to flight. Because of the difficulties of flight tests, the reasons could not be definitely established. One of the principal objectives of the tests reported here was to study treatment insertion loss in a controlled tonal sound field. Figure 7 shows that test conditions were sufficiently controllable that IL measurements could be repeated from day to day.

Tonal effects were studied as follows. The narrowband IL was calculated by subtracting two narrowband interior SPLs, such as those shown in Fig. 14, obtained with the same exterior SPL. Thus, no tones were generated; however, specific narrowbands were chosen from the broadband data. A fundamental frequency of 125 Hz was chosen since the blade passage frequency of this aircraft is near 125 Hz. Flight studies suggest that propeller tones above the fourth harmonic contribute much less to the interior noise than the lower tones; therefore, only tones up to 625 Hz were studied.

In Fig. 15, the IL values for the 1.5-fiberglass/windows-uncovered configuration and the far-source position are shown. This figure shows that the IL at a given frequency varies substantially with position in the cabin. For example, at 125 Hz the IL varies from zero at position 5 to 6 dB at position 3. At 625 Hz the IL varies from -6 dB to $+14$ dB, a difference of 20 dB. In addition, the average IL has a maximum value of 10 dB at 375 Hz and is only about 3 dB at 125 and 625 Hz. In this case the average IL was determined by first calculating the IL for each microphone position and averaging the six individual ILs. The magnitude of this variation with position and the relatively small value at 625 Hz is consistent for all the fiberglass configurations with the source at the far position. Figure 16 for the near-source position shows the IL for the 1.5-fiberglass/windows-covered configuration, while in Fig. 17 for the near-source position, the data were acquired for the 3-fiberglass configuration. In Fig. 17, a slight decrease in average IL is seen at 500 Hz. The magnitude of the variation of IL with position is about the same for the fiberglass treatments shown in Figs. 15-17 and is similar to the results obtained in flight. These results suggest that the variations of IL with position are a characteristic of the treatment and fuselage structure and not solely a result of nonrepeatability of such test conditions as source noise characteristics.

Figure 18 shows the IL of the 3-fiberglass configuration relative to the 1.5-fiberglass/windows-uncovered configuration. These results for the addition of 1.5 in. of fiberglass over an existing 1.5 in. of fiberglass are shown to examine the

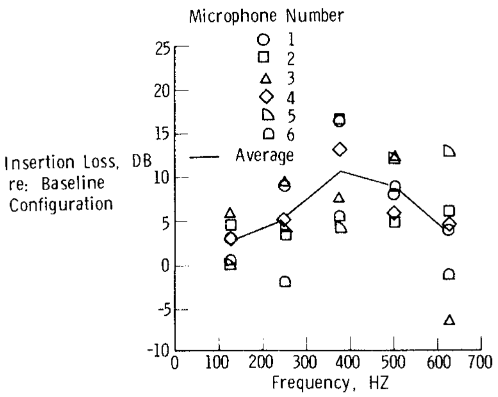


Fig. 15 Narrowband IL for 1.5-fiberglass/windows-uncovered configuration, far-source position.

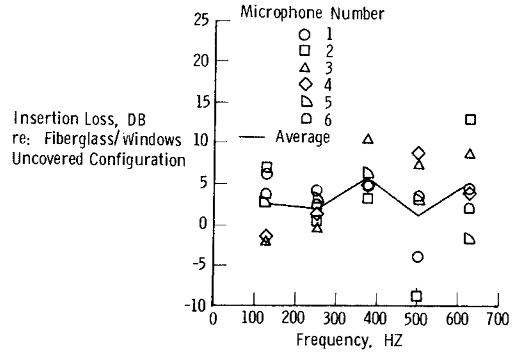


Fig. 18 Narrowband IL for 3 fiberglass configuration re 1.5-fiberglass/windows-uncovered configuration, near-source position.

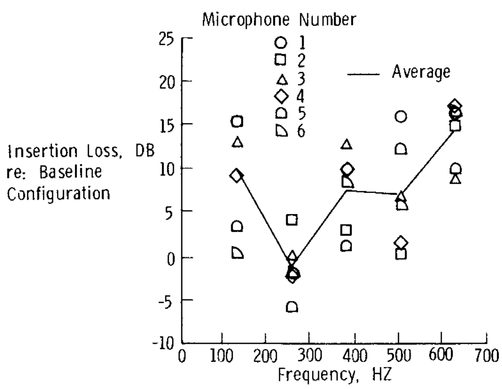


Fig. 16 Narrowband IL for 1.5-fiberglass/windows-covered configuration, near-source position.

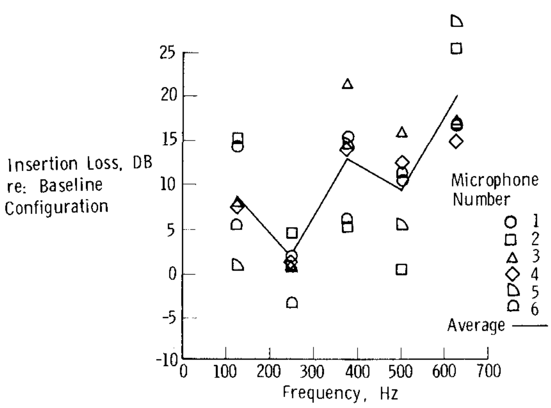


Fig. 17 Narrowband IL for 3-fiberglass configuration re baseline configuration, near-source position.

possibility that strong acoustic modes in the untreated baseline configuration might be responsible for the variations shown in Figs. 15-17. The variation of IL from position to position in Fig. 18 is slightly less for the lower-frequency tones than for the cases shown in Figs. 15-17, where the reference condition is the baseline fuselage. However, for the two highest-frequency tones in the study, whether the reference condition is the baseline fuselage or a fiberglass treatment, the amount of variation in IL over the six interior positions appears to be about the same.

A wide variation of IL over the six microphone positions at specific tones is evident in Figs. 15-18. This suggests that the treatment does not affect the interior space uniformly. One passenger may receive a great deal of benefit from a certain treatment, while the noise for a nearby passenger may be affected very little. The information presented in these figures also helps to explain some of the IL variations shown for in-flight tests.[8] Variations due to changes in the cabin acoustics or unsteadiness of the source, among other possible reasons, were not separated in flight. However, as was seen in this paper, large fluctuations may occur even when the source is kept constant. In addition, negative insertion losses observed in flight might be attributed to an unsteadiness of the propeller. Figures 15-18 also show negative insertion losses at specific tones and microphone positions where the source remains unchanged.

Concluding Remarks

This paper describes an experimental study of fuselage side-wall add-on treatments for cabin noise control. A complete production-line fuselage of a general-aviation aircraft was used to include both cabin acoustics and side-wall transmission effects on the treatment. Treatments included a double-wall production-type interior and several configurations of fiberglass blankets. The performance of the treatments was measured in terms of insertion loss (IL).

Treatments were compared based on one-third-octave spectra and overall SPL averaged over the six cabin microphones. Treatment insertion loss was shown to increase as greater amounts of fiberglass were added, and substantial IL occurred at all frequencies above 100 Hz. Insertion loss was predicted using measured transmission loss results and absorption estimated from material constants. The predicted IL agreed with the measured IL in overall trend with frequency and with the magnitude of the change of IL for various treatments. The double-wall treatment showed IL values generally equal to or less than the IL of the fiberglass, even though the double-wall treatment weighs substantially more than the fiberglass. This result suggests that factors such as cabin absorption and double-wall dynamics have important effects on insertion loss.

The behavior of the fuselage treatments in a propeller noise spectrum was examined by selecting SPL values with 2.5-Hz bandwidth from the broadband spectra. Frequencies were chosen to correspond to the blade passage frequency and its harmonics. The IL values associated with these tonal spectra showed a large variation with location in the cabin, with occasional negative IL values. Similar results were observed in flight of a propeller aircraft. For the laboratory tests it was shown that test conditions such as source noise could be repeated closely from day to day, which suggests that the variability of IL with position is not solely a result of variations in source noise but may also be associated with the dynamics of the side-wall structure and cabin acoustics.

References

[1] Waterman, E. H., Kaptein, J., and Sarin, S. L., "Fokker's Activities in Cabin Noise Control for Propeller Aircraft," SAE TP 830736, April 1983.

[2]Wilby, J. F., "The Prediction of Interior Noise of Propeller Driven Aircraft: A Review," SAE TP 830737, April 1982.

[3]Pope, L. D., Rennison, D. C., Willis, C. M., and Mayes, W. H., "Development and Validation of Preliminary Analytical Models for Aircraft Interior Noise Prediction," *Journal of Sound and Vibration,* Vol. 82, No. 4, 1982, pp. 541-575.

[4]Vaicaitis, R. and Slazak, M., "Design of Sidewall Treatment for Cabin Noise Control of a Twin-Engine Turboprop Aircraft," NASA CR 1722245, Dec. 1983.

[5]Rennison, D. C., Wilby, J. F., Marsh, A. H., and Wilby, E. G., "Interior Noise Control Prediction Study for High-Speed Propeller-Driven Aircraft," NASA CR 159200, Sept. 1979.

[6]Grosveld, F. W., "Noise Transmission Through Sidewall Treatments Applicable to Twin-Engine Turboprop Aircraft," AIAA Paper 83-0695, April 1983.

[7]Prydz, R. A., Revel, J. D., Hayward, J. L., and Balena, F. J., "Evaluation of Advanced Fuselage Design Concepts for Interior Noise Control on High-Speed Propeller-Driven Aircraft," NASA CR 165960, Sept. 1982.

[8]Mixson, J. S., O'Neal, R. L., and Grosveld, F. W., "Investigation of Fuselage Acoustic Treatment for a Twin-Engine Turboprop Aircraft in Flight and Laboratory Tests," NASA TM 85722, Jan. 1984.

[9]Barton, C. K. and Mixson, J. S., "Noise Transmission and Control for a Light Twin-Engine Aircraft," *Journal of Aircraft*, Vol. 18, July 1981, pp. 570-575.