Effects of Acoustic Treatment on the Interior Noise of a Twin-Engine Propeller Airplane

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A study of the cabin acoustics of a Fairchild Merlin IVC twin-engine propeller airplane is described. The sound field was measured at six locations inside both an untreated "green" airplane and a completely finished airplane. Several flight conditions were tested, including different altitudes, engine power settings, and cabin pressures. The overall sound pressure level for each test condition and microphone position was computed from a one-third octave band analysis of the data. The blade passage frequency and its integral multiples, which dominate the low-frequency noise spectrum, were examined using a narrowband analysis of the data. The insertion loss due to the added acoustical treatment was determined by comparing the narrowband results from the two airplanes. These insertion loss values varied widely, depending on many factors, such as position in the cabin, multiple of blade passage frequency, cabin pressure, and engine torque. The space-averaged sound pressure levels corresponding to specific tests of the treated airplane were found to be in good agreement with predictions from the Propeller Aircraft Interior Noise (PAIN) computer program.

Introduction

THE prediction, measurement, and reduction of the noise levels inside currently available propeller aircraft can provide valuable information to help improve interior noise prediction methods for new aircraft, especially the proposed fuel-efficient high-speed turboprop. Propeller-generated noise, transmitted through the fuselage sidewall, is a major contributor to the interior noise levels of twin-engine turboprop airplanes. The low-frequency spectrum of this noise is very tonal in nature, being dominated by the blade passage frequency (fundamental) and integral multiples of that frequency. The propeller noise, acoustic transmission paths, and interior absorption characteristics need to be controlled in order to reduce the interior noise to levels that meet passenger acceptance criteria.

The many factors contributing to the sound field inside propeller aircraft have led to extensive research directed toward identifying and improving techniques for interior noise reduction. Theoretical methods have been developed that predict the noise generated by high-speed propellers[1,2] and experiments have been performed to verify these prediction methods as well as to examine the distribution of the exterior sound field on the fuselage surface.[2,3] The transmission of noise through various types of aircraft panels has been studied analytically and experimentally.[4-9] Recently, some research has been undertaken to better understand the noise that is transmitted and reradiated into the cabin by way of structure-borne vibrations.[10-12] The interior noise field itself has been measured under both ground and flight test conditions and the insertion loss of various sidewall acoustical treatment configurations has been determined.[13-16]

The purpose of this paper is to present the results of interior noise measurements of a Fairchild Merlin IVC twin-engine propeller airplane in flight. One set of measurements was taken onboard an untreated "green" airplane (bare walls with some fiberglass insulation material). A second set of measurements was taken onboard a completed Merlin IVC outfitted with the manufacturer's executive trim configuration. The data were analyzed in both narrowband and one-third octave formats so that integral multiples of the blade passage frequency could be examined and the overall sound pressure levels computed. The results focus on the effects of the sidewall trim and flight operation conditions on the interior noise field. The paper concludes with a brief description of a recently developed computer program that calculates the space-averaged interior noise levels in propeller aircraft. Results of the first full-scale test comparison of this prediction model, made with the Merlin IVC airplane, are presented.

Experimental Procedure

Aircraft Description

The Fairchild Merlin IVC used in this study has a maximum takeoff weight of 14,000 lb and can accommodate 11 passengers. Each of the two 1000 shp turboshaft engines drives a four-bladed propeller that is 2.7 m (8 ft, 10 in.) in diameter and has a 17 cm (6.75 in.) tip clearance from the fuselage sidewall. The engine rpm was set at 97% throughout the study, resulting in a blade passage frequency (BPF or fundamental) of 105 Hz. The automatic synchrophasing was turned on for the test cases presented in this paper.

As stated previously, there were two versions of the Merlin IVC in which the interior noise field was measured. The interior of the untreated, or "green," airplane was bare except for certain items required by safety regulations. There were no trim panels. Thermal insulation was provided by 2 in. of bagged fiberglass that was uniformly distributed over the sidewalls between the ring frames. The fiberglass did not cover the windows. There was no carpeting and only four passenger seats (for the technical staff).

In contrast to the "green" airplane, the completely finished version was quite luxurious. This "executive" interior included the manufacturer's standard sidewall trim configuration, carpet, leather upholstered seats, and a refreshment/entertainment center that contained food storage and preparation facilities as well as television and stereo equipment. Of

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particular interest to this study is the sidewall trim, which consisted of 2 in. of bagged fiberglass (as in the "green" airplane) and a trim panel of sandwich construction. This trim panel sandwich had a cellular core made from blended plastic resins; its facings were made of laminated fiberglass. The surface mass of the trim was 1.95 kg/m^2 (0.4 lb/ft^2).

Flight Conditions and Instrumentation

The flight test of the treated airplane was performed on a different day than that of the "green" airplane. Weather conditions on the two days were very similar. The air temperature was within 2°F at each of the three altitudes at which the interior noise levels were measured. The sky was clear and no significant rough air was encountered during the data recording.

The interior noise field was measured with six 0.5 in. condenser microphones positioned inside the airplane as illustrated in Fig. 1. The microphones were suspended from the ceiling (clamped to the exposed ring frames in the "green" airplane, taped to the ceiling trim in the treated airplane) so that the sound field could be measured at typical passenger ear levels. There was no appreciable sway of the microphones during flight. The interior noise was recorded on high quality AM recorders under various flight conditions, including changes in altitude, engine power settings, and cabin pressurization. Table 1 lists the operating conditions of the flight tests presented in this paper.

Test runs 6-8 of the treated airplane include data collected by microphones 5 and 6 over a cross section of the cabin at axial locations 7 and 8, respectively (see diamond symbols in Fig. 1). The microphones were hand held and swept over the path shown in Fig. 2. The sweep path was traversed twice; each traverse took approximately 15 s. These sweep data were used in conjunction with data from microphones 2 and 3 in order to determine a space-averaged interior noise level that could be compared with results from the Propeller Aircraft Interior Noise (PAIN) prediction model.[17]

Data Analysis

The tape-recorded interior noise data were reduced in the laboratory using commercially available one-third octave and narrowband spectrum analyzers. The one-third octave analysis covered a frequency range of 50-20,000 Hz and was used to determine overall sound pressure levels (OASPL). The narrowband analysis was performed over a frequency range of 20-2000 Hz with a 5 Hz bandwidth. A typical narrowband analysis consisted of an average of 64 fast Fourier transforms taken over 16 s. Figures 3 and 4 illustrate the narrowband results for the "green" and treated Merlin IVC, respectively, at microphone position 2 under the flight conditions of run 1 (see Table 1). It is clear from these figures that the blade passage frequency and its multiples dominate the low-frequency noise spectra of this airplane.

Discussion of Results

The analysis of the interior noise data presented in the following paragraphs of this paper is divided into three sections. In the first section the insertion loss, defined as the difference in noise levels measured under nearly identical conditions inside the two airplanes, in examined. This approach helps isolate the effect that the added acoustical treatment has on the interior noise field. The second section examines the influence of different flight operation conditions on the interior noise field. Here, results are presented in terms of the actual sound pressure levels measured in each airplane. Finally, the data collected from specific flight tests are compared to and used to validate a recently developed analytical model that predicts the space-averaged noise levels inside propeller aircraft. The flight test data presented in each section concentrates on the blade passage frequency (BPF = 105 Hz) and integral multiples of that frequency (2 × BPF = 210 Hz, 3 × BPF = 315 Hz,...).

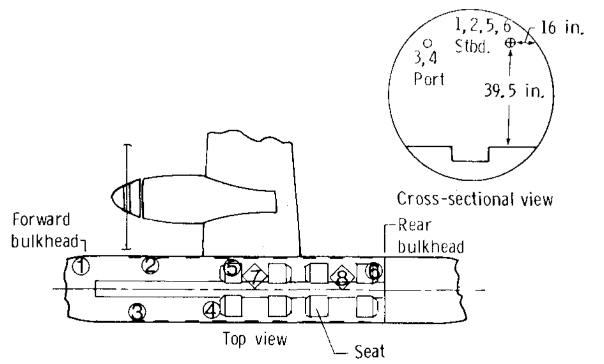

Fig. 1 Microphone locations relative to the interior plan of the treated airplane.

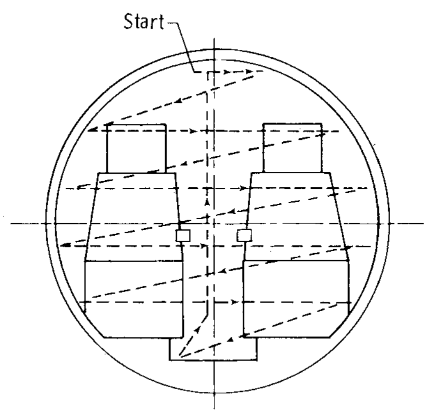

Fig. 2 Microphone sweep path for hand-swept interior noise measurements at locations 7 and 8.

Table 1 Flight operation conditions for the "green" and treated Merlin IVC airplanes

Run no.	Altitude, ft × 10^3	Airspeed, kias	Torque, port/starboard,%	Cabin pressure differential, psi	Air temperature, °F	Fuel level, lb
1	17.5	192	56/56	6.9	21	2000
2	17.5	188	50/50	6.9	21	2000
3	12	210	63/63	5.4	45	1800
4	12	210	60/60	2.9	45	1700
5	12	210	60/60	0.2	45	1700
6	5	238	74/74	2.5	63	1700
7[a]	5	216	57/57	2.5	63	1700
8[a]	5	165	35/35	2.5	63	1700

[a]Data from these runs are available only for the treated airplane.

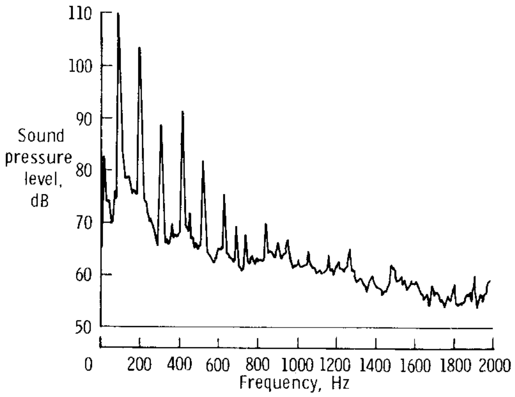

Fig. 3 Narrowband analysis at microphone 2 for the flight conditions of run 1 ("green" airplane).

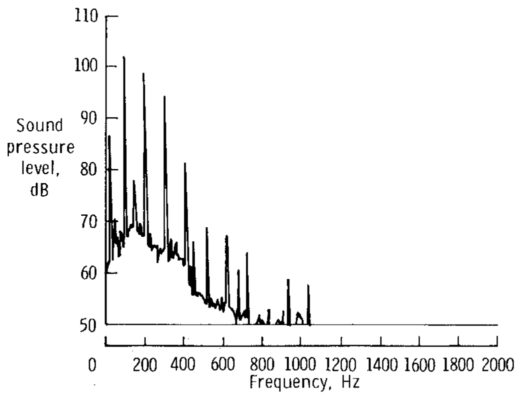

Fig. 4 Narrowband analysis at microphone 2 for the flight conditions of run 1 (treated airplane).

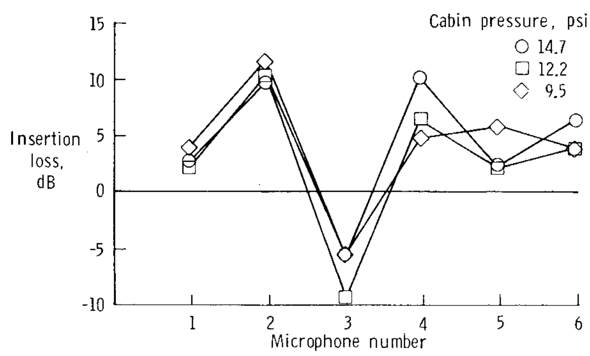

Fig. 5 Spatial variation of the insertion loss at the BPF (105 Hz) for three cabin pressures.

Effect of Trim on Interior Noise

As stated previously, the effect of the added acoustical treatment (the sidewall trim configuration, in particular) on the interior noise field can be determined by studying the change in sound pressure levels inside the treated airplane relative to those measured inside the "green" airplane. This insertion loss information can be calculated quite easily for the blade passage frequency and its multiples using the narrowband analyses mentioned earlier. It is a function of frequency, microphone position in the cabin, flight operation conditions, and acoustical treatment. It is usually expected that the insertion loss is positive, which indicates a reduction in the interior noise; however, a negative insertion loss may sometimes occur, as will be shown.

Figures 5 and 6 illustrate the variation of insertion loss with microphone position for test runs 3-5. As indicated in Table 1, the cabin pressure differential (inside to outside) is the control parameter that is varied for these runs. The actual cabin pressure (as given in the figure legends) for runs 3-5 was calculated to be 14.7, 12.2, and 9.5 psi, respectively. Figure 5 shows the variation with position for the blade passage frequency (BPF = 105 Hz), while Fig. 6 shows the variation for the frequency twice the fundamental (2 × BPF = 210 Hz).

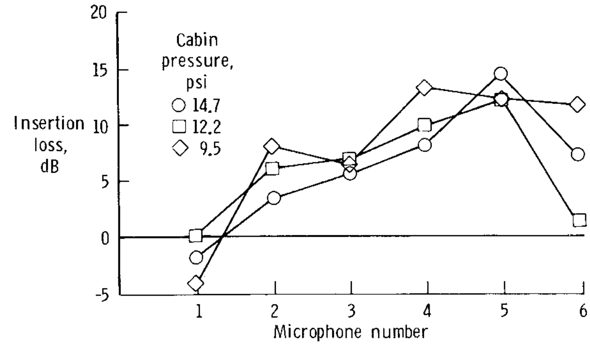

Fig. 6 Spatial variation of the insertion loss at 2 × BPF (210 Hz) for three cabin pressures.

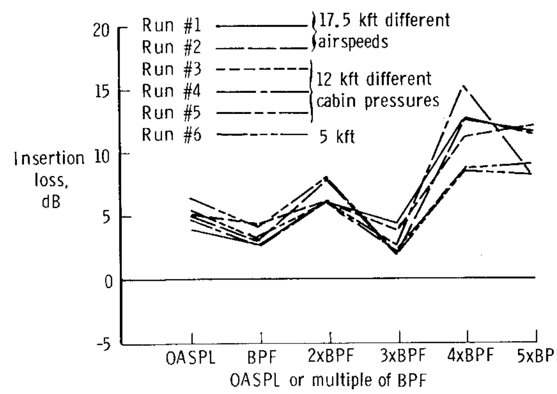

Fig. 7 Space averaged insertion loss for OASPL and multiples of the BPF for six flight conditions.

Before examining these figures in detail, their overall characteristics should be emphasized. First, it should be noted that the general trend of the data in each figure is the same, irrespective of the specific cabin pressure. This observation suggests that changes in the cabin pressure alone will have little effect on interior noise levels. Second, when Fig. 5 is compared to Fig. 6, it becomes obvious that the insertion loss is not constant with respect to frequency. It is also clear that the insertion loss is not constant from one microphone location to another, even though the sidewall acoustical treatment is fairly uniform throughout the cabin.

A close examination of Figs. 5 and 6 reveals some information that requires explanation. For instance, the small amount of insertion loss found at microphone location 1 is probably due to the fact that little additional treatment was present in the cockpit of the treated airplane. Therefore, the interior noise levels at that location did not differ much between airplanes. The negative insertion loss for the blade passage frequency found at microphone location 3 (Fig. 5) is also within reason, considering the circumstances of the tests. The treated airplane had two additional windows on the port side near the plane of the propeller. These windows probably provided less noise reduction at the blade passage frequency than the aluminum and fiberglass at these locations in the "green" airplane. Thus, the treated airplane had a higher interior noise level at this frequency in the vicinity of the added windows (microphone 3), which resulted in a negative insertion loss. Another apparent inconsistency in the data can be seen at microphone 6 for twice the blade passage frequency (Fig. 6). This large spread of data may be due to an oversight of the technical staff that left the rear bulkhead partially open during flight tests of the treated airplane. In general, it is felt that the variability between test runs (±4 dB) was reasonable for this type of test and is consistent with results found by other researchers.[15,16]

Whereas Figs. 5 and 6 show the variation of the insertion loss as a function of position inside the airplane cabin, other characteristics of the sound field become apparent by examining the variation of the space-averaged insertion loss as a function of frequency, as shown in Fig. 7. In this figure, the insertion loss values corresponding to the overall sound pressure level (OASPL), blade passage frequency, and multiples of the blade passage frequency were numerically averaged over the six microphone positions and plotted for each of the six pertinent flight tests. The trend in the figure is similar for each of the six runs and the variation between runs is tolerable. As expected, the insertion loss increases with frequency as the added acoustical treatment becomes a more effective absorber. The large variation shown at four times the blade passage frequency ($4 \times \mathrm{BPF} = 420$ Hz) may be due to the electrical noise generated at that frequency by the extra electronic amenities inside the treated airplane.

Effect of Flight Conditions on Interior Noise

Figures 8-10 show the actual interior noise levels of the "green" and treated airplanes that result from the variation of two basic flight operation conditions: cabin pressure and engine torque. Each data point on these figures represents an energy average of the noise levels measured at the six microphone locations. The OASPL was determined from the one-third octave band data, and averages for the blade passage frequency and its multiples were calculated using the narrowband data. The connecting lines do not indicate calculated or measured broadband noise levels; they merely connect common data points and help to illustrate trends.

Figures 8 and 9 show a slight increase in the interior sound pressure level as a function of cabin pressure (runs 5, 4, and 3: actual cabin pressure is 9.5, 12.2, and 14.7 psi, respectively). This is apparent in both the "green" airplane (Fig. 8) and the treated airplane (Fig. 9), although the absolute noise levels differ due to the different sound transmission characteristics of the two sidewall configurations. Usually, one would expect that increasing the pressure in the cabin would stiffen the fuselage structure, thereby reducing the amount of noise transmitted to the interior. In this airplane, however, the sidewall construction is already very stiff, so that changes in the cabin pressure do not significantly alter the transmission characteristics of the fuselage. The slight increase in sound pressure levels shown in Figs. 8 and 9 may be caused by the different characteristic acoustic impedances resulting from the different cabin pressures. Note that the overall sound pressure level is dominated by the blade passage frequency in both the "green" and treated airplanes.

The increase of interior noise levels associated with three different engine torque settings (run 8: 35%, run 7: 57%, and

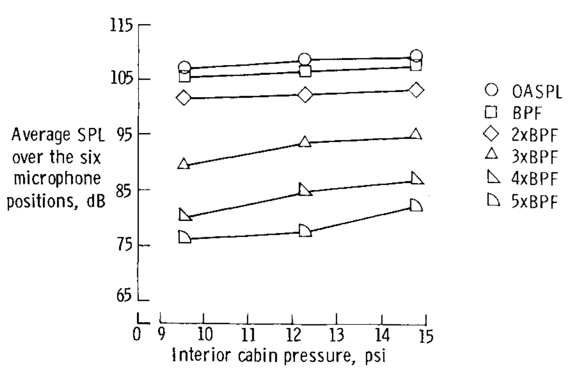

Fig. 8 Effects of cabin pressure on space averaged sound pressure levels for the "green" airplane.

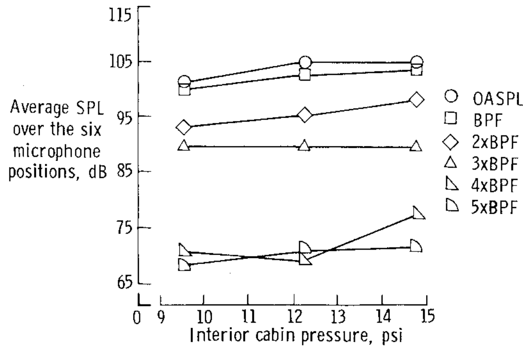

Fig. 9 Effects of cabin pressure on space averaged sound pressure levels for the treated airplane.

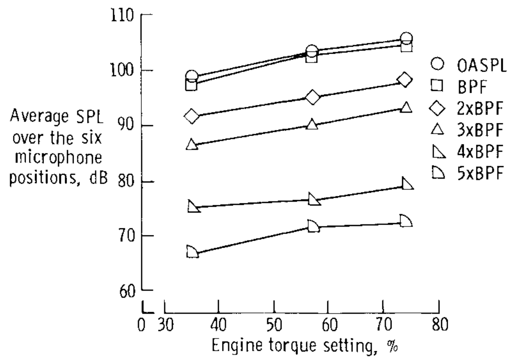

Fig. 10 Effects of engine torque on space averaged sound pressure levels for the treated airplane.

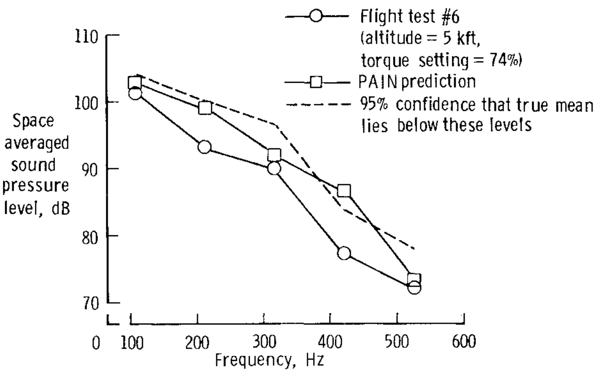

Fig. 11 Measured and predicted space averaged sound pressure levels (treated airplane, 74% high engine torque).

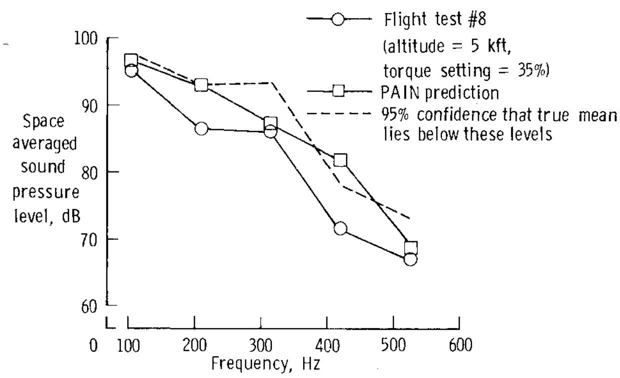

Fig. 12 Measured and predicted space averaged sound pressure levels (treated airplane, 35% low engine torque).

run 6: 74%) is shown in Fig. 10 for the treated airplane only. It is reasonable to assume that the additional noise transmitted to the cabin interior at the higher torque settings is caused by increased propeller loading noise and possibly by increased vibration and structure-borne noise. Again, note that the blade passage frequency dominates the overall noise level. (In order for the noise control engineer to reduce the low-frequency overall level in this airplane, an effective means of reducing the lowest blade passage frequencies, especially the fundamental, must be found.) The data presented in Fig. 10 (from runs 6-8) were also used for comparison with and validation of an interior noise prediction model.

Comparison of Flight Results to Theoretical Prediction Model

A computer program, entitled PAIN (Propeller Aircraft Interior Noise), has been developed for predicting the sound levels inside propeller-driven aircraft.[17] The program calculates the space-averaged sound pressure levels in the cabin space at the blade passage frequency and integral multiples of that frequency. The PAIN model is very comprehensive; it addresses three major factors that influence the sound field inside the cabin. First, the analysis requires a precise description of the propeller noise (pressure amplitude and phase) defined over a grid that lies on the fuselage skin. The data for the present study were calculated using a NASA-developed propeller noise prediction program, entitled ANOPP (Aircraft Noise Prediction Program).[18] The model next determines the structural modal properties (mode shapes and resonance frequencies) for the fuselage structure, which includes a ring-stringer stiffened cabin shell, stiffened floor, and sidewall trim. Finally, the PAIN model calculates the acoustic modal properties of the cabin space, taking into account the geometry of the cabin space and the absorption characteristics of the sidewall trim.

The preliminary validation of the PAIN program was performed in the laboratory on an idealized fuselage model (an aluminum cylinder with stringers, ring frames, and a structurally integral floor).[17] The agreement between experiment and theory in the laboratory situation was very good. The present set of flight measurements provided the opportunity to validate the model on an actual turboprop aircraft; runs 6-8 were used for this purpose. Recall that the sound pressure levels for these runs were measured at microphone locations 7 and 8 (Fig. 1) by sweeping microphones 5 and 6 over a cross section of the cabin (Fig. 2). The results of this swept data were used in conjunction with data from microphones 2 and 3 (located in the plane of the propeller) to determine the space-averaged noise levels in the cabin. This experimentally determined space average was then compared to predictions from the PAIN computer program.

Figures 11 and 12 show the flight test results from runs 6 and 8 compared to corresponding PAIN model predictions for the blade passage frequency and its multiples. The predictions for four of the five discrete frequencies fall within the 95% confidence limits of the measurements. Only the cases for four times the fundamental frequency indicate large discrepancies between the predicted and measured levels. This may not be a shortcoming of the PAIN program, however, since other results also showed a large variation at that frequency (e.g., Fig. 7). The electrical noise around 420 Hz inside the treated airplane may influence the space-averaged levels and, in turn, the variability of the measured results. With this in mind, it is felt that the agreement between the predicted and experimental data confirms the general validity of the PAIN prediction model.

Conclusions

This paper has described the results of interior noise measurements taken during flight on two airplanes, one with only fiberglass insulation covering the sidewalls and the other completely outfitted with an executive trim. The insertion loss, or difference between interior noise levels, of the two airplanes for the same flight conditions, was examined to determine the effect of the manufacturer's trim on the interior sound field. Overall, the average insertion loss values indicated that the trim provided 5-10 dB additional noise reduction. The actual sound pressure levels inside the cabin were dependent on position, frequency, and flight operation conditions, such as cabin pressure and engine torque. The results of specific flight tests performed on the airplane with trim were compared with predictions from a newly developed analytical model (the Propeller Aircraft Interior Noise model). The generally good agreement between the measurements and predictions provide flight validation of the model, which had previously been validated only in the laboratory.

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References

[1]Farassat, F., "Linear Acoustic Formulas for Calculation of Rotating Blade Noise," *AIAA Journal*, Vol. 19, 1981, pp. 1122-1130.

[2]Mixson, J.S., Farassat, F., Leatherwood, J.D., Prydz, R., and Revell, R.D., "Interior Noise Considerations for Advanced High-Speed Turboprop Aircraft," AIAA Paper 82-1121, June 1982.

[3]Mixson, J.S., Barton, C.K., Piersol, A.G., and Wilby, J.F., "Characteristics of Propeller Noise on an Aircraft Fuselage Related to Interior Noise Transmission," AIAA Paper 79-646, March 1979.

[4]Bhat, R.B. and Mixson, J.S., "A Theoretical Investigation of Noise Reduction Through the Cylindrical Fuselage of a Twin-Engine Propeller-Driven Aircraft," NASA TP-1325, Dec. 1978.

[5]Rennison, D.C., Wilby, J.F., and Wilby, E.G., "Prediction of the Interior Noise Levels of High Speed Propeller-Driven Aircraft," AIAA Paper 80-998, June 1980.

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

[7]Mixson, J.S., Roussos, L.A., Barton, C.K., Vaicaitis, R., and Slazak, M., "Laboratory Study of Efficient Add-On Treatments for Interior Noise Control in Light Aircraft," AIAA Paper 81-1969, Oct. 1981.

[8]Vaicaitis, R., Grosveld, F.W., and Mixson, J.S., "Noise Transmission Through Aircraft Panels," AIAA Paper 84-911, May 1984.

[9]Grosveld, F.W., "Field-Incidence Noise Transmission Loss of General Aviation Aircraft Double-Wall Configurations," *Journal of Aircraft*, Vol. 22, Feb. 1985, pp. 117-123.

[10]Howlett, J.T. and Schoenster, J.A., "An Experimental Study of Propeller-Induced Structural Vibration and Interior Noise," SAE Paper 790625, April 1979.

[11]Metcalf, V.L. and Mayes, W.H., "Structureborne Contribution to Interior Noise of Propeller Aircraft," SAE Paper 830735, April 1983.

[12]Vaicaitis, R. and Slazak, M., "Design of Sidewall Treatment for Cabin Noise Control of a Twin Engine Turboprop Aircraft," NASA CR-172245, Dec. 1983.

[13]Mixson, J.S., Barton, C.K., and Vaicaitis, R., "Investigation of Interior Noise in a Twin-Engine Light Aircraft," *Journal of Aircraft*, Vol. 15, April 1978, pp. 227-233.

[14]Prydz, R.A., Revell, 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.

[15]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.

[16]Heitman, K.E. and Mixson, J.S., "Laboratory Tests on an Aircraft Fuselage to Determine the Insertion Loss of Various Acoustic Add-On Treatments," AIAA Paper 84-2330, Oct. 1984.

[17]Pope, L.D., Wilby, E.G., and Wilby, J.F., "Propeller Aircraft Interior Noise Model," NASA CR-3813, July 1984.

[18]Zorumski, W.E., "Aircraft Noise Prediction Program Theoretical Manual," NASA TM 83199, 1981.