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EFFECTS OF ACOUSTIC TREATMENT ON THE INTERIOR NOISE LEVELS OF A TWIN-ENGINE PROPELLER AIRCRAFT-- EXPERIMENTAL FLIGHT RESULTS AND THEORETICAL PREDICTIONS

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Abstract

This paper describes a study of the cabin acoustics of a Fairchild Merlin IVC twin-engine propeller airplane. Measurements of the interior sound field were obtained at six locations inside both an untreated "green" airplane and a completely finished airplane which contained the manufacturers executive trim configuration. Several flight conditions were tested, including different altitudes, engine power settings, and cabin pressures. A one-third octave band analysis was applied to the data so that the dBA and SIL weighted noise measures, and the OASPL, could be determined for each test condition and microphone position. The harmonics of the blade passage frequency, which dominate the low frequency noise spectrum, were examined using a narrowband analysis of the data. The insertion loss, defined as the reduction of interior noise levels that occurs after the addition of some acoustical treatment, was calculated from the results of the two airplane flights. These insertion loss values varied widely depending on many factors, such as, position in the cabin, blade passage harmonic number, cabin pressure, and engine torque. The space averaged sound pressure levels, determined for specific test conditions of the treated airplane, were found to be in good agreement with predictions from the Propeller Aircraft Interior Noise (PAIN) model developed by L. D. Pope.

Introduction

The prediction, measurement, and control of the noise levels inside currently available propeller aircraft can provide valuable information for use in interior noise prediction methods of 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 aircraft. The low frequency spectrum of this noise is dominated by the fundamental and harmonics of the blade passage frequency. The propeller source noise, acoustic transmission paths, and interior absorption characteristics, must all be controlled in order to reduce the interior noise to levels that meet passenger acceptance criteria.

The many factors that contribute 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.[2,3] The transmission of noise through various types of aircraft panels has been studied analytically and experimentally.[4-7] In addition, some research has been undertaken to better understand the noise that is transmitted and radiated into the cabin by structureborne vibration.[8-10] Finally, the interior noise field itself has been measured and the insertion loss of various sidewall acoustical treatment configurations has been calculated for both ground and flight tests.[11-15]

The purpose of this paper is to present the results of interior noise measurements of a Fairchild Merlin IVC twin-engine airplane, in-flight. One set of measurements was taken on board an untreated "green" airplane (bare walls with some fiberglass insulation material). A second set of measurements was taken on board a completed Merlin IVC, which contained the manufacturers executive trim configuration. The data were analyzed in both narrowband and one-third octave formats so that the harmonics of the blade passage frequency could be examined, and weighted noise measures, such as dBA and SIL, could be calculated. Some of the results presented here will emphasize the spectrum of the interior noise in terms of the actual measured sound pressure levels of each test airplane under a variety of operating conditions. In order to focus attention directly on the added acoustical treatment (trim configuration), some of the results will be presented in terms of insertion loss, defined as the reduction of interior noise levels caused by the addition of some acoustical treatment.

Experimental Procedure

Aircraft Description

The Fairchild Merlin IVC used in this study has a maximum takeoff weight of 6350 kg and can accommodate eleven passengers. Each of the two 1000 SHP turboshaft engines drives a four-bladed propeller that is 2.7 m in diameter and has a 17 cm tip clearance from the fuselage sidewall. The fundamental blade passage frequency was 105 Hz because the engine rpm was set at 97% throughout this study.

The sound field inside the cabin was measured under two different sidewall acoustic treatment configurations. The interior of the untreated "green" airplane was bare except for those items required to satisfy safety regulations. There were no trim panels, but the sidewalls were covered with fiberglass material in order to provide sufficient thermal insulation. There was no carpeting and only four passenger seats (for the technical staff).

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In contrast to the untreated airplane, the completely finished version was quite luxurious. This "executive" interior included the manufacturers 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. The sidewall trim consisted of 0.05 m of bagged fiberglass and a trim panel of sandwich construction. The core of the sandwich had closed cells made from blended plastic resins and facings of laminated fiberglass. The surface mass of the trim was 1.95 kg/m^2.

Flight Conditions and Instrumentation

Weather conditions were very similar on the two days that the flight tests were performed. The air temperature was within 1° C at each of the three altitudes that interior noise levels were recorded. The sky was clear and no significant rough air was encountered during the data recording.

The interior noise field was measured with six half-inch condenser microphones positioned inside the airplane as illustrated in Figure 1. The microphones were suspended from the ceiling (clamped to the exposed ring frames in the untreated 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 for many different flight conditions including changes in altitude, engine power settings, and cabin pressures. Table 1 shows the operating conditions for the flight tests presented in this paper.

Microphone locations 7 and 8, indicated by the diamonds in Figure 1, were selected for hand-swept space average measurements of the interior noise field. The microphone sweep path is shown in Figure 2. The sweep data were collected by microphones 5 and 6, for runs 6, 7, and 8 of the treated airplane only, and were used for comparison with the Propeller Aircraft Interior Noise (PAIN) prediction model.[16]

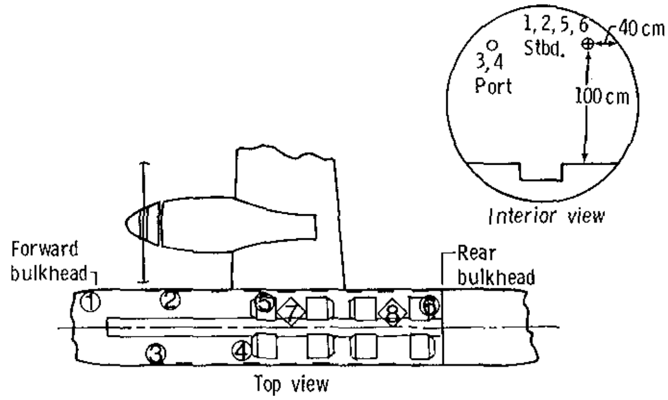

Fig. 1.- Microphone locations relative to seating arrangement of completely finished airplane.

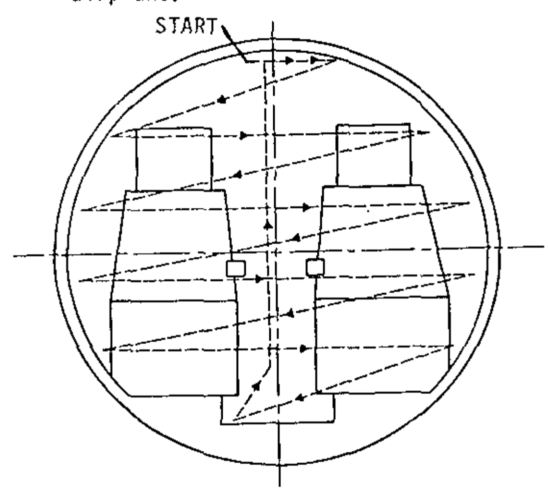

Fig. 2.- Microphone sweep path for hand-swept space averaged interior noise measurements at locations 7 and 8 (about 15 sec/circuit, traversed twice).

Table 1. Flight operation conditions for untreated and treated Merlin IVC airplane.

RUN NUMBER	ALTITUDE (ft x 10^3)	AIRSPEED (KIAS)	% TORQUE PORT/STARBOARD	CABIN PRESSURE DIFFERENTIAL (psi)	AIR TEMPERATURE (°C)	FUEL LEVEL (lbs)
1	17.5	192	56/56	6.9	-6	2000
2	17.5	188	50/50	6.9	-6	2000
3	12	210	63/63	5.4	7	1800
4	12	210	60/60	2.9	7	1700
5	12	210	60/60	0.2	7	1700
6	5	238	74/74	2.5	17	1700
7*	5	216	57/57	2.5	17	1700
8*	5	165	35/35	2.5	17	1700

*Data from these runs is available only for the treated airplane.

Data Analysis

The tape recorded interior noise data were reduced in the laboratory using commercially available one-third octave and narrowband spectrum analyzers. One-third octave analysis covered the frequency range from 50 Hz to 20,000 Hz and was used to determine the overall sound pressure level (OASPL), the A-weighted sound pressure level (dBA), and the speech interference level (SIL). A narrowband analysis was performed over the frequency range from 20 Hz to 2000 Hz with a 5 Hz noise bandwidth. A typical narrowband analysis consisted of an average of 64 separate Fast Fourier Transforms taken over 16 seconds. Figures 3 and 4 illustrate the narrowband results of the untreated and treated Merlin IVC at microphone position 2 under the flight conditions of Run #1 (see Table 1). It is clear from these figures that the harmonics of the blade passage frequency (105 Hz, 210 Hz, 315 Hz, ...) dominate the low frequency noise spectra.

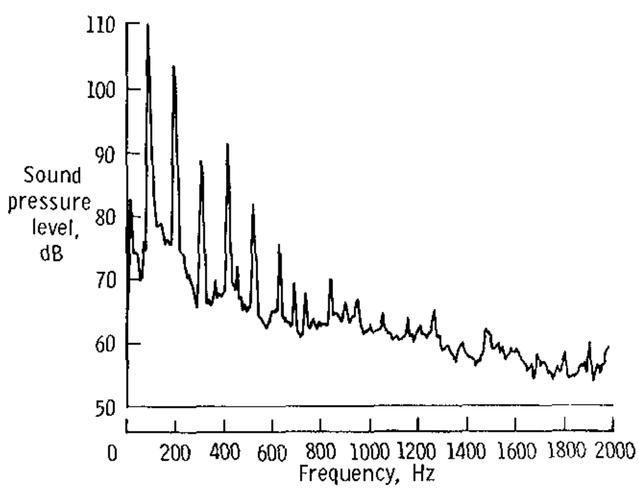

Fig. 3.- Narrowband spectral analysis of sound field at microphone 2 under the flight conditions of run 1 (untreated airplane).

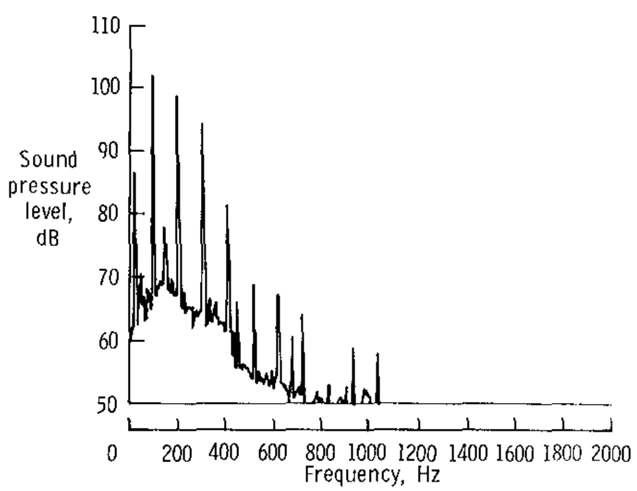

Fig. 4.- Narrowband spectral analysis of sound field at microphone 2 under the flight conditions of run 1 (treated airplane).

Discussion of Results

There are three different approaches to the analysis of the interior noise data that will be discussed in the following paragraphs. First, the effect of the added acoustical treatment on the interior noise levels will be examined by studying the insertion loss values calculated from measurements taken from each airplane. Next, the effects of different flight operation conditions on the interior noise will be compared using the actual measured sound pressure levels. Finally, the data obtained from specific flight tests will be compared to and used to validate recent analytical methods that predict the interior noise of propeller aircraft. The analysis of the flight test data will concentrate on the harmonics of the blade passage frequency (or blade passage harmonics, BPH), which dominate the low frequency interior noise levels of this airplane.

Effect of Trim on Interior Noise

The insertion loss of the treated airplane relative to the untreated airplane was calculated using the narrowband analysis of the two airplane flight tests. The insertion loss is a function of frequency, microphone position in the cabin, flight operating conditions, and acoustical treatment. A positive insertion loss indicates a reduction in the interior noise, but negative insertion loss values are also possible, as will be shown.

Figures 5 and 6 illustrate the variation of the insertion loss with microphone position for runs 3, 4, and 5. As indicated in Table 1, the cabin pressure differential (inside to outside) is the parameter that is varied for these runs. The actual cabin pressure (given on the figures) for runs 3, 4, and 5 is 14.7 psi, 12.2 psi, and 9.5 psi, respectively. Figure 5 shows the variation of the first harmonic of the blade passage frequency (BPH1 or fundamental: 105 Hz) while Figure 6 shows the variation of blade passage harmonic two (BPH2: 210 Hz).

A few important items of interest should be emphasized about these figures. First, the results for each of the three cabin pressurizations follow the same general trend. The shapes of each figure are different because insertion loss varies as a function of frequency. The small amount of insertion loss at microphone 1 is probably due to the fact that little additional treatment was present in the cockpit of the treated airplane so that interior noise levels at that location did not change much between airplanes. The negative insertion loss at microphone 3 for BPH1 (Figure 5) can also be explained. The treated airplane had two additional windows in the propeller plane on the port side. These windows provided much less transmission loss than the aluminum panels and fiberglass of the untreated airplane. Therefore,

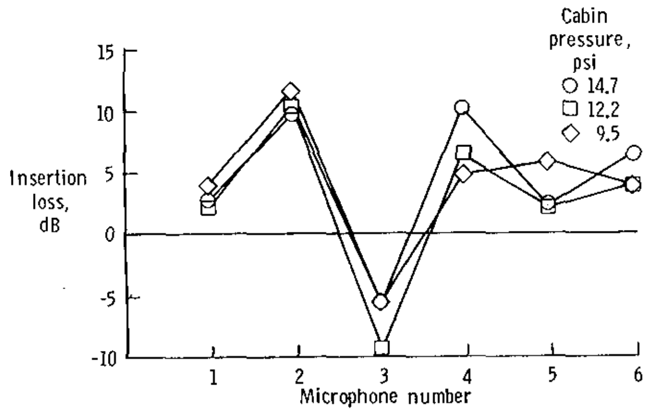

Fig. 5.- Insertion loss of the fundamental blade passage frequency (105 Hz) at the six microphone locations for three different cabin pressures.

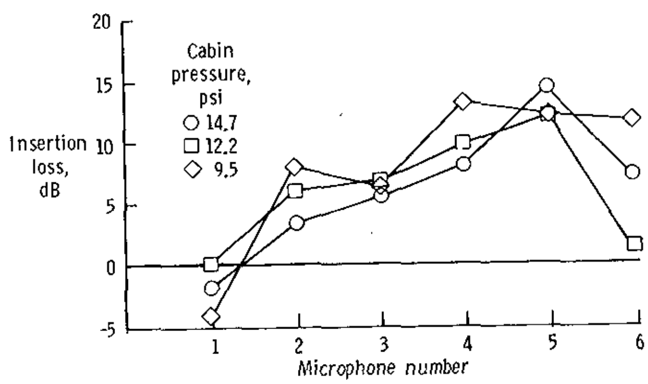

Fig. 6.- Insertion loss of the second blade passage harmonic (210 Hz) at the six microphone locations for three different cabin pressures.

the first blade passage harmonic had a higher interior noise level at microphone 3 of the treated airplane, yielding a negative insertion loss. In general, it is felt that the variability between runs (± 4 dB) was reasonable for this type of test. The large variation at microphone 6 for BPH2 (Figure 6) may be due to an oversight of the technical staff that left the rear bulkhead partially open during flight tests of the treated airplane.

Whereas Figures 5 and 6 give the insertion loss of a single frequency as a function of position, the space averaged insertion loss as a function of blade passage harmonic, as shown in Figure 7, is also informative. The insertion loss of the OASPL and first five blade passage harmonics were numerically averaged over the six microphone positions and plotted for each of the six flight tests. The trend of the figure is similar for each of the six runs and the variation between runs is within reason. As expected, the insertion loss tends to increase as the frequency increases because the added acoustical treatment is more effective at higher frequencies. The large variation of BPH4 (420 Hz) may be due to additional noise at that frequency generated by the extra electronic amenities in the treated airplane.

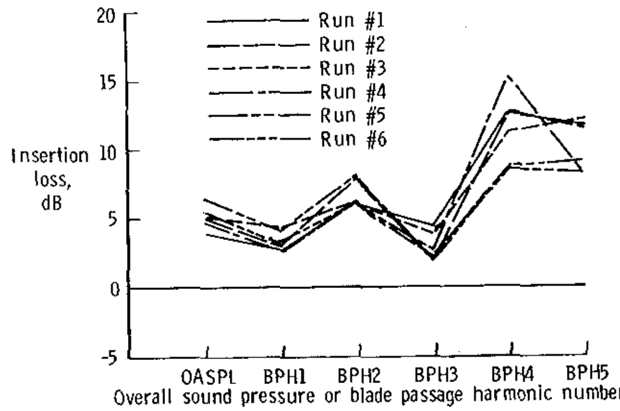

Fig. 7.- Variation of the space averaged insertion loss as a function of overall SPL and BPH for the six flight conditions tested.

Effect of Flight Conditions on Interior Noise

The effects of two flight operation conditions, cabin pressure and engine torque, on the interior noise of the treated and untreated airplanes are shown in Figures 8-10. The symbols on these figures represent spatial energy averages of the overall sound pressure level (OASPL) and the measured sound pressure levels of the first five blade passage harmonics (BPH1-BPH5). These averages were calculated by summing corresponding levels over the six microphone positions, as determined from the narrowband spectral analysis. The connecting lines do not indicate calculated or measured broadband noise levels; they merely connect common data points.

Figures 8 and 9 show an increasing trend of the interior sound pressure level as a function of cabin pressure (runs 3, 4, and 5: actual cabin pressure is 14.7 psi, 12.2 psi, and 9.5 psi, respectively). This trend is apparent in both the untreated airplane (Figure 8) and the treated airplane (Figure 9), although the absolute noise levels differ because of the different transmission characteristics of the two sidewall configurations. In general, 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 Figures 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 (OASPL) is dominated by the first blade passage harmonic for both the untreated and treated airplanes.

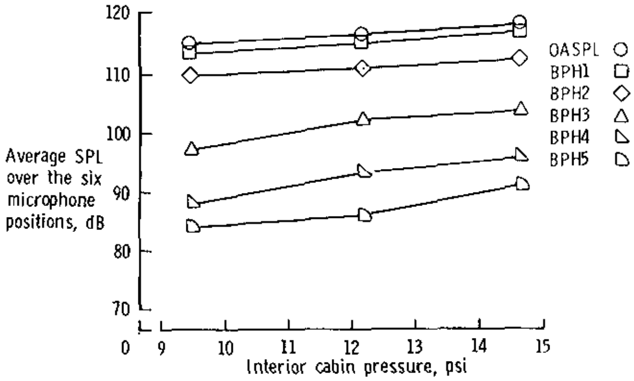

Fig. 8.- Space averaged SPL measured on untreated airplane at different cabin pressures.

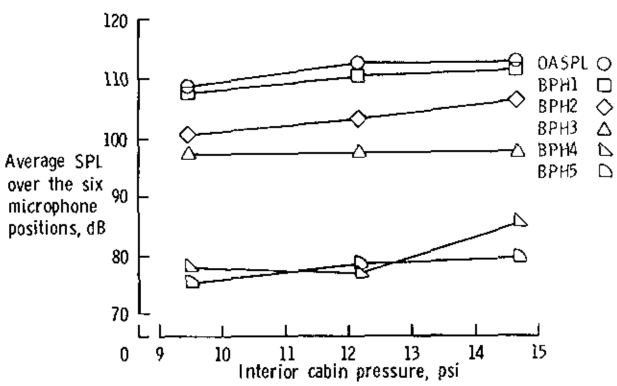

Fig. 9.- Space averaged SPL measured on treated airplane at different cabin pressures.

Figure 10 illustrates the increase in interior noise levels associated with increases in engine torque for the treated airplane (runs 8, 7, and 6). It is likely 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 structureborne noise. Again, note that the lowest blade passage harmonic (BPH1) dominates the overall noise level. These results were used for comparison and validation of an interior noise prediction model, briefly described next.

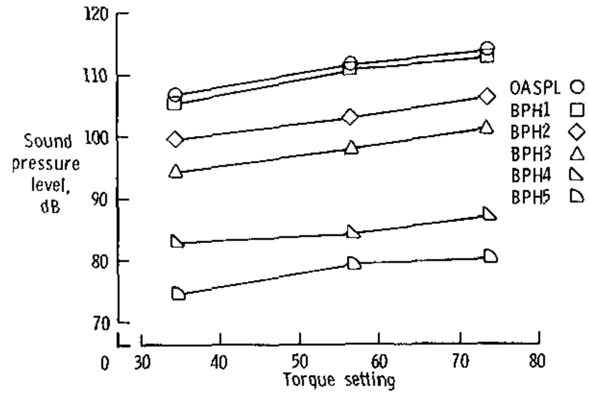

Fig. 10.- Space averaged SPL measured on treated airplane at different engine torque settings.

Comparison of Flight Results to Theoretical Prediction Model

A computer program, entitled PAIN (an acronym for Propeller Aircraft Interior Noise), has been developed for predicting the sound levels inside propeller driven aircraft.[16] PAIN can calculate the space average sound pressure levels in the cabin space at the blade passage frequency and its harmonics. The PAIN model is very comprehensive; it takes into account three important parameters which influence the sound field inside the cabin. First, the analysis requires a precise description of the propeller noise (pressure field) on the fuselage skin. The propeller noise data are calculated using a propeller noise prediction program, such as PROPFAN[17] or NASA ANOPP (Aircraft Noise Prediction Program).[18] Second, the structural modal properties (mode shapes and resonance frequencies) must be determined for a fuselage structure that 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, including the specific cabin shape and absorption properties of the trim.

In order to validate the PAIN program, predicted sound pressure levels had to be compared to actual interior noise measurements taken from a full scale aircraft in flight. In the present test, runs 6, 7, and 8 were used for this purpose. Recall that the sound pressure levels for these runs were measured at microphone locations 7 and 8 (Figure 1) by sweeping microphones 5 and 6 over a cross section of the cabin (Figure 2). The results of this swept data were used in conjunction with data from microphones 2 and 3 (located in the propeller plane) to determine the space average noise levels in the cabin, required for comparison with the PAIN predictions.

Figures 11 and 12 compare the experimental results of runs 6 and 8 to the PAIN predictions for the first five blade passage harmonics. Predictions for four of the five harmonics fall below the 95% confidence limits of the measurements. Only the fourth harmonic has a large discrepancy between predicted and measured levels. This may not be a shortcoming of the PAIN program however, since other results also showed a large variation at the fourth blade passage harmonic (see Figure 7 for example). The extra electronic noise in the treated airplane at this frequency may influence the space average levels and in turn the variability of the measured results. With this in mind, the good agreement between the predicted and experimental data confirms the general validity of the PAIN prediction model.

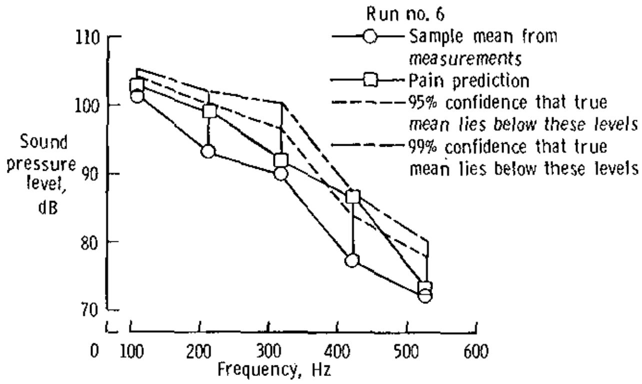

Fig. 11.- Space averaged SPL from swept data of run 6 compared to PAIN predictions.

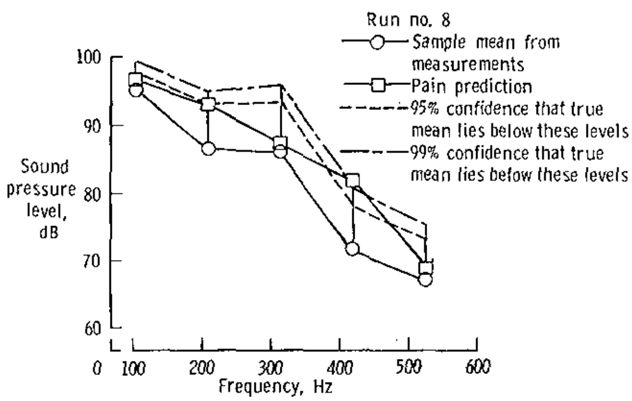

Fig. 12.- Space averaged SPL from swept data of run 8 compared to PAIN predictions.

Concluding Remarks

This paper has described the results of interior noise measurements taken during flight on an untreated airplane and a treated airplane. The insertion loss was examined to determine the effectiveness of the manufacturers trim relative to the "green" aircraft (which only had fiberglass insulation covering the sidewalls). In general, the addition of the trim provided between 5-10 dB of noise reduction. The actual sound pressure levels inside the cabin were found to depend on position, frequency, and flight operation conditions, such as cabin pressure and engine torque. The results of specific flight tests, performed on the treated airplane, were compared with predictions from the PAIN program and found to be in good agreement.

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