Interior Noise in the Untreated Gulfstream II Propfan Test Assessment Aircraft

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Test results of the interior noise measurements made on the Gulfstream II Propfan Test Assessment aircraft are presented in this paper. The program objectives were to evaluate the relative external and internal sound pressure levels in flight, to determine the main paths of acoustic energy entering the cabin, and to have a basis for comparison with flight tests with an experimental cabin treatment. A two-phase program of ground and flight tests was carried out. The first phase included a ground test series in which a shaker was used to vibrate the wing at three locations and a loudspeaker to excite the fuselage sidewall and the underside of the wing, each at a single location. The second phase consisted of a flight-test series in which the aircraft was flow at various altitudes, air speeds, propeller rotational speeds, and cabin pressurizations. The results show the relative importance of energy transmission paths into the cabin interior. The major contributor to the cabin noise was determined to be the airborne propfan blade passage frequency tones. In addition, we show that as altitude increases the radiated sound pressure level of the propfan increases. The average noise reduction, from the fuselage exterior to the cabin interior, remains relatively constant at all altitudes. The wing vibrations at the blade passage frequency and harmonics are less influential as the altitude increases.

Nomenclature

<SPL> = power average of sound pressure levels from a spatial transducer array (dB re 20 μPa)
<NR> = fuselage exterior <SPL>-cabin interior <SPL>
<AL> = power average of acceleration levels from a spatial transducer array (dB re 1 μg)

Introduction

PROPELLER and turboprop engines were used extensively until the advent of turbojet and, then, turbofan engines. Although some propfan development was pursued,[1] the fuel efficiency of prop aircraft was not perceived as important until the 1974 oil embargo. The embargo returned the fuel efficient turboprop to consideration, and propfan development proceeded in earnest. Successive generations of propfan blade development led to the SR-7 series of blades, of which the eight-bladed SR-7L was used on the Propfan Test Assessment (PTA) aircraft. The propfan fuel efficiency has been estimated to be up to 19% more efficient than turbofan jet efficiency.[2] A disadvantage of the propfan is that the high helical Mach number (M) and high blade count leads to the generation of high-frequency blade passage tones and numerous harmonics. The exterior sound pressure levels for the SR-7L at the fundamental have been predicted to be as high as 147 dB[3] on the PTA fuselage. The overall sound pressure level (SPL) on the fuselage could be as high as 149 dB[2] (free field + 6 dB) as opposed to 133 dB for a modern turbofan. Without large increases in the noise reduction of the fuselage, this SPL difference represents a regression in passenger comfort and acceptance. Additional weight for acoustic treatment needs to be designed into a propfan aircraft. Limiting this additional weight became an important consideration.

In 1985, the Lockheed-Georgia Company was awarded a contract to modify a Gulfstream II aircraft, reinforce the wing, and attach an Allison Model 501-M78B engine, a Rohr Quick Engine Change nacelle, and the 2.74-m (9-ft) diam, eight-bladed Hamilton-Standard SR-7L propfan [rated for 4476 kW (6000 hp) at 1698 rpm].[4] The Gulfstream II aircraft has an effective fuselage diameter of 2.4 m (7.9 ft) in the propfan plane [fuselage station (FS) 301]. The tip clearance to the fuselage was 1.69 m (5.55 ft). The standard skin thickness is 1-mm (0.040-in.) 2024-T3 aluminum with 0.8-mm (0.032-in.) 2014-T6 aluminum doublers around the windows and in other selected areas. The frame is made from 1.7-mm (0.063-in.) 2014-T6 aluminum and spaced between 0.305 (12 in.) and 0.41 m (16 in.) along the length and between 0.41 (16 in.) and 0.76 m (30 in.) circumferentially. The windows are ellipsoidal with major and minor diameters of 0.66 and 0.47 m (26 and 18.5 in.) and a center to center spacing of 1.27 m (50 in.).

The present study was made to provide baseline measurements for the Advanced Acoustic Treatment Program (NASA Contract NAS1-18036) by Lockheed Aeronautical Systems Company at the Kelly Johnson Research and Development Center in Saugus, California.[5,6] The Lockheed PTA program is the only evaluation of an in-flight, single-rotating, wing-mounted, tractor propfan. These tests afforded us the singular ability to analyze the external[7,8] and internal sound fields, wing vibration effects on cabin noise, the noise reduction of an untreated aircraft, and the importance of different acoustic energy paths into the cabin.

Numerous acoustical tests were performed during our parts of the Lockheed/NASA PTA program.[5,9] These tests were used to determine the relative contributions of acoustic and vibration sources to the cabin interior sound pressure levels during various flight conditions. The two-phase program included ground and flight tests. The ground test series included using a shaker to vibrate the wing at three locations and using a loudspeaker to excite the fuselage sidewall and the underside of the wing, each at a single location. During the flight-test series, the aircraft was flown at various altitudes, air speeds, propeller rotational speeds, and cabin pressurizations. Measurements were made using 19 wing and 18 fuselage accelerometers and 12 wing, 22 fuselage, and 32 cabin-interior microphones. The transducers were used to determine the spatial characteristics of the sound and vibration fields. Approximate locations of external and fixed internal transducers are

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noted on the sketch of the PTA aircraft in Fig. 1. The exact locations and mounting methods are given in Ref. 10. References 7 and 8 depict the locations of external fuselage and wing microphones, respectively. 15 interior-cabin microphones were mounted on a moveable tram that could travel a distance of 4.8 m (15.7 ft) along the length of the cabin.

The ground and flight test results were combined in the analysis to determine the relative importance of the acoustic energy transmission paths into the cabin interior. For these tests the cabin was untreated; the cabin wall was the aircraft skin, no absorptive materials were included in the cabin, and the cabin was empty except for instrumentation, several seats, and a number of people.

The transducer data were recorded on a 28-track (10 channels/track) FM recorder. For each tape an electrical system calibration was performed. Calibration levels were within ±0.2 dB. Individual transducers were monitored and, if problems occurred, replaced. The calibration levels were incorporated into the data during digitization. During the analysis, individual transducer data were checked. When transducer data were questionable, they were excluded from the averaging. Because of the care taken in calibration and checking and the number of microphones averaged, the error is assumed to be well within a ±1-dB range. This assumption is reinforced in comparing the empirical equation with measured external fuselage <SPL> data. The standard deviation between the measured and calculated <SPL> for all the flights was 2.3 dB.

Ground Tests

Two sets of ground tests were performed in order to determine the separate influences of the airborne and structure-borne excitation on the cabin interior sound pressure levels. In each case, the input signal to the source transducer consisted of the first three harmonics of the blade passage frequency (226, 452, and 677 Hz). The excitation levels approximated the acoustic and vibration levels of the flight tests. Four excitation levels were used and each level was 6 dB higher than the next lowest level. These four levels allowed for the evaluation of the system linearity. Both systems were found to be linear at the higher levels. At the lower levels, the background noise interfered.

For the acoustic excitation tests, a loudspeaker horn and driver set was placed at two different locations, one under the left wing (inboard of the engine and behind the propfan blade tips) and one on the fuselage (in the prop plane at the midline of the fuselage). The horn mouth was 0.23 m^2 (2.5 ft^2), and the highest sound pressure levels at the first three harmonics were 124, 131, and 138 dB (re 20 μPa).

For the vibration excitation tests, a shaker with a force transducer was attached at three different locations under the left wing, two at the front spar (one inboard and one outboard of the engine) and one at the rear spar (inboard of the engine). The largest forces at the first three harmonics were 68.9, 29.3, and 14.2 N (15.5, 6.6, and 3.2 lb). The average vibration responses of the wing to this input varied with force location, but a typical response at the three harmonics was 106, 117, and 122 dB (re 1 μg).

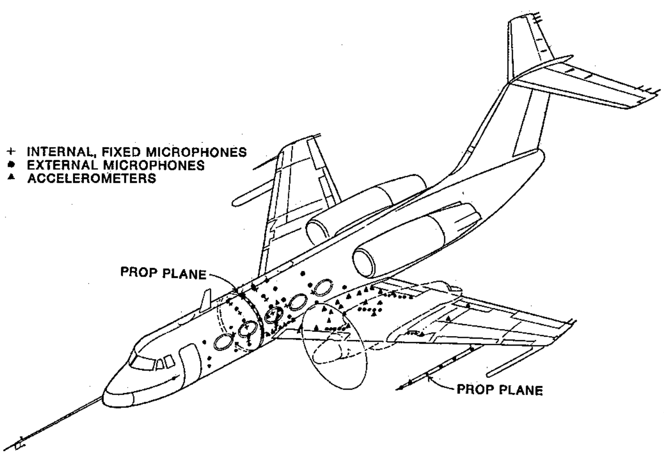

Fig. 1 Sketch of the PTA aircraft with superimposed transducers.

Flight Tests

The flight tests discussed here were performed at altitudes ranging from 1520 to 12,200 m (5000 to 40,000 ft). The flight speeds ranged from 0.20 to 0.82 M. The associated fundamental blade passage frequencies ranged from 174 to 237 Hz, the propfan tip speed ranged from 0.55 to 0.85 M, and the propeller shaft power ranged from 370 to 4480 kW (500 to 6000 hp). The helical tip speed ranged from 0.70 to 1.18 M. Table 1 enumerates the parameter ranges at each altitude.

Test Results

Figure 2 shows the acoustic spectrum levels (with and without the propfan) measured at a fuselage point 63.5 cm (25 in.) behind the prop plane and immediately below the cabin windows. The majority of the acoustic energy is found at the blade passage frequency harmonics of which eight are shown. The relative strengths of the higher frequency harmonics varied with measurement location.

Figure 3 shows the acoustic spectrum levels (with and without the propfan) measured at an ear-height position inside the cabin in the prop plane. These cabin sound pressure levels are dominated by the blade-passage frequency harmonic levels. The higher frequency tones (greater than the fourth harmonic) are not as influential as outside the cabin. At positions away from the propfan plane, the levels were both higher and lower than in the prop plane.

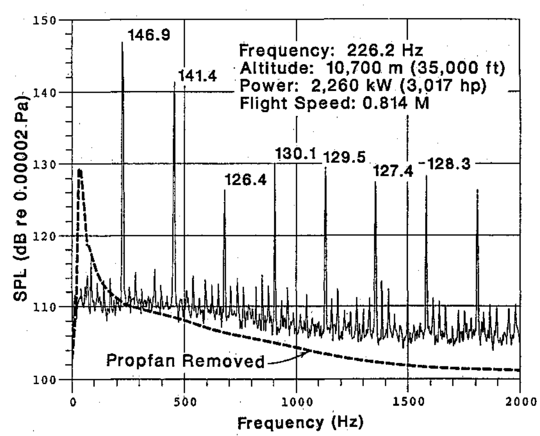

Fig. 2 Fuselage sound pressure level spectra measured 63.5 cm (25 in.) behind the prop plane with and without the propfan.

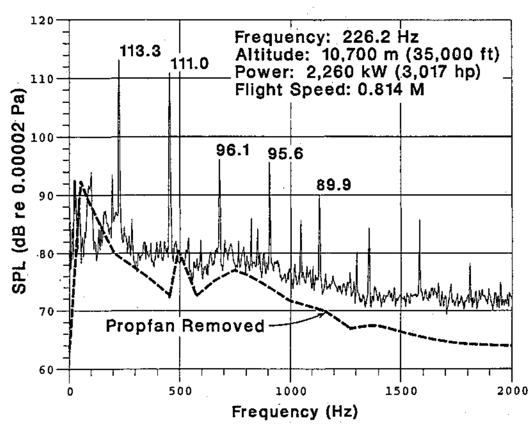

Fig. 3 Cabin sound pressure level spectra measured in the prop plane with and without the propfan.

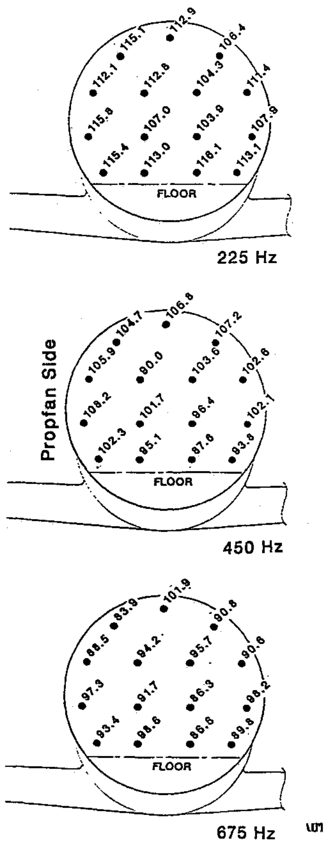

Fig. 4 Tram microphone sound pressure levels measured in the prop plane at the first three harmonics (conditions as in Fig. 2).

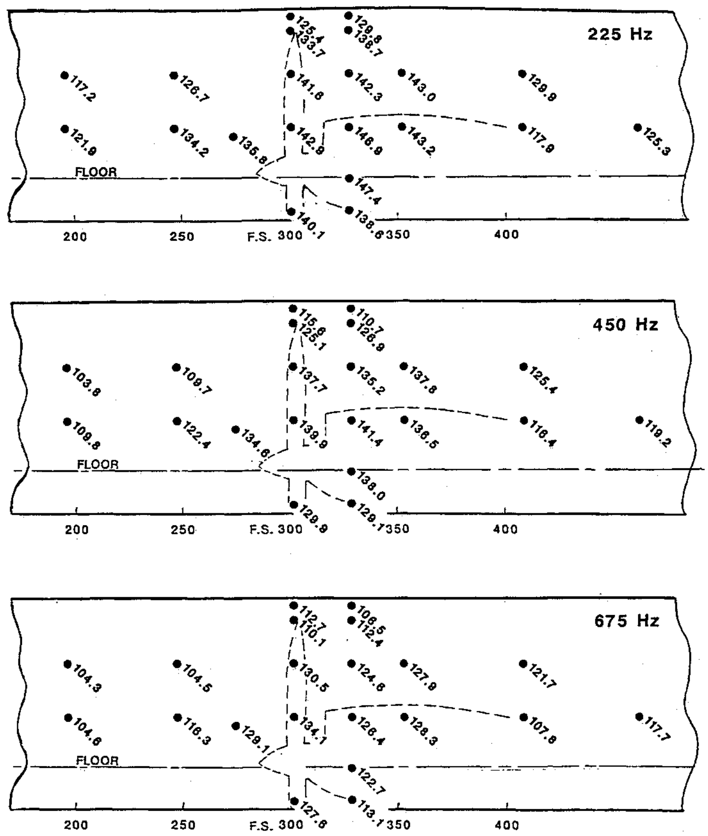

Fig. 5 Fuselage sound pressure levels measured at the first three harmonics (conditions as in Fig. 2).

Figure 4 shows the distribution of the sound pressure levels for the first three harmonics in the prop plane for the same test condition as in Fig. 2. Note that the sound pressure levels tend to be higher around the periphery of the cabin and highest on the propfan side. The propfan sweeps upward on the inboard side; higher levels are found in the area of the wall near the floor. This area is the region of closest approach for the propfan.

Figure 5 shows the distribution of the sound pressure levels on the outside of the fuselage for these same test conditions. Note that, except for the third harmonic, the sound pressure levels peak in the row of microphones 63.4 cm (25 in.) behind the prop plane. The rolloff of the sound pressure levels along the fuselage axis is steeper forward of the prop plane than aft of the prop plane. The air flowing by the aircraft (0.814 M) convects the sound toward the aft of the aircraft and, with the boundary layer, affects the differential slopes and the location of the peak sound pressures.

Fuselage and cabin sound pressure levels vary with propfan rotational frequency, helical Mach number, flight Mach number, shaft power, and altitude. In Fig. 6 internal and external <SPL> values are plotted vs the propfan blade passage frequency. The altitude was constant at 8840 m (29,000 ft), and the flight speed was kept as constant as possible. As the propfan rotational frequency increases, the tip Mach number and, in this case, the helical Mach number increase proportionately. The shaft power can remain relatively constant with rotational speed, or large changes, as shown in Fig. 6, may be made. The helical Mach number varies from <1 to >1, and there is a smooth increase in the sound pressure level. This same smooth increase through the transonic region is seen in each test series. This result should be expected because, as the tip speed increases, larger areas of the leading edge and blade area are incorporated in forming the shock fronts.[11] From these results and the flight test series of Fig. 7, a simplified empirical equation was fit to the average sound pressure level measured on the fuselage of the aircraft. The average fuselage sound pressure level is

Table 1 Summary of flight-test parameter ranges

Nominal altitude, m (ft)	Flight Mach number	Helical Mach number	Shaft power, kw (hp)	Cabin Pressurization differential $N/m^2 * 10^5$ (psi)
1520	0.29–0.56	0.70–0.93	410–4400	1.2–1.5
(5000)			(550–5900)	(1.7–2.2)
3660	0.597–0.612	0.828–0.977	3480–4140	3.96–4.00 & 0.193–0.198
(12,000)			(4670–5550)	(5.75–5.81 & 0.280–0.287)
4570	0.35–0.67	0.76–1.02	430–4000	
(15,000)			(570–5300)	5.3–5.7
8840	0.70–0.74	0.093–1.08	420–2600	(7.7–8.3)
(29,000)			(560–3400)	5.9–6.5
10,700	0.61–0.82	0.87–1.18	430–2400	(8.6–9.5)
(35,000)			(570–3200)	

$$<L_{pf}> = 12\log(P) + 40\log(\mathrm{BPF}/f_0) + 25.8{*}H + 5\log(A/A_0) + K$$

where P is the shaft power in watts (horsepower), BPF the blade passage frequency, $f_0 = 225$ Hz, H the helical Mach number, A the mean sea level altitude in meters (feet), $A_0 = 8840$ m (29,000 ft), and K an empirical constant 34.3 dB (68.8 dB). The equation was fit to the 46 data points shown in Figs. 6 and 7. When compared to a total of 99 data points in the flight tests, the standard deviation was 2.3 dB.

In 1970, an empirical fit to static test results on an early model of a shrouded propfan indicated that the acoustic power output changed with 20 log(P).[1] In considering this relation and applying additional constraints to the present data, the 12 log(P) term was determined to be a better fit to the data. The blade passage frequency was used as a parameter because it relates directly with our present and future work.[5,6] The effects of tip speed, aircraft speed, and temperature are linked together in the helical Mach number parameter H. Finally, the altitude incorporates the effects of air density. Each parameter is inter-related and each is known, or calculable, as in the case of power. Because this is the only full-scale, single-rotor SR-7L propfan to fly, it is not known if the equation may be applied to other propfans of different blade slopes, counts, and loadings without major modifications.

As is shown in Fig. 6, the difference between the average fuselage and cabin sound pressure levels remains relatively constant. This constant <NR>, and later comparisons to vibration data, helps to support the conclusion that the cabin sound pressure levels are dependent on the acoustic signal on the fuselage rather than the vibration signal traveling through the wing.

Figure 7 shows the predicted and measured fuselage sound pressure levels and the cabin sound pressure levels at three different altitudes: 10,700, 4570, and 1529 m (35,000, 15,000 and 5000 ft), respectively. In each case, the predicted sound pressure levels are close to the average fuselage sound pressure level. Note that, for the greater part of the data, the cabin and fuselage sound pressure level changes parallel each other.

The changes in the average fuselage and cabin sound pressure levels of the first three blade passage frequency harmonics vs altitude are shown in Fig. 8. These data were taken at the cruise condition (226 Hz) and match four of the flight conditions in Figs. 6 and 7. As noted, the sound pressure levels at the fundamental frequency on the fuselage and in the cabin increase in the same fashion as altitude increases. The cabin sound pressure level at 8840 m (29,000 ft) is lower than would be expected in extrapolating from the fuselage sound pressure level. For the second harmonic above 1520 m (5000 ft), the cabin and fuselage sound pressure levels are relatively constant. The sound pressure levels for the third harmonic show a sizeable drop between 8840 and 10,700 m (29,000 and 35,000 ft). The drop in the level of the third harmonic at the higher altitudes may be caused by a larger area of the blade being supersonic (note the higher Mach number) and thus causing some interference between the harmonic energy generated at and propagated from the eight individual blade tips and the nonlinear shift of energy from the fundamental to the higher harmonics.

Figure 9 shows the average noise reduction <NR> measured at the blade-passage frequency over the frequency range of 177–237 Hz for the cases described in Figs. 6 and 7.

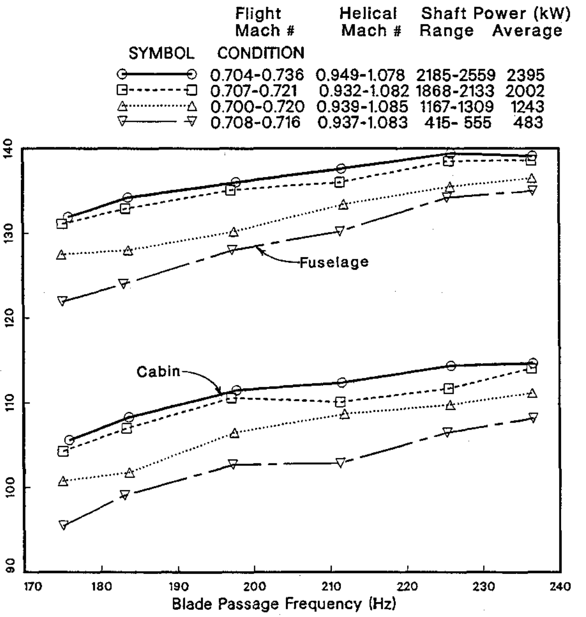

Fig. 6 Fuselage and cabin average sound pressure levels vs blade-passage frequency and four average shaft powers at 8840 m (29,000 ft).

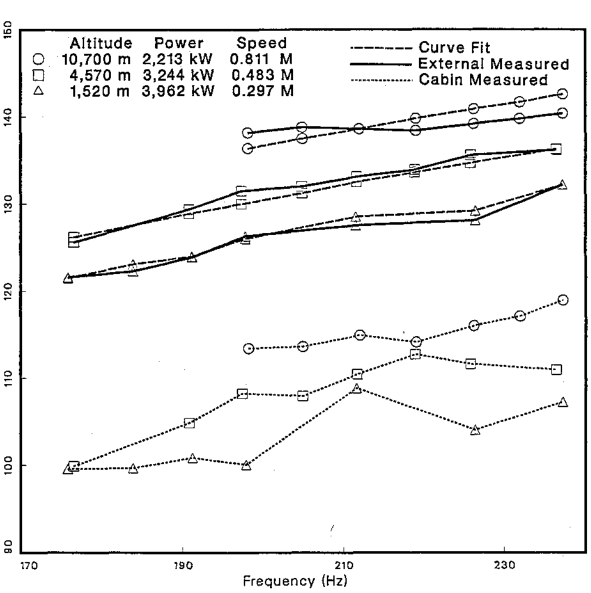

Fig. 7 Fuselage and cabin average sound pressure levels vs blade-passage frequency at three altitudes.

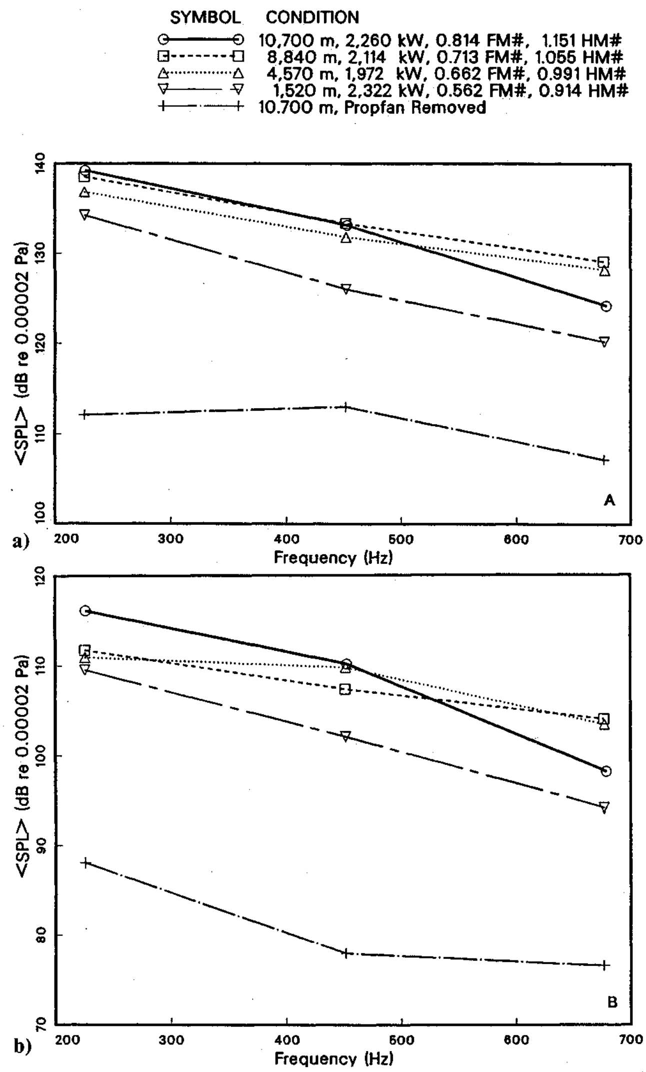

Fig. 8 a) Fuselage and b) cabin average sound pressure levels for the first three harmonics of the blade-passage frequency at four altitudes and without the propfan at 10,700 m (35,000 ft).

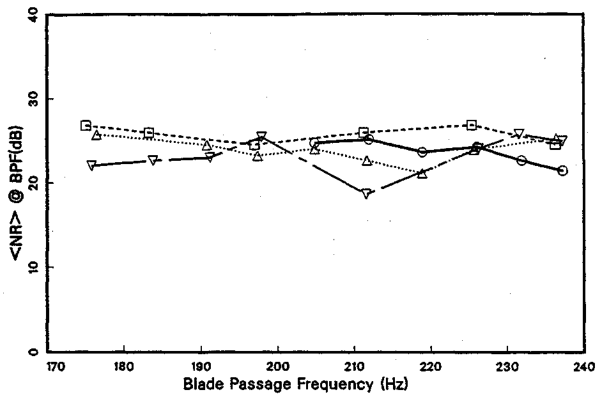

Fig. 9 Average noise reduction vs blade-passage frequency at four altitudes (symbols as in Fig. 8).

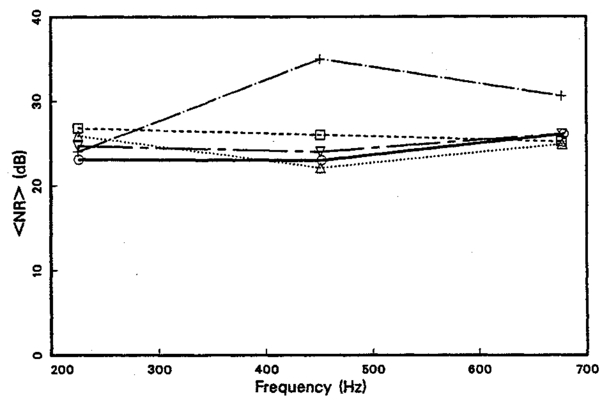

Fig. 10 Average noise reduction for the first three harmonics of the blade passage frequency at four altitudes (symbols as in Fig. 8).

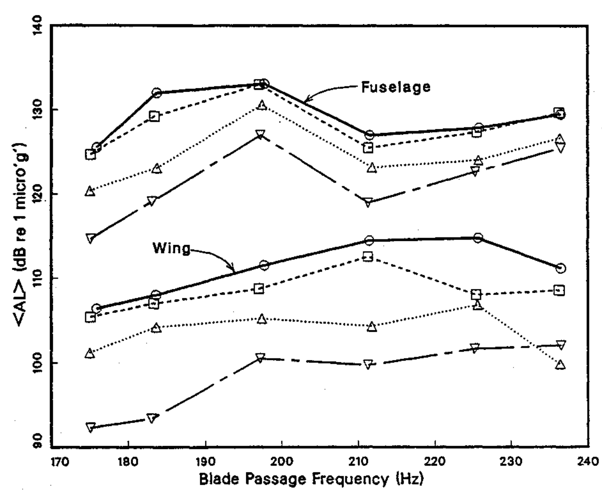

Fig. 11 Fuselage and wing-average acceleration levels vs blade-passage frequency at 8840 m (29,000 ft) (symbols as in Fig. 6).

Except for one point, the <NR> is seen to stay in a range of 20–27 dB. Figure 10 shows the <NR> measured at the first three blade-passage frequency harmonics for the cruise condition at four altitudes and without the propfan. These figures show, except for what appear to be minor structural effects, that the <NR> is essentially constant over the frequency and altitude ranges of interest. This result was not anticipated. For one reason, the differential pressurization at the various altitudes was expected to influence the structure and the radiation efficiencies of the sound.

Figure 11 shows the average wing and fuselage acceleration levels for the same tests as described in Fig. 6. At the lower frequencies, an increase in power or blade rotation rate increases

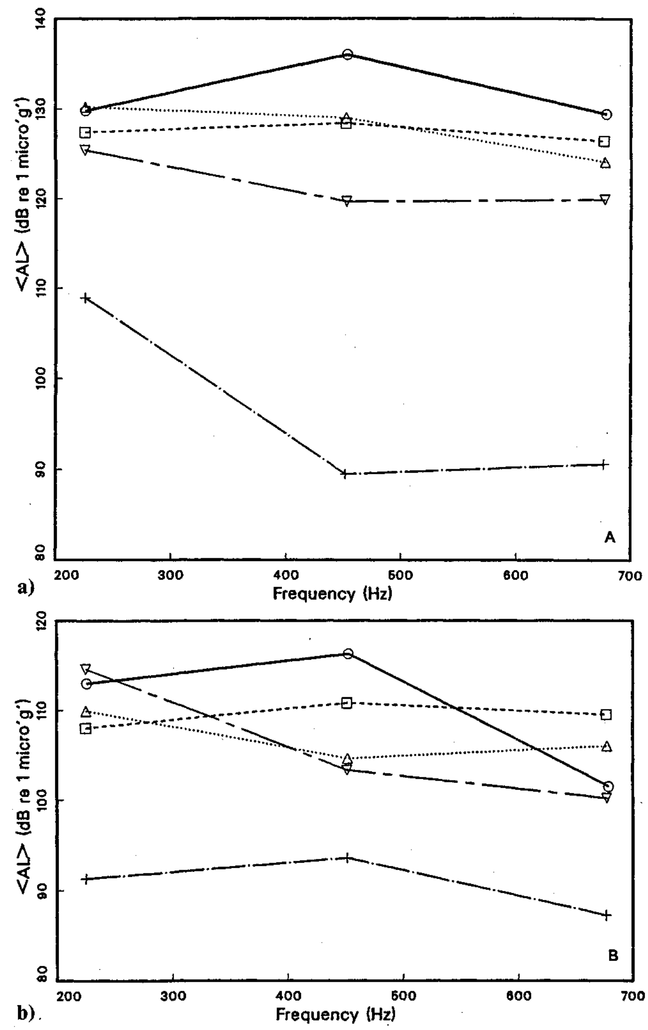

Fig. 12 a) Fuselage and b) wing-average acceleration levels for the first three harmonics of the blade-passage frequency (symbols and flight conditions as in Fig. 8).

the vibration levels of the wing. At the higher frequencies, the vibration levels tend to decrease with frequency. The curves have different slopes than the sound pressure level curves in Fig. 6. In addition, note that the fuselage vibration level curves have an inflection between 195 and 215 Hz. This inflection does not appear in the cabin sound pressure level curves in Fig. 6. The poor correlation between the wing vibration results and the cabin sound pressure level results is an indication that the cabin sound pressure levels are less dependent on the wing vibrations than on the fuselage sound pressure levels.

The fuselage and wing acceleration levels for the first three harmonics at four different altitudes are shown in Fig. 12. The acceleration levels at the blade passage frequency do not increase in the same manner with altitude as did the sound pressure levels in Fig. 8. In addition, at the second harmonic, the acceleration level spread is much larger than the cabin sound pressure level spread.

Figures 13 and 14 show the predicted and measured average cabin sound pressure levels at 10,700 and 1520 m (35,000 and 5000 ft), respectively. Except at the second harmonic, the predictions based on the acoustic excitation of the fuselage are in good agreement with the measured results. The poor agreement at the second harmonic appears to be caused by the limited area and placement of the loudspeaker on the fuselage during the ground tests. Acoustic excitation of the wing was found to be unimportant to the cabin sound pressure levels. The predictions based on the structure-borne sound measurements indicate that the structure-borne sound is not an impor-

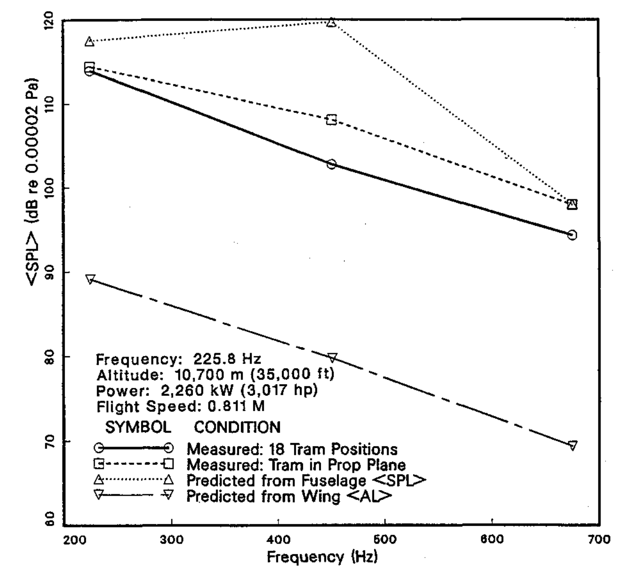

Fig. 13 Cabin average sound pressure levels for the first three harmonics measured at 10,700 m (35,000 ft) and predicted from the ground/flight wing acceleration and fuselage sound pressure analyses.

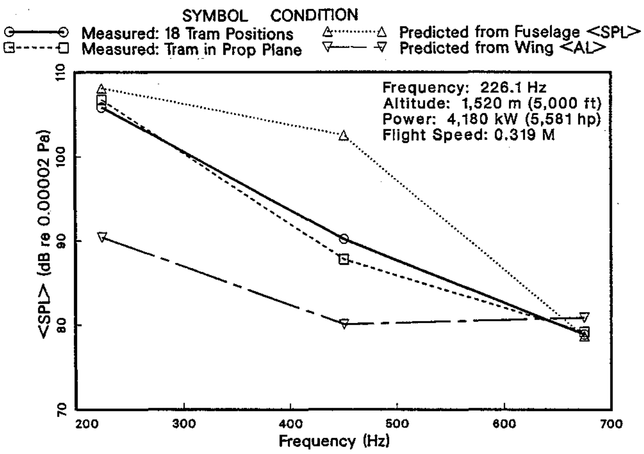

Fig. 14 Cabin average sound pressure levels for the first three harmonics measured at 1520 m (5000 ft) and predicted from the ground/flight wing acceleration and fuselage sound pressure analyses (symbols as in Fig. 13).

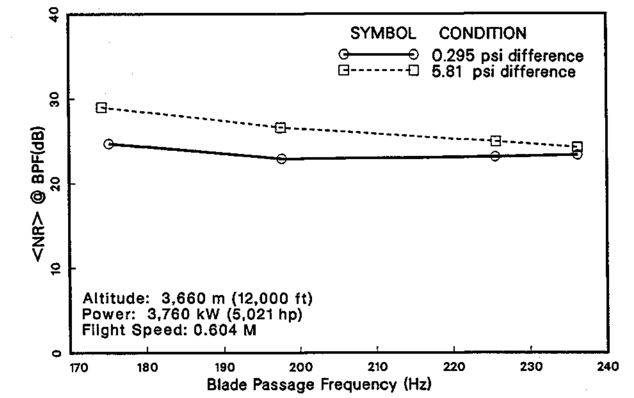

Fig. 15 Average noise reduction vs the blade-passage frequency and cabin pressurization.

tant factor in the cabin noise. In fact, the structure-borne energy has an effect only at low altitude and high frequency (675 Hz), where the sound pressure levels are lowest.

Pressurization effects on the cabin <NR> are shown in Fig. 15. As the pressure differential is reduced, the <NR> of the fuselage increases. The majority of this effect is caused by the air density change in the cabin and is supported by earlier laboratory work.[12]

Conclusions

The major noise source for cabin interior noise in the untreated PTA aircraft was the acoustic signal striking the fuselage. Sound travels directly from the propfan through the skin into the cabin interior. The tonal excitation of the wing is the source for vibrational energy introduction to the cabin. The vibrational energy travels from the wing spars into the fuselage shell and the aircraft floor, which radiates sound into the cabin. Relative to the airborne energy, the structure-borne energy was not significant, except at low altitude [1,520 m (5000 ft)] and high frequency (675 Hz), and then the contribution of the two sources were of the same order. At all altitudes, the average noise reduction of the fuselage was relatively constant (an average of 23 dB) over the frequency range of the first three harmonics. The acoustic output of the propfan, as measured on the fuselage at the blade-passage frequency, depended on the shaft power, helical Mach number, blade-passage frequency, and altitude. Positive cabin pressurization adversely affected the noise reduction of the fuselage by about 3 dB at 3660 m (12,000 ft). Smooth transition of increasing sound pressure levels with increasing helical Mach number are found.

The blade passage frequency was varied from 174–237 Hz. The cruise condition frequency was 225.6 Hz. The results of these tests and analyses are being used as the baseline to the cabin treatment tests that were performed later in a companion program. The wing vibrations at the blade-passage frequency remained fairly constant with altitude and were less influential as the altitude increased.

Acknowledgments

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