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Structure-Borne Noise Transmission in the Propfan Test Assessment Aircraft

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Estimates of the level of structure-borne noise transmission in the Propfan Test Assessment (PTA) aircraft were carried out for the first three blade passage frequencies. The procedure used combined the frequency response functions of cabin sound pressure level to wing strain response obtained during ground test of the PTA aircraft with in-flight measured wing strain response data. The estimated structure-borne noise levels varied from 64 to 84 dB showing very little dependence on engine/propeller power, flight altitude, or flight Mach number. In general, the bare cabin in-flight noise levels decreased with increasing propeller tone frequency, giving rise to a plausible structure-borne noise transmission problem at the higher frequency blade passage tones. Without knowledge of the effects of a high insertion loss sidewall treatment on structure-borne noise transmission of the bare cabin no quantitative conclusions could be made on the level of structure-borne noise transmission in a treated production aircraft.

Introduction

UNDER a contract from the NASA Lewis Research Center, the Lockheed-Georgia Company modified a Gulfstream GII business jet transport to evaluate the application of an advanced turboprop propulsion system on a transport aircraft. The primary aircraft modification was the addition of a Hamilton Standard/NASA SR-7L propfan and Allison model 501-M78 6000 horsepower drive system to the left wing of the 66,500 pound maximum takeoff gross weight aircraft. The modified Gulfstream was called the Propfan Test Assessment (PTA) aircraft. The various aircraft modifications are shown schematically in Fig. 1. The PTA program objective was to evaluate the propfan structural integrity, propfan source noise, and propfan cabin noise and vibration.[1]

The PTA aircraft underwent flight test evaluation during the March 1987 to March 1988 time period. Results from the flight test were documented and presented to the aircraft community as a PTA Flight Test Results Review at NASA Lewis Research Center on November 14, 1988. One of the primary concerns of the propfan configuration is the cabin noise environment. The PTA flight test aircraft consisted of a pressurized bare cabin with noise levels dominated by blade-order tones of maximum level 120 dB with a 15–20-dB variation within the cabin. It was concluded that a sidewall treatment with a target insertion loss near 40 dB would be required to reduce the interior noise levels to an overall of about 80 dBA.[1]

Ground tests were also conducted to detect structure-borne noise transmission into the PTA cabin via application of discrete and random forces to the wing front and rear spars, using an electromagnetic shaker. From correlation of the generated cabin noise and wing accelerations with in-flight wing vibration levels it was concluded that structure-borne noise transmission levels due to combined propeller wake/vortex impingement on the wing surface and engine/gear box vibration was not evident, but in certain circumstances it could be plausible.[1]

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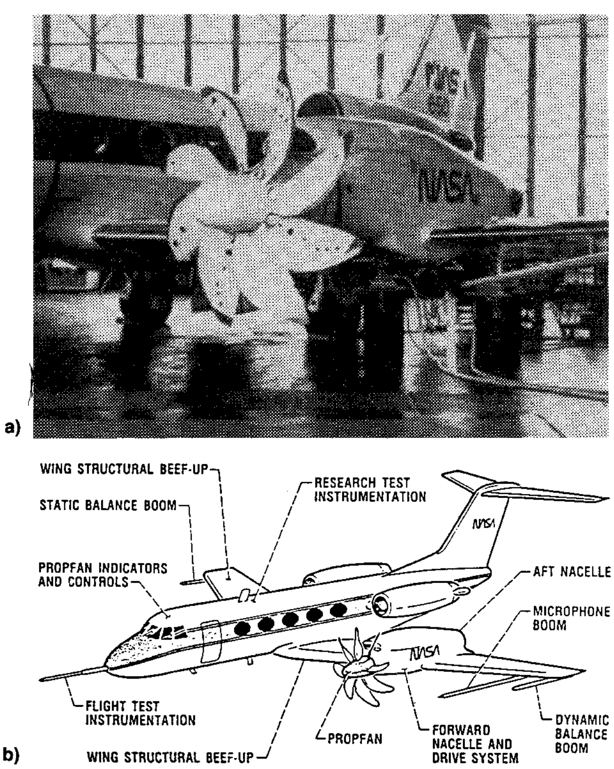

a)
b)

Fig. 1 PTA testbed aircraft: a) laboratory setup; b) general features.

The investigation reported herein is an independent evaluation of the in-flight structure-borne noise (SBN) transmission levels in the PTA test aircraft based on the in-flight measured wing front and rear spar dynamic strain levels. The structure-borne noise detection technique employed was previously developed under laboratory simulation[2] and is briefly described below.

In-Flight Structure-Borne Noise Detection Technique

The laboratory-based development of a procedure for the detection of structure-borne noise transmission in an aircraft due to propeller wake/vortex impingement on the wing structure or due to engine/propeller vibration is reported in Refs. 2 and 3. The test procedure is most easily described with reference to the schematic of Fig. 2. The structural path, being

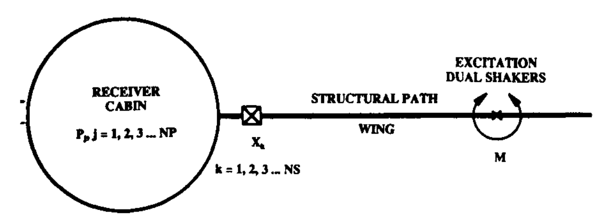

Fig. 2 In-flight structure-borne noise detection concept.

the wing structure, is excited with a dynamic moment M in the area of the propeller wake and NS structural response measurements X_k are acquired, along with NP interior microphone responses P_j. During ground test measurements, the pressure response to input moment

$$HPM(\omega)_j = P(\omega)_j/M(\omega)$$

frequency response functions (FRFs) are computed along with structural response to input force FRFs:

$$HXM(\omega)_k = X(\omega)_k/M(\omega)$$

The pressure response to structural excitation FRFs are then computed as

$$HPX(\omega)_{jk} = HPM(\omega)_j/HXM(\omega)_k$$

During flight test, the structural responses $\bar{X}(\omega)_k$ are acquired, and estimates of interior structure-borne noise levels $\bar{P}(\omega)_{jk}$ are computed for the ground-based FRFs as

$$\bar{P}(\omega)_{jk} = HPX(\omega)_{jk}{}^{*}\bar{X}(\omega)_k$$

A variation in computed interior levels occurs from use of multiple structural response measurements and multiple microphone response locations within the receiving cabin.

In the original development of the above procedure various methods of wing excitation were evaluated including hammer impact at discrete wing locations, single shaker discrete frequency excitation, and dual shaker sweep excitation.[3] However, it was found that for propeller wake/vortex simulation the use of dual shakers, driven 180 deg out of phase, provided the proper excitation, a pure dynamic moment about the propeller axis.[4] It was also found that wing spar strain was a more reliable structural response parameter than wing or cabin acceleration response.

PTA Flight Test Data

The PTA testbed aircraft was equipped with a variety of acoustic, vibration, and propeller and aircraft performance monitoring instrumentation wired into an on-board data acquisition system for in-flight collection of the various parameter responses. A total of 37 interior cabin microphones were used during the PTA flight test. However, only the 18 fixed-position wall-mounted microphone locations were used during the present evaluation. The fixed wall-mounted microphone locations are schematically shown in Fig. 3.

The PTA testbed aircraft wing was heavily instrumented with 44 microphones, 33 accelerometers, and 14 strain gauges. The only strain gauges used on the aircraft were mounted inboard on the wing front and rear spars, an ideal location for the present study.[2] A general schematic of the strain gauge locations is given in Fig. 4. The strain gauges were Micro-Measurement type CEA-13-062 UW/350 with a gauge factor of 2.15.

The PTA flight test covered a range of flight altitudes from 5000 to 40,000 ft, flight Mach numbers ranging from 0.28 to 0.85, and engine/propeller power ranging from approximately 560 to 5950 shaft horsepower. The resulting fundamental blade passage frequency varied from 173.7 to 236.8 Hz. The effect of nacelle tilt angle was also evaluated with test data acquired

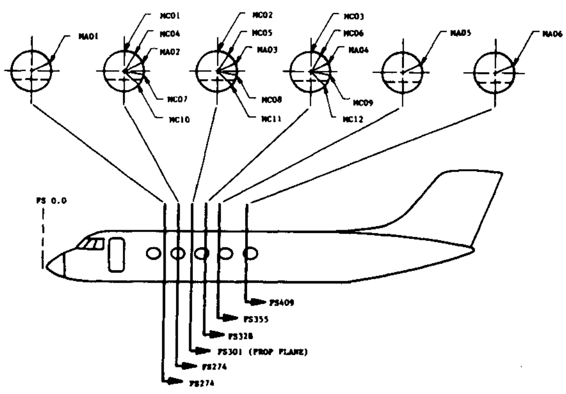

Fig. 3 Cabin microphone locations.

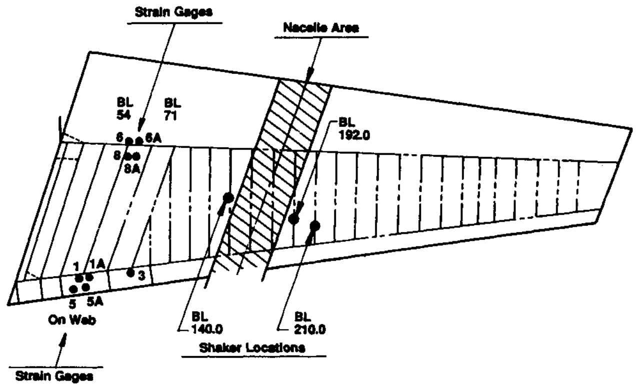

Fig. 4 Shaker and strain gauge locations.

at nacelle tilt angles of −1, −3, and +2 deg. Data were acquired for a total of 549 test points. The present evaluation was limited to the primary nacelle tilt angle of −1 deg.

The data made available for the present evaluation were in the form of peak microphone and strain responses at the fundamental blade passage frequency and its first nine harmonics. Only responses at the first three propeller tones were of interest in the present study, due mainly to limited strain response data above the background noise at frequencies above 800 Hz. Details of the data contained in the PTA data bank can be found in Ref. 5. In general, no response was recorded on microphone MC03, and typically strain responses at the third propeller tone were limited to only a few gauges or none at all.

PTA Ground Test

Ground-based tests on the PTA aircraft were carried out at NASA Lewis Research Center. The objective of the ground tests was to acquire frequency response functions of interior microphone to wing strain response for the purpose of estimating the level of interior structure-borne noise transmission during aircraft flight. The test setup, instrumentation, signal conditioning and control equipment, and data acquisition and reduction are discussed briefly in the following paragraphs.

Test Setup

The general arrangement of the test apparatus is shown in Fig. 5. Two Unholtz Dickie model 1 modal, current-driven shakers were attached to the PTA lower wing hard structure. The shakers were driven harmonically, in the frequency range from 150 to 750 Hz, 180 deg out-of-phase to produce a pure dynamic moment excitation simulating the propeller wake excitation. The maximum output force of either shaker was 30 lb. The shakers were originally attached to the wing ribs symmetric about the engine nacelle at BL 140.0 and BL 192.0, as indicated in Fig. 4. However, it was found that constant force control at the outboard shaker location (BL 192.0) could not be achieved, due to local compliance, which required

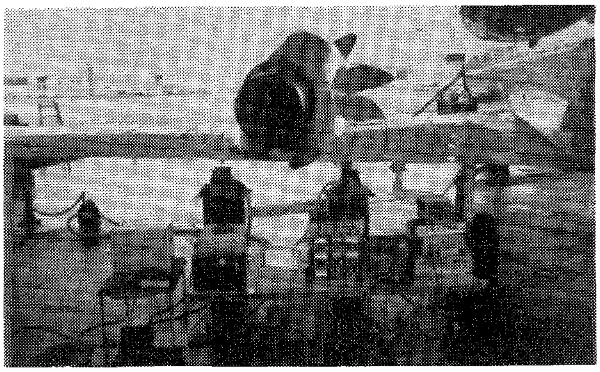

Fig. 5 General arrangement of test apparatus.

movement of the shaker to the next outboard rib at BL 210.0. The 70-in. shaker spacing resulted in a maximum excitation of 2100 in.-lb (175 ft-lb) dynamic moment. The frequency range of excitation covers the first three propeller tones for the various propeller speeds encountered during the PTA flight tests.

Instrumentation

Interior noise level measurements at the 18 fixed microphone locations used during the PTA flight tests were recorded during the shaker-induced wing excitations. The data at the 18 locations were acquired with three microphones during six independent data runs. Bruel & Kjaer ½-in. type 4166 microphones and type 2615 preamplifiers were used to acquire the cabin acoustic response. A Bruel & Kjaer type 4230 sound level calibrator supplying a 94 dB (ref. 2×10^{-5} Pa) sound pressure level at 1 kHz provided calibration of the microphones.

Figure 4 schematically shows several of the wing root strain gauge locations. The adjacent gauges, such as 5 and 5A, provided only redundant data for structure-borne noise (SBN) estimates and therefore only the eight primary gauges were of interest during the ground test. Dynamic response calibration of the strain gauge signals was based on the 2.15-gauge factor.

Kistler Instruments Model 9212 force cells were attached between the wing and the modal shakers to regulate and record the excitation force levels. While current supplied to the modal shaker is generally a good indicator of the input load, the force cell provided a much more accurate indication of actual input force due to potential compliance of the shaker to wing attachment rods.

Signal Conditioning and Control

The signal conditioning and control equipment used to conduct the SBN ground tests is also shown in Fig. 5. A detailed description of the equipment used during the ground test is given in Ref. 5, and only a brief description will be given herein. Shaker control is ideally achieved via routing of the amplified force cell signals to a pair of amplitude servo/monitors. The servo/monitors also receive a desired drive signal from a sweep oscillator and adjust their output to drive the modal shakers to compensate for any deviations in the monitored shaker force cell signals. The shaker current amplifiers are equipped with a front panel switch to achieve a 180-deg phase shift. Unfortunately, one of the amplitude servo/monitors was damaged during shipment to NASA and could not maintain amplitude control. Thus, a single amplitude servo/monitor was used to control the outboard shaker while the inboard shaker was driven open loop with the outboard shaker drive signal. As is shown in the results presented below, this arrangement resulted in surprisingly good moment excitation control. Such good moment control with a single controller is attributed to the use of a matched pair of shakers and amplifiers and nearly equivalent driving point impedance at the shaker to wing attachments.

Signals for the three cabin mounted microphones were high pass filtered and then amplified for recording with a nominal gain of 20 via instrumentation amplifiers. The eight channels of wing root strain signals were routed directly to a strain gauge conditioner/amplifier which provided a balancing bridge with a gain of 2100 on all channels. The low-frequency (150–750 Hz) strain signals were quite weak, nominally less than 1 micro strain, which required additional amplification on the order of 100 supplied by instrumentation amplifiers.

Data Acquisition and Reduction

The strain gauge, microphone, and load cell signals were recorded on a 14-channel cassette data recorder. Six data runs were required for recording interior noise levels at all 18 fixed microphone locations. A logarithmic frequency sweep in the range from 150 to 750 Hz was made at a sweep rate of 0.1 decade per min. A sweep rate of 0.3 decade per min was shown to yield equivalent responses and therefore the slower rate was felt to be adequate. Sine wave calibration signals were recorded on the tape prior to data acquisition and a segment of background noise was recorded after completion of the six data runs.

On site data reduction and signal monitoring was carried out via a 4 channel spectrum analyzer for time window and spectral analysis and an oscilloscope was used for continuous time signal monitoring. A 386 personal computer (PC) was used as a control terminal to the spectrum analyzer. The sweep data were spectrally analyzed in a 1000-Hz data window with 2.5-Hz bandwidth of analysis using a periodic flat-top data window with an effective 23% data overlap. Under these conditions, the analyzer required approximately 1365 sample averages to complete the logarithmic sweep.

Post data analysis used a similar setup as that used for on-site data reduction; however, permanent digital data records were stored in the 386 PC for frequency response functions between all microphone and strain responses (18 microphones by 8 strain gauges to yield 144 FRFs). During the data reduction process, the low-level strain response signals were passed through a narrow band tracking filter driven by the shaker load cell response signal. The narrow band filtering greatly enhanced the strain signal-to-noise ratio. The microphone signals were of sufficient quality to allow direct analysis and therefore no additional filtering was necessary. Since only the magnitude of the FRFs are of interest in estimating SBN, the phase shifts in the various signal conditioning, recording, and data analysis setups between the strain and microphone signals were not taken into account in the data reduction process.

Typical Ground Test Results

The frequency response function between the force excitation at the inboard shaker to that of the outboard shaker, controlled to a constant 30-lb amplitude, yields a quantitative measure of success in producing a pure dynamic moment excitation. The data of Fig. 6 gives the desired FRF wherein it can be seen that shakers remained 180 deg out of phase well above 700 Hz, and only after 700 Hz did the force ratio vary more than approximately 20%. It is of interest to note that the highest blade passage frequency (BPF) of interest for SBN estimates for the PTA tests was 237.5 Hz. This translates to 712.5 Hz for the third BPF as indicated by the dashed line in Fig. 6. Only small deviations from the desired pure dynamic moment excitation existed in the frequency range of interest to this study.

Typical signal background noise levels recorded during the ground test are given by the dashed line data in Fig. 7. The background strain level shown for SG05A exhibits a nominal amplitude of 0.03 micro strain in the 150–750-Hz frequency range. The PTA interior background noise levels for microphones MA05 and MA06 are nominally below 50 dB. Typical signal spectral levels for strain gauge SG05A and microphones

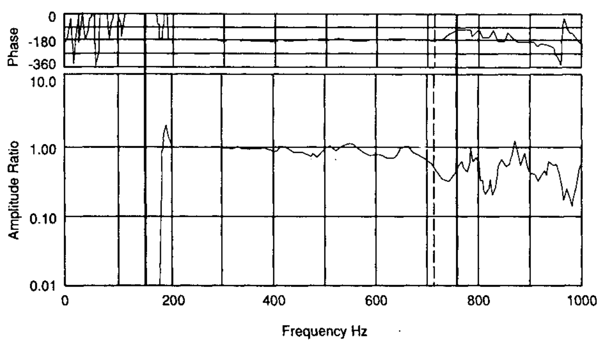

Fig. 6 FRF ratio shaker excitation $F_{\mathrm{INDB}}/F_{\mathrm{OUTBD}}$.

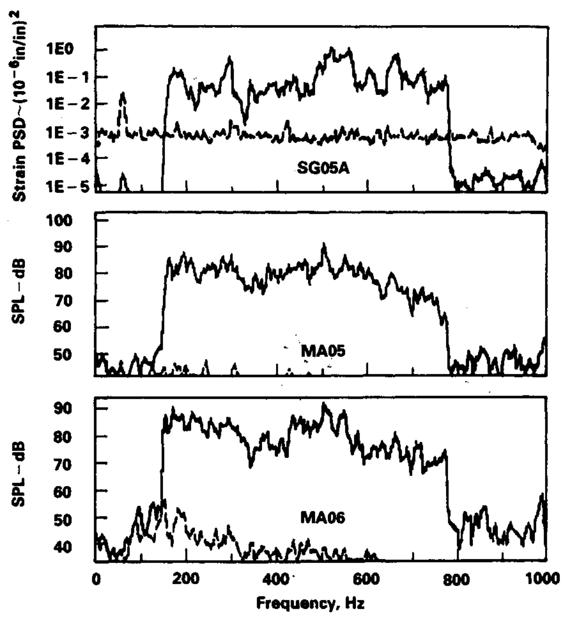

Fig. 7 Typical recorded signals.

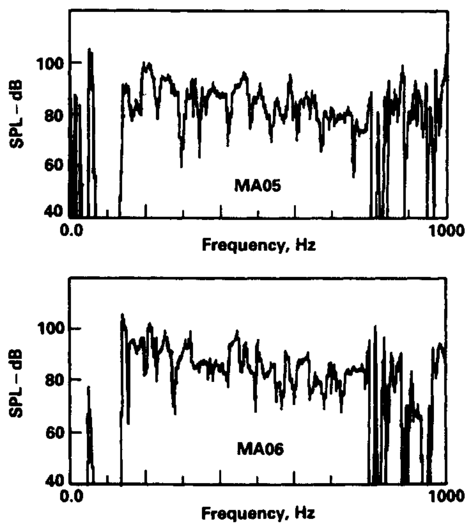

Fig. 8 Interior SPL response to unit micro strain at SG05A.

MA05 and MA06 are also given in Fig. 7. As can be seen, the recorded microphone signals are well above the recorded background noise levels with a 30–40-dB margin. The SG05A strain level varies from 0.14 to 1.0 micro strain corresponding to a signal-amplitude-to-noise ratio in the range of approximately 5–33, or 13–30 dB. It is felt that while the recorded strain levels were very low, the signals were sufficiently strong to establish the necessary FRF database required for in-flight structure-borne noise transmission estimates for the PTA aircraft. It is of interest to note that the ground test strain levels recorded were on the same order as those measured during the PTA flight test.

Typical strain to interior sound pressure level (SPL) frequency response functions are given in Fig. 8 wherein the SPL at microphones MA05 and MA06 are given for a unit micro strain at SG05A. In general, it appears that an 80–100-dB interior sound pressure level will result from a wing unit micro strain. The FRFs of Fig. 8 are quite rich in what appears to be resonant response of both the wing structure and the coupled fuselage/cabin structural acoustic environment.

PTA In-Flight SBN Estimates

Approximately 50 PTA testbed flight conditions were initially evaluated with 40 resulting in apparently valid data. A variety of flight altitudes, Mach numbers, and engine/propeller horsepower settings were evaluated. While nacelle tilt angles of -3, -1, and 2 deg were evaluated during the flight test, generally very poor data, either due to interior microphone dropout or erratic strain level data, were found for the -3- and 2-deg cases. The present study was therefore confined to the -1-deg nacelle tilt configuration which was the primary PTA test configuration.

Estimation Procedures

The interior noise to strain frequency response function data obtained during the ground test of the PTA aircraft allowed prediction of in-flight structure-borne noise levels at the 18 microphone locations for in-flight measured responses from each of the eight wing-mounted strain gauges. Thus, there exists a possibility of eight noise level estimates at each microphone and a possibility of 144 noise level estimates for the overall cabin response. The in-flight strain level databank used in this study consisted of peak strain levels at each of the first three propeller tones. In-flight strain levels beyond the third propeller tone were generally not above the background noise. If no identifiable peak occurred in the strain spectrum in the area of the propeller tone, no contribution to the analysis was taken from that response. The aircraft a.c. power fundamental was a 400-Hz signal which masked the strain response corresponding to the second propeller tone for a number of flight conditions. For these cases the strain responses were also set to zero to eliminate their influence on overall noise estimates (this was manually carried out upon review of the in-flight databank). The interior microphone at location MC03 was inoperative for all in-flight configurations evaluated, however, estimates of structure-borne noise transmission were made for all 18 microphone locations.

Results

Energy average overall cabin structure-borne and in-flight noise level estimates were made by equally weighting all responding microphone locations. The results of the analysis for the first three propeller tones are given in tabular form in Ref. 5 for each of the 40 flight test conditions evaluated. Only a summary of these data is presented herein.

Various plots of both the estimated structure-borne and measured in-flight sound pressure levels vs power applied to the propeller, aircraft flight altitude, and aircraft Mach number were carried out to evaluate flight parameter effects on cabin noise. Typical results of this evaluation are given in Figs. 9–11. Variation in cabin noise levels for the first propeller tone vs power applied to the propeller is given in Fig. 9. As can be seen, the estimated structure-borne noise levels are well separated from the measured in-flight noise levels with no noticeable level change with increasing power.

Similar data are shown in Fig. 10 for the structure-borne and in-flight noise levels at the second propeller tone vs aircraft altitude. These data show a slight trend of decreasing noise level with increasing aircraft altitude. However, similar data plots for the first and third propeller tones did not show similar trends. In comparison to data for the first propeller tone the structure-borne and in-flight noise levels are less

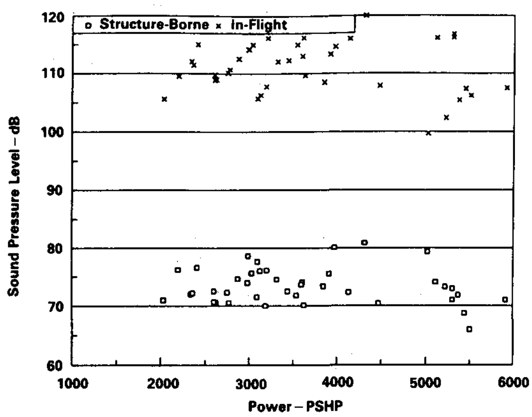

Fig. 9 PTA in-flight SBN vs engine/propeller power, first blade passage tone.

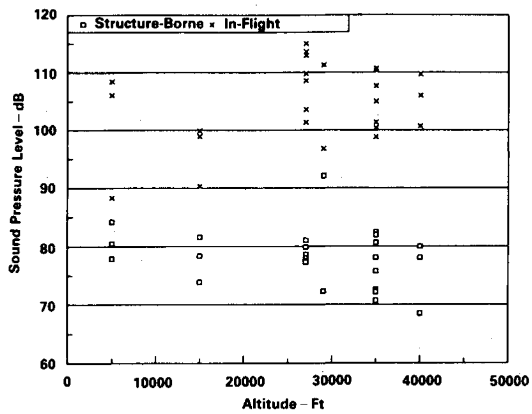

Fig. 10 PTA in-flight SBN vs flight altitude, second blade passage tone.

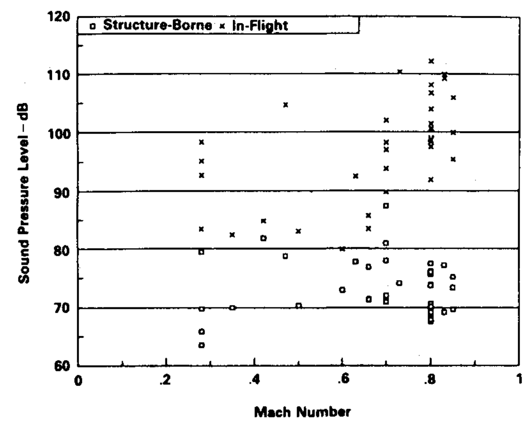

Fig. 11 PTA in-flight SBN vs Mach number, third blade passage tone.

separated. This trend continues as is shown by the noise levels given in Fig. 11 for the third propeller tone vs aircraft Mach number.

The difference in measured in-flight and estimated structure-borne noise levels is an indication of the relative importance of the propeller airborne sidewall and structure-borne noise sources. This difference vs propeller frequency is shown in Fig. 12 for all data cases analyzed. The data for the first propeller tone are quite distinct in the lower frequency region with the second propeller tone data in the 350–470-Hz range. In general, the trend is for decreasing differences with increasing propeller tone, however, the variation in the data also increases with increasing propeller tone. Overall data trends are best seen by the summary data of Table 1, wherein the maximum and minimum levels and level differences are

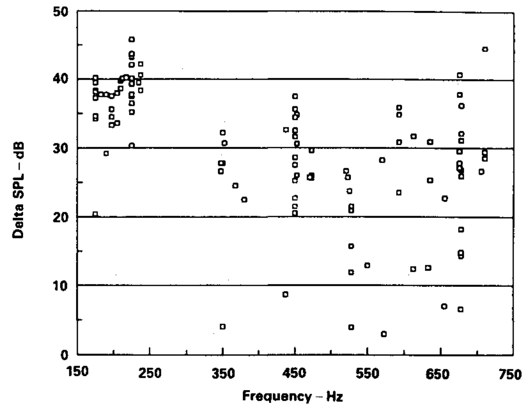

Fig. 12 Difference of in-flight and structure-borne noise levels vs frequency.

Table 1 Cabin overall noise level summary

	Structure-borne, dB	In-flight, dB	Delta, dB
1st Propeller tone			
Maximum	80.9	120.4	45.8
Minimum	66.0	99.7	20.4
Average	73.4	111.2	37.8
Std. dev.	3.1	4.5	4.4
2nd Propeller tone			
Maximum	84.2	115.0	37.5
Minimum	68.5	88.3	4.1
Average	77.7	104.6	26.9
Std. dev.	3.9	6.4	7.2
3rd Propeller tone			
Maximum	81.8	112.2	44.6
Minimum	63.5	79.9	3.0
Average	73.3	97.3	24.0
Std. dev.	4.4	8.3	10.0

given along with the average and standard deviation for each propeller tone.

Discussion

Based on the data presented, it does not appear that the PTA aircraft has a propeller-induced structure-borne noise transmission problem. However, the test aircraft was not fitted with a high-loss sidewall transmission interior trim sufficient to reduce the airborne noise level to an acceptable 80 dBA; in fact, the cabin was bare. The effect of a 40-dB insertion loss interior trim on the structure-borne noise transmission is not known; however, one should not expect a one-to-one noise reduction since the basic transmission paths for airborne and structure-borne noise are quite different.

It is to be noted that the difference between recorded in-flight noise levels and the estimated structure-borne noise levels decreases with increasing propeller tone (increasing frequency). This trend is mainly due to a general decrease in recorded in-flight noise levels, since the average SBN transmission level remains relative constant with increasing frequency, as can be seen from the average values given in Table 1. With sidewall treatments generally increasing in effectiveness at higher frequencies, the possibility of a dominating structure-borne noise problem in the frequency range of the third propeller tone could be realized. At the time of this evaluation, no data could be found to indicate the relative effectiveness of a high insertion loss sidewall trim on propeller-induced structure-borne noise transmission and therefore no further evaluation of this potential problem area could be carried out.

Conclusions and Recommendations

Estimates of the level of structure-borne noise transmission in the Propfan Test Assessment aircraft were carried out for the first three blade passage frequencies. The procedure used combined the frequency response functions of cabin SPL to wing strain response obtained during ground test with in-flight measured wing strain response data. The following conclusions are drawn from the results of this study:

1) The estimated PTA aircraft cabin overall structure-borne noise levels varied from 64 to 84 dB, with average levels on the order of 74 dB.

2) In general, the structure-borne noise levels showed little dependence on engine/propeller power, flight altitude, or flight Mach number, with the only exception being the second blade passage tone which showed a slight decrease in level with increasing flight altitude and flight Mach number.

3) In general, the bare cabin in-flight noise levels decreased with increasing propeller tone giving rise to a plausible structure-borne noise transmission problem at the higher blade passage tones. Without knowledge of the effects of a high-insertion-loss sidewall treatment on structure-borne noise transmission, no quantitative conclusions can be made. It is highly recommended that full-scale data can be obtained on the relative effectiveness of a high-insertion-loss sidewall treatment for airborne noise reduction on the reduction of structure-borne noise transmission due to propeller-induced or engine-induced wing vibrations.

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