Installation Effects on Propeller Wake/Vortex-Induced Structure-Borne Noise Transmissions

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The expected levels of propeller wake/vortex-induced structure-bone noise (SBN) transmission in new generation aircraft are unknown and can only be assumed to be a potential problem area. A laboratory-based test apparatus was employed to investigate the effects of power plant placement, engine/nacelle mass installation, and wing-to-fuselage attachment methods on propeller-induced structure-borne noise transmission levels and their effects on developed noise control measures. Data are presented showing that SBN transmission is insensitive to propeller spanwise placement, however, some sensitivity is seen in propeller-to-wing spacing. Installation of an engine/nacelle mass and variation in wing-to-fuselage attachments have measurable influences on SBN transmission and control measures.

Introduction

HISTORICALLY speaking, interior noise levels of propeller-driven aircraft are much higher than the acceptable levels of present-day turbofan aircraft, even after apparently ample application of noise control measures. Engine vibration-induced, structure-borne interior noise transmission has been shown to be equal to or greater than the direct airborne noise transmission levels in a single-engine, propeller-driven aircraft.[1] The potential for engine vibration as a source of structure-borne interior noise in twin-engine aircraft has not been thoroughly investigated; nevertheless, adequate procedures for engine vibration isolation system evaluation have been developed.[2,3] A potentially more important source of structure-borne interior noise transmission is provided by the interaction of the propeller wake and aircraft wing structure. The wing surface downstream of the propeller may experience significant aerodynamically induced, fluctuating pressures due to the propeller wake, especially from the tip vortex.[4] Extensive ground tests of a Twin Otter aircraft revealed that the propeller-wake and tip-vortex interaction with the wing surface was the major source of interior noise for the aircraft at 50% or greater engine torque.[5] The interior noise spectra were dominated by contributions at the propeller blade passage frequency and its harmonics.

Reference 6 describes a test apparatus built to study propeller wake/vortex-induced structure-borne noise (SBN) transmission under controlled laboratory conditions. The principal approach to the test apparatus design was to provide a physical means of separating the airborne and SBN components so that the SBN transmission response could be studied directly without airborne noise contamination. The test apparatus has been instrumental in developing procedures for detection of in-flight SBN transmission[7] and evaluation of several SBN control measures.[8]

This paper describes the results from a study of installation effects on propeller wake/vortex-induced SBN transmission levels and their effect on noise control measures. The effect of power plant placement, engine/nacelle mass, and wing-to-fuselage attachment on SBN transmission is discussed in the following sections.

Test Apparatus

The test apparatus used during the investigation is shown in Fig. 1. The major components of the test apparatus are the 28-in.-diam propeller source (maximum 5700 rpm) with a 33-in.-diam blower providing 70 ft/s inlet flow, the 80-in. span, 31-in. constant chord NASA 0012 wing providing the structural transmission path, and the 40 in.-diam, 72-in.-long ring frame and stringer constructed fuselage with integral floor structure and interior trim providing the receiving acoustic volume. The 5-1/2 in.-thick, 54-in.-i.d., 7-ft-long concrete structure provides an acoustic shield for the fuselage from direct airborne noise radiation from the propeller. A noncontacting acoustic seal at the wing penetration into the acoustic shield provides adequate airborne noise isolation for the fuselage structure.[7] A schematic of the test apparatus is provided in Fig. 2, showing the relative location of the instrumentation, propeller source, and wing panel and cells used during the study.

Installation Configuration

Power Plant Placement

The effect of power plant placement on the transmission of structure-borne noise was studied by recording interior noise levels at several propeller speeds while varying the position of the propeller source relative to the wing. A cabin microphone

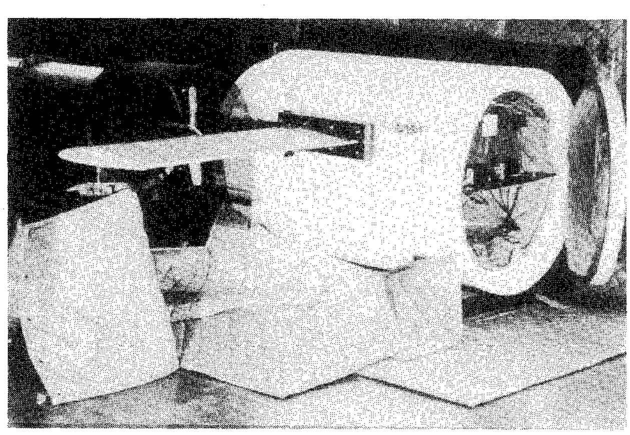

Fig. 1 Structure-borne noise test apparatus.

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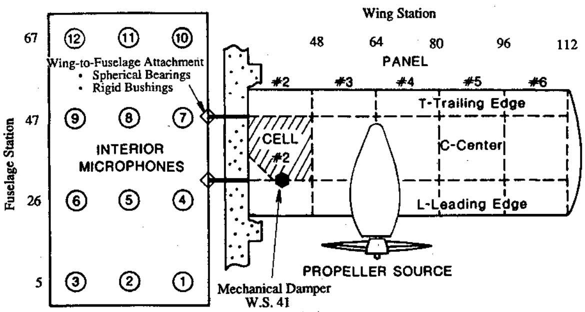


Fig. 2 Installation configurations.

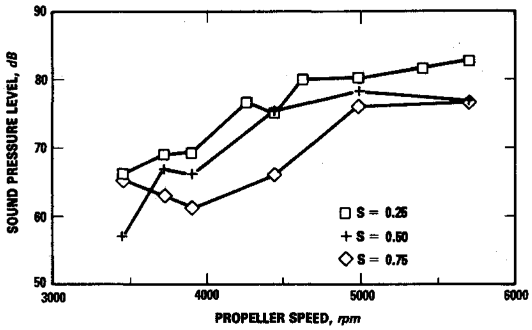


Fig. 3 Effect of propeller/wing separation on SBN transmission, clean wing, wing station 80.

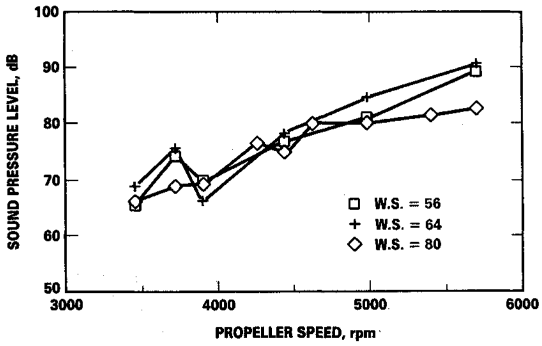


Fig. 4 Effect of propeller spanwise placement on SBN transmission, clean wing, $S = 0.25$.

array was averaged and continuously swept along the length of the cabin to obtain space average sound pressure levels. The propeller source was placed in the wing chord plane at wing station 80 and then moved forward from a wing leading edge separation distance of $S = 0.25$ propeller diameters (7 in.) to $S = 0.5$ and then to $S = 0.75$. The spatial average *SPL* recorded at the various propeller/wing separation distances is shown in Fig. 3. In general, the data of Fig. 3 indicate that the strength of the propeller-induced forces contributing to wing excitation and subsequent structure-borne noise propagation somewhat falls off as the propeller-to-wing separation distance increases. With the propeller/wing separation distance fixed at $S = 0.25$, a similar variation in spanwise placement of the propller source was carried out. The corresponding data are shown in Fig. 4. As can be seen from the data in Fig. 4, there does not appear to be a consistent trend relating spanwise propeller placement and structure-borne noise transmission. Throughout the remaing evaluations, the propeller source was fixed at wing station 64 with a propeller to wing separation distance of $S = 0.25$.

Engine/Nacelle Mass

To establish a reasonable mass to simulate the effects of an engine and nacelle installation for the SBN test apparatus, typical full-scale twin engine aircraft data were obtained and scaled based on bare-wing weights and propeller diameters. The data in Table 1 were obtained from a general aviation manufacturer for one of their more popular twin engine aircraft.

The significant SBN test apparatus specifications are: Bare-wing weight, 29.55 lb, and propeller diameter 28.00 in.

Using the test apparatus to full-scale bare wing weight ratio of 0.032 and ratio of propeller diameters of 0.267, the engine/nacelle parameters listed in Table 2 resulted. These design parameters were computed based on the assumption that the aircraft engine would be mounted on vibration isolators, which would provide dynamic isolation of the engine mass on the order of 1/8 of its static value. The engine effective radius of gyration was computed based on an equivalent compact cylindrical mass and then scaled by the propeller diameter ratio. The engine nacelle was assumed to have a circular cross section.

Table 1

Bare-wing weight, lb	925
Engine weight, lb	850
Engine roll inertia, lb-in.^{2}	76,747
Nacelle weight, lb	430
Nacelle frontal area, ft.^{2}	7.65
Propeller diameter, in.	105

Table 2

	Design	As built
Wing added weight, lb	17.1	17.6
Wing added inertia, lb-in.^{2}	912.0	183.7
Nacelle diameter, in.	10.0	10.2

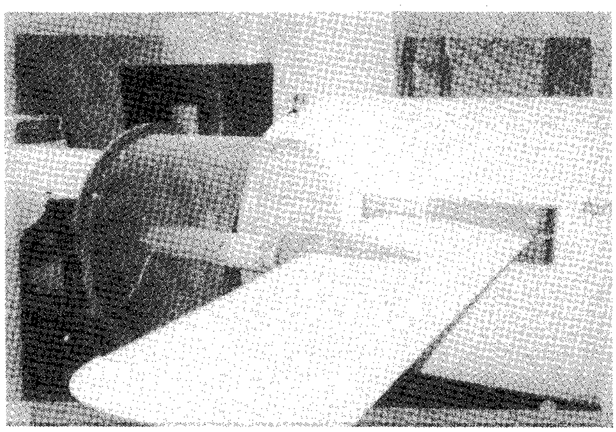


Fig. 5 Installed engine/nacelle mass.

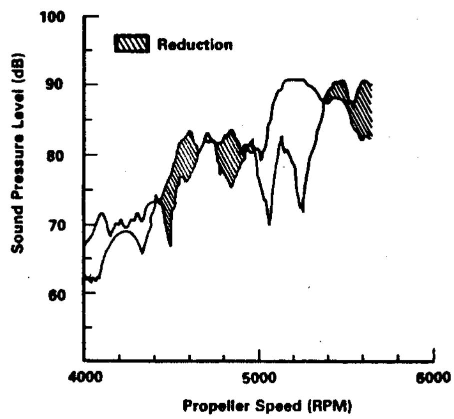


Fig. 6 SBN transmission, engine/nacelle installed vs clean wing, spherical bearings, microphone 7.

The engine/nacelle for the test appparatus was constructed from a solid block of Philippine mahogany. The installed article is shown in Fig. 5. The engine/nacelle is fixed to the wing via a forward clamping arrangement, bolted rear connection to the rib at wing station 64 and solid contact along the main spar via surface adhesives. The engine/nacelle installed parameters are given in Table 2. The roll inertia was determined using a parallel pendulum suspension with a roll excitation. The natural frequency of the excited item then determines the roll inertia (plus fixture inertia).

Propeller speed sweeps were carried out while recording the interior noise levels of the first propeller tone at four interior microphones, no. 4 (P2 at F.S. 26), no. 6 (P4 at F.S. 26), no. 7 (P2 at F.S. 47), and no. 9 (P4 at F.S. 47), as schematically shown in Fig. 2. The resulting sound pressure levels were compared to clean wing levels recorded prior to the engine/nacelle installation. Typical changes in transmitted noise levels are shown in Fig. 6 as recorded at microphone 7. As can be seen, the addition of the simulated engine/nacelle mass shows bands of increased and decreased SBN transmission. In general, a decrease in SBN transmission occurred in the propeller speed range from approximately 4400 to 5000 rpm and from 5400 to 5700 rpm. A small increase in SBN transmission occurred below aproximately 4400 rpm, while a measurable increase was recorded in the 5000–5400 rpm range, with the peak increase occurring around 5220 rpm. For the two-bladed propeller, the major increase in SBN transmission occurs at the first blade passage frequency or 174 Hz.

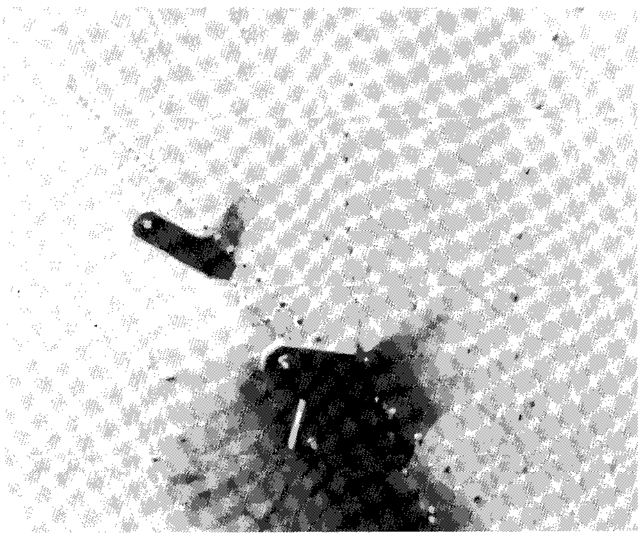


Fig. 7 Wing-to-fuselage front and rear carrythrough attachments.

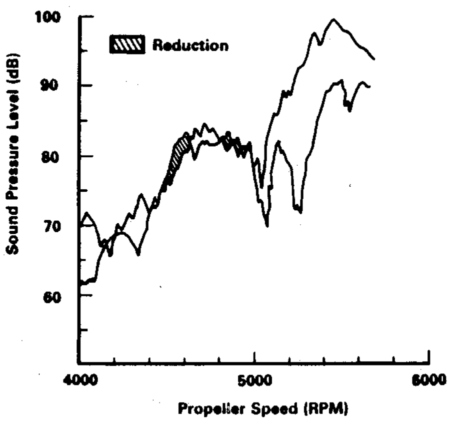


Fig. 8 SBN transmission, solid wing/fuselage attachment vs spherical bearings, bare wing, microphone 7.

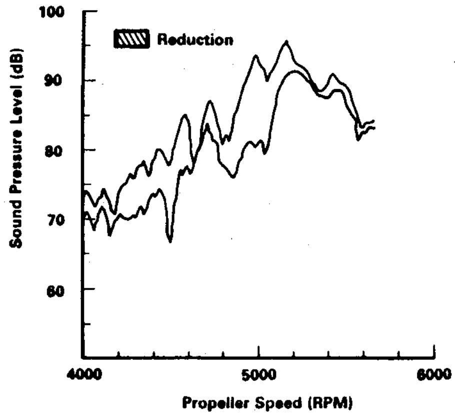


Fig. 9 SBN transmission, solid wing/fuselage attachment vs spherical bearings, engine/nacelle installed, microphone 7.

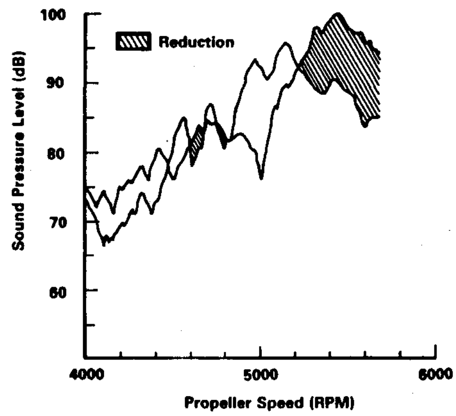
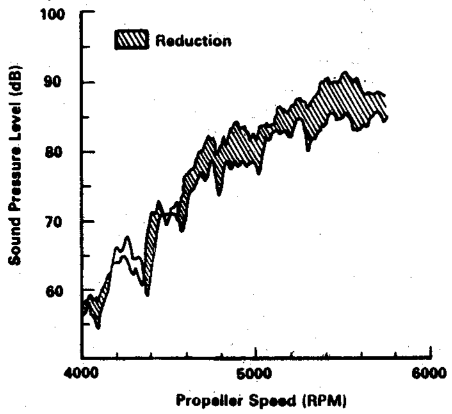


Fig. 10 SBN transmission, engine/nacelle installed vs clean wing, solid wing/fuselage attachment, microphone 7.

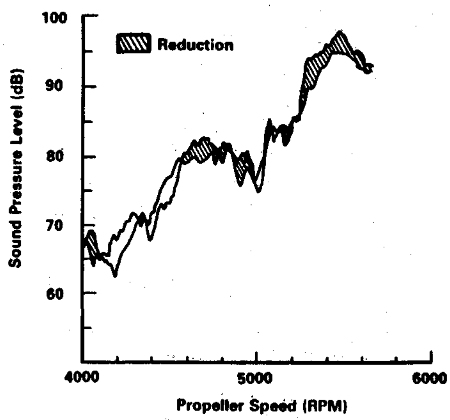
Wing/Fuselage Attachment

Spherical bearings were originally used at each of the three wing-to-fuselage attachment points, as shown in Fig. 7. This allowed simplified analytical modeling as well as a representative configuration for chordwise moment transfer for a majority of general aviation and military-type aircraft. However, larger commercial passenger aircraft are generally constructed with an integral wing spar, which passes through the fuselage. The latter configuration is more closely represented by a solid wing/fuselage attachment. To simulate the solid wing/fuselage attachment, the spherical bearings were replaced with solid bushings, which allowed moment transfer about all axes at the attachments. Propeller sweep data were recorded for the solid wing/fuselage attachment configuration and compared to the bare wing data recorded with spherical bearings at the attachments. A typical data comparison is shown in Fig. 8. For the most part, SBN transmission was unaffected by the wing/fuselage attachment changes for propeller speeds below 5000 rpm. Above 5000 rpm, significant increases in SBN transmission occurred. Similar comparison of the effects of solid wing/fuselage attachment vs spherical bearings for the case when the engine/nacelle mass was installed is shown in Fig. 9. Here, the increase in SBN transmission is more broadly distributed across the 4000–5700 rpm sweep range.

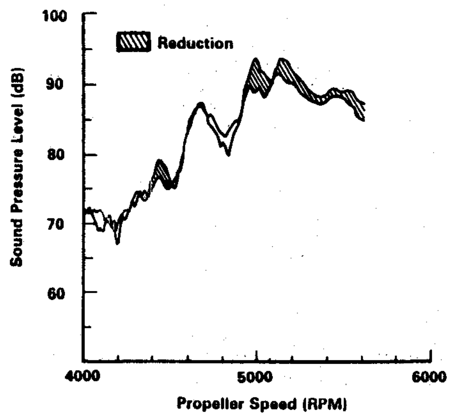
One possible explanation for the increased SBN transmission for a solid wing/fuselage attachment is that the local wing panel disturbances produced by the propeller are partially transmitted into overall wing spar bending waves, which can be propagated into the fuselage via differential lateral shear at the wing/fuselage attachments. This type of transmission will take place for either type of attachment. However, the local disturbances that do not conform to global wing bending are



a) Bare wing, spherical bearings



b) Bare wing, solid wing-to-fuselage attachment



c) Engine/nacelle mass installed, solid wing-to-fuselage attachment

Fig. 11 Installation effects on SBN transmission effectiveness of simulated fuel in wing cell 2, microphone 7.

reflected from the spherical bearing attachments as they see a highly reflective zero impedance termination. The solid attachment provides a nonzero impedance, and thus some transmission is possible.

To complete the data comparisons for the two installation effects evaluated, data comparisons were made for the case when the solid wing/fuselage attachments were installed and the engine/nacelle was installed vs the bare wing. This data comparison is shown in Fig. 10, and, as can be seen, the bands of increased and decreased SBN transmission appear much the same as for the spherical bearing wing/fuselage attachment data given in Fig. 6.

SBN Control Measures

Various wing structural response modifications were examined that showed promise for SBN control measures,[8] namely the blocking mass effect of wing fuel and the use of wing-mounted tuned mechanical dampers inboard of the propeller. The effect of the various installation configurations on the performance of the SBN control measures will now be discussed.

Blocking Mass/Fuel

The addition of 17.3 lb of simulated fuel to the most inboard wing cavity between the front and rear spars, cell 2 in Fig. 2, resulted in the noise reduction given in Fig. 11a. The data of Fig. 11 are typical for all interior microphone response; for consistency, the data set for microphone 7 is used. When rigid wing-to-fuselage attachments were installed, a measurable reduction in SBN control resulted as shown in Fig. 11b. While similar response occurred at microphone 7 for the addition of the engine/nacelle mass (see Fig. 11c), the control measure effectiveness nearly disappeared at many of the other microphone locations.

Tuned Mechanical Damper

The use of a pair of elastomerically damped, tuned resonators attached to the upper and lower wing spar caps at wing station 41, see Fig. 2, proved to be a most efficient SBN control measure.[8] Figure 12 shows a photograph of the highly damped (5% critical) elastomeric damper design evaluated for SBN transmission control. The damper configuration consists of a base elastomeric (natural rubber) "sandwich mount," 1.5-in. diam × 1.0-in. tall, rated as 350 lb/in. in shear at 50 lb load, and 2800 lb/in. in compression at 420-lb load. The sandwich mount weighing 0.11 lb supports a 2.15-lb weight with a mass center approximately 3.5 in. above the base of the mount. The high mass center allows damper response to various base input excitation. Base and support mass mounted accelerometers were used to obtain a measure of the frequency response characteristics of the damper. The external mounting of the damper facilitated mounting and monitoring of the damper's response. The propeller airstream did not impinge on the damper.

The data presented in Fig. 13a show the comparative effects (see Fig. 13 for spherical bearing attachments) of rigid wing-to-fuselage attachments (see Fig. 13b), and the combined effect when adding the engine/nacelle mass (see Fig. 13c). As can be seen in Fig. 13b, the tuned damper effectiveness was decreased in the propeller speed range below 5100 rpm and somewhat increased at the higher propeller speeds for rigid wing-to-fuselage attachments. When the engine/nacelle mass was added, see Fig. 13c, increased effectiveness of the damper was realized except at the highest of propeller speeds. In general, tuned mechanical dampers appear to work very well for

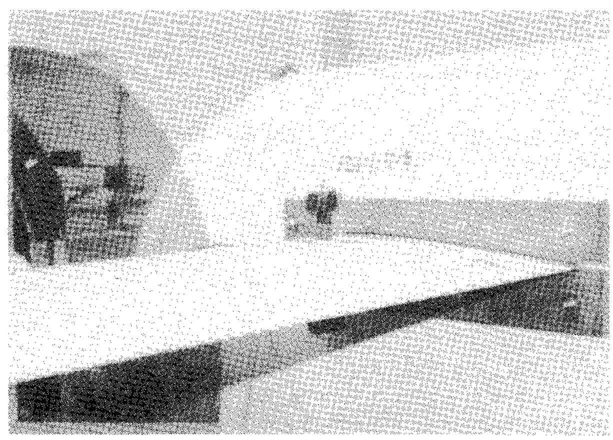
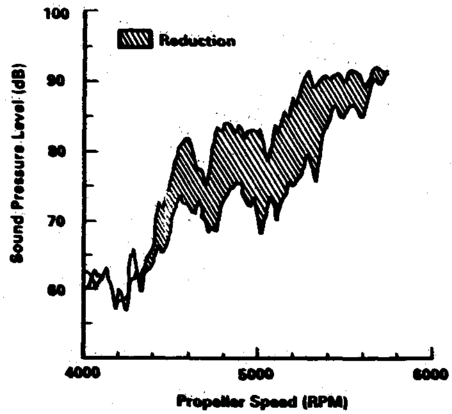
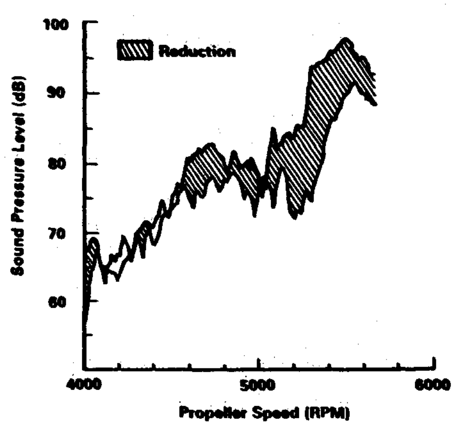


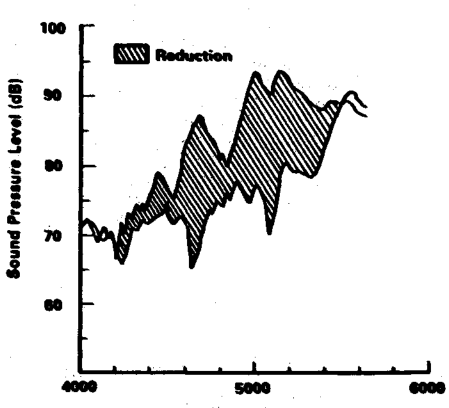
Fig. 12 Tuned mechanical damper installation.



a) Bare wing, spherical bearings



b) Bare wing, solid wing-to-fuselage attachment



c) Engine/nacelle mass installed, solid wing-to-fuselage attachment

Fig. 13 Installation effects on SBN transmission effectiveness of tuned dampers at wing station 41.

most installations, and it is believed that one could obtain increased SBN control with additional tuning for a particular installation and propeller-speed combination.

Conclusions

A laboratory-based test apparatus was used to study installation effects of structure-borne noise transmission due to propeller-induced wake/vortex excitation of an aircraft wing surface and to evaluate their influence on known SBN control measures. The following conclusions are drawn from this study.

1) Because of the spatial extent of the propeller excitation of the wing surface, SBN transmission is a weak function of power plant spanwise placement and is somewhat sensitive to propeller-to-wing, leading-edge separation.

2) The installation of an engine/nacelle mass results in bands of increased and decreased SBN transmission with measurable increases for the higher propeller speeds.

3) The method of attachment of the wing to fuselage can significantly influence the SBN transmission. Restricting local moment transfer at the attachments via the use of spherical bearings reduces the level of SBN transmission at the higher propeller speeds (above 5000 rpm).

4) The use of inboard wing fuel appears to be an effective SBN control measure for spherical bearing wing-to-fuselage attachments. However the SBN control benefits are noticeably reduced when rigid wing-to-fuselage attachments are employed and become negligible when the effects of the engine/nacelle mass are included.

5) The use of inboard, wing-spar-mounted, tuned mechanical absorbers of highly damped design was found to be an effective SBN control measure, which was only modestly influenced by installation effects.

Acknowledgments

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