Structure-Borne Noise Control for Propeller Aircraft

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A laboratory test apparatus was developed that would allow the study and development of propeller wake/vortex-induced structure-borne interior noise control measures. Various methods of wing structural modification, including blocking masses, surface damping treatments, and tuned mechanical absorbers, were evaluated relative to reduced interior noise levels. Inboard wing fuel was found to act as an effective blocking mass. Wing panel add-on damping treatment in the form of a single, constrained layer was not an effective control measure, except in the area of the propeller wake. However, highly damped, tuned mechanical absorbers were found to be the most efficient structure-borne noise control measure.

Introduction

INTERIOR noise control for propeller aircraft has historically focused on the propeller direct airborne components via improved sidewall treatments. More recent efforts in this area have been aimed at the advanced high-speed turboprop aircraft, wherein the direct airborne propeller-generated noise appears to be most critical for the success of this new generation aircraft.[1] The interaction of the propeller wake/vortex with the downstream aircraft wing or empennage structure also provides a potentially equivalent source of structure-borne interior noise transmission.[2] Most recently, procedures for detection for in-flight propeller-induced, structure-borne noise (SBN) have been proposed and evaluated under laboratory conditions.[3] The laboratory evaluation showed the propeller airborne sidewall transmission and propeller wake/vortex-induced, structure-borne interior noise contributions to be equal at the higher propeller speeds. Likewise, engine vibration-induced, SBN transmission has been shown to be equal to or greater than the direct airborne noise transmission in a single-engine, propeller-driven aircraft.[4] The potential for engine-induced SBN in twin-engine aircraft has not been thoroughly evaluated. Nevertheless, adequate procedures for engine vibration isolation system design/evaluation have been developed.[5] The turbine engine of the advanced turboprop aircraft should not provide significant engine vibration as is characteristically experienced by piston-driven powerplants. On the other hand, propeller imbalance may be a driving source of engine vibration.

A research program supported by NASA Langley Research Center was undertaken to develop an understanding of the propeller wake/vortex-induced, SBN transmission phenomena. The program approach was to develop a laboratory test apparatus that would allow the study and development of reliable SBN detection techniques and allow systematic evaluation of potential noise control measures. The design, construction, and evaluation of the laboratory facility is complete and has been reported in Ref. 6. The development of reliable SBN detection techniques has also been reported.[3] In the present paper, results from evaluation of several propeller wake/vortex-induced noise control measures, as applied to the wing structure, will be reported.

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Test Apparatus

The SBN test apparatus is well documented in Ref. 6 and is shown in Fig. 1. The basic apparatus consists of fuselage and wing structures of aircraft-type construction, and a propeller source to induce wake/vortex wing excitation for SBN transmission. The 72-in.-long, 40-in.-diam ring-stiffened (8.0-in. spacing) fuselage cylinder is supported on low-frequency elastomeric mounts within a 7-in. thick concrete cylinder that provides acoustic shielding from propeller airborne noise. The fuselage cabin is acoustically treated and has an integral floor. The cabin is fitted with three microphones that may be variably positioned along the fuselage length. The interior microphones were positioned at would-be passenger head heights on the right side, center, and left side of the cabin.

The SBN path is provided by a wing structure consisting of a 31.0-in. constant chord NACA 0012 section airfoil, with an exposed span of 80 in. The structure is of conventional sheet metal and rivet construction, with ribs on 16.0-in. centers. The wing front and rear spars, at 29 and 75% chord, extend an additional length of 13.5 in. beyond the skin surface to accommodate penetration through the fuselage acoustic shield. Spherical bearings are used in the wing-to-fuselage attachment structure at each of the three attachment points to eliminate local moment transfer; only shear transfer is allowed. Overall wing moments are reacted by lateral differential shear in the front spar only. This physical arrangement confines the SBN transmission path to well-defined motions at the wing/fuselage attach point. Both the front and rear spar fuselage-to-wing attachments are directly secured to the fuselage floor beams and ring frames.

The propeller source is a 28-in.-diam, two-bladed propeller with a nearly constant 3⅛-in. chord modified Clark-Y section. The propeller is powered by an 18-hp hydraulic motor with a maximum speed of 6000 rpm. A vane axial fan, powered by a 20-hp electric motor, provides a 33-in.-diam, 70-ft/s inlet flow to the propeller to simulate forward flight. Thrust and torque curves for the propeller are given in Ref.6.

Test Results

The SBN test apparatus was fitted with a servocontrol valve on the propeller source to allow slow run-up of the propeller source. In this manner, a continuous spectrum of excitation/response may be developed via the use of narrow-band (2 Hz) tracking filters centered on individual propeller tones. To maintain a high level of signal-to-noise, efforts were concentrated on the transmission of the fundamental propeller tone in the propeller speed range from 4000 to 5700 rpm (the 133 to

190 Hz response range). A sweep rate of 30 rpm/s was found to be adequate to insure resolution of the peak response.

Repeated sweeps within a 2–3 h period, both with increasing and decreasing propeller speed, resulted in repeatability within ±1.0 dB. Nevertheles, baseline data (clean wing) were recorded as often as possible during the various test runs to eliminate long-term variations. Typical long-term variation of the baseline microphone responses, taken over a four-week period, is shown in the data of Fig. 2. The effectiveness of the various control measures was evaluated relative to the most recent baseline data available, which was acquired just after removal of the control measures.

In the discussion of the results to follow, data from 2 of 12 interior microphones are given to show relative data trends. These two microphones are felt to be representative of the responses at all other microphones, the only exception being the centerline microphones that often exhibited low interior levels due to being near nodal lines of responding acoustic resonances.

Blocking Mass

A schematic of the test setup is shown in Fig. 3. The two most inboard wing cavities were fitted with a liquid retaining bladder. Cell 1 is in the wing leading-edge area forward of the front spar and, when filled with water, contained 7.4 lb of simulated fuel. Cell 2 occupied the volume between the front and rear spars and, when filled with water, contained 17.3 lb of simulated fuel. The most aft cell in the area behind the rear spar would hold, at most, 0.3 lb of simulated fuel and, therefore, was not used. Baseline, no fuel, runs were made and sound pressure level responses were recorded at several interior microphone locations. When simulated fuel was added to cell 1, negligible reduction in interior noise levels resulted. However, when simulated fuel was then added to cell 2, a measurable noise reduction was achieved above 4800 rpm (160 Hz for the first propeller tone), as is shown in Fig. 4a. Upon removal of the simulated fuel in cell 1, leaving cell 2 full, the noise reduction persisted (see Fig. 4b).

From this data, it appears that fuel in the wing area between the front and rear spars inboard of the propeller is an effective SBN control measure. In an attempt to discover the mechanism responsible for the reduced levels of vibration transmission into the fuselage, solid masses with a total weight and center-of-gravity simulating the liquid in cell 2 were attached to the wing front and rear spars in the panel 2 area, and the noise transmission data acquisition was then repeated. A photograph of the attached solid masses is shown in Fig. 5. The masses were attached to both the upper and lower wing spar flanges. As can be seen by the data given in Figs. 6a and 6b, the blocking masses were quite effective in reducing SBN levels.

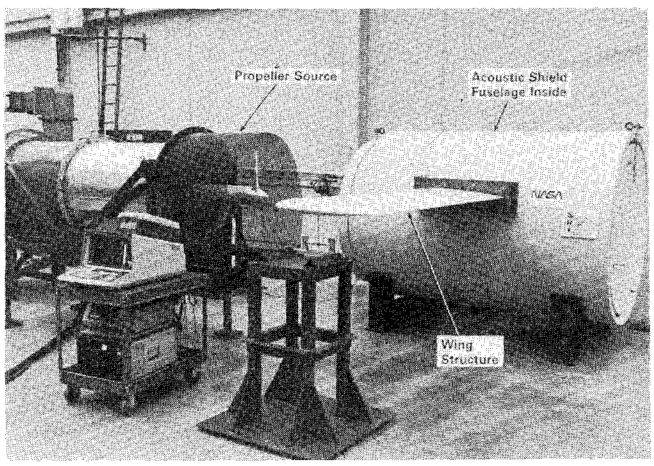


Fig. 1 Propeller-induced structure-borne noise test apparatus.

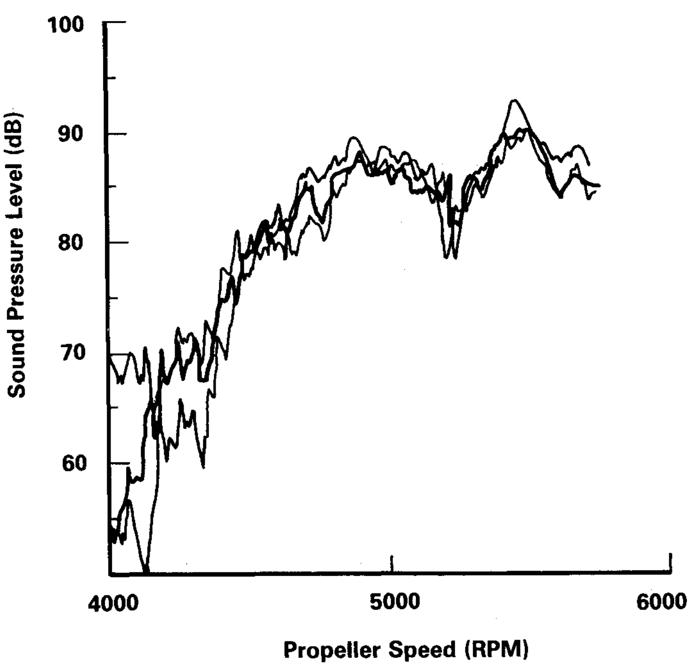


Fig. 2 Typical baseline repeatability, four-week period.

Damping Treatment

The effect of applying damping material to the surface of panel 2 was also carried out. A commercially available self-adhesive, low-weight, 0.16 lb/ft^2 constrained layer damping material of thickness 0.016 in. was used in the study. The 0.040-in.-thick aluminum wing skin exhibited an increase in structural loss factor from 0.018 to 0.080 upon application of a single layer of the damping material. The damping measurements using a single degree-of-freedom circle fit technique were made in the frequency range from 155 to 169 Hz at a nominal test temperature of 70°F. The fundamental panel frequency increased upon application of the damping material, reflecting a single constrained layer configuration.[7] Typical reduction in SBN transmission is shown by the data in Fig. 7. As can be seen, the effect of the added damping treatment was negligible as compared with the blocking mass or simulated wing fuel. It must then be concluded that the mechanism responsible for the SBN control effectiveness of the simulated wing fuel must be its blocking mass effect. As with most liquids, only a portion of the liquid in cell 2 acted as an effective mass, thus accounting for the reduced SBN effectiveness as compared to the solid equivalent masses.

Damping material was also systematically applied to various panels and panel combinations along the entire wing span in both upper and lower surfaces, as is shown in Fig. 8. The use of surface damping treatment was, for the most part, ineffective, except on the center panel areas of wing panels 3 and 4,

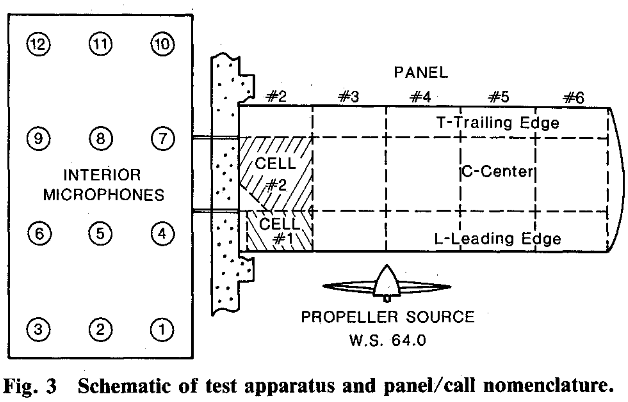
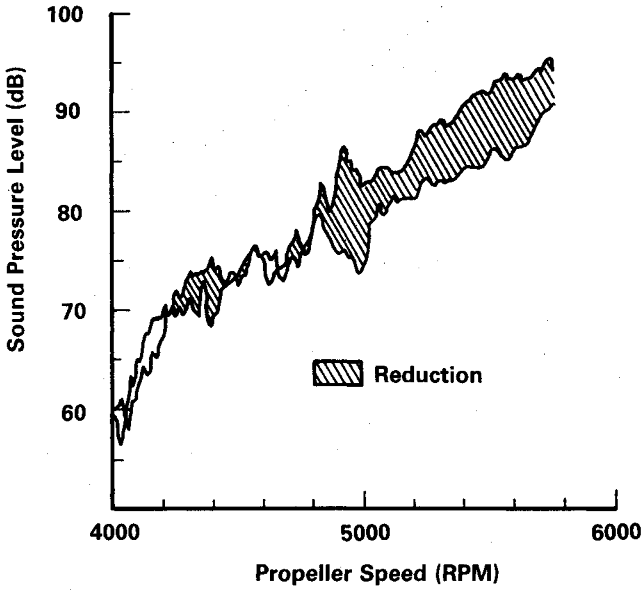
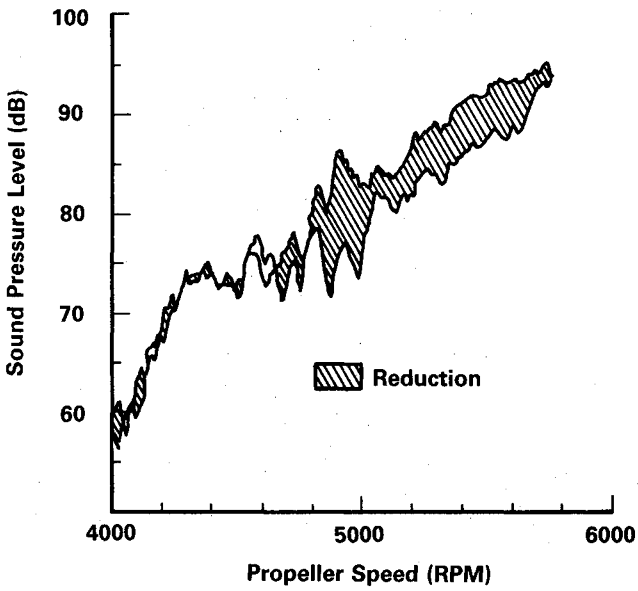


Fig. 3 Schematic of test apparatus and panel/call nomenclature.



a) liquid in cells 1 and 2



b) liquid in cell 2 only

Fig. 4 Effect of simulated wing fuel, microphone 9: a) liquid in cells 1 and 2; b) liquid in cell 2 only.

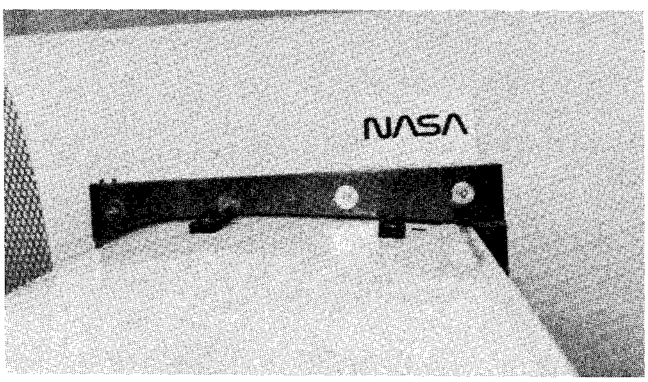
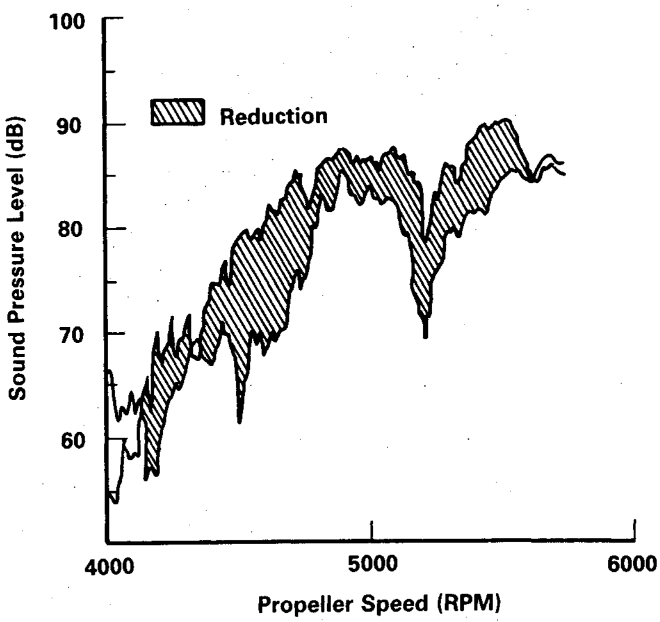
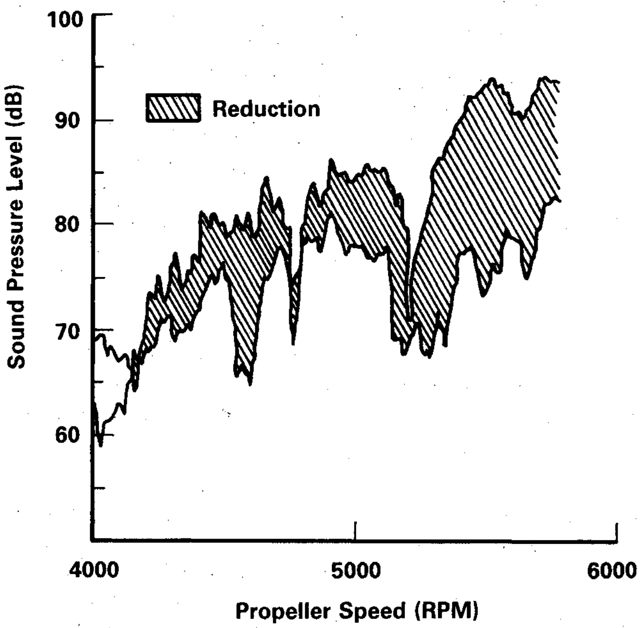


Fig. 5 Wing blocking masses.



a) microphone 7



b) microphone 9

Fig. 6 Effect of solid masses on structure-borne noise transmission: a) microphone 7; b) microphone 9.

which were the panels directly in the wake of the propeller. The most effective use of panel damping occurred when it was used in conjunction with the blocking masses, as is seen in Fig. 9. Here, we can see the damping treatment improve the SBN transmission losses of the system below 5100 rpm and somewhat degrade the reduction at the higher speeds. Note that the center panel first mode frequency occurred around 169 Hz (5070 rpm for first propeller tone). One might view the propeller-induced wing vibrations as traveling waves being reflected by the blocking masses on the wing spar, then dissipated by the damping material as they are regenerated and re-reflected.

Wing Leding-Edge Treatment

Treatment of the wing leading edge in an attempt to reduce the impact forces of the propeller wake was evaluated. Several types of damping material and/or foam products were used to

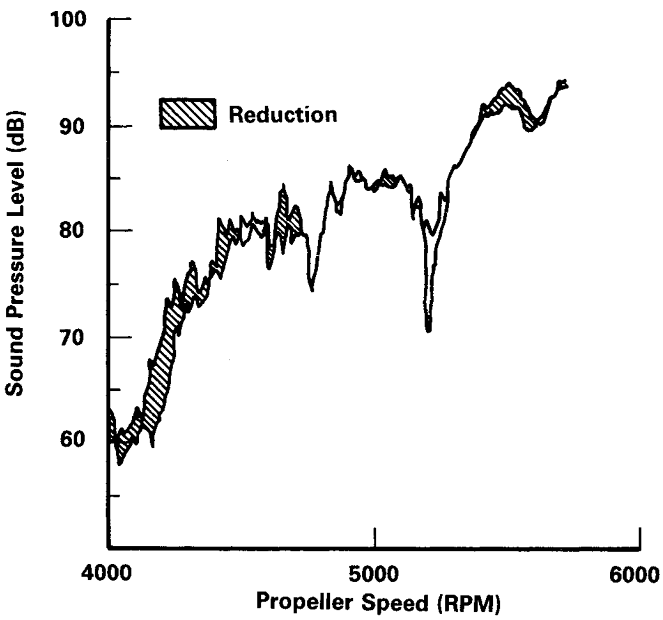


Fig. 7 Effect of damping material application, panel 2, center, microphone 9.

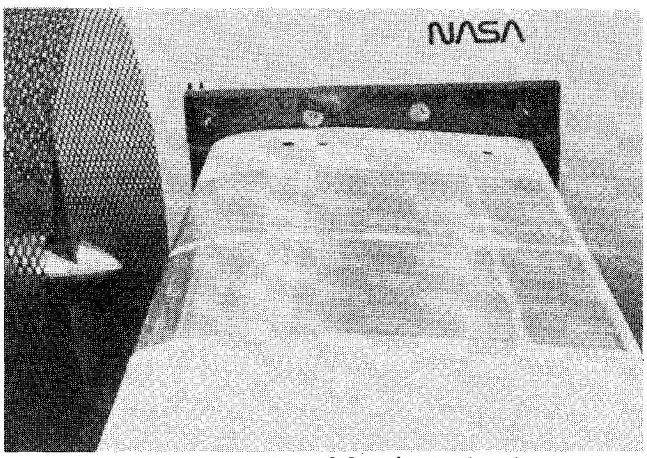


Fig. 8 Typical panel damping treatment.

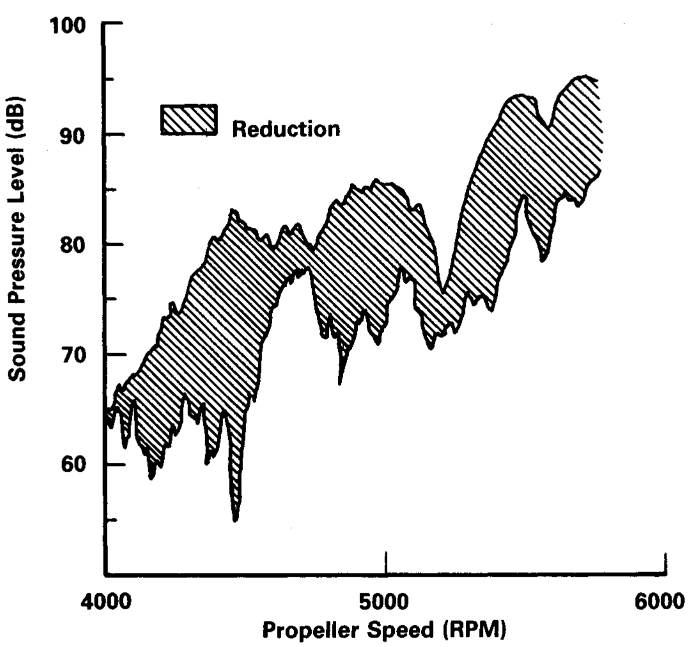


Fig. 9 Effect of blocking mass and panel damping treatment, microphone 9.

shield the wing leading edge, up to 5 in. aft, along the span of the propeller. No significant reduction in SBN transmission occurred. To verify that the primary loading is more uniformly distributed, a piece of 6-in. diam PVC pipe was cut lengthwise and used as a noncontacting wing leading-edge shield. The leading-edge shield showed little or no effect on SBN transmission. Thus, it may be concluded that the propeller source is not confined to the leading edge but to a more uniformly distributed source.

Tuned Mechanical Damper

In the frequency range from 133 to 190 Hz, which contains the dominant first propeller harmonic, the design and implemenation of low-damped, high-Q, tuned dampers were found to be quite difficult. Such dampers, which rely solely on structural damping of the tuned beam material, exhibit extremely narrow half-power bandwidths (around 1 Hz or less). Coupled with a relatively compliant wing mounting base (the main spar), the performance of such a bench-proven damper design fell considerably short of expectation when excited by the propeller source.

However, the use of an elastomerically damped tuned resonator appears to be a viable SBN transmission control measure. The highly damped design with increased system half-power bandwidth (out to say 16 Hz) provides adequate tuning design margin and propeller speed variation compensation. Such a system exhibited 10 to 15 dB interior noise reduction.

Figure 10 shows a photograph of the highly damped (5% critical) elastomeric damper design evaluated for SBN transmission contol. 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 approxiamtely 3.5 in. above the base of the mount. The

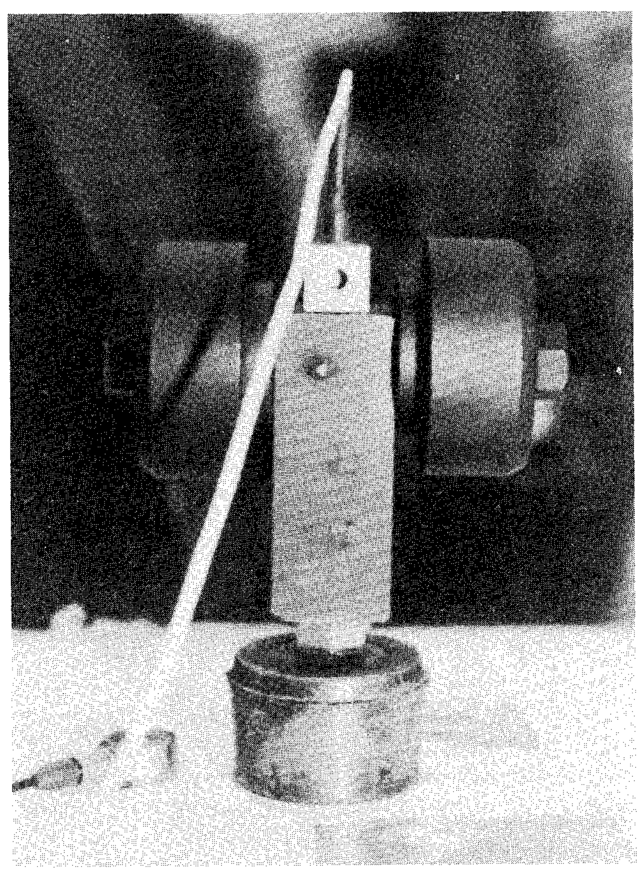


Fig. 10 Mechanical damper.

high mass center allows damper response to various base input excitation. Base and support mass mounted accelerometers were used to obain a measure of the frequency response characteristics of the damper. As shown in Fig. 11, identical dampers were mounted on the upper and lower flanges of the wing front spar (at wing station 41.0). The external mounting of the damper facilitated mounting and monitoring of the damper's response. The propeller airstream did not impinge on the damper.

An electrodynamic shaker attached to the wing front spar at wing station 48.0 was used to obtain damper design installation effects and primarily provide for quick-look screening of candidate damper designs. The mechanical damper in Fig. 10 shows a mass-to-base vertical resonant response of around 160 Hz, using the shaker as a source of excitation. The damper vertical excitation resonant response decreased to 150 Hz under propeller excitation. Typical SBN transmission reduction obtained with the mechanical damper is shown in Fig. 12. A resonant response in the frequency range of 150 to 160 Hz would not normally be expected for an oscillatory spring rate of 2800 lb/in. and mass of 2.15 lb. However, recall that elastomeric materials are preload sensitive and, under dynamic loading, increase in stiffness by a factor of as much as 2 or 3.[8] This being the case, a shift from an expected 110 Hz, based on static properties, to 155 Hz, under dynamic excitation, appears reasonable.

To verify that energy extraction was the principal mechanism of the tuned damper, a dummy sandwich mount was constructed from a cylindrical section of aluminum, duplicating the outside diameter, height, and weight of the elastomeric mount. The rigid damper was also tested, and the results are given in Fig. 13. As can be seen, the damper provided only a small amount of blocking mass and, thus, dissipation is the primary mechanism for reduced SBN transmission from the elastomeric damper.

It is of interest to note that for a base wing weight of 29.55 lb, an added total damper weight of 4.52 lb produced 10 to 15 dB of interior noise reduction in a broad range of propeller speeds, while 17.3 lb of liquid fuel mass in the same wing area produced approximately 6 dB noise reduction over a much more limited propeller speed range.

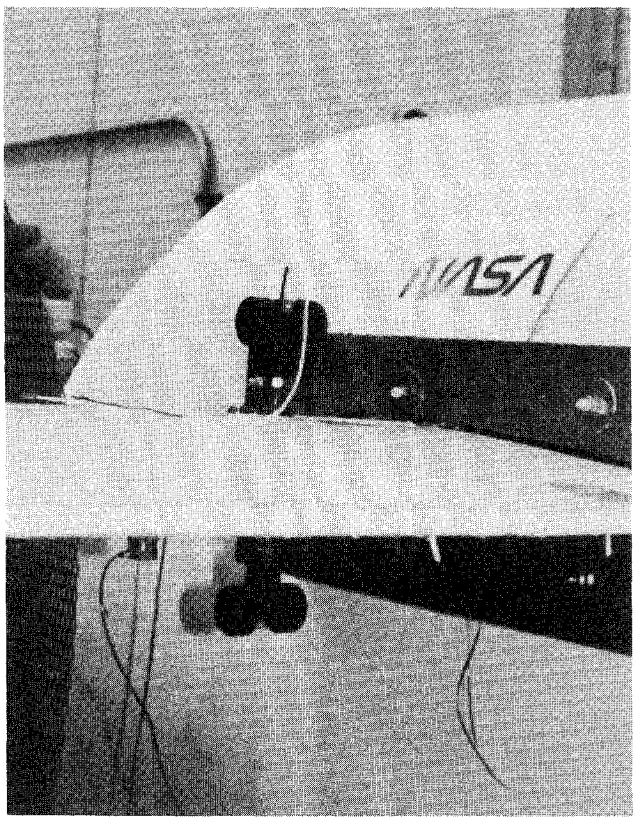


Fig. 11 Tune damper installation.

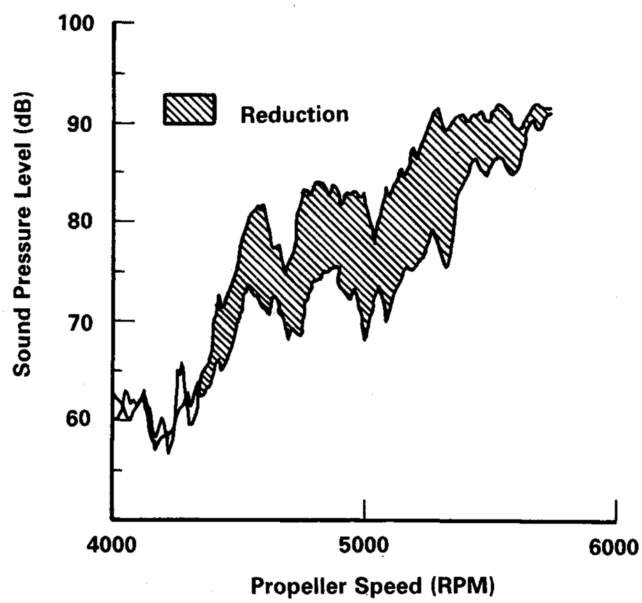


Fig. 12 Effect of elastomeric damper, microphone 7.

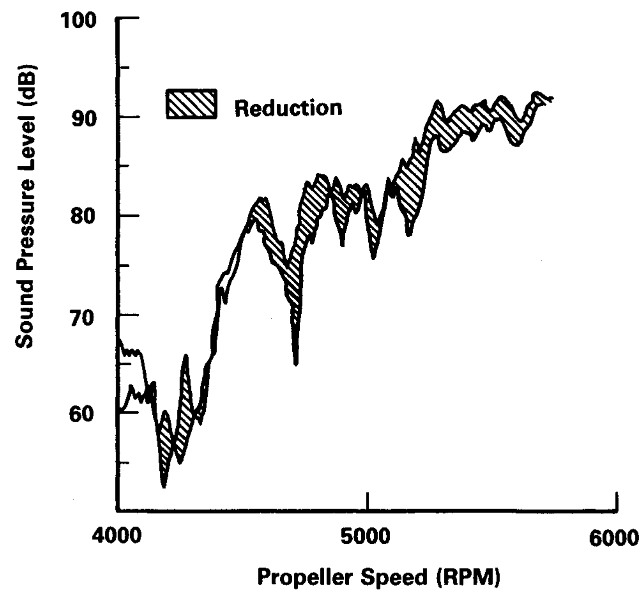


Fig. 13 Effect of rigid damper, microphone 7.

Conclusions

A laboatory test apparatus was developed that would allow the study and development of propeller wake/vortex-induced SBN control measures. Various methods of wing structural modification were evaluate as SBN control measures. Results of the study support the following conclusions:

1) The use of inboard wing fuel appears to be an effective SBN control measure. The fuel acts principally as a blocking mass, reflecting energy back into the wing structure. The effective solid blocking mass is less than the total fuel mass.

2) The use of damping material on the wing panels in the area of the propeller wake is a somewhat effective SBN control measure. However, the use of damping material in the propeller wake area, plus inboard fuel, is a more effective SBN control measure.

3) The use of wing panel damping treatment outside of the propeller wake is not an effective SBN control measure.

4) The use of tuned mechanical dampers, with high levels of damping, can be a very effective SBN control measure.

Acknowledgments

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