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An Estimate of the Noise Shielding on the Fuselage Resulting From Installing a Short Duct Around an Advanced Propeller

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AN ESTIMATE OF THE NOISE SHIELDING ON THE FUSELAGE RESULTING FROM INSTALLING A SHORT DUCT AROUND AN ADVANCED PROPELLER

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SUMMARY

A simple barrier shielding model was used to estimate the amount of noise shielding on the fuselage that could result from installing a short duct around a wing-mounted advanced propeller. With the propeller located one-third of the duct length from the inlet, estimates for the maximum blade passing tone attenuation varied from 7 dB for a duct 0.25 propeller diameter long to 16.75 dB for a duct 1 diameter long. Attenuations for the higher harmonics would be even larger because of their shorter wavelengths relative to the duct length. These estimates show that the fuselage noise reduction potential of a ducted compared with an unducted propeller is significant. Even more reduction might occur if acoustic attenuation material is installed in the duct.

INTRODUCTION

Advanced turboprop aircraft such as those depicted in figure 1 have the potential for significant fuel saving over equivalent-technology turbofan powered aircraft. To investigate this potential, the National Aeronautics and Space Administration has an ongoing advanced turboprop program (ref. 1). The noise from these advanced, high-speed propellers is of concern since it may present a cabin environment problem for the airplane at cruise. A new type of ducted propeller (such as shown in fig. 2) is presently being considered for a wing-mounted system (ref. 2). Short ducting on a propeller presents significant potential for reducing the tone noise impacting an airplane fuselage at cruise. This paper presents a simple estimate of the amount of fuselage shielding that might be accomplished by encasing a propeller in a short duct.

MODEL FOR DUCT SHIELDING OF PROPELLER TONE NOISE

Shielding Model

A half-span sketch of the head-on view of a turboprop airplane is shown in figure 3(a). The propeller generates tone noise at the blade-passing frequency and its harmonics. This noise is generated on the advancing side of the propeller blade (ref. 3) as it approaches the fuselage. The installation of a duct around the propeller (fig. 3(b)) blocks some of the noise from the fuselage. The noise generated by the propeller now has to travel around the ends of the duct (as in fig. 4) before reaching the fuselage. This shields some portion of the airplane fuselage from the propeller noise.

A simple barrier shielding model is used here to estimate the amount of shielding resulting from the installation of a short duct. To apply this model, it is assumed that the duct is sufficiently short that acoustic modes in the duct can be neglected. A simple ray acoustic model for diffraction around a barrier is used (ref. 4). The model is an analytical approximation of experimental data and can be derived from optical diffraction theory. Point source and receiver locations are shown in figure 5 (redrawn from ref. 4). The attenuation of the sound at the receiver depends on its frequency and the location of the barrier. The attenuation is as follows

$$\text{Attenuation} = 20 \log \left[\frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}}\right] + 5 \text{ dB} + 20 \log \left[\frac{A + B}{d}\right] \qquad (1)$$

$$\text{for } N \geq -0.2$$

$$\text{Attenuation} = 0 \qquad \text{for } N < -0.2$$

where the Fresnel number is given as

$$N = \pm\frac{2}{\lambda}(A + B - d) \qquad (2)$$

and where λ is the sound wave length, d is the straight-line distance (direct path) between source and receiver, and A + B is the shortest diffracted path length of wave travel between source and receiver (fig. 5). For the receiver in shadow and bright zones, the signs of positive and negative are used, respectively.

The first term in the expression

$$20 \log \left[\frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}}\right] + 5 \text{ dB}$$

represents the amount of barrier shielding (insertion loss) since the sound now travels the diffracted path A + B instead of the direct path d. The second term, 20 log (A + B)/d, accounts for the greater spherical divergence of the diffracted wave because of the longer path length.

This model of the shielding is used because of its relative simplicity and because of reasonable success in the past (ref. 3). It is believed to be somewhat conservative in the sense that it may predict less attenuation than would actually be measured. The model is for a uniform source that radiates equally in all directions, an advanced propeller is typically a more directive source. Figure 6 shows the fuselage directivity of the blade passing tone for a single rotation advanced propeller (ref. 5). This directivity is for a 2.74-m (9-ft) diameter SR-7 propeller located 0.8 diameter (D) from the propeller tip to the fuselage and is projected from a model propeller tested in a wind tunnel. As can be seen from this curve faired through the data projections, the propeller noise peaks slightly behind the plane of rotation and decays quickly towards the front and rear. On the same plot is shown the decay that a uniform source would have if it were in the propeller plane of rotation at 0.8D from the fuselage. The actual propeller directivity falls off more toward the front and rear than does the uniform source.

The shielding at a particular receiver location is the difference between the direct path noise and the diffracted path noise. This shielding is based on both the direct and diffracted waves starting at the same noise level. Since the strength of the propeller sound waves that actually diffract around the edges of the duct (fig. 4) would start at a lower level than those for the direct wave, the attenuations being observed should be more than predicted and, in this sense, the model is conservative.

It should be noted here as it was in reference 3, that the effect of the high free-stream Mach number on the diffracted wave has not been included in this shielding model. The observed effect in reference 3 was that the shielding occurred somewhat downstream of the predicted position but that the amount of shielding predicted was reasonable.

Model Geometry

To apply the barrier attenuation model to the ducted propeller situation, the barrier geometry must first be specified. The head-on geometry is shown in figure 7. For calculation purposes a source location position is chosen on the blade. This noise location is shown at a radius of $\alpha(D/2)$. At the assumed point of maximum radiation toward the fuselage, the distance to the duct (barrier) in the propeller plane is

$$\alpha_1 D = \sqrt{\left(\frac{1}{2}\right)^2 - \left(\frac{\alpha}{2}\right)^2}\ D \tag{3}$$

The distance from the duct (barrier) to the fuselage can also be calculated from figure 7. The distance from the propeller tip to the fuselage is set at βD so the total distance from the noise source to the fuselage is

$$\sqrt{\left(\beta + \frac{1}{2}\right)^2 - \left(\frac{\alpha}{2}\right)^2}\ D \tag{4}$$

and the distance $\alpha_2 D$ is then

$$\alpha_2 D = \sqrt{\left(\beta + \frac{1}{2}\right)^2 - \left(\frac{\alpha}{2}\right)^2}\ D - \sqrt{\left(\frac{1}{2}\right)^2 - \left(\frac{\alpha}{2}\right)^2}\ D \tag{5}$$

The distances $\alpha_1 D$ and $\alpha_2 D$ can then be seen in figure 8 as the straight-line distances from the source to the duct (barrier) and from the duct (barrier) to the fuselage. The duct itself is some number of diameters long $\gamma_\ell D$, the source is $\gamma_s D$ from the leading edge of the duct, and the receiver is $\gamma_r D$ forward of the propeller plane (fig. 9). The path lengths around the leading and trailing edges of the barrier can then be calculated as well as the distance d to the receiver. For example, for the front path around the leading edge of the duct (fig. 9)

$$A = \sqrt{(\gamma_s D)^2 + (\alpha_1 D)^2} \tag{6}$$

$$B = \sqrt{(\alpha_2 D)^2 + [(\gamma_s - \gamma_r)D]^2} \tag{7}$$

$$d = \sqrt{[(\alpha_1 + \alpha_2)\ D]^2 + (\gamma_r D)^2} \tag{8}$$

Then, if the wave length λ in the expression for the Fresnel number (eq. (2)), is specified, the attenuation for this path can be calculated.

The attenuation for the path around the trailing edge of the duct (fig. 4) is similarly calculated. The source noise is assumed to divide equally upstream and downstream in the duct, that is, half the power propagates in each direction. The noise from the two paths (around the duct leading and trailing edges) can then be added together at the receiver to obtain the noise at that location. The amount of shielding from the installation of the duct can then be calculated.

Source Behavior

This shielding model predicts the amount of attenuation provided by the duct. Implicit in its use to get a new fuselage noise level after the duct installation is the assumption that the propeller noise does not change when the duct is installed. This assumption is believed to be conservative for the following reasons.

The installation of the duct is felt to have two major effects on the propeller noise. First, the diffusion of the flow in the duct inlet will somewhat lower the axial velocity at the propeller face, and the propeller will operate at a higher loading. Velocity has a stronger effect on noise than does loading (ref. 5), so the lower velocities would result in less propeller tone noise. The actual noise reduction with the duct would then be more than the model would predict, and, again, the method is conservative.

The other effect of the duct installation is the interaction noise generated because of the presence of the duct struts. Experiments with a counterrotation propeller (ref. 6) have shown that the interaction noise is at least 10 dB below the propeller-alone noise at cruise in and around the plane of rotation of the propeller. Since the duct struts, being stationary, will be exposed to lower relative velocities than the second-stage propeller blades, the interaction noise due to the struts should not affect the noise on the fuselage.

RESULTS AND DISCUSSIONS

The previously described model for the duct shielding of the fuselage noise can now be used to estimate the noise advantage of the ducted propeller. Specific geometry is needed to make this estimate along with some choices of source and receiver locations.

Specific Geometry

A detailed analysis of the shielding would involve taking each hub to tip section of the blade, evaluating its contribution to the generated noise, and calculating the shielding for a source at that location. Then the noise contribution from each of the shielded sources would be added together at the fuselage to obtain the shielded levels. For the purposes of this estimate, the noise sources on the blade are assumed to be adequately represented by a single source at some mean radial location. Mean radial locations for evaluation purposes are located at about 75 percent of the blade span for subsonic tip speed propellers (see ref. 7). Since the noise varies strongly with the velocity, the location for a supersonic tip speed propeller is even farther out. For the following estimates, the source location is chosen conservatively at 0.8D/2, which is approximately 75 percent of the propeller span for a 0.25 hub to tip diameter ratio.

A typical installation on an airplane has the propeller tip clearance to the fuselage of about 0.8D. This, then, results in the specific head-on geometry shown in figure 10(a). Calculations then show α_1 to be 0.3 and α_2 to be approximately 0.94.

The duct side view is shown in figure 10(b). The duct is assumed to be positioned such that the propeller is located one third of a duct length from the leading edge.

Estimates are made for four duct lengths, 0.25D, 0.50D, 0.75D and 1.0D, so that the effect of the duct length on the shielding could be determined. Referring to figure 6, the major tone noise is located near the plane of rotation and has decayed by approximately 20 dB at 1D forward and 12 db at 1D aft. Therefore, the shielding is calculated for receiver locations at 0.2D intervals from 1D to -1D along the fuselage.

The wave length of the blade passing tone for the eight bladed propellers tested is typically about D/2, which results in a Fresnel number of

$$N = \frac{4}{D}(A + B - d)$$

Higher harmonics would have higher Fresnel numbers and, in turn, higher predicted shielding. Estimates are made here primarily for the blade passage tone.

A precise calculation of the shielding requires amplitude and phase predictions at the receiver for each radial and circumferential source location. Interference fringes would occur because of varying source locations and path length differences around the leading and trailing edges of the duct. For these estimates the noise sources have been lumped together at one mean radial and circumferential location, and the waves around the leading and trailing edges of the duct are treated as if the phases were random.

Shielding Estimates

Shielding estimates for the propeller blade passing tone were done for duct lengths of 0.25D, 0.5D, 0.75D, and 1.0D. Figure 11 shows the amounts of shielding obtained between the ±1D locations when the propeller was located one third of the duct length from the inlet. As can be seen, the maximum shielding varied from 7 dB, for a duct 0.25D long duct to 16.75 dB for a 1D long duct. These estimated shielding attenuations, particularly for a 1D long duct, could result in a significant improvement in noise levels on the airplane.

The effect of source location in the 1D long duct is shown in figure 12. Maximum shielding (17.25 dB) is obtained when the propeller is located midway in the duct (0.5D). This maximum occurs in the plane of rotation of the propeller. As the source is moved closer to the duct inlet, 0.33D and then 0.2D, the maximum attenuation decreases slightly and occurs farther aft. At the 0.33D source location, the direction of maximum shielding is approximately the same as the maximum of the propeller noise directivity (fig. 6). At the 0.20D source location the maximum shielding is located behind the location of maximum propeller noise, and the effect of the shielding is therefore diminished.

When the attenuations for the 0.33D location were applied to the propeller noise directivity of figure 6, the directivities in figure 13 resulted. As can be seen, not only are the amounts of attenuation significant, but also the attenuations are located at positions such that the peaks in the directivities are significantly reduced.

Figure 14 shows the resultant directivities when the shielding for the three source locations in a 1D long duct are applied to the propeller data of figure 6. The curves for the propeller at 0.33D and 0.50D show approximately the same maximum level. The curve at 0.2D is less effective. Lower maximum shielding and the shift of the maximum to aft of the peak propeller noise location diminishes the effect of shielding for this case. This indicates that propellers located close to the duct inlet would have less effective shielding than those located farther inside the duct.

The previous attenuations were calculated for the blade passing tone of the propeller. Because the harmonics have shorter wave lengths, larger reductions would be estimated. Figure 15 shows attenuations for the first 10 harmonics at the sideline location of the maximum blade passing tone reduction (0.4D aft) for the 1D long duct with the propeller at 0.33D. As can be seen the higher harmonics show even more predicted attenuations. As expected from equation (2), the shielding increases 3 dB at every doubling of the harmonics frequency. Although the shieldings shown in figure 13 are higher, the practical barrier attenuation is empirically observed to be around 24 dB (ref. 4), and it is probable that harmonics higher than those shown in figure 15 would have this limiting amount of attenuation.

CONCLUDING REMARKS

A barrier shielding model was used to estimate the amount of noise shielding at various fuselage locations that would result from installing a short duct around an advanced propeller. Estimates were obtained of the blade passing tone attenuation for four duct lengths varying from 0.25 to 1 propeller diameter. When the propeller was located one-third of the duct length from the inlet (0.33D), the maximum noise attenuation varied from 7 dB for the 0.25D long duct to 16.75 dB for the 1D long duct. This shielding was applied to the blade passing tone directivity of an existing advanced propeller. Not only were the attenuations significant but they occurred at locations such that the peak noise was greatly reduced.

Shielding was also estimated for the propeller located at 2/10 and 1/2 of the duct length for a 1D length duct. The most attenuation occurs when the shielding effect maximizes in the same direction as the propeller noise maximizes. As the propeller is located closer to the duct inlet the effective shielding is reduced.

Attenuations for the higher harmonics are greater than for the blade passing tone because their wavelengths are smaller. Maximum attenuations for the 1D length duct were 19.75 dB for the second harmonic and 16.75 dB for the blade passing tone.

Although these attenuations were obtained using a simple barrier model, the results show a significant fuselage noise reduction potential for the ducted propeller. The presence of the duct also allows for other noise reduction techniques, such as the application of acoustic absorbing material to the duct walls. The net result being that a ducted propeller could exhibit large noise reductions on an airplane fuselage compared with the unducted configuration.

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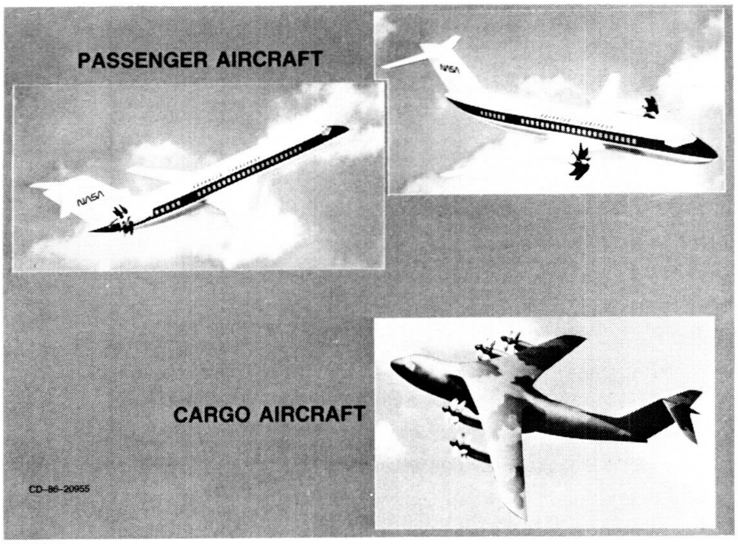


FIGURE 1. - ADVANCED TURBOPROP APPLICATIONS.

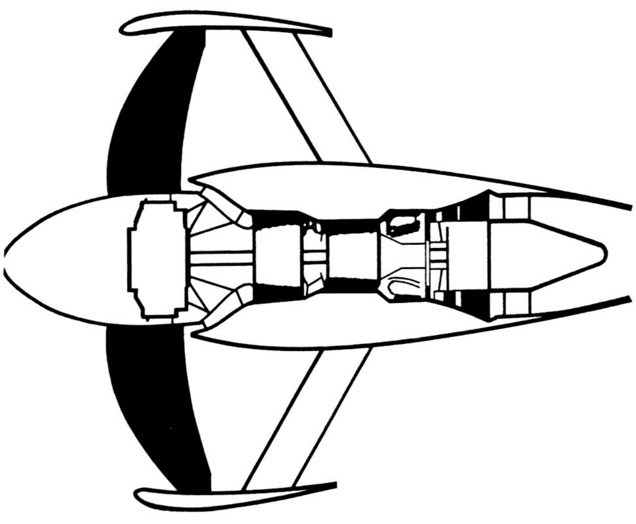
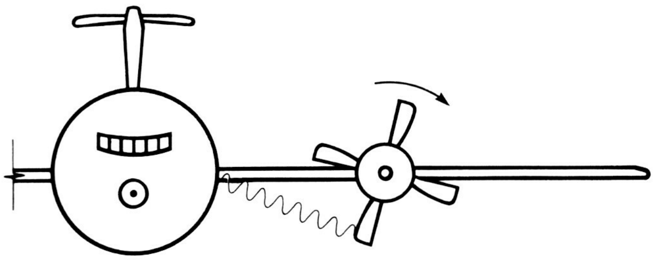
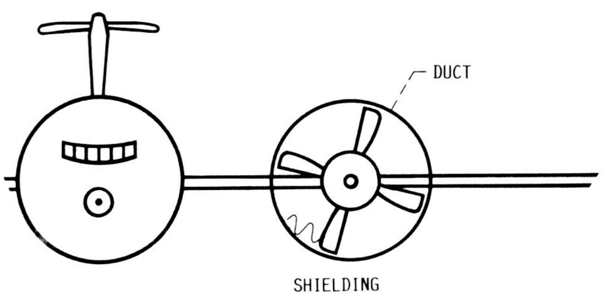


FIGURE 2. - DUCTED PROPELLER ENGINE.



(A) NOISE IMPACTS FUSELAGE WITHOUT DUCT IN PLACE.



(B) DUCT SHIELDS FUSELAGE FROM NOISE.

FIGURE 3. - DUCT SHIELDING - HEAD ON.

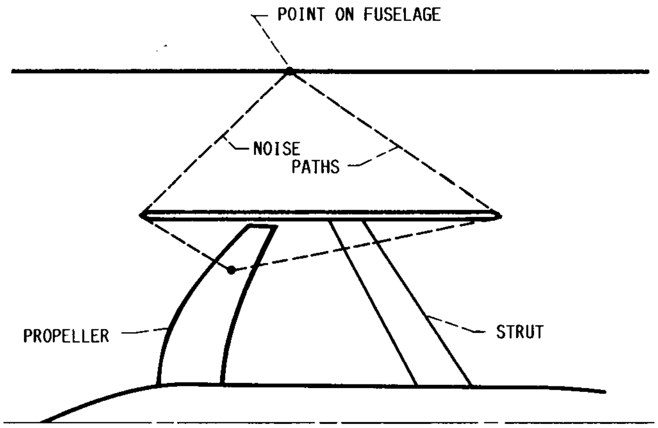


FIGURE 4. - DUCT SHIELDING - FORE AND AFT.

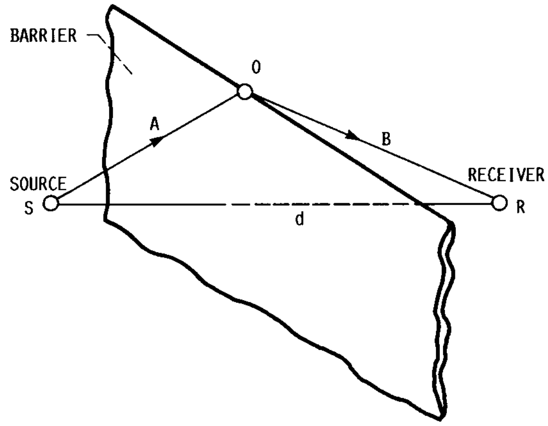


FIGURE 5. - BARRIER GEOMETRY.

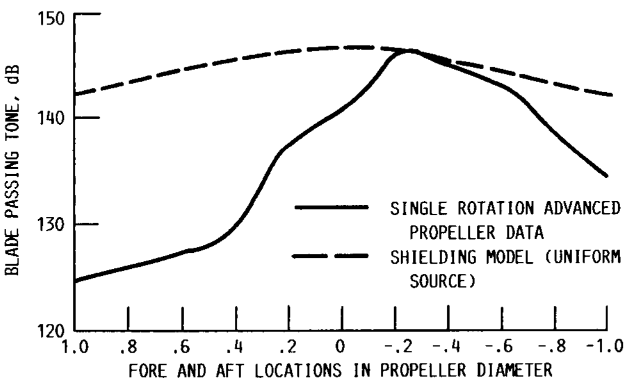


FIGURE 6. - PROPELLER DIRECTIVITY COMPARED WITH UNIFORM SOURCE DIRECTIVITY ON FUSELAGE 0.80 FROM PROPELLER TIP.

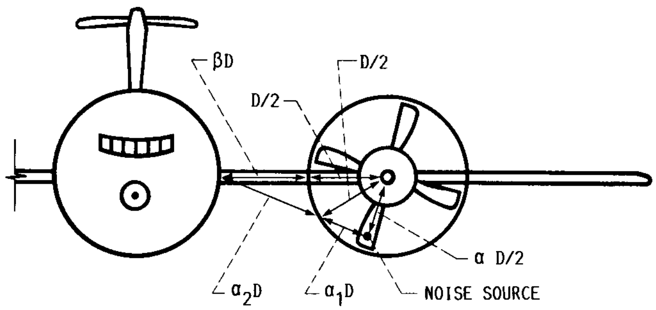


FIGURE 7. - HEAD ON GEOMETRY.

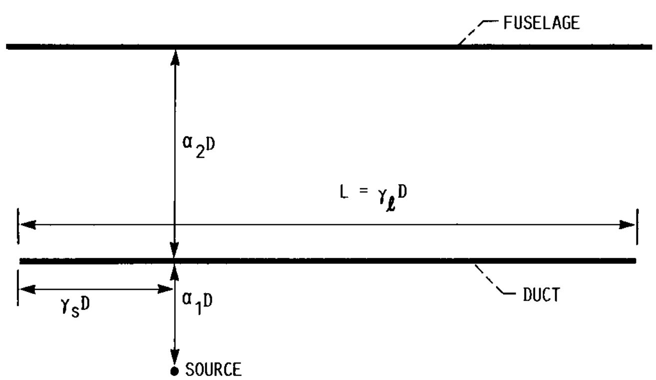


FIGURE 8. - FORE-AND-AFT GEOMETRY.

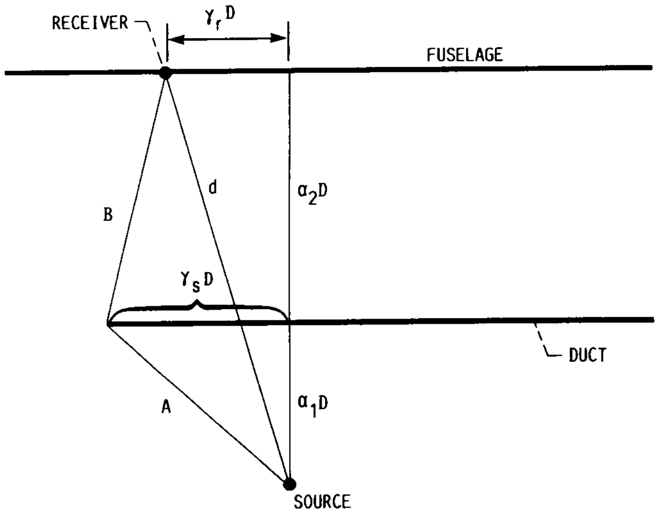
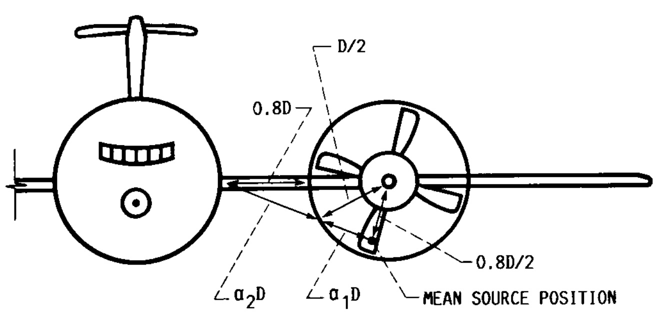
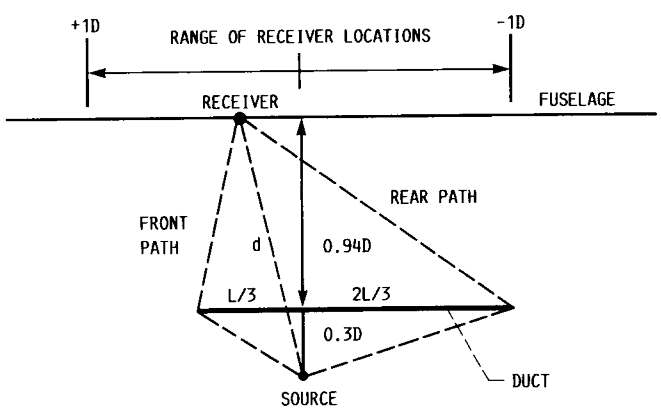


FIGURE 9. - PATH LENGTHS - FRONT PATH AROUND DUCT.



(A) HEAD ON.



(B) FORE AND AFT.

FIGURE 10. - SPECIFIC GEOMETRY.

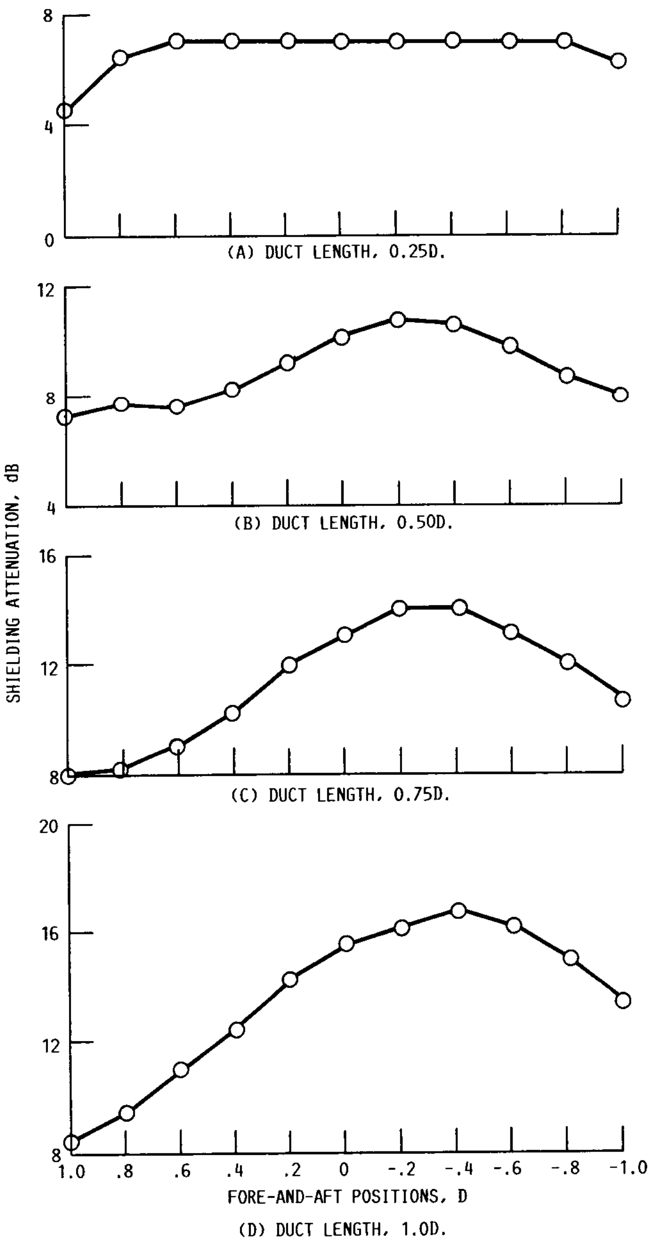


FIGURE 11. - ESTIMATED SHIELDING ATTENUATION (PROPELLER ONE-THIRD OF DUCT FROM INLET).

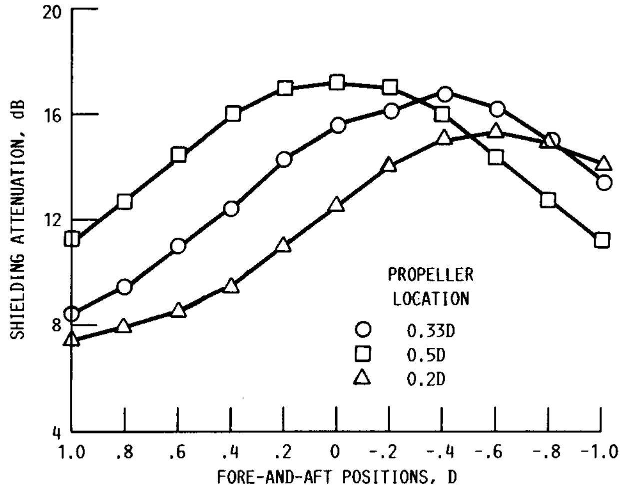


FIGURE 12. - SHIELDING FOR DIFFERENT PROPELLER LOCATIONS. DUCT LENGTH, 1.0D.

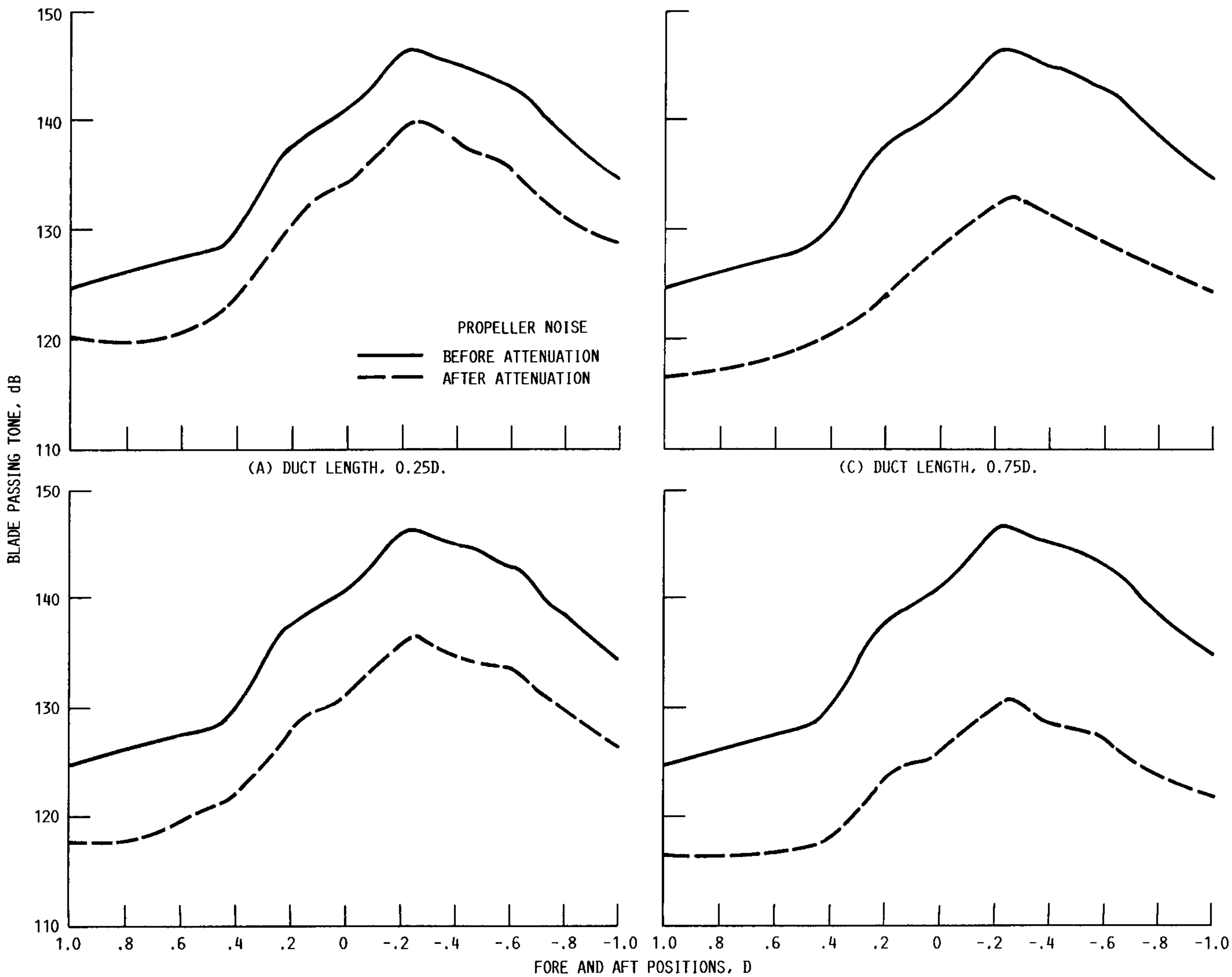


FIGURE 13. - PROPELLER NOISE DIRECTIVITY BEFORE AND AFTER DUCT INSTALLATION (PROPELLER AT ONE THIRD OF DUCT FROM INLET).

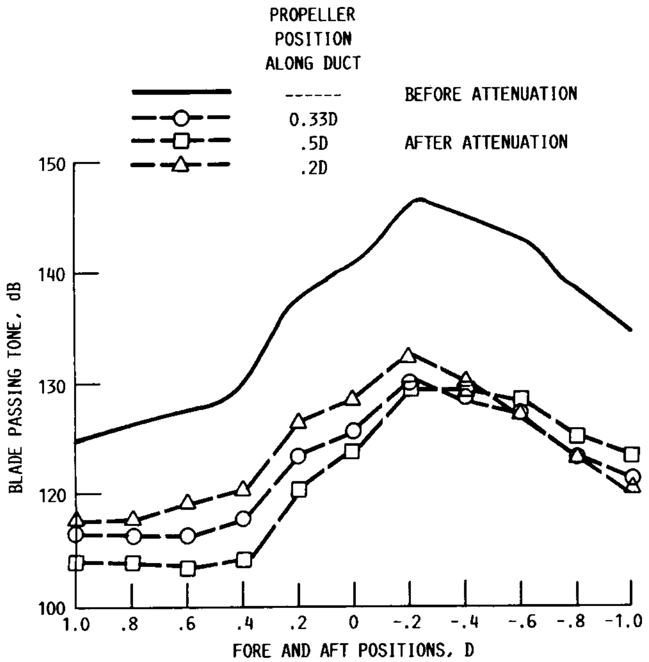


FIGURE 14. - PROPELLER NOISE DIRECTIVITIES; DUCT LENGTH, 1.0D.

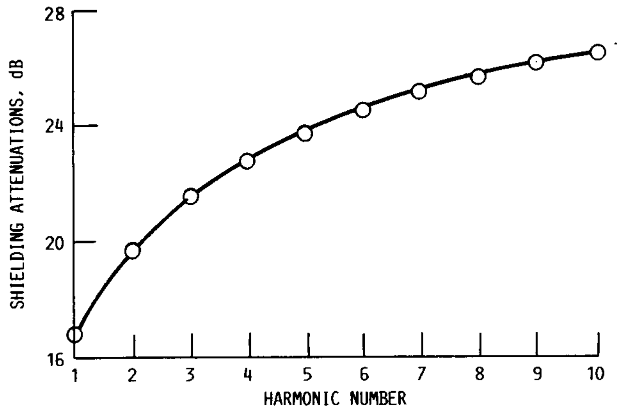


FIGURE 15. - ESTIMATED SHIELDING ATTENUATIONS AT HIGHER HARMONICS.

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15. Supplementary Notes

16. Abstract

A simple barrier shielding model was used to estimate the amount of noise shielding on the fuselage that could result from installing a short duct around a wing-mounted advanced propeller. With the propeller located one-third of the duct length from the inlet, estimates for the maximum blade passing tone attenuation varied from 7 dB for a duct 0.25 propeller diameter long to 16.75 dB for a duct 1 diameter long. Attenuations for the higher harmonics would be even larger because of their shorter wavelengths relative to the duct length. These estimates show that the fuselage noise reduction potential of a ducted compared with an unducted propeller is significant. Even more reduction might occur if acoustic attenuation material was installed in the duct.

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