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## SYMBOLS

| | |
|---|---|
| A,B,C,D | configuration symbols |
| $b$ | half baffle thickness, m |
| $h$ | half distance between baffles, m |
| IL | silencer insertion loss (decrease in noise level at a point caused by the insertion of a silencer in the system), dB |
| $k_1$ | empirical constant related to pressure loss at the nose section of the baffles |
| $k_2$ | empirical constant related to pressure loss along the straight section of the baffles |
| $k_3$ | empirical constant related to pressure loss at the baffle boattails |
| $\ell$ | streamwise length of acoustic treatment in baffles, m |
| $n$ | ratio of specified acoustic treatment length to baffle passage width |
| $P_o$ | reference total pressure measured upstream of the baffles, $N/m^2$ |
| $P_t$ | local total pressure at the survey station aft of the baffles, $N/m^2$ |
| $P_s$ | local static pressure at the survey station aft of the baffles, $N/m^2$ |
| $q_o$ | average wake dynamic pressure, $\frac{1}{2w}\int_{-w}^{w}(P_t - P_s)dy$, $N/m^2$ |
| $q_1$ | average dynamic pressure between baffles, $N/m^2$ |
| $\Delta P$ | average total pressure drop or loss streamwise through the baffle set, $P_o - \frac{1}{2w}\int_{-w}^{w} P_t \, dy$, $N/m^2$ |
| $\omega$ | vane spacing, 0.457 m |

# EFFECT OF BOATTAIL GEOMETRY ON THE AEROACOUSTICS OF PARALLEL BAFFLES IN DUCTS

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## SUMMARY

Sound attenuation and total pressure drop of parallel duct baffles incorporating certain boattail geometries were measured in the NASA Ames Research Center 7- by 10-Foot Wind Tunnel. The baseline baffles were 1.56 m long and 20 cm thick, on 45-cm center-to-center spacings, and spanned the test section from floor to ceiling. Four different boattails were evaluated: a short, smooth (nonacoustic) boattail; a longer, smooth boattail; and two boattails with perforated surfaces and sound-absorbent filler. Acoustic measurements showed that the acoustic boattails improved the sound attenuation of the baffles at approximately half the rate to be expected from constant-thickness sections of the same length; that is, 1.5 dB/n, where n is the ratio of acoustic treatment length to duct passage width between baffles. The aerodynamic total pressure loss was somewhat sensitive to tail geometry. Lengthening the tails to reduce the diffusion half-angle from 11° to 5° reduced the total pressure loss approximately 9%. Perforating the boattails, which increased the surface roughness, did not have a large effect on the total pressure loss. Aerodynamic results are compared with a published empirical method for predicting baffle total pressure drop.

## INTRODUCTION

A series of experiments were conducted in the NASA Ames Research Center 7- by 10-Foot Wind Tunnel of inlet guide vanes to be used in a new 80- by 120-Foot Wind Tunnel at Ames. The acoustically treated guide vanes are designed to direct the airflow into the open inlet of the 80- by 120-Foot Wind Tunnel and, simultaneously, to attenuate sound propagating out the inlet from the wind tunnel. The primary purpose of the experiments was to find ways to control the airflow through the guide vanes so that the velocity field in the test section would be steady, uniform, and only slightly turbulent. To that end, various devices such as honeycombs, vortex generators, screens, and special boattails were evaluated aerodynamically. Those results are reported in reference 1. (See also "Two-Dimensional Downstream Flow Characteristics of Inlet-Vanes for Open-Circuit Wind Tunnels" by G. Unnever, M. Dudley, and D. Regan — NASA TM in preparation.) This report deals with the aspects of the study pertinent to the design of parallel baffles for attenuating duct-borne sound. Designers of acoustic baffles for ducts are generally unconcerned with the details of the flow downstream of the baffles as long as the velocities are reasonably uniform. Rather, they are concerned with the sound attenuation and the total pressure drop of the airflow. Knowledge of a silencer pressure drop is as important as knowledge of the sound attenuation since one constrains the other. For example, increasing duct blockage increases sound attenuation at the cost of higher pressure drop and

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subsequently increased power required by the system propulsion device. Although there is a fairly large body of literature dealing with the sound attenuation of duct baffles, there is little information available on the aerodynamic pressure drop of baffles, especially as it is affected by the boattail geometry. A poorly designed boattail can have turbulent, separated-flow regions which produce unnecessarily high pressure loss. In general, the total pressure drop induced by boattails is much greater than the losses from all other baffle components put together. In addition to a low loss, a user may wish to have an acoustically absorbent boattail if the total length of the baffle is restricted for some reason. Consequently, measurements of sound attenuation and pressure loss were made for duct baffles with various boattail geometries. (The aerodynamic pressure-loss data are to be published in Letter-to-the-Editor, Noise Control Engineering, by P. T. Soderman.) The vane geometries studied here are similar to those reported in references 2 and 3, which were baffles tested in the same facility, but with boattails unchanged.

## MODELS AND APPARATUS

### Baffle Geometry

Figures 1 and 2 illustrate the parallel baffles installed in the Ames 7- by 10-Foot Wind Tunnel test section. The 1.56-m-long baffles were 20 cm thick and were placed on 46-cm centers for 43% duct blockage. They spanned the 2.1-m-high test section from floor to ceiling. The straight acoustic sections were 83 cm long and were composed of 48-kg/m$^3$ fiberglass bats, 3.8 cm thick, contained by a very porous cloth and mounted to both sides of metal septa placed diagonally in the baffles. The perforated metal side panels had 6.4% open area formed by 1.59-mm-diam holes on 5.56-mm centers. This low porosity was chosen to duplicate an existing damped, resonant-cavity design similar to those described in references 2 and 3. For that application, the baffle thickness, length, and spacing are half scale, but the results will be presented here as measured (i.e., unscaled). The constant-thickness sections of the vanes were unchanged. The boattails were removable so that various designs could be evaluated. At the free-stream flow speed of 20 m/sec, the chord-based Reynolds number of the baseline baffles was $2.13\times10^6$.

### Boattails

Four different sets of boattails were evaluated: configurations A, B, C, and D (fig. 3). Configuration A was considered the baseline configuration since its boattail shape is typical of existing designs. Both configurations A and D had solid, sheet metal surfaces and were, therefore, nonacoustic. Configuration B had perforated surfaces and internal sound-absorbent materials similar to those in the constant-thickness sections of the baffles. The last 20 cm of the tip had a solid surface. Configuration C was similar to B except that C slipped over the baseline boattail, thereby leaving only 43 cm of length acoustically active. Configuration C was chosen as an inexpensive modification of the baseline. Configuration D had the same shape as configurations B and C, but with unperforated surfaces. Note that the baseline boattail had a curved surface with an average diffusion half-angle of 11° (the diffusion half-angle being the angle between the boattail surface and duct axis). The other configurations were wedge-shaped over most of their length and had a diffusion half-angle of 5.1°. The ratio of length to maximum thickness was 2.65 for configuration A and 6.0 for configurations B, C, and D. Configuration C was slightly bowed out where it fit over the baseline boattail.

## Acoustic Source

To simulate a duct/inlet/baffle configuration with a noise source in the duct, a loudspeaker system was placed downstream of the baffles, as shown in figure 2. Four loudspeakers were installed in an aerodynamically shaped enclosure that was 190 mm thick, 890 mm high, and 1.11 m long. (A photograph of the source is shown in ref. 3.) The two low-frequency speakers (one on each side) or two high-frequency speakers (one on each side) were driven simultaneously with uncorrelated, random (pink) noise filtered in octave bands. When the enclosure was oriented streamwise, the sound reflected off the test section walls, creating a semireverberant sound field. When the enclosure was rotated 90°, the sound tended to beam along the duct axis, creating a semiplane-wave sound field. The actual directivity pattern of the source was not measured.

## Acoustic Instrumentation

Four microphones upstream and four microphones downstream of the vanes were used to measure the noise reduction of the silencer, as shown in figures 2. The microphones were 86 cm above the floor (approximately 40% of the duct height). The 12.7-mm-diam, omnidirectional microphones had aerodynamically shaped nose cones pointed upstream. The microphone signals were monitored, recorded, and processed as shown in figure 4.

## Pressure Measurements

The aerodynamic pressure drop through the baffles was measured with total pressure probes upstream and downstream of the baffles. The probe downstream was mounted on a traverse mechanism which moved horizontally through the baffle wakes as shown in figure 5. The total pressure probes along with static pressure probes were also used to record dynamic pressure for velocity computations. The same instrumentation was used in the studies described in reference 1.

# EXPERIMENTAL METHOD

## Acoustic Data Reduction

Because of the wind-tunnel background noise, it was necessary to make the acoustic measurements with the wind off. This should have little effect on acoustic comparisons of the baffle boattails. The average noise level at each duct cross section was determined by first finding the average of the pressure-squared signals from the four microphones, and then computing the decibel level of the average. It was possible to measure the insertion loss of the silencer by measuring the sound in the duct with and without the silencer installed between the source and microphones. However, since frequent removal of the baffles was inconvenient, and because the source output could change over a period of days, the insertion loss was estimated in the following manner. First, the difference in noise level across the silencer (noise reduction) was measured and then corrected for sound attenuation due to the distance between the two sets of microphones (the sound attenuation having been measured in the wind tunnel with the silencer removed). That correction was 2.0 dB. Next, the data were corrected for reverberation buildup measured on the source side of the baffles;

approximately 1.0 dB above 200 Hz. The final value is the muffler insertion loss. To summarize:

$$IL = NR - \Delta dB_1 - \Delta dB_2 \qquad (1)$$

where $\Delta dB_1$ = sound attenuation due to distance between microphone arrays, silencer out and $\Delta dB_2$ = reverberation buildup due to the silencer's presence.

### Pressure Loss

The aerodynamic pressure loss of the baffles was measured in the following manner (ref. 1). A total pressure probe was traversed across the duct aft of the baffles in a plane perpendicular to the baffle spans. That gave a total pressure distribution through the baffle wakes. Many traverses were made, some as close as 25.0 cm behind the boattails, others as far as 2.2 m behind the boattails. The data were integrated over the center portion of the duct to avoid wall effects, resulting in average total pressure downstream of the baffles. That value was then subtracted from the measured total pressure upstream of the baffles to give an average pressure drop or loss caused by the presence of the baffles in the duct. The pressure drop was then normalized by the average dynamic pressure at the traversing probe station.

## RESULTS AND DISCUSSION

### Acoustic Performance

The attenuation of the acoustically treated boattails can be determined by comparing the total insertion loss of the baffles and boattails (configurations B and C) with the insertion loss of the baseline (configuration A, baffles with nonacoustic boattails). Figures 6-8 show the measured insertion loss of configurations A, B, and C for the two types of sound fields used in this experiment, semireverberant and semiplane. The insertion loss of the baseline configuration was 10.0 to 20.0 dB above 250 Hz when exposed to semireverberant sound, and 5.0 to 18.0 dB when exposed to semiplane-wave sound, depending on frequency. As expected, the semiplane-wave sound tended to beam through the baffle passages whereas the semireverberant sound attenuated faster because of the many duct cross modes which are more easily absorbed by the baffles.

The effect of the acoustic boattails is best seen by subtracting the baseline insertion loss from the insertion loss of configurations B and C. Since the constant-thickness portions of the baffles were unchanged, the differences are due entirely to the changes in boattail geometry.

The longer, absorbent boattails improved the attenuation of the baffles as shown in figure 9. The increase in attenuation over the short, nonabsorbent boattails was 2.0 to 5.0 dB from 300 Hz to 12.8 kHz for semireverberant sound and 0 to 6.0 dB over the same frequency range for semiplane-wave sound. It is common to specify baffle attenuation in decibels per $n$, where $n$ is the ratio of length to passage width (width = 25.0 cm). When the 1.0-m length of fiberglass was used in the boattail, the attenuation was 0.5 to 1.3 dB/n (semireverberant sound) and 0 to 1.5 dB/n (semiplane-wave sound). These attenuation rates are lower than one would get from a constant-thickness acoustic section. From previous studies of similar baffles, the attenuation due to increasing the length of constant-thickness section is approximately 3.0 dB/n.

The average decibel per n value of a silencer is usually greater than 3 because of the high attenuation of cross modes in the front end of the silencer. The baseline configuration, for example, had an average value of 3.0 to 6.0 dB/n for semireverberant sound and 1.5 to 5.4 dB/n for plane-wave sound. Thus, the addition of a treated boattail is about half as effective as the addition of a constant-thickness acoustic section of the same length. It should be noted that these results are for a duct/inlet configuration. In an exhaust configuration, the effectiveness of treated boattails may be different than was found here.

Results for configuration C, the acoustic boattail with only 43.0 cm of fiberglass, are shown in figure 10. The increase in attenuation over the nonabsorbent boattails was only 0 to 3.0 dB. However, using a length of 43 cm (n = 1.72), the maximum attenuation rate was 1.7 dB/n, approximately the same rate as configuration B, the longer absorbent boattails.

## Pressure Loss

Table 1 lists the normalized total pressure drop for the three configurations, A, B, and D, evaluated aerodynamically. (Ref. 1 shows the same data with less discussion, but includes data from other configurations such as honeycombs, screens, vortex generators, etc.) The data indicate that the baseline boattails (configuration A) were a poorer design aerodynamically than the longer boattails (configuration D). Tufts on the vanes showed that the flow separated about halfway along the baseline boattail, which created high turbulence and total pressure loss. The baseline boattails had a ratio of length to maximum thickness of 2.65. By increasing the boattail length so that the ratio of length to maximum thickness equaled 6.0 (configuration D), the normalized total pressure loss dropped from 0.33 to 0.30, a 9% reduction. There is some uncertainty in the value of that reduction because the data scatter was about ±0.03. The penalty due to short boattails was small compared to the penalty caused by other devices such as honeycombs and screens (ref. 1). Nonetheless, it was clear that the longer boattails improved the flow and reduced the total pressure loss. The key parameter is the diffusion angle which controls how the flow decelerates from the silencer passages to the duct area downstream. A rule of thumb is that the diffuser half-angle (angle between the tail surface and the duct axis) should be no more than 4° to achieve an unseparated, smooth flow. Since the half-angles of the short and long boattails tested were approximately 11° and 5°, respectively, the short boattails caused flow separation, whereas the long boattails did not, despite having a diffusion angle slightly greater than the above criterion.

Perforating the longer boattails with 1.59-mm diam holes on 5.56-mm centers and inserting fiberglass in the cavities for sound absorption (configuration B) did not have a large adverse effect on the total pressure loss despite the increased surface roughness (see table 1). The total pressure loss fell between those of the short and long smooth boattails (configurations A and D). Without more data, it was impossible to relate the pressure drop to some geometric parameter such as hole size, porosity, or density of filler material, all of which might influence the effective surface friction and pressure loss.

## Comparison of Pressure Loss With Empirical Predictions

The measured, aerodynamic, total pressure-loss data can be compared to Mechel's empirical equations for pressure loss (ref. 4) as follows:

$$\frac{\Delta P}{q_1} = k_1 \frac{b/h}{1 + b/h} + k_2 \frac{\ell}{2h} + k_3 \left(\frac{b/h}{1 + b/h}\right)^2 \tag{2}$$

$$\frac{\Delta P}{q_o} = \frac{q_1}{q_o} \frac{\Delta P}{q_1} \tag{3}$$

where

$k_1$ = 0.5, Mechel's empirical constant for round leading edges

$k_2 = 2.5 \times 10^{-3}$, Mechel's friction factor for perforated sheet metal

$k_3$ = 0.6, Mechel's empirical constant for boattail angles 6° from streamwise

Configuration A (baseline): $\ell$ = 83 cm

$\Delta p/q_o$ = 0.46 from equations (2) and (3) ($\Delta p/q_o$ = 0.6, assuming $k_3$ = 0.9 for 11° boattail angle)

$\Delta p/q_o$ = 0.33 measured (table 1)

Configuration D: $\ell$ = 83 cm

$\Delta p/q_o$ = 0.46 from equations (2) and (3) ($\Delta p/q_o$ = 0.4, assuming $k_3$ = 0.5 for 5° boattail angle)

$\Delta p/q_o$ = 0.30 measured (table 1)

Configuration B: $\ell$ = 2.03 m

$\Delta p/q_o$ = 0.50 from equations (2) and (3) ($\Delta p/q_o$ = 0.14 assuming $k_3$ = 0.5 for 5° boattail angle)

$\Delta p/q_o$ = 0.32 measured (table 1)

The predictions using equations (2) and (3) are somewhat high, but appear to be reasonable. It appears that the empirical constant, $k_3$, is critical to the prediction and should actually be a function of boattail geometry in some way. However, Soderman's previous criticism of Mechel's method stating that the pressure drop is grossly underpredicted by Mechel's equations (see refs. 2 and 3) is invalid, because of a subsequent discovery that the pressure loss data in references 2 and 3 were biased by a wind tunnel flow problem. In those studies, the pressure loss was determined by measuring the streamwise static-pressure distribution along the duct floor through the baffles. It is now clear that the baffles caused the wind tunnel diffuser flow to separate from the walls. This resulted in a reduction in effective duct area, and therefore distorted the static pressure reading used to estimate baffle pressure drop. The method described in this paper avoids that problem.

It is important to optimize the boattail design because 70% to 80% of the baffle pressure loss occurs at the boattail according to Mechel's empirical equations. The higher pressure drop due to short boattails would necessitate a higher fan thrust and power consumption to maintain a given mass flow rate.

## CONCLUSIONS

An experimental study of acoustically treated boattails for parallel-duct baffles has shown that the configurations evaluated improved the baffle sound attenuation at approximately half the rate to the expected from constant-thickness sections of the same length. The improvement in normalized attenuation rate was approximately 1.5 dB/n, where n is the ratio of acoustic treament length to duct passage width between baffles. These results are for a duct/inlet simulation without wind, and depend on acoustic frequency.

The baffle total pressure loss was somewhat sensitive to boattail geometry. Short boattails (ratio of length to maximum thickness = 2.65) had early flow separation and unnecessarily high pressure loss. By lengthening the boattails (ratio of length to maximum thickness = 6.0), the baffle pressure loss was decreased approximately 9%. The boattail diffusion half-angles, which control the pressure gradients and resulting flow separation, were 11° and 5°, respectively. The low-diffusion half-angle of the long boattails retarded flow separation, and thereby reduced the total pressure loss compared to the short boattails. Perforating the longer boattails for sound absorption increased the surface roughness, but did not have a large adverse effect on total pressure loss.

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1. Dudley, M. R.; Unnever, G.; and Regan, D. R.: Two-Dimensional Wake Characteristics of Inlet Vanes for Open-Circuit Wind Tunnels. AIAA Paper 84-0604, March 1984.

2. Soderman, P. T.: Design and Performance of Resonant-Cavity Parallel Baffles for Duct Silencing. Noise Control Engineering, vol. 17, no. 1, 1981, pp. 12-21.

3. Soderman, P. T.: A Study of Resonant-Cavity and Fiberglass Filled Parallel Baffles as Duct Silencers. NASA TP-1970, 1982.

4. Mechel, F. P.: Design Criteria for Industrial Mufflers. Inter-Noise 75 Proceedings, Sendai, Japan, 1975, pp. 751-760.

TABLE 1.- PRESSURE LOSS COEFFICIENTS[a]

| | Configuration | $\Delta P/q_o$ |
|---|---|---|
| A | 53-cm smooth (nonabsorbent) boattail | 0.33 |
| D | 1.2-m smooth (nonabsorbent) boattail | .30 |
| B | 1.2-m perforated (absorbent) boattail | .32 |

[a]C was not measured for $\Delta P/q_o$.

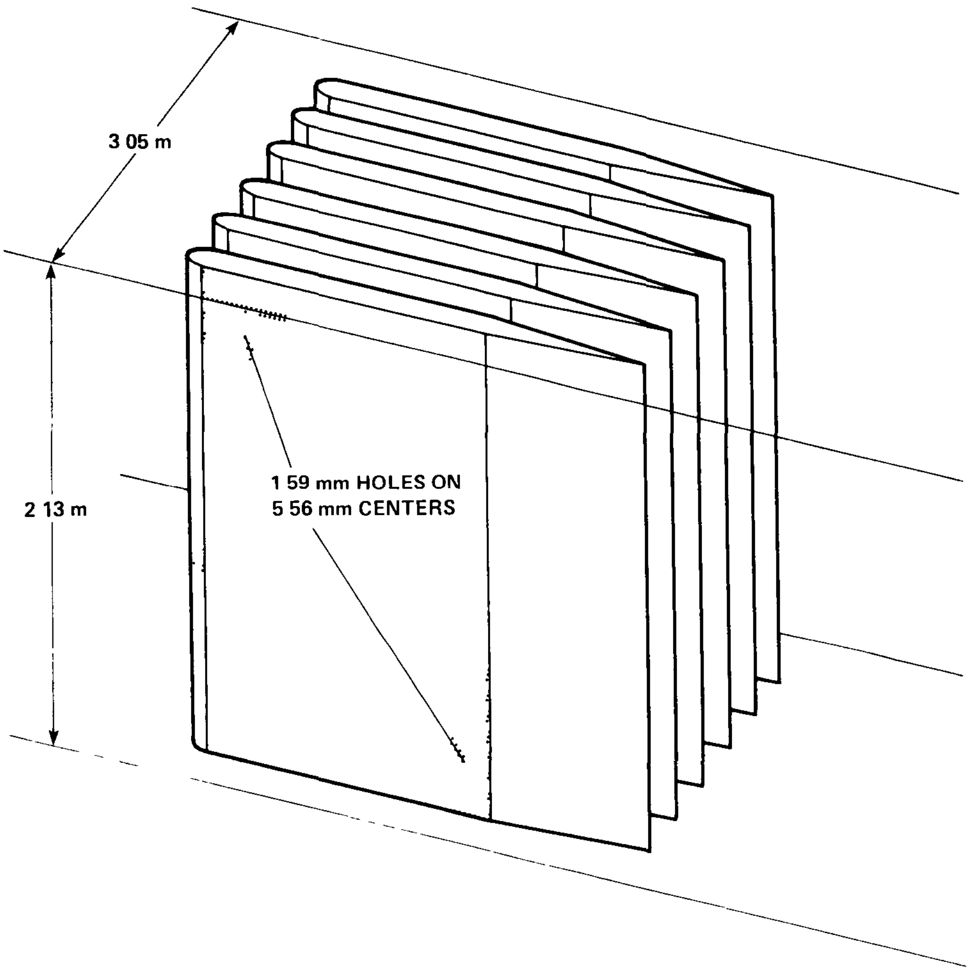


Figure 1.- Six parallel baffles in the Ames 7- by 10-Foot Wind Tunnel (baseline configuration.)

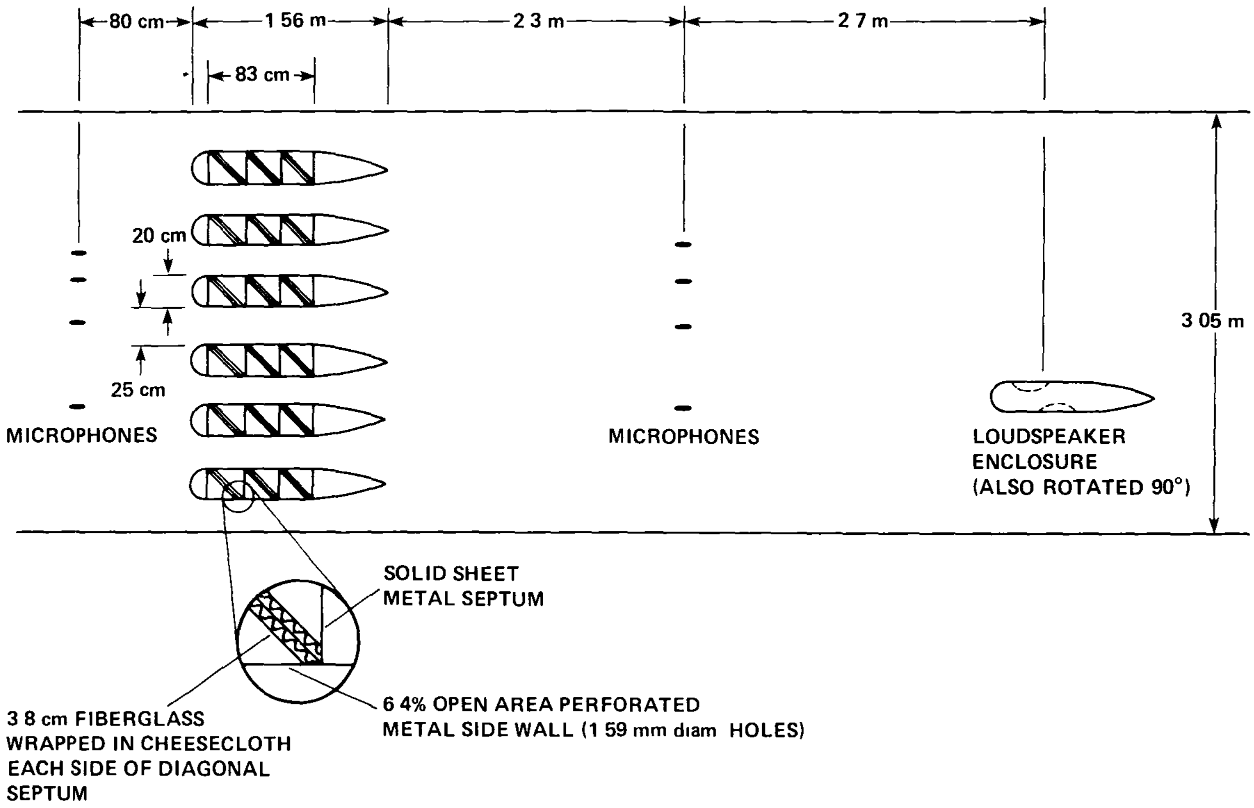


Figure 2.- Plan view of baffles, microphones, and acoustic source in test section.

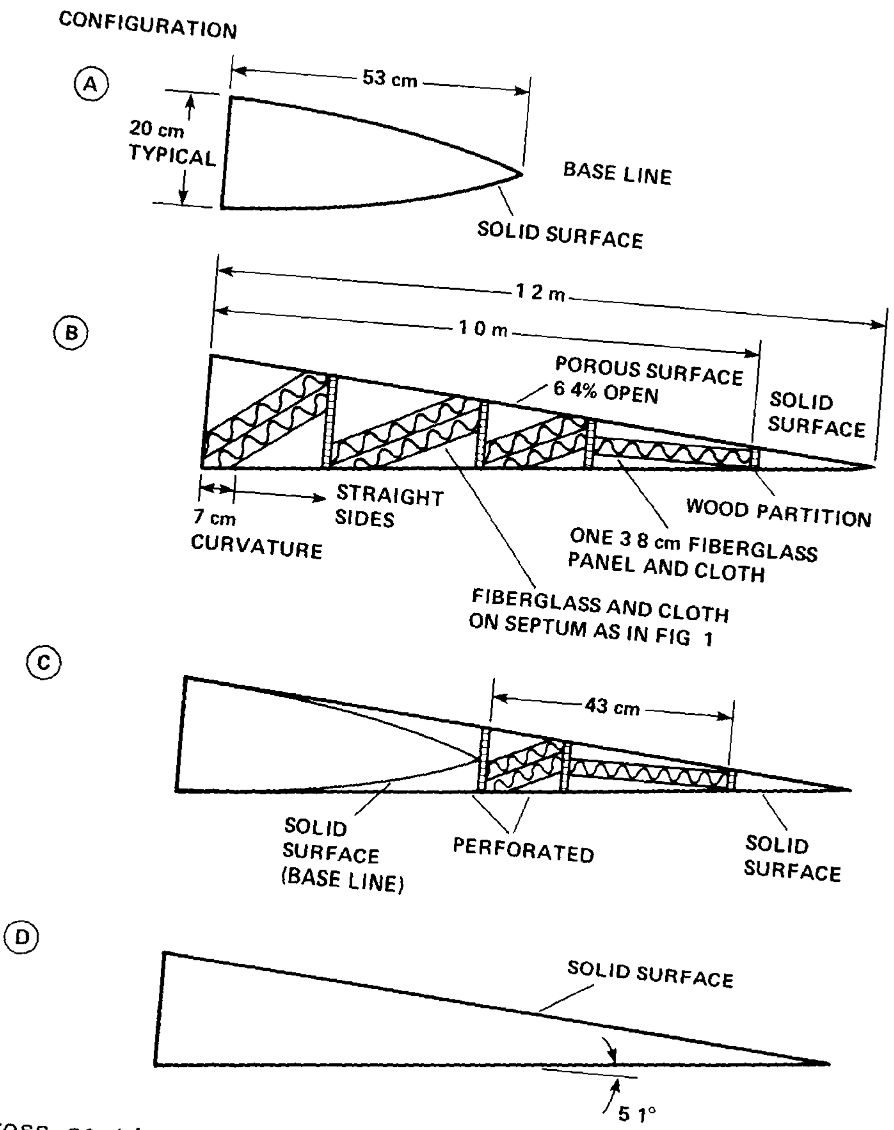


Figure 3.- Cross sections of the four baffle boattails evaluated. Configurations B, C, and D have same external shape.

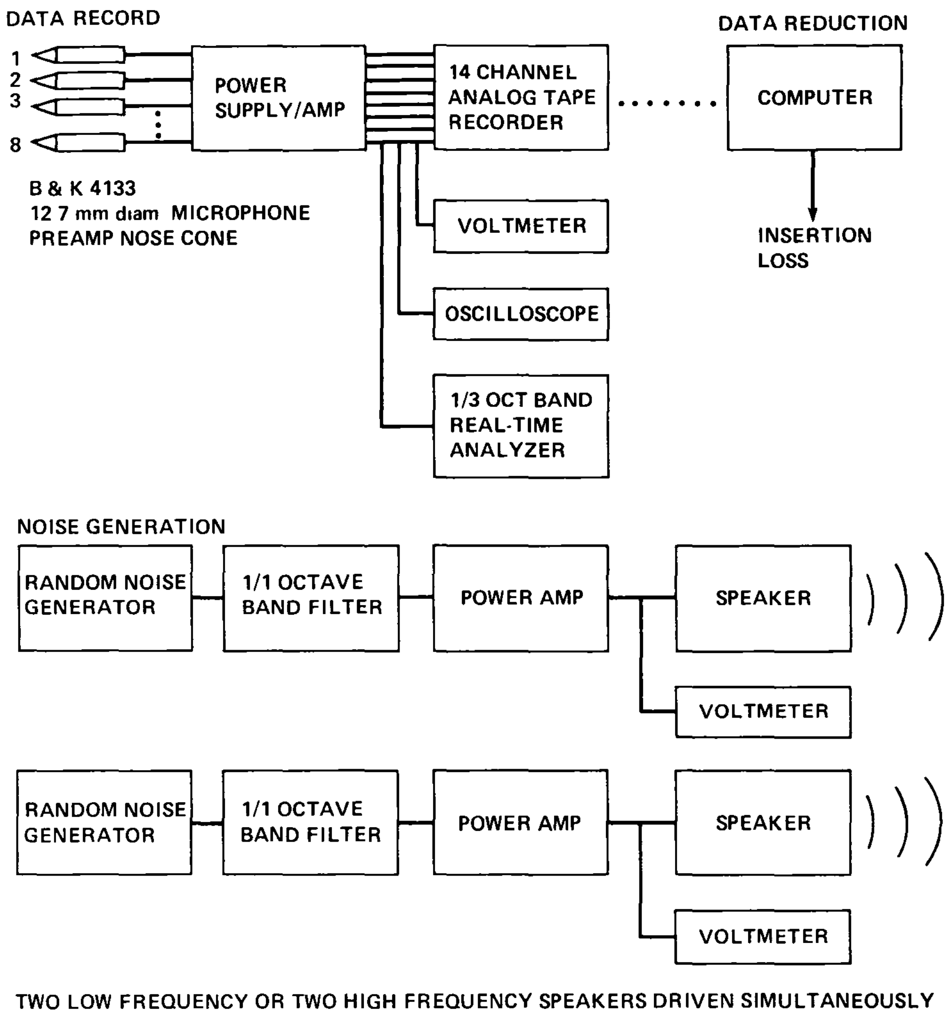


Figure 4.- Acoustic instrumentation.

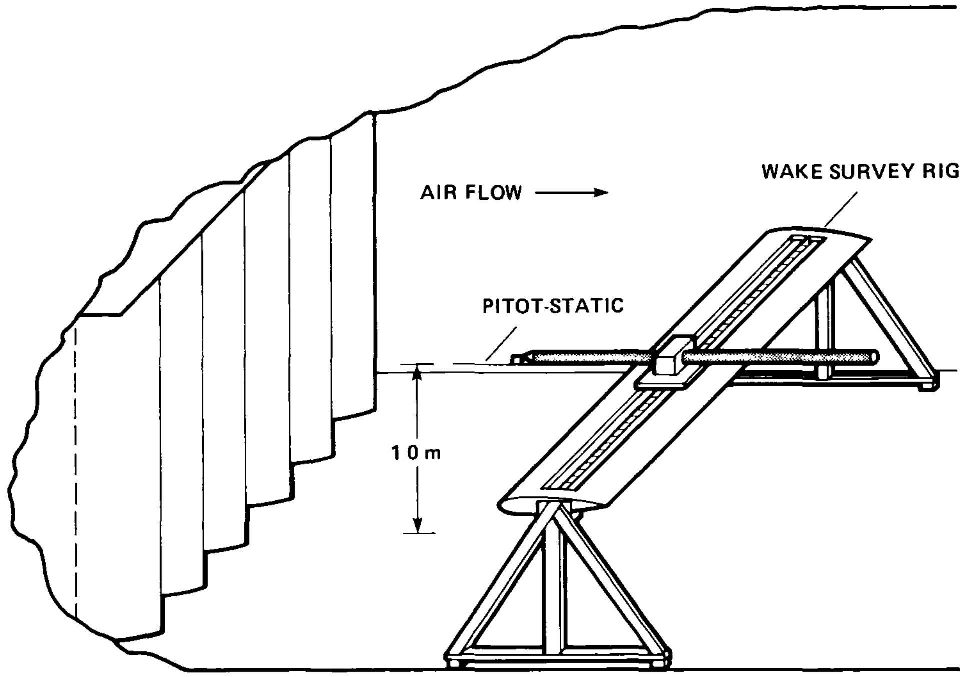


Figure 5.- Survey apparatus used to measure total pressure and dynamic pressure distribution downstream of the baffles.

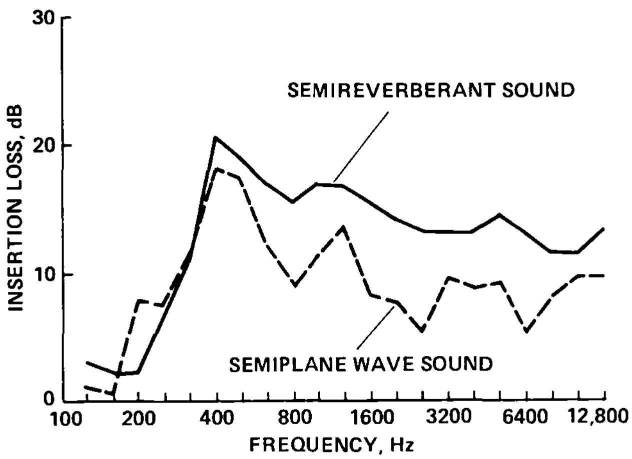


Figure 6.- Insertion loss of configuration A: baffles with 53-cm nonabsorbent boattails.

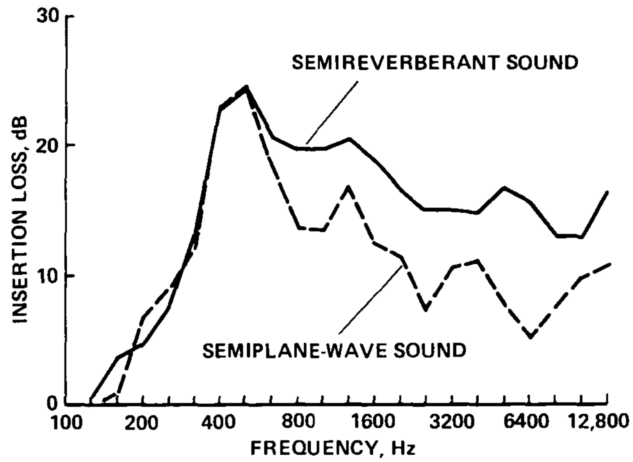


Figure 7.- Insertion loss of configuration B: baffles with 1.0 m of acoustic treatment in boattails.

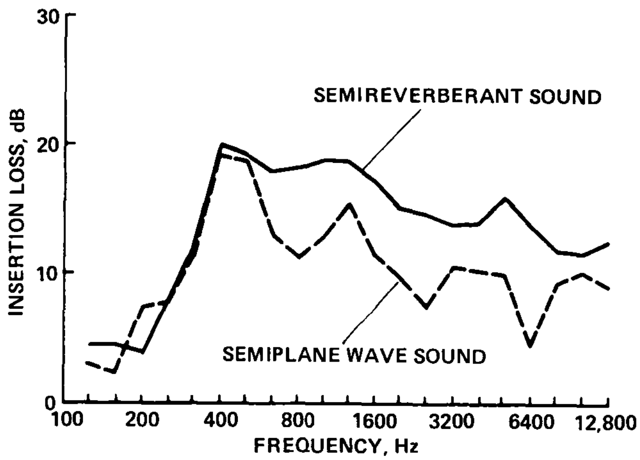


Figure 8.- Insertion loss of configuration C: baffles with 43 cm of acoustic treatment in boattails.

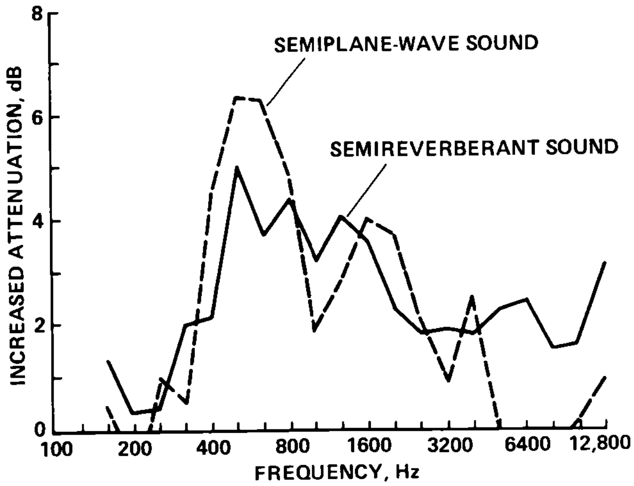


Figure 9.- Increased attenuation relative to the baseline boattails due to the long boattails with 1.0 m of fiberglass (configuration B).

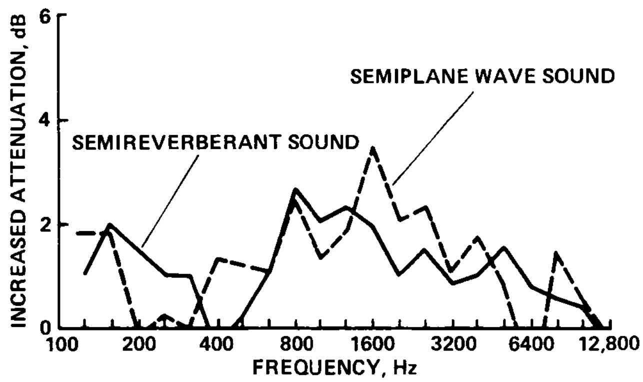


Figure 10.- Increased attenuation relative to the baseline boattails due to the long boattails with 43-cm of fiberglass (configuration C).

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15 Supplementary Notes

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16 Abstract

Sound attenuation and total pressure drop of parallel duct baffles incorporating certain boattail geometries were measured in the NASA Ames Research Center 7- by 10-Foot Wind Tunnel. The baseline baffles were 1.56 m long and 20 cm thick, on 45-cm center-to-center spacings, and spanned the test section from floor to ceiling. Four different boattails were evaluated: a short, smooth (nonacoustic) boattail; a longer, smooth boattail; and two boattails with perforated surfaces and sound-absorbent filler. Acoustic measurements showed that the acoustic boattails improved the sound attenuation of the baffles at approximately half the rate to be expected from constant-thickness sections of the same length; that is, 1.5 dB/n, where n is the ratio of acoustic treatment length to duct passage width between baffles. The aerodynamic total pressure loss was somewhat sensitive to tail geometry. Lengthening the tails to reduce the diffusion half-angle from 11° to 5° reduced the total pressure loss approximately 9%. Perforating the boattails, which increased the surface roughness, did not have a large effect on the total pressure loss. Aerodynamic results are compared with a published empirical method for predicting baffle total pressure drop.

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