Engineering Notes

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Acoustically Transparent Walls for Wind-Tunnel Applications

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I. Introduction

THE need for testing aircraft models and components for sound emissions has resulted in the development of acoustic wind tunnels which usually have the form of an open-jet test region surrounded by an anechoic chamber. Mufflers are used upstream and downstream of the test region to quiet the airflow. An example of such a facility is described in Ref. 1.

In an open-jet wind tunnel, the region usable for model testing is reduced because of the high growth rate of the free mixing layer surrounding the test region. Also, the noise is increased because of the high turbulent intensity in the mixing layer. The mixing layer can be eliminated by using a test section closed by solid walls; however, the solid walls would be unsatisfactory for acoustic testing using microphones outside the test section because the acoustic signals could not penetrate the wall. A solution to this problem is to construct the walls so that they are essentially opaque to the test region airflow but are transparent to sound transmission. The term "acoustically transparent wall" (ATW) is used in this paper to refer to such a wall, either in its ideal from where it stops all aerodynamic flow but offers not impedance to acoustic wave, or in its practical form where it only approaches the ideal performance.

If an ideal ATW could be constructed, the performance of the acoustic tunnel could be improved as follows: a) less power would be required to operate the tunnel; b) larger models could be accommodated because test region would have a larger cross section; c) models could be viewed acoustically over a wider range of angles because the test region could be made longer; d) additionally, the jet noise and the acoustic distortions generated in the free shear-layer would be reduced. A design problem would be to design the ATW so that noise generation from the flow over the ATW would be minimized.

This report describes one approach to such an ATW design and the results of testing the wall performance. The possibility of using a laminar boundary layer to reduce flow noise is discussed briefly.

II. Test Setup

The Douglas Long Beach low-speed wind tunnel was used to test the performance of an ATW made up of an acoustic material, Brunsmet, which in manufactured in several varieties by the Brunswick Corporation of Milford, Conn. The material consists of a stainless-steel backing plate with many small holes, covered on one side by a thin mat made up of many fine stainless-steel wires sintered together and to the plate. For the present test, the backing plate thickness is 0.025 in. and the hole diameters are 0.040 in. The plate open area ratio is 0.34 and the acoustic resistance, which is largely the resistance of the mat, is given as 100 mks rayls. The side with the sintered wires is smooth to the touch, and was installed flush with the east wall of the tunnel, as indicated by Fig. 1. The tunnel cross section is 38 × 54 in. and the plate was installed between tunnel Stations 33 and 71 in the streamwise direction. The plate extended 23 in. in the vertical direction, centered about the wall centerline. Since the plate was thin, it was stretched between its supports with enough tension that plate vibration was quite small even with airflow going past the plate.

A sound meter was mounted with its microphone 40 in. from the center of the ATW, as indicated by Fig. 1. The constant-speed tunnel fan was used as a natural noise generator for the acoustic testing. Because the tunnel is of the closed-circuit type, noise propagates to the test section in both the upstream and downstream directions; this noise propagates through the ATW and to the microphone at a level considerably greater than the room background noise. The test section dynamic pressure q was varied between 0 and 50 lb/ft^2; the fan noise was much greater than the background noise even with $q=0$. Data were also taken with the ATW replaced by a plywood wall (Configuration A), with the ATW backed up by a plywood board 1 in. to the east of the ATW (Configuration C), and with the ATW window area completely open (Configuration D). Configuration B was used to denote the installation of the ATW.

The various configurations are summarized in Table 1. In Configuration F, the fan motor was shut off so that microphone reading represented only the room background noise.

Boundary-layer surveys of the various configurations were carried out by traversing a pitot tube perpendicular to the tunnel wall so as the measure pitot-pressure profiles through the tunnel boundary layer. Measurements were taken along the centerline of the east wall at Stations 22 and 62. From the pitot pressure and static pressure the boundary-layer velocity profiles were calculated.

A 0.012-in.-thick boundary-layer trip, made up of triangular elements pointing upstream, was placed laterally across the tunnel east wall at Station 0. The triangular elements ensured that the east wall boundary layer would be turbulent, which was desired so as to eliminate the possibility that variations in the boundary-layer transition point, with changes in the configuration, might obscure the experimental results.

III. Aerodynamic Test Results

At Station 22, 11 in. upstream of the ATW leading-edge location of Configuration B, the boundary-layer thickness was approximately 1.0 in. and the velocity profile closely approximated the 1/7 power law that is typical for turbulent boundary layers in zero pressure gradient. Like results were obtained, as expected, for Configurations A and C.

Boundary-layer measurements taken at Station 62 were not the same for Configurations A, B, and C. The boundary-layer thickness had grown to about 1.5 in. and the 1/7 power law was again followed closely for the solid wall, Configuration A. With the ATW in place, Configuration B, the velocity profile became fuller, and some air leakage through the wall could be felt by holding a hand near the outside of the wall.

Presented as Paper 76-92 at the AIAA 14th Aerospace Sciences Meeting, Washington, D. C., Jan., 26-28, 1976; submitted Feb., 12, 1976; revision received April 14, 1976.

Index category: Aircraft Noise, Aerodynamics (including Sonic Boom).

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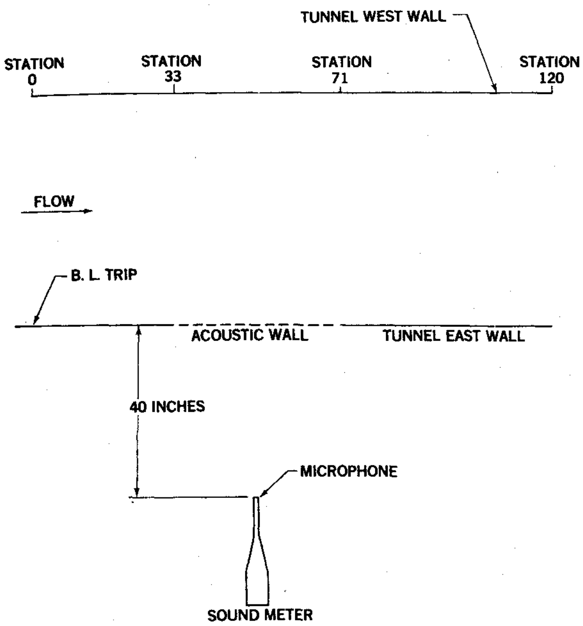

Fig. 1 Test arrangement.

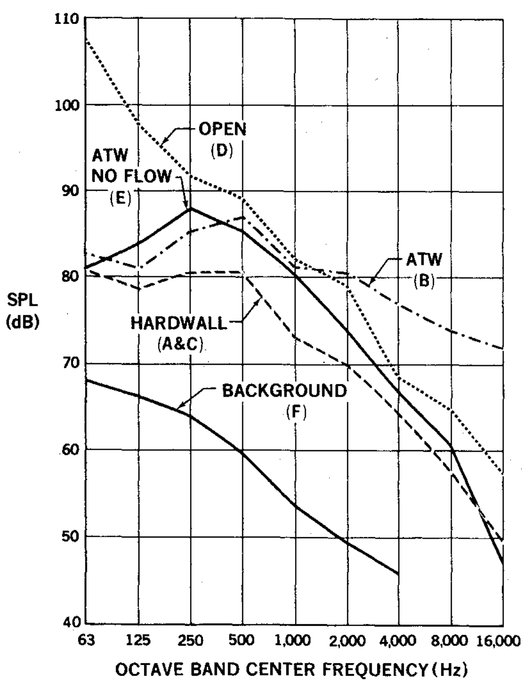

Fig. 2 Sound pressure level measurements comparing different wall configurations.

The placement of the hard wall 1 in. to the east of the ATW to create Configuration C was done in order to seal off any net air leakage through the ATW screen, although air could still leak outward through one part of the screen and inward though another. The air near Station 62 must have been leaking inward, as the profile was less full than Configuration A, where the leakage was zero. These tests showed that the boundary-layer shape was controlled by the leakage allowed through the screen, and that the natural leakage though the ATW was not so large as to greatly change the boundary-layer profile.

No boundary-layer or shear-layer measurements were taken with the open wall, Configuration D, but by holding one's hand near the downstream end of the open window it was found that the edge of the shear layer extended approximately 6 in. outside of the tunnel east wall. Since the window open length was 38 in., and since the rate at which a free-jet edge grows outward is 0.158 times the steamwide length,[2] a 6-in. outward travel of the jet edge would be expected. Hence, the velocity profile for the open jet, Configuration D, is greatly different from that of the ATW. The air leakage through the open window was clearly many times greater than the leakage through the ATW, as could be determined by feeling the air flow by hand for both cases.

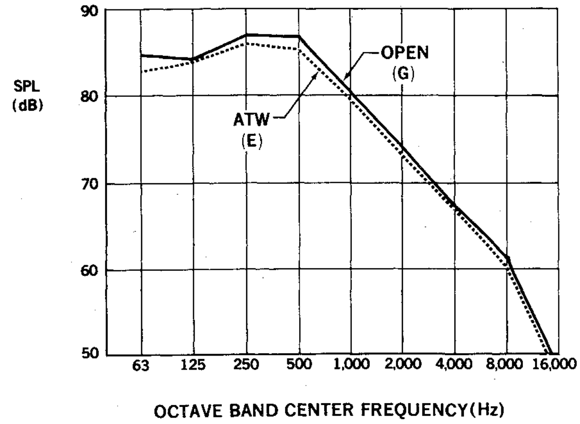

Fig. 3 Sound pressure level measurements showing the transmission loss through the acoustic wall.

IV. Acoustic Test Results

Sound pressure levels measured in octave bands are shown in Fig. 2. Notice that the tunnel room background noise level, Configuration F, is much lower than for all other configurations. Configurations A and C, having hard walls around the test section, are much noiser than F. Still louder is Configuration E, which is the ATW operated at $q=0$. When q is increased to 50 lb/ft^2, Configuration B, the noise is increased in the higher frequency bands, indicating that the boundary layer interacts with the ATW to generate sound. When the ATW is removed, Configuration D, the boundary-layer interaction noise disappears, although the sound pressure levels at high frequencies are still larger than for Configuration E. However, at low frequencies Configuration D is much louder than any other configuration. Hence, the open-jet low-frequency noise may be greatly attenuated by using the ATW although this is done at the expense of more high-frequency noise.

The high-frequency noise may be due to the interaction of the boundary layer with the ATW holes, an edge-tone effect such as discussed in Refs. 3 and 4. At $f=8000$hz where the effect is rather strong, the Strouhal number based on tunnel speed of 210 fps and hole diameter of 0.0033 ft is $S=(fd/U_\infty)=0.13$ which is typical of edge-tone phenomena. Hence, this noise might be reduced by using a different type of structure to support the fine stainless-steel wires that form the surface of the ATW.

The data in Fig. 3 were taken to determine the transmission loss through the ATW. This shows that the measured sound

Table 1 Summary of test configurations

Letter	Geometry	Tunnel q (lb/ft^2)	Comment
A	Hard wall	50	
B	ATW	50	
C	ATW and hard wall	50	
D	Open	50	
E	ATW	0	Fan rotating
F	Hard wall	0	Fan stopped
G	Open	0	Fan rotating

pressure level is 1.0 dB higher with the ATW removed than with it in place. The data indicate that the ATW causes the 1.0 dB reduction almost uniformly over all the frequencies for which data were taken.

The small differences between the Configuration E data shown in Fig. 2 and that in Fig. 3 are due to experimental inaccuracy, some of which may be attributed to the fact that the two sets of data were taken on two different days. All of the data in Fig. 2 were taken on the same day; those in Fig. 3 were taken 11 days later.

V. The Possibility of a Laminar Boundary Layer Over an ATW Test Section

Although the design of a laminar inlet and test section of an aeroacoustic tunnel poses some problems, they seem to be of the kind that are easy to solve in principle and not too difficult in practice. As indicated[5] the amount of suction required to maintain a boundary-layer laminar is extremely small. According to Eqs. (17.5) and (17.6) in Ref. 5, the required suction velocity normal to the wall is no more than $-V_o = 1.2 \times 10^{-4} U_\infty$. For $U_\infty = 210$ fps $-V_o = 0.025$ fps. More suction than this will cause the boundary layer to become very thin. Equation (13.7) gives the displacement thickness $\delta^* = (\nu / V_o)$. Hence, if $V_o = -0.1$ fps, $\delta^* = 0.0016\, ft = 0.019\, in$. From such relations it is found that the boundary layer is quite thin and the power required for suction is small.

This assumes uniform suction; an actual ATW will never be quite uniform, so more than the minimum required suction is needed. The suction could be provided in practice by pumping to reduce the pressure in the anechoic chamber that surrounds the ATW test section. The chamber pressure would need to be only very slightly less than the test-section static pressure. With some experimental development, such a facility might give a very quiet environment for aeroacoustic testing.

VI. Conclusions

A preliminary test of the ATW concept has been carried out, giving the following results: a) the ATW was very effective in improving the test-section flow as compared to that of an open jet. The boundary-layer development over the ATW was like that of a conventional wind tunnel, much thinner than the shear layer of an open jet; b) the ATW was effective in transmitting sound; only 1.0 dB transmission loss was incurred as compared to an open window; c) the four advantages of the ATW concept over the open-jet concept listed in Sec. I were all realized; however, some high-frequency noise was generated by the boundary-layer flow over the ATW; d) the ATW concept lends itself to the design of a tunnel test section with an all-laminar boundary layer. The boundary layer would be maintained in a laminar state by sucking test section air through the ATW into a surrounding anechoic chamber. Such an aeroacoustic tunnel might be made much quieter than any other tunnel if the suction airflowcan be kept at a low velocity and hence quiet.

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Design for Minimum Fuselage Drag

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Introduction

FUSELAGE drag in general aviation airplanes ranges from 30-50% of the total zero-lift drag of the airplane. It is important that the designer of such airplanes have a method for sizing the fuselage such that zero-lift drag is minimized under constraints of cabin volume (utility) and stability. This Note suggests such a method and shows that several existing general aviation airplane fuselages are not optimum from a drag viewpoint. Symbols used in this Engineering Note are defined in Ref. 1.

Discussion of Fuselage Fineness Ratio

Table 1 presents some data on fuselage fineness ratios for several current general aviation airplanes. It is interesting to note that with one exception, all have values of around $\ell_B/d = 5$ to 6. In Ref. 1, the fuselage (or body) drag is estimated from

$$C_{D_{O_B}} = C_{f_B} [1 + \frac{60}{(\ell_B/d)^3} + 0.0025 (\frac{\ell_B}{d})] \frac{S_{\text{wet body}}}{S_{\text{wing}}} \quad (1)$$

This equation assumes zero base drag. Figure 1 shows how the [ ]-term in Eq. (1) is related to ℓ_B/d. Note that the [ ]-term no longer decreases significantly after $\ell_B/d = 6.0$ is exceeded. This would indeed suggest that values of 5 to 6 for ℓ_B/d are about optimum. However, there are three other factors to contend with: 1) increasing ℓ_B/d will decrease C_{f_B} because of increasing Reynolds number; 2) increasing ℓ_B/d will increase $S_{\text{wet body}}$; and 3) increasing ℓ_B/d will decrease empennage wetted area requirements, for constant stability levels.

It appears that a more detailed examination of fuselage fineness ratio is therefore in order. The next section presents a method for minimizing the sum of fuselage and empennage friction drag, under constant directional and longitudinal stability constraints.

Minimizing General Aviation Airplane Fuselage and Empennage Zero-lift Drag

Fuselage Drag

It is assumed that the fuselage from nose to passenger compartment is defined roughly as in Fig. 2, and that this part of the fuselage is kept constant to satisfy volume and utility constraints. It is also assumed that the tail cone can be represented by a skewed cone as in Fig. 2. The equivalent fuselage diameter is defined as follows

$$\frac{\pi}{4} d^2 = S_{\text{fus ref.}} \quad \text{so that } d = \left[\frac{4 S_{\text{fus. ref.}}}{\pi} \right]^{1/2} \quad (2)$$

The wetted area of the fuselage can now be written as

$$S_{\text{wet body}} = S_{\text{wet nose}} + S_{\text{wet cone}} = S_{\text{wet nose}} + F \cdot \pi \cdot \frac{d}{2} \left[(\frac{d}{2})^2 + \ell_c^2 \right]^{1/2} \quad (3)$$

where F is a correction factor accounting for the fact that the rear fuselage is *not* a cone. F can be found by comparison to existing aircraft.

Received Sept. 22, 1975; revision received April 2, 1976.

Index categories: Aircraft Configuration Design; Aircraft Handling, Stability and Control; Aircraft Performance.

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