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Technical Notes

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Aeroacoustic Carousel

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Nomenclature

d = diameter of duct
g = gravitational acceleration
K = screen coefficient
p = pressure
R = radius of toroidal chamber
r = radius of chamber cross section
U_f = linear velocity of screen
U_m = mean linear velocity of air
u = velocity
α = U_m/U_f
β = $f/K \times R/r$
ρ = air density

Introduction

CLOSED-CIRCUIT wind tunnels in which air is driven by fans are widely used for aerodynamic testing. For aeroacoustic tests, in which the radiated sound field must be measured in the presence of flow, they have two major problems: the fan makes them noisy, and the hard walls make them reverberant. The ideal aeroacoustic test facility would be quiet and anechoic. It is difficult to satisfy these requirements in a standard wind tunnel because anechoic and noise-muffling treatments tend to increase flow resistance so that the fan has to work harder resulting in more noise. In this Note a novel alternative that will eliminate the fan and allow as much anechoic treatment as desired will be proposed.

Aeroacoustic Carousel

The proposed aeroacoustic carousel (Fig. 1) consists of a toroidal chamber whose interior walls are treated with wedges (not shown) to make them anechoic and are also sufficiently thick to prevent transmission of sound into the chamber from outside. A model to be tested can then be held inside the chamber by means of a sting, which protrudes through a slit in the inner wall. Another sting (shown here on the opposite side) holds one or more flow screens to damp out any turbulence in the flow downstream of the model. The model and screens are rotated about the central axis. In an alternative implementation the model and screens could be kept stationary while the chamber is rotated about the axis. This Note contains a discussion of the issues that would affect the operational success of such a device, and how they would vary with its size and speed. In this way the feasibility and likely size of the aeroacoustic carousel will be examined.

Acoustic Issues

The aeroacoustic phenomena that would be investigated in such a facility scale with the Mach number of the flow. To get significant levels of sound generation, it would be desirable to be able to operate over a range of Mach numbers. The desired operating speed will also, of course, depend on the application. Automotive tests would require Mach numbers up to 0.15 or so, whereas aerospace tests might require Mach numbers up to 0.9. The carousel would not be suitable for supersonic tests for a number of reasons.

In most tests it is desirable to measure the acoustic radiation in the far field, which means that the cross section of the chamber must be large compared with the wavelength of radiated sound, not including the space taken up by the anechoic treatment. For typical tests an area of at least 1 m^2 would be desirable and more would be preferable. To measure the effect of a body traveling in a straight line through quiescent fluid, the radius of the carousel should be as large as possible so as to minimize the curvature of the streamlines.

Despite the absence of a fan, there will be a number of noise sources that must not be allowed to contaminate the measurements. Noise transmitted through the slit will be hard to eliminate because there must be an air gap to allow motion. One possibility would be to overlap the slit and have the model support shaped so as to pass through without touching (Fig. 2). The portion of the support that encountered the flow would have an aerofoil section to minimize flow noise generation.

Instrumentation Issues

In conventional aeroacoustic tests microphones are mounted on aerofoil section stands and are fitted with nose cones to minimize the generation of flow noise. This technique could be employed in the carousel; alternatively microphones could be embedded in the wall whose signals could be processed using standard de-Dopplerization techniques to retrieve the required measurements.

Aerodynamic Issues

The flow behind the model will contain a nonuniform wake that will gradually be filled in by viscous diffusion or turbulent mixing.

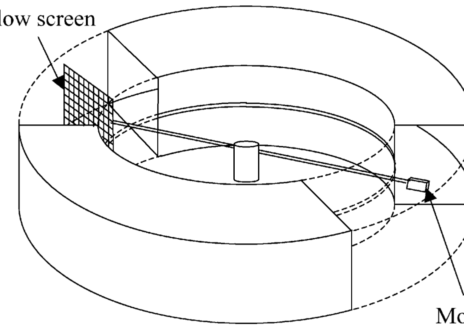

Fig. 1 Aeroacoustic carousel.

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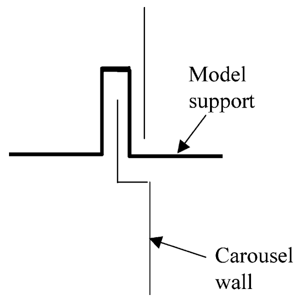

Fig. 2 Arrangement of the support so as to reduce noise transmission.

The carousel will have to be sufficiently large so that the circumferential air path is long enough for this to happen. Because the model and the flow screens will exert some force on the air, it will move relative to the chamber. This relative motion will reduce the effective testing speed, but will in turn be reduced by increasing the radius of the carousel, and hence the length of the path around it and the total drag force imposed on the air by it. An estimate of the typical dimensions of a useful carousel can be made by comparing the magnitudes of the two forces or, equivalently, the pressure change they induce.

Size Estimates

To estimate the size of a useful carousel, it will be assumed 1) that R, the radius of the the carousel, is sufficiently large that curvature can be neglected; and 2) that the friction drag in the carousel is that in a straight circular pipe of radius r, given by Darcy's formula.[1] For the purposes of initial estimates, the influence of the model will be neglected; the requirement is to find U_m the steady-state linear mean velocity of air in a toroidal chamber with a screen of specified characteristics moving around it at linear velocity U_f. The screen is assumed to fit perfectly but have no mechanical friction.

The pressure drop over the screen is given by by[2]

$$\Delta p = (\rho K/2)(U_f - U_m)^2 \tag{1}$$

where K is a screen coefficient that depends on porosity, Reynolds number, and Mach number.[3] Along the "pipe" section Darcy's formula gives[1]

$$\Delta p/\rho g = (4fl/d)(u^2/2g) \tag{2}$$

where f is the roughness dependent friction factor, l the length of the pipe, and u the mean flow velocity (volumetric flow rate divided by area). In terms of the present problem, this can be written as

$$\Delta p = 2\pi\rho f R U_m^2 \big/ r \tag{3}$$

Once the carousel has reached steady state, these two pressure differences will be equal. Equating Eqs. (1) and (3) and writing

$$\alpha = U_m/U_f \tag{4}$$

$$\beta = f/K \cdot R/r \tag{5}$$

gives

$$(4\pi\beta - 1)\alpha^2 + 2\alpha - 1 = 0 \tag{6}$$

which gives (choosing the appropriate sign)

$$\alpha = 1\big/\left(1 + 2\sqrt{\pi\beta}\right) \tag{7}$$

which is plotted in Fig. 3.

A moderate value of K would be 1.0 (Prandtl, quoted in Ref. 2). It would be desirable to have r the radius of the carousel cross section large enough to allow measurements to be made in the acoustic far field, so that $r = 1$ m as a first estimate. It is likely that anechoic treatment on the walls will lead to a high skin friction; for the time being $f = 0.05$ will be chosen as being in the upper range of f values.[1] Using these values, we can construct Table 1, which shows the necessary carousel radius for given ratios of U_m to U_f.

Table 1 Estimated carousel radius to achieve selected ratios of air speed to screen speed

U_m/U_f	R, m
0.5	1.6
0.4	3.6
0.3	8.7
0.2	25.5
0.1	128.9

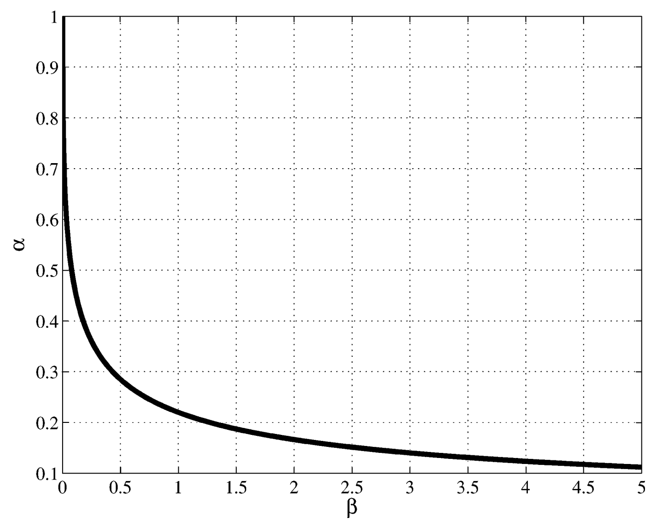

Fig. 3 Variation of air speed relative to screen speed with physical parameters of the carousel.

From this table it can be seen that while achieving values of U_m that are very low in comparison with U_f would require a very large carousel, nonetheless usable values are obtainable at feasible radii. The analysis given here suggests that the velocity ratio α will be independent of the absolute velocity. In practice this will not be so because K will vary with $U_f - U_m$, as will the pressure change caused by the flow in the chamber.

There are other reasons why it would be desirable for the radius to be large. The curvature of the streamlines has already been mentioned. Another factor is that isotropic turbulence generated by the screen must be allowed to decay between the screen and the model.[4,5] This will determine the relative spacing between the screen and the model, which need not be diametrically opposite as shown in Fig. 1; they could be arranged at a different angle and balanced with counterweights at a smaller radius. Aerodynamically it would be desirable for the model to be placed as soon as after the screen as turbulence decay will allow because this will minimize the boundary-layer growth caused by the difference between U_m and U_f. Acoustically, however, this separation should not be too small because of the danger of the screens generating aeroacoustic self-noise, which could influence the measurements. In practice these two concerns will have to be balanced.

Conclusions

A novel aeroacoustic test facility has been described, and a rough estimate has been made of the issues that would determine its feasibility and size. It should be possible to make a considerably more sophisticated model of the steady-state mean flow and to determine the likely levels of turbulence and associated internal noise generation. The possibility of using suction and blowing on each side of the screen(s) could also be investigated.

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