Engineering Notes

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Development of a Vorticity Meter

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Introduction

FLOWS with strong vorticity occur in the vortex wakes of aircraft wings and in the leeside of slender bodies at incidence. In such flows, analysis unaided by experiments has not been sufficient to provide a clear understanding. Thus there is considerable interest in measurements of vorticity in these flows. Indirect methods of measuring vorticity, such as measuring the distribution of velocity and deriving vorticity from it, are cumbersome and time-consuming, and attempts have been made[1-5] to design instruments to measure vorticity directly. Such instruments, referred to as vorticity meters, employ a rotor, either in the form of a small propeller with unpitched vanes or a circular cylinder, mounted on suitable bearings so that the rotor is free to turn about its axis. It is easily seen that, if bearing friction is neglected, the rotation speed of a sufficiently small rotor is the component of vorticity along its axis in the flow in which the meter is installed. But in any practical design there is always some bearing friction, and though some elaborate efforts have been made to reduce the friction to an insignificant level (e.g., by using air bearings[3]), it is not clear that the friction can be negligible even in such cases. Normally friction is reduced to the smallest extent possible by reducing the bearing size, and bearings as small as 0.5 mm in diameter[5] have been used. Even in such cases, friction is not insignificant, and friction corrections have been derived[5] by rotating the body of the instrument in vorticity-free flow and measuring the rotor speed. These corrections do not take into account the differences in bearing friction between that in the calibrating flow and in the actual flow with vorticity. In the actual flow, there can be a net aerodynamic side load on the bearings; thus the friction could be different from that in calibrating flow which does not necessarily produce the same aerodynamic side force. To correct this deficiency, a vorticity meter which permits use of a novel and simple calibration method has been evolved and is described below. Basically, it is an instrument which can accommodate more than one shaft (and bearing) in sequence. Friction correction is obtained by extrapolation of rotor speed to that corresponding to zero shaft size (which corresponds to zero friction). The instrument has been reliable and repeatable in operation and should be generally useful for studying flows with vorticity.

Description of Instrument

The instrument is shown in Fig. 1 and consists of a shaft in the form of a hollow spindle extended by using steel pins at its ends. This unit is supported by a pivot bearing at one end. At the other end, the pin goes through a jewel bearing and carries the rotor at its end. The rotor is 10 mm in diameter with four unpitched vanes and is made of aluminum to minimize the weight. For measuring the rotor speed, the spindle carries a small shutter which intercepts a strongly focused beam of light once every revolution. The beam of light is produced by using an electric bulb with a condensing front followed by tapering rod of perspex which acts as a light conductor. The beam of light, after crossing the shutter, falls on a photodiode (SEMSI 100) which thus produces a periodic signal whose frequency corresponds to the rotor speed. Because of the strong focusing of the light beam, the signal from the photo-diode has an amplitude of about 3 V and is suitable for direct connection to a digital pulse counter; thus, problems of signal handling are minimal. The above assembly involving the rotor and the speed sensing system is incorporated in a brass casing. It is arranged such that spindles and jewel bearings of different diameters can be installed in the same casing in sequence, so that the effect of varying the shaft diameter at the jewel bearing (which is the main parameter governing friction torque) can be studied easily.

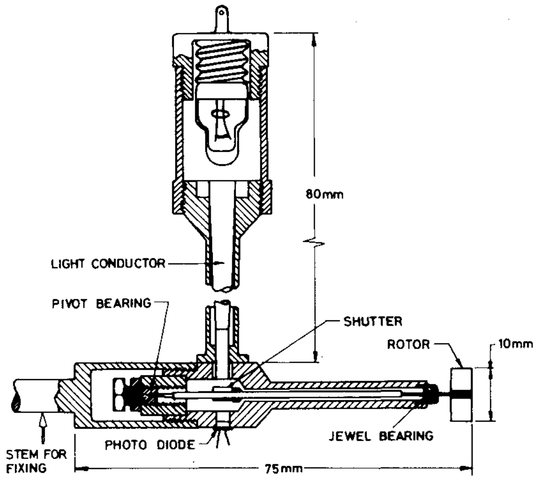

Fig. 1 The vorticity meter.

Analysis of Bearing Friction

The rotor is supported at the two bearings. The pivot bearing at the end produces contact over a very small radius. Further, a simple equilibrium analysis indicates that the side load on it is only a small fraction of the load acting on the rotor (due to its weight and any aerodynamic side force that may be present). Thus it is reasonable to ignore the friction at the pivot bearing and consider only that due to the jewel bearing near the rotor.

At small rotation speeds, it is reasonable to assume that the friction at the jewel bearing is of the solid friction type. In this case, the frictional torque is proportional to the product of the bearing load and the shaft diameter for a given combination of materials of the shaft and bearing. As the rotation speed increases, it is possible for the shaft to float up with a film of air separating it from the bearing. Calculations based on Ref. 6 indicate that, for the instrument described earlier, this air bearing range is reached at rotor speeds above 500 rev/s and in all the tests the rotor speed has always been far below this. Thus it may be safely assumed that the friction at the jewel bearing is of the solid friction type and we can relate the friction torque T_F to the shaft diameter D and the side force S as

$$T_F = K_f DS \qquad (1)$$

where K_f is half the coefficient of friction.

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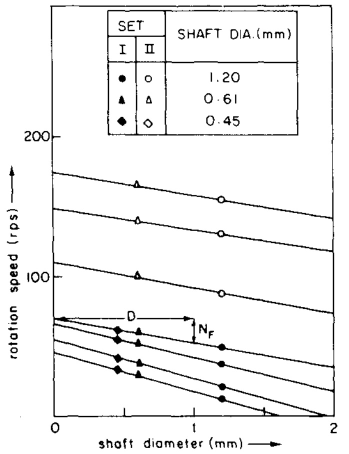

Fig. 2 Loss of rotor speed due to friction.

For a rotor without bearing friction placed in any flow with vorticity, steady rotation corresponds to the condition of zero aerodynamic torque due to the flow. If there is friction, the rotation speed falls until the net torque produced due to the flow balances friction. The torque is produced by the blades of the rotor acting like airfoils, and hence is proportional to the product of the dynamic pressure relative to the blades (which is very nearly $\frac{1}{2}\rho V^2$, where V is the freestream velocity) and the change of incidence due to loss or rotation speed. This may be written as

$$T_A = K_2 (\tfrac{1}{2}\rho V^2)(N_F/V) \tag{2}$$

Where ρ is the air density and N_F is the loss of rotation speed due to friction. N_F/V is proportional to the change of incidence. K_2, which depends on the rotor geometry, is a constant for a given rotor if one ignores the slight Reynolds number dependence of the lift-curve slope. Equating T_F to T_A, we derive an expression for N_F as

$$N_F = \frac{2K_I DS}{K_2 \rho V} \tag{3}$$

which indicates that the loss of rotation speed due to friction is directly proportional to shaft diameter, other things being fixed. This indicates a simple method to correct for bearing friction. One can measure the rotor speed for two values of D and then linearly extrapolate to get the speed corresponding to $D=0$, which is rotor speed in the absence of friction.

Test Setup and Results

To test the instrument and to verify the correctness of Eq. (3), a flow with a trailing vortex was created in a 30 cm × 30 cm wind tunnel at the Indian Institute of Science by spanning the tunnel with an airfoil of about 8 cm chord. A vortex was produced at the center of the wind tunnel by setting one half of the airfoil at an angle of attack equal and opposite to the other half. The strength of the vortex could be varied by changing the tunnel speed and/or angle of attack of the airfoil. The vorticity meter was mounted on a traverse and was located so that the rotor plane was about 180 cm from the trailing edge of the airfoil. The meter was tested with three shaft sizes: 1.2, 0.6, and 0.45 mm in diameter. The rotor speed was measured by the meter and checked by a stroboscope.

Two sets of experiments were conducted. In the first set, the angle of attack of the airfoil was set at 5 deg. After locating the vortex center by using the traverse, readings of the instrument were taken with the three shafts installed in sequence. Tests were repeated for four values of tunnel speed. The results are shown in Fig. 2 and identified as set I. It is seen that the test points for a given tunnel speed all lie on a straight line, indicating that loss of speed due to friction is proportional to shaft diameter, in agreement with Eq. (3).

In the second set of experiments, the tunnel speed was held constant and the angle of attack of the airfoil was varied. Tests were conducted with two shaft sizes. These are also plotted in Fig. 2 and identified as set II. In these tests, for each value of the vortex strength (i.e. angle of attack of airfoil) the slope N_F/D of the resulting line is independent of the angle of attack and is in agreement with Eq. (3), which indicates that N_F/D depends on freestream velocity only and this was constant in these tests. We may note here that, in these tests, the rotor was located at the center of the trailing vortex and aligned along its axis, thus ensuring that the side force S was merely the weight of the rotor and was thus constant.

Table 1 Pitch and yaw effects on the rotation speed (rev/s) of the vorticity meter[a]

Yaw, deg	Pitch, deg −10	−5	0	5	10
−10	108	119	121	112	112
−5	114	121	124	116	113
0	113	122	126	117	113
5	114	120	125	117	112
10	111	118	125	112	110

[a] Conditions: shaft diam. = 1.2 mm, V = 20 m/s, α = 10 deg, core location at 35 cm from the airfoil trailing edge.

Pitch and Yaw Effects

The instrument is sensitive to the inclination of flow relative to rotor axis. Flow inclination affects the rotor characteristics and also bearing friction through the aerodynamic side load. Though friction correction can be obtained as in previous section, change of aerodynamic behavior is not easily allowed for and one can avoid the problem only by aligning the instrument with the flow direction. But such a procedure is time-consuming; thus it is useful to know the errors that may arise if the instrument is not aligned with the flow. To estimate these errors, tests were conducted with the instrument set at various pitch and yaw angles using the test setup described earlier. A sample of these results is indicated in Table 1. These data show that the effects of pitch and yaw do not obey any simple rule. Effects of pitch and yaw are insignificant only when these are of the order of ±5 deg or less. Thus to obtain quantitative data on vorticity in any flow, it will be necessary to make sure that the axis of the instrument is not inclined to the local flow direction by more than about 5 deg.

Conclusions

A vorticity meter which is simple to construct and reliable in operation has been designed and fabricated. It has been shown that correction to the measured rotor speed arising due to bearing friction obeys a simple law and can be easily derived by using two shaft (and bearing) sizes in sequence in the same instrument. Errors arising due to the inclination of the flow to the axis of the instrument have been shown to be insignificant for inclinations of the order of 5 deg. The instrument is expected to be useful in studying flows with vorticity, such as trailing vortices.

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