Vanes for Sensing Incidence Angles of the Air from an Aircraft

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ABSTRACT

Two types of vanes that were used to measure the angle of the airstream with respect to an aircraft are described, analyzed and compared. One type is a rotating vane that is free to align itself with the airstream and the angle is sensed by an angle transducer. The other type is constrained from rotating and the angle is obtained by measuring the force exerted on the vane by the airstream and dividing by the pitot-static pressure. The free vane measures the angle directly and is not sensitive to acceleration, while the constrained vane has a faster response time and has no bearing friction. At an aircraft speed of 70 m sec^{-1}, both vanes are able to resolve changes in angle of less than 0.02°, which corresponds to a gust velocity of about 2 cm sec^{-1}, and respond to within 5% of a step-function change in angle in a distance of less than 5 m. An inflight comparison between the two vanes indicates that they both measure the same angle with a correlation coefficient of 0.97.

1. Introduction

The use of aircraft as instrument platforms for the study of atmospheric motions is becoming increasingly widespread as technological advances occur in airplane instrumentation. Aircraft are used for turbulence measurements from within a few meters of the earth's surface to well into the stratosphere, and from scales of motion of several millimeters to several kilometers. The available evidence indicates, however, that at heights above 30 m above the earth's surface a wavelength of 5 m and a velocity-component resolution of 1 or 2 cm sec^{-1} is adequate for most measurements of turbulent energy and turbulent fluxes.

The velocity of the air with respect to the earth is obtained from an aircraft by measuring both the velocity of the air with respect to the aircraft and the velocity of the aircraft with respect to the earth. Here we discuss the characteristics of two different types of vane sensors used for the measurement of airplane angle of attack and sideslip, which are then used to calculate the vertical and lateral air velocity components. The angle of attack, α, is defined as the angle of the airstream with respect to the aircraft in the vertical plane of the aircraft, and the angle of sideslip, β, is the angle of the airstream with respect to the aircraft in the horizontal plane of the aircraft. A comparison of simultaneous measurements with both types of vanes is made, with the vanes and a pitot-static tube mounted on a nose boom as shown in Fig. 1, about 5 m in front of the NCAR de Havilland Buffalo aircraft. Normally, the airstream angles encountered by this aircraft do not exceed ±5°.

The true airspeed U of the airplane is obtained from a pitot-static pressure differential measurement using the air temperature and static pressure to calculate the air density. Axford (1968) has derived the equations used to calculate the air velocity components, but he assumed that the pitot-static system measures only the component of airspeed along the axis of the airplane. In general, this is not the case. The angle of attack and sideslip sensitivities of the pitot-static tube (U. S. Air Force Type MA-1) used on the airplane for the comparisons reported here were measured in a wind tunnel. For small angles the pitot-static pressure was found to be more nearly a measurement of the magnitude of the total air velocity. The method used for calculating the air velocity components is to first correct U for angle-of-attack and sideslip sensitivities; then the components of air velocity in the aircraft frame of reference are $U\cos\alpha \cos\beta$ along the longitudinal axis, $U\sin\beta$ along the lateral axis and $U\sin\alpha$ along the vertical axis.

One of the two types of vanes considered here is free to align itself with the airstream and the angle is obtained directly from the output of an angle transducer. The other type of vane is constrained from rotating and the angle is obtained by measuring the force exerted on the vane by the airstream, dividing this by the dynamic pressure and multiplying by a constant.

2. The free vane

The design of a free vane is essentially a compromise between obtaining a sufficiently short response time and adequate damping to measure the shortest required wavelength of air velocity, and keeping the static friction between the shaft and its housing small compared

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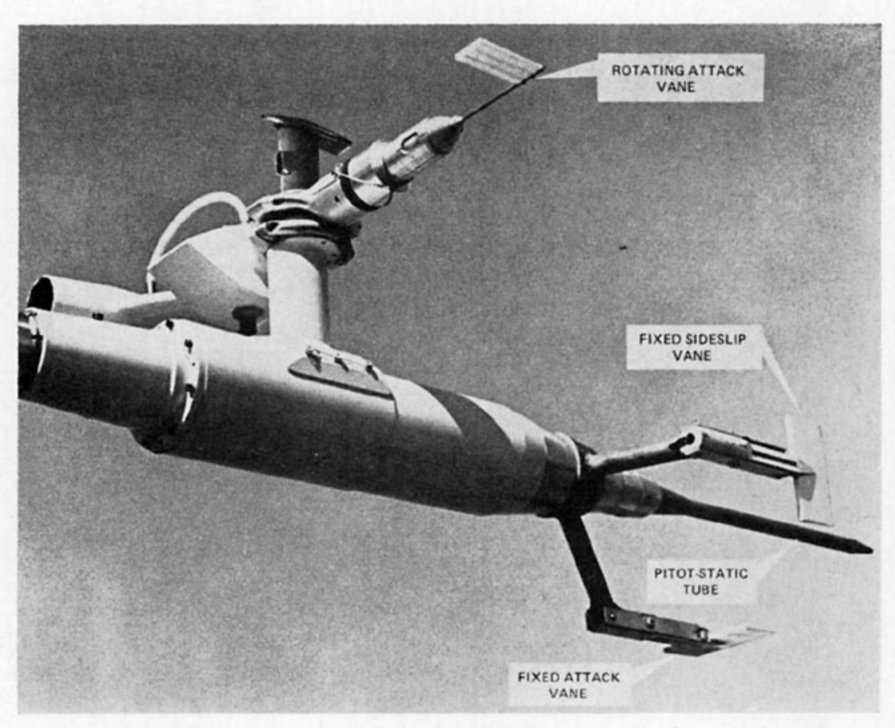

FIG. 1. Air sensing probe on the NCAR Buffalo aircraft. The probe is located at the tip of a 5 m nose boom.

to the force required to rotate the vane through the minimum angle the vane is required to measure. The advantages of a free vane are: 1) the angle is measured directly, and 2) the vane can be mass-balanced to eliminate acceleration sensitivity.

The equation of motion of a free vane can be quite accurately expressed as a second-order linear differential equation, provided the vane angle of attack does not become so large that the torque vs angle-of-attack characteristic is no longer a straight line. In practice, the torque is quite linear for an angle of attack $<6°$. This is an order of magnitude larger than any angle the vane is likely to encounter.

Wieringa (1967) has summarized the classical approach to wind vane design and has compared vanes of various shapes. The data used for calculating vane response are obtained mainly from experiments with airfoils with application to aircraft. For such applications, it is desirable that the ratio of the lift force (perpendicular to the airstream) to the drag force (parallel to the airstream) be large and that the maximum lift coefficient be large. This means that flow separation is undesirable and airfoils are designed to minimize it. The drag and maximum lift coefficient are not as important in vane design since the angle of attack is small and the drag force does not appear in the equation of vane response.

From Newton's second law of motion, the torque N (dyn cm) on the vane times the negative angular displacement from the equilibrium or zero moment position, $-\alpha$, is equal to the moment of inertia J (gm cm^2) times the angular acceleration $\ddot{\alpha}$ plus the damping coefficient D (dyn cm sec) times the angular velocity. Thus,

$$J\ddot{\alpha}+D\dot{\alpha}+N\alpha=F(t), \qquad (1)$$

where $F(t)$ is the vane forcing function. The torque N is the force perpendicular to the surface of the vane times the distance r between the axis of rotation and the center of the applied force. This distance, according to standard aerodynamics texts, is approximately 1/4 the chord length C from the leading edge for an airfoil of infinite aspect ratio (defined as span-squared/area; for a rectangular vane, this reduces to width/length), and not very much different from 1/4 for an aspect ratio of 0.2 (Durand, 1935). The center of applied force has a velocity $r\dot{\alpha}$ which changes the effective attack angle by $(r\dot{\alpha})/U$. This term can be included, along with the bearing friction, in D of (1) and is equal to $(Nr)/U$.

In practice it is difficult to construct a fast-response vane that must be able to survive cloud penetrations at 100 m sec^{-1} and is critically damped solely by means of the term $(Nr)/U$. [Another approach is described by Telford and Warner (1962), who constructed a vane that was damped by a silicone fluid.] As an example, a smooth, flat vane 6.2 cm long, 2.5 cm wide (aspect ratio$=$0.4) and 0.35 cm thick was built and tested. The vane, as shown in Fig. 2, was made of cast polyester-fiberglass with a wall thickness of 0.025 cm, hollow inside except for two longitudinal support ribs 0.1 cm thick. An eccentrically bored brass cylinder was clamped to the shaft inside the protective housing to statically counterbalance the vane. The moment of inertia of the vane, shaft and counterweight is about 20 gm cm^2. A rotary variable differential transformer (Schaevitz Engineering Company, Pennsauken, N. J., Model No. R4BS) was used as the angle transducer. One major advantage of this device is the absence of electrical contacts between the rotating and the fixed part of the transducer. Thus, the only friction is bearing friction, which was measured to be less than 30 dyn cm sec while the shaft was rotating.

The vane was tested in a wind tunnel with $U=70$ and 100 m sec^{-1}. The lift force is given by

$$F=aqS\alpha, \qquad (2)$$

where q is the dynamic pressure $(1/2\rho U^2)$, S the vane area, and a is approximately constant for angular displacements of $<6°$. The value of a was obtained from measurements of the torque at various angular displacements of the vane from the equilibrium position. Thus,

$$a=F/(qS\alpha)=\left(\frac{N}{r\alpha}\right)\left(\frac{1}{qS}\right)\approx\left(\frac{4N}{C\alpha}\right)\left(\frac{1}{qS}\right). \qquad (3)$$

The value of a was measured to be about 1.3. For $U=70$ m sec^{-1}, we have $N=8\times10^5$ dyn cm and $(Nr)/U=177$ dyn cm sec, which is about six times the damping from bearing friction. The natural frequency, $(2\pi)^{-1}(N/J)^{\frac{1}{2}}$, and the damping ratio, $\frac{1}{2}D(JN)^{-\frac{1}{2}}$, are 32 Hz and 0.025, respectively. MacCready and Jex (1964) outline a procedure for obtaining these parameters from a step-function response. The bottom curve of Fig. 3 is a typical response obtained by rotating the vane away from its equilibrium position in the wind tunnel and releasing it. The natural frequency and damping ratio were measured to be 33 Hz and 0.044, respectively. In order to critically damp a vane of this size and shape, the moment of inertia must be decreased by a factor of 4.8 to about 4.2 gm cm^2. For comparison, a balsa vane of the same size and shape has a moment of inertia (excluding the shaft and counterweight) of about 10 gm cm^2.

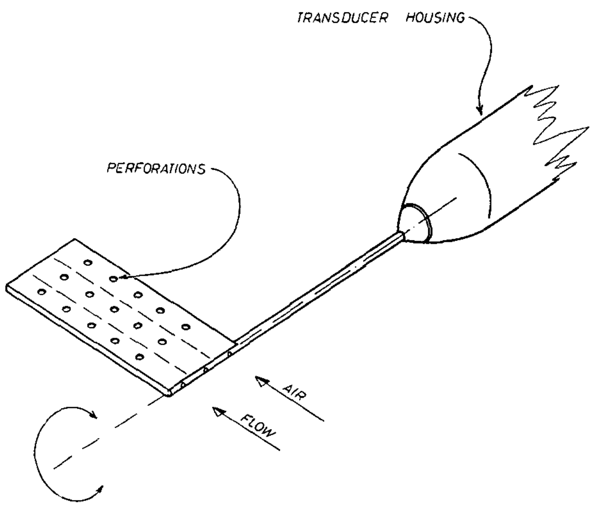

Fig. 2. Free vane for measuring the airstream angle of an aircraft.

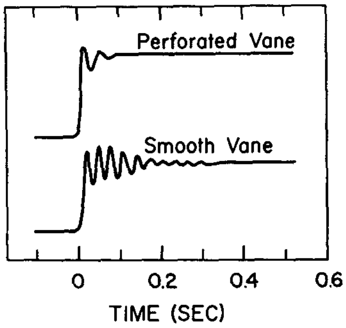

Fig. 3. Response of two types of free vanes to a step-function change in airstream angle, measured in a wind tunnel.

The damping of the vane, with the size, shape and mass held constant, is proportional to $r^{\frac{1}{2}}$, while the natural frequency is proportional to $r^{-\frac{1}{2}}$. Therefore, the damping coefficient can be increased at the expense of the natural frequency yb increasing the distance of the vane from the pivotal axis, but from the standpoint of achieving fast response, it is advantageous to minimize r by attaching the vane directly to the shaft. Consequently, it is desirable to use some other additional damping force to utilize the inherent fast response of a small vane. Similarly, if the shape and mass per unit area are held constant, the natural frequency is proportional to $C^{-\frac{1}{2}}$. Thus, if we used a vane with an area of 1 cm^2, the natural frequency would be 130 Hz.

We notice that the measured damping coefficient of the vane is about 1.8 times the calculated value. One reason for this may be its shape; the front edge of the vane is a semicircle with three protruding screw heads. Thus, considerable turbulence is generated, and the measured drag of the vane is increased to more than twice that of a smooth airfoil at zero angle of attack (Durand, 1935). We then tried various modifications of the vane, including adding side plates, adding a row of fins to the top and bottom surfaces immediately in back of the front edge of the vane, and making a hollow vane, open at both the front and the rear. Surprisingly, all these modifications increased the damping coefficient to some extent, without appreciably changing the natural frequency or the value of a.

The simplest and most effective modification was drilling a series of holes through the vane, as shown in Fig. 2. The hole diameter is 0.2 cm. Drilling larger holes did not increase the damping coefficient, but did decrease somewhat the value of a. The back end of the vane was also left open; the major effect was to slightly decrease the moment of inertia. A typical step-function response of the perforated vane is given in Fig. 3. The damping ratio is measured to be 0.25, or about ten times the theoretical value for a smooth, flat plate while the natural frequency has remained almost constant. The result is a free vane that remains within 5% of a step-function change in angle of attack in a distance of less than 5 m, and has never suffered damage during repeated cloud penetrations.

3. The constrained vane

Instead of measuring the angle of a vane that is free to rotate, we can constrain its rotation and measure the force exerted on the vane by the airstream. From (3), the angle of the airstream is given by

$$\alpha = F/(aqS). \tag{4}$$

Fig. 4 is an example of a vane of this type. [This vane was originally made by Lockheed, California Co., Burbank, and is described by Crooks (1964)]. The vane is constrained from rotating by a slotted aluminum beam that has a strain gage mounted on each of the four corners. Applying a downward force on the vane causes the top rear and bottom front gages to lengthen and the other two to contract. The force and the airstream angles were measured to be proportional to the changes in resistance for angles $<\pm 7.5°$. The resistance changes are sensed by a Wheatstone bridge circuit. Hysteresis and temperature sensitivity are less than 0.01° and 0.03 $(°\mathrm{K})^{-1}$, respectively, at 70 m sec^{-1}. The vane has a span of 10.1 cm, a chord of 5.1 cm and a wedge angle of 5.6°. It was originally constructed of aluminum honeycomb covered with a 0.013 cm thick aluminum skin, but later vanes were built of cast polyester-fiberglass. Several advantages of this type of vane are: 1) it has no moving surfaces in contact with each other to cause static friction, 2) the frequency response can be made much higher than a free vane, and 3) the electrical circuitry is simple and reliable. Major disadvantages are its acceleration sensitivity and its minimum of damping.

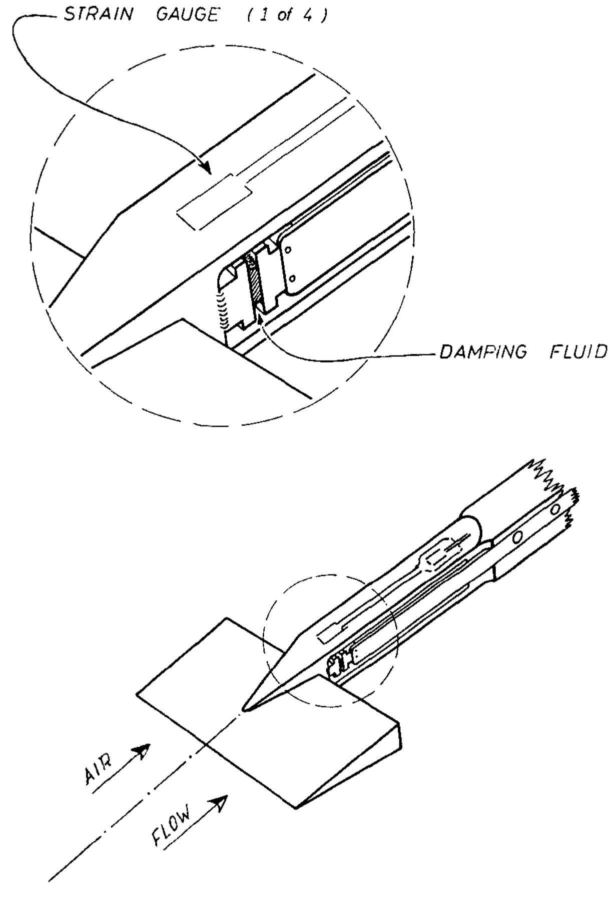

FIG. 4. Constrained vane used for measuring the airstream angle of an aircraft. Magnified view illustrates the technique used to damp the vane response.

The equation for the constrained vane response is the same as the free vane, with the vane displacement z replacing the angle of attack, the effective mass of the vane M replacing J, and the Hooke's Law constant K replacing N. The damping ratio of this vane was measured to be about 0.008, the acceleration sensitivity at 70 m sec^{-1} was 0.032 deg m^{-1} sec^{2}, the value of a in (3) was 0.0475 deg^{-1} and the natural frequency was 165 Hz. Thus, at 70 m sec^{-1} the force on the vane is 6.1×10^{4} dyn deg^{-1}. The deflection of the vane can be measured by three different methods: 1) apply a force and measure the deflection directly, 2) measure the change in resistance for a given applied force and use the specified strain gage factor and the beam dimensions to calculate the deflection, or 3) calculate the deflection using the dimensions of the beam and Young's modulus of the aluminum alloy used for the beam. The first two methods yielded a value of $K^{-1} = 5\times 10^{-8}$ cm dyn^{-1}, while the last method gave a value about 20% larger, which indicates the value of Young's modulus used in the calculation may be 20% too small. The effective mass of the vane was measured to be 17 gm from the measured change in force obtained by turning the vane upside down. Thus, the calculated natural frequency of the vane, $(2\pi)^{-1}(K/M)^{\frac{1}{2}}$, is 174 Hz.

We can now also calculate the damping force required to give a damping ratio of about 0.7, which is about the middle of the desired range for optimum high-frequency response. Thus,

$$D = 1.4K/\omega_n \approx 2.7\times 10^{4} \text{ dyn sec cm}^{-1}. \tag{5}$$

Several methods were tried to generate this force. The beam slot was filled with cork, felt and several high viscosity fluids encased in rubber. All these substances provide damping, but at a sacrifice. The natural frequency is decreased and an intolerably large hysteresis is added. A method that was successful is shown in Fig. 4. Two flat plates 1.8 cm by 1.0 cm, separated by 0.038 cm, were attached to the vane and the vane mount, respectively, so that the mutual displacement of the plates is the same as the vane displacement. If the gap d between the plates, of area A, is filled with fluid with a dynamic viscosity μ, the damping force is $(A\mu)/d$. Thus,

$$D = 1.4K/\omega_n = A\mu/d. \tag{6}$$

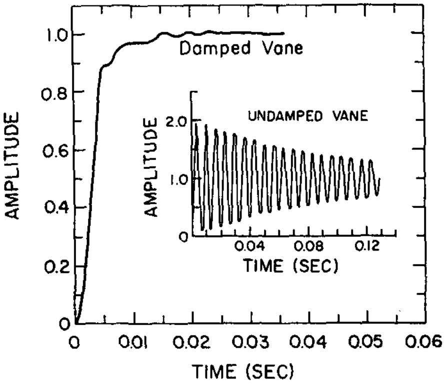

FIG. 5. Response of the damped and undamped constrained vane to a step-function change in force on the vane.

Solving for μ, we have

$$\mu = \frac{1.4Kd}{A\omega_n} \approx 103 \text{ poise.} \qquad (7)$$

A silicon fluid (Dow Corning 200 Fluid) with $\mu = 122$ poise was inserted in the gap. As can be seen in Fig. 5, the vane is now very nearly critically damped, with no increase in hysteresis or decrease in sensitivity.

4. Comparison of the vanes

Concurrent flight measurements of airplane angle of attack with both types of vanes are presented in Fig. 6. For ease of comparison, the outputs are displaced in this figure. The outputs are recorded and plotted 64 times per second, after being smoothed with a 3-pole Butterworth analog filter with a cutoff frequency of 32 Hz and a 3-point digital smoothing of weights $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$. The correlation coefficient of the two vane measurements shown in Fig. 6 is 0.97. It appears from a more detailed comparison of the two sensors that the major part of the difference in the measured angle between the two sensors is due to the slower time response of the free vane.

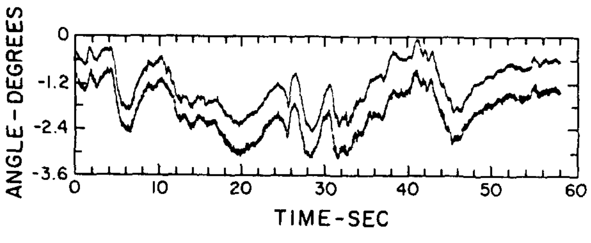

FIG. 6. Concurrent angle-of-attack measurements during an airplane flight with a free vane (top) and constrained vane (bottom). Curves are displaced for comparison.

Both sensors appear to be able to measure the airstream angles of an airplane adequately for most airborne air motion studies for wavelengths >5 m. The main advantage of the free vane is that it measures the airstream angle directly and it is not sensitive to acceleration, while the constrained vane has the advantages of a faster response time and no bearing friction.

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