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Response Characteristics of a New Bidirectional Vane

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Abstract

The design and construction of a bivane to measure horizontal and elevation angle fluctuations in the atmosphere are presented. Wind tunnel tests indicated a reasonably high-frequency response. Field comparisons with a commercially available instrument gave good results. A unique feature in the design of this bivane is its ruggedness in combination with good frequency response.

1. Introduction

Measurements of instantaneous lateral and vertical velocities from towers have several micrometeorological applications. Studies related to atmospheric diffusion, boundary layer development, sea breeze phenomena, wind gust characteristics, siting of nuclear and fossil fueled power plants, etc., require information regarding longitudinal and lateral atmospheric turbulence. Several meteorological instruments are available to make such measurements, *viz.*, sonic anemometers, three-dimensional hot-wire and hot-film anemometers, and vane-propeller sensors, to mention a few. Each has its own advantages and disadvantages. Sensors that measure wind based on cooling of constant temperature hot-wire and hot-film sensors have the advantage of high-frequency response but the disadvantage of having to face the wind due to their cosine response characteristics. Their delicate features cause susceptibility to loss of calibration and breakage during exposure in the atmosphere. Split-film sensors help in sensing the direction of wind with better accuracy, but they need correlation of six different outputs, which is difficult for continuous long-term measurements. On occasion, when high-frequency response (~500 Hz) is a necessity, hot-wire sensors are ideal. Sonic anemometers are more rugged, but the three-dimensional types involve complex electronics requiring constant attention and maintenance. They are certainly well suited for particular experiments in the range of a few hours to a few days in places where background noise is not a problem.

This leaves us with the conventional vane-type sensors for prolonged measurements. They orient themselves with the wind continuously and have second-order dynamic response characteristics (MacCready and Jex, 1964). Bivanes that measure lateral and vertical wind gusts in terms of deviations from mean positions are available. Vane-propeller sensors combine a propeller with the bivane. The need exists for a bivane that will be rugged but at the same time have reasonably high-frequency response. Annular-type bivanes have been used in the past at Brookhaven National Laboratory (BNL) (Mazzarella, 1952). The bivane described in this paper is also an annular type, but it is several times smaller and is very rugged. It was in continuous operation for 1 year on a meteorological tower and maintained its calibration. More recently, it was used for 6 months for over-water measurements of atmospheric turbulence at an air-sea interaction buoy anchored 5 km offshore (SethuRaman *et al.*, 1978a, b) in the Atlantic Ocean. It was found to perform well and did not have mechanical or electrical difficulties over this period of time. Due to its low power consumption and easy adaptation to ac or dc power supply, its use is unlimited for various meteorological applications. This paper describes its basic design features, wind tunnel tests for response characteristics, and comparative field measurements with other similar sensors.

2. Design features

The bivane consists of a vertical housing and a sensor assembly. The sensor assembly is a tripod, horizontally mounted, supporting an annular fin at its base and an adjustable weight at the apex.

As indicated in Fig. 1, counterbalancing is carried out by three counterweights. The small wire "trim" counterweight serves to either return the vane to a horizontal position after the last gust or leave it in the direction of the last gust. Its position along the horizontal rod determines this feature.

Vertical zero adjustment is accomplished by a setscrew arrangement on the short, horizontal chain drum shaft. Vertical dc output is normally plus or minus, with zero as horizontal. An operational amplifier changes this to all positive.

The electrical analog of vertical displacement is obtained via a lightweight chain running over a drum and down a hollow shaft to a linear displacement transducer giving a dc output. Horizontal shifts were recorded with a potentiometer for these tests. The instrument has since been modified to replace the potentiometer with a small synchro. The synchro output is converted to dc sine and cosine for recording. This method eliminates the zero crossing problem. The outputs are combined during data processing to produce absolute directions.

This design represents a one-third reduction in physical size and almost a factor of 10 reduction in weight over the previous annular design used at BNL.

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3. Response characteristics

The bivane has a second-order system response to an angular displacement. This response depends on the input and the first and second derivatives of the response. Two parameters commonly used to define the response are the undamped natural frequency (ω_n) and the ratio of the actual damping to critical damping called the damping ratio (η). The differential equation for the response of the bivane will be of the form

$$d^2\theta/dt^2 + 2\omega_n\eta\, d\theta/dt + \omega_n^2\,\theta = f(t), \qquad (1)$$

where θ is the angular displacement of the vane with respect to a fixed direction and $f(t)$ is a time dependent forcing function. For direct meteorological applications, distances (λ) are more appropriate than frequencies (ω).

Wind tunnel tests were performed on the bivane at different wind speeds. The method consisted of moving the vane in the vertical plane by several angles (*viz.*, 10°, 25°, 30°, and 40°) and then releasing it instantaneously to measure its response. The same angles were repeated for horizontal angle response. Voltage outputs were recorded with an analog tape recorder and then digitized at a rate of 16 samples per second. The step response of the bivane for the horizontal angle for a mean wind speed of 5 m/s is shown in Fig. 2. Figure 3

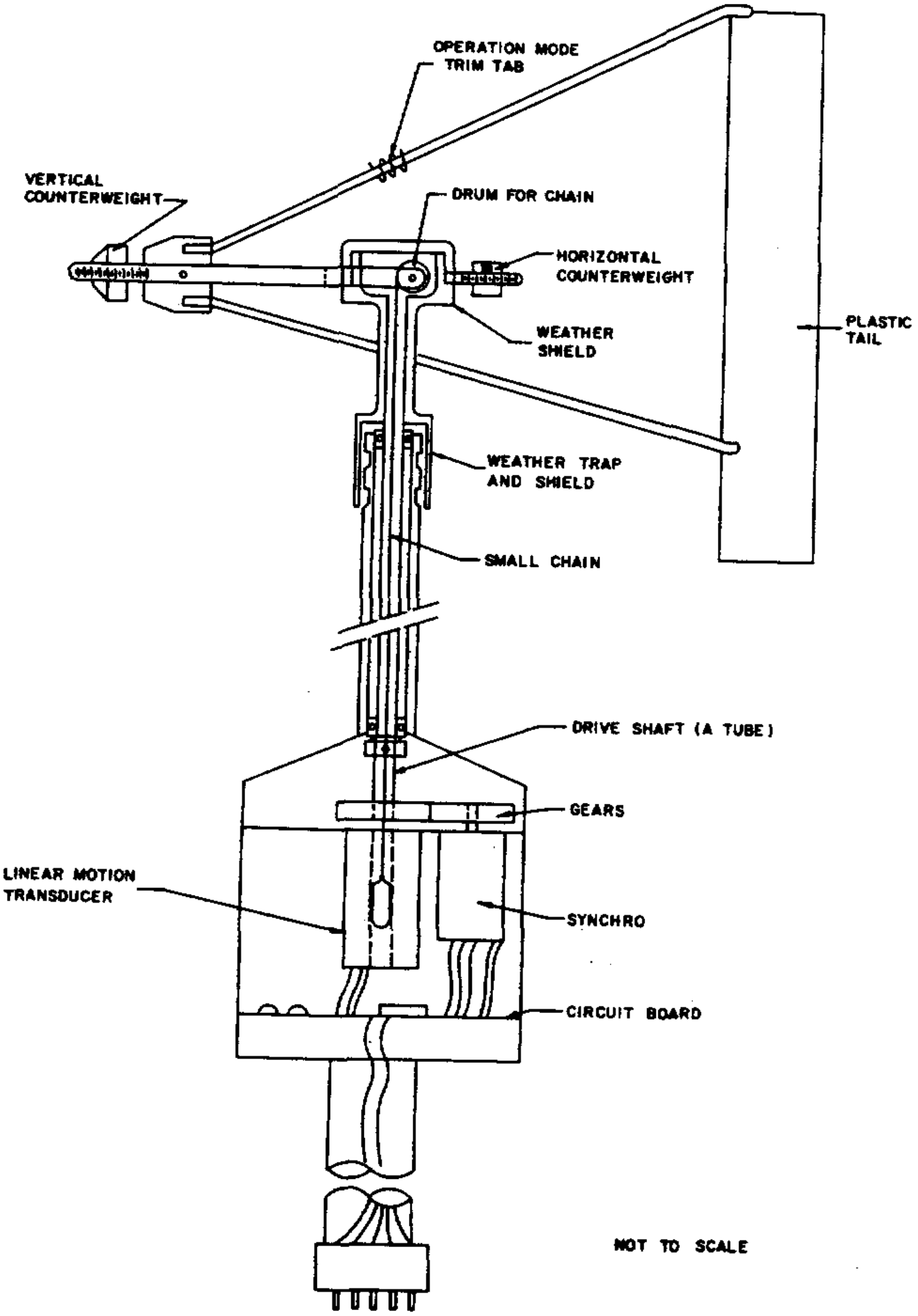

FIG. 1. A line diagram of the BNL bivane showing the details of construction.

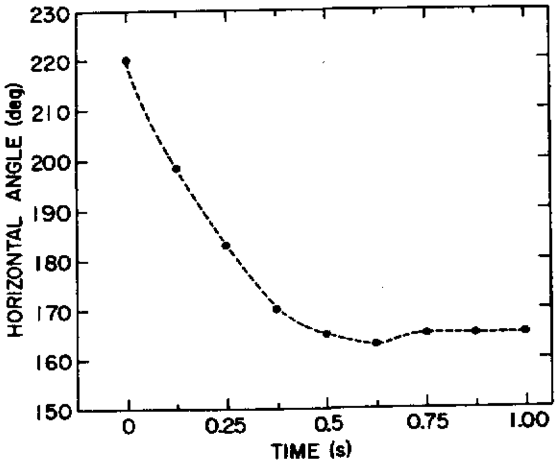

FIG. 2. Response curve for a step change in the horizontal angle. Mean wind speed (U) in the wind tunnel was 5 m/s.

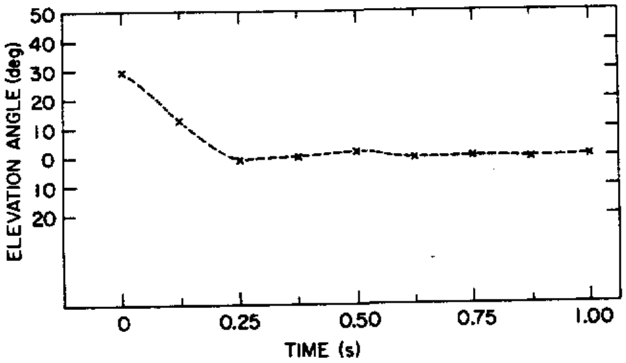

FIG. 3. Response curve for a step change in the elevation angle. Mean wind speed (U) in the tunnel was 5 m/s.

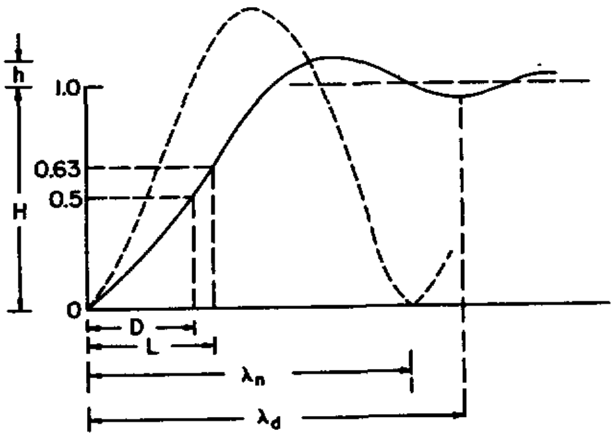

FIG. 4. Definition of the various parameters in a typical response curve.

TABLE 1. Typical parameters for an angular displacement of 30° and U = 5 m/s.

	Elevation Angle	Horizontal Angle
Overshoot (h/H)	1.2/30	2.3/55
Overshoot, %	4.0	4.2
Damped wavelength (λ_d), m	1.25	1.25

shows the step response for the elevation angle for the same wind speed.

From the response curves, several parameters can be computed. A definition of the parameters is given in Fig. 4. The overshoot is given by h/H. The overshoot ratio (h/H) and η are related by

$$h/H \simeq \exp\,[-\pi\eta/(1-\eta^2)^{\frac{1}{2}}]. \tag{2}$$

Delay distance (D) and delay time ($T_D = D/U$) are the values for the vane to move from the initial to 50% of the final equilibrium values, where U is the wind speed. The damped wavelength (λ_d) is given by alternate crossings of the response curve before it reaches the final equilibrium value. Response distance (L) corresponds to the time for the vane to move from the initial to 63% of the final equilibrium value; $T_L = L/U$ gives the response time. The natural wavelength (λ_n) is computed indirectly from the following relationships (MacCready and Jex, 1964):

$$\lambda_n = D(6.0 - 2.4\eta) \tag{3}$$

and

$$\lambda_n = \lambda_d(1-\eta^2)^{\frac{1}{2}}. \tag{4}$$

Values of the parameters obtained from wind tunnel tests for Figs. 2 and 3 are shown in Table 1. Response characteristics indicated in Table 2 were computed using (2), (3), and (4). The wind tunnel tests were conducted for several angular displacements, and a mean value was taken. The variation in the values of the response parameters given in Table 2 for different tests were small, typically in the range of 10–15% of the means. There was no evidence of stalling for angular displacements of 25° and higher for wind speeds ranging from 1.2 to 10 m/s. Slight increase in the response distance for the horizontal angle is probably due to the use of the potentiometer. Proposed use of selsyn and sine/cosine transformer should make responses equal in both directions. At lower wind speeds (Fig. 5), the overshoot was slightly more and the delay time was larger, although delay distance remained reasonably constant. Estimation of λ_d was at times difficult due to the high damping ratio of the BNL bivane.

TABLE 2. Response characteristics of BNL bivane.

	Elevation Angle	Horizontal Angle
Delay distance, m	0.60	0.63
Response distance, m	0.78	1.25
Natural wavelength, m	1.74	1.79
Damping ratio	0.74	0.71

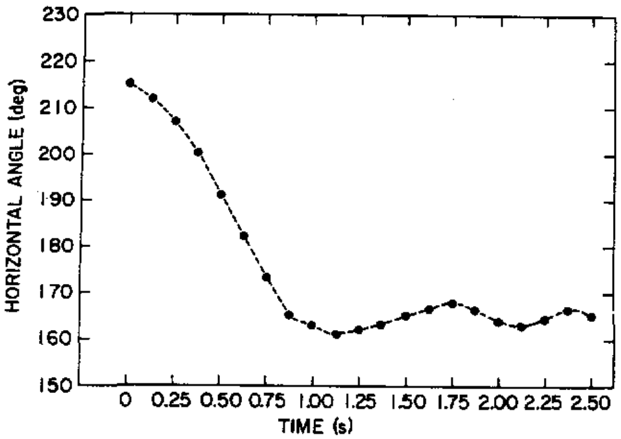

FIG. 5. Response curve for a step change in the horizontal angle. Mean wind speed (U) in the tunnel was 1.2 m/s.

TABLE 3. Comparison of observations in the field.

	Single Sensor Hot-Wire		Propeller-type Vane				BNL Bivane	
Test	U, m/s	σ_u, m/s	U, m/s	σ_u, m/s	σ_θ, deg	σ_ϕ, deg	σ_θ, deg	σ_ϕ, deg
1	7.37	1.26	7.21	1.10	8.0	3.2	11.8	3.8
2	8.40	1.15	8.20	1.03	5.8	2.8	9.3	3.5

4. Field comparison

A comparison study of different wind sensors was done in the atmospheric surface layer with a 24 m high meteorological tower. A BNL bivane, a propeller-type vane, a metal-clad single hot-wire sensor, and a BNL cup anemometer were used, as shown in Fig. 6. The propeller-type vane used has a frequency response of ~2 Hz; the rugged hot-wire, ~5 Hz; and the cup anemometer, ~1 Hz. The horizontal velocities measured by the hot-wire were used in conjunction with the instantaneous horizontal angle and elevation angle outputs to obtain lateral and vertical velocities, respectively. The observations from all instruments were recorded in analog form on magnetic tapes, digitized at 8 per second after passing through low-pass resistance-capacitance (RC) filters, and analyzed for mean and variance. The standard deviations of the horizontal and elevation angles (σ_θ and σ_ϕ, respectively) measured by the BNL bivane and the Meteorology Research, Inc. (MRI), Vector Vane are given in Table 3. The mean wind speed (U) and the standard deviation of the longitudinal ve-

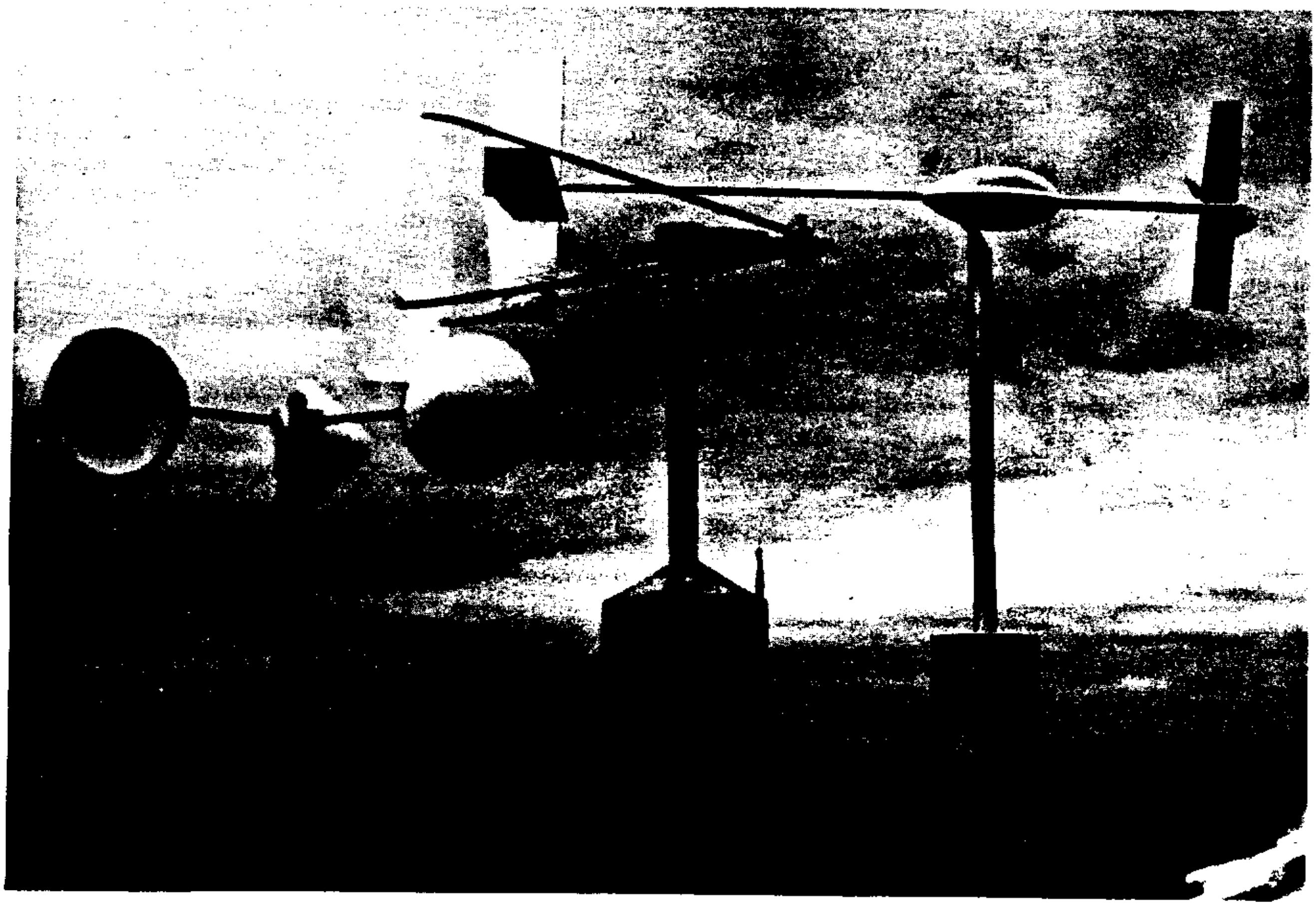

FIG. 6. Field comparison of measurements made by different instruments at a height of 24 m. The instruments (from left to right) are a BNL cup anemometer, the BNL bivane, a metal-clad single hot-wire sensor, and the MRI VectorVane.

locity fluctuations (σ_w) are also given as additional information.

The sampling period for each test was 30 min. The standard deviations of the elevation angle fluctuations (σ_ϕ) measured by both instruments were about the same with slightly higher values for the BNL bivane. The difference was larger for the horizontal angle fluctuation (σ_θ) values. Higher-frequency response of the BNL bivane may be the reason for this difference.

5. Conclusions

Wind tunnel and field tests indicated the response characteristics of the BNL bivane to be reasonably good. Response distance for the elevation angle was found to be 0.78 m, and for the horizontal angle it was 1.25 m. Damping ratios for the two directions were also good with not much overshoot, and there were small response errors in high frequencies.

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