BNL 18431

Conf-731205--4

A Comparison of Wind Speed and Turbulence Measurements Made by a Hot-Film Probe and a Bivane in the Atmospheric Surface Layer

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ABSTRACT

Two independent systems for determining wind speed and turbulence levels are being used in an on-shore diffusion study on Long Island near Brookhaven National Laboratory. Results obtained from the two instrument systems are compared to illustrate the differences in the measured values of the vector wind, mean wind speed, variance, turbulence level and energy spectra.

Details of the physical characteristics and relative advantages of a commercial Vector Vane and a three-dimensional hot-film sensor are also presented. Measurements of the mean wind speed and the turbulence level compared well. The Vector Vane underestimated spectral densities for frequencies above 1 hertz.

INTRODUCTION

Wind speed and turbulence in the atmospheric boundary layer are important parameters related to environmental quality. A knowledge of their magnitude and character is important in the formulation of prediction models of environmental pollutants and for monitoring purposes. Frequently the results obtained from an experimental program are compared with those from another program or with observations at different locations in the same program. Some knowledge of the relative characteristics of the instruments involved is essential in order to understand the properties being observed. The relative comparison of the instruments in actual field conditions is helpful in interpreting the results obtained after giving due consideration to their characteristics and capabilities.

Over-water dispersion off the south shore of Long Island, New York, is being studied by the Meteorology Group of Brookhaven National Laboratory. This study will provide information for environmental impact analyses for possible siting of offshore power plants. Diffusion of oil fog smoke, released from an anchored boat off the coast, is measured at various distances downwind. Meteorological variables are measured with instruments mounted on a 16-m portable tower over the beach and from an aircraft. A bivane (Vector Vane, manufactured by Meteorology Research, Inc.) and a three-sensor hot-film probe with constant temperature anemometers (manufactured by Thermo Systems, Inc.) are two of the instruments used for measuring turbulence. The present study was undertaken to compare the characteristics and capabilities of the Vector Vane and the three-dimensional hot-film sensor exposed to the same flow conditions. Both instruments were mounted at the 16-m level of the tower, as close as possible, and carefully levelled. The hot-film sensor was aligned facing the direction of the wind. These two instruments formed part of an array on the tower consisting of cup anemometers, directional vane, and mean temperature measuring sensors. The arrangement of the two instruments being compared in this study is shown in Figure 1.

DESCRIPTION OF THE INSTRUMENTS

A brief description of the instruments, their operation, and calibration characteristics are given in this section. The mode of operation of the Vector Vane and the hot-film anemometer is so different that a brief comparison of each instrument's operation procedure and errors involved will be made. Photographs of the Vector Vane and the hot-film probe are shown in Figure 2.

Vector Vane

(a) Nature of Operation and Response Characteristics

The Vector Vane has a sensitive windmill-propeller with four light magnesium blades. The tail fins are made of plastic covered with a thin coating of aluminum. The vane is free to rotate 360° in the horizontal and ±60° in the vertical. Two potentiometers provide resistance changes proportional to the azimuth and elevation angles. A light beam chopper, attached to the propeller in combination with a miniature photocell and light source, provides a pulsed output proportional to the wind speed.

The dynamic response of the propeller can be represented by the differential equation for a first-order system

$$\tau \frac{dv}{dt} + v = f(t) \qquad (1)$$

Research performed under auspices of the U. S. Atomic Energy Commission.

where τ is the time constant (time for the system to respond to 1 - 1/e or 63% of a step change),

v is the indicated wind speed,

t is the time, and

f(t) is a time dependent forcing function.

The dynamic response of the vane can be defined by the differential equation for a second-order system

$$\frac{d^2\theta}{dt^2} + 2\omega_n \zeta \frac{d\theta}{dt} + \omega_n{}^2\theta = f(t) \qquad (2)$$

where θ = angular displacement of the vane with respect to a fixed wind direction,

ω_n = natural or undamped angular frequency of the system, and

ζ = damping ratio, the ratio of the actual damping to the critical damping.

The Vector Vane has been studied extensively for its response characteristics(1,2) which are as follows:

Starting threshold	Speed	0.22 m/sec
	Direction	0.22 m/sec
Response distance	Speed	0.61 to 0.91 m
	Direction	0.61 to 0.91 m
Damping ratio	Direction	0.4 to 0.7

The response distance is defined as the distance over which the wind travels corresponding to 63% of a step function change and is independent of the wind speed. It can be shown that a system with a first-order response measures 81% of true energy for an input wavelength 16 times the response distance, L, for a sine input function in equation (1). For a wavelength of 3.7 L the indicated energy is 25% of the true value and for an input wavelength of L, the system indicates only 2.6% of the actual energy(1). Although atmospheric turbulence does not necessarily follow a sinusoidal forcing function, the above figures give a rough indication of the importance of having response distances of small magnitudes in order to increase the frequency response of the instruments. The input wavelength λ may be defined in terms of the other pertinent variables as

$$\lambda = \frac{1}{k} = \frac{U}{f} = \frac{2\pi U}{n} \qquad (3)$$

where λ = wavelength (distance per cycle),

k = wavenumber (cycles per unit distance),

f = frequency (cycles per second),

U = wind speed (distance per second) and,

n = angular frequency (radians per second).

A knowledge of the response distance will be helpful to determine the frequencies above which the energies are under-estimated.

(b) Calibration

Speeds from the propeller of the Vector Vane are calibrated in a 0.61-m diameter, 6-m long, circular wind tunnel. Both the azimuth and the vertical angles are calibrated by moving the vane known angles in the horizontal and vertical directions. The calibrations are linear for the speed, azimuth, and vertical angles.

(c) Errors Involved and Practical Considerations

The propeller on the Vector Vane is calibrated in the wind tunnel over a range of steady, low turbulence, wind flows. In strong turbulence close to the ground, the ability of the instrument to measure the true wind speed will largely depend on its response characteristics. Due to the inability of the vane to continuously align itself with the vector wind, the propeller cannot always measure the true wind speed. When a propeller is present, the downwash from the propeller and the gradient of wind along the vane cause changes in the response characteristics of the vane. The response of the vane depends largely on the damping ratio. A damping ratio between 0.5 and 0.7 is considered reasonable with little overshoot and relatively fast response. The errors involved due to the above factors for the Vector Vane have been discussed by MacCready and Jex(1) and MacCready(2). An error in mean wind speed of about 2% was computed for the Vector Vane by MacCready(2). Errors involved in measuring the turbulent energy can be estimated from a knowledge of the distance constant or frequency response of the instrument. Based on the values of input wavelengths computed for a sine wave input function, a 75% energy under-estimation is possible for a wind fluctuation frequency of about 5 hertz. (Wind speed of 10 m/sec and distance constant of 0.6 m were assumed for this computation.)

From a practical standpoint, the Vector Vane is relatively rugged, easy to use, and holds a steady linear calibration for long periods of time. In addition, it is easily calibrated in the field before and after each experiment.

Three-Sensor Hot-Film Probe

(a) Nature of Operation and Response Characteristics

Hot-film sensors used for this study are quartz rods with platinum film on the surface. Gold plating on the ends of the rod isolates the sensitive area and provides a contact for fastening the sensor to the supports. The platinum film thickness is less than 1000 Angstroms and the diameter of the cylindrical film sensor is 0.025 mm. Figure 2 shows the probe consisting of three mutually perpendicular sensors operated by three constant temperature anemometers.

The detecting element of a hot-film anemometer is heated by an electric current. Ordinarily, the film is cooled by the wind which causes the temperature to drop, resulting in a decrease in

Superior numbers refer to similarly-numbered references at the end of this paper.

electrical resistance of the film. When a constant temperature anemometer is used, the electrical resistance of the film is kept as constant as possible. Any slight variation in temperature is immediately compensated for by an electronic feedback system. Voltage required to drive the necessary current through the sensor is obtained as output. For subsonic flow King's "potential flow" relation holds for heat loss. It is expressed as

$$\frac{E^2}{(t_s - t_e)} = A + B\,(\rho V)^{k/n} \qquad (4)$$

where E is the bridge voltage output,

V is the wind speed,

ρ is the density of the fluid,

t_s is the sensor operating temperature,

t_e is the environmental or fluid temperature,

A and B are constants that depend on fluid properties, and n is an exponent that varies with the Reynolds number of the flow. For air under subsonic flow conditions n takes a value of about two.

Although theoretical evaluations based on heat transfer properties are available for the response of the hot-film, direct calibration based on Equation (4) is commonly adopted since this eliminates the variability in the characteristics of the film material, supports, or other unknown factors. If the fluid temperature t_e happens to be the same during calibration and experimentation, no correction for the bridge voltage output is needed for a constant temperature anemometer. Most often, these temperatures are not the same, necessitating a correction for the voltage output. This correction factor can either be computed and applied to the observed values during the analysis or the sensor may be electronically compensated by using fast response temperature sensors mounted close to the speed sensors. For this study, temperature compensation was achieved by measuring the air temperature near the sensor and correcting the voltage during the analysis. Air temperature near the sensor remained constant throughout the experiment.

Frequency response of the hot-film anemometer was found to be near 1000 hertz and varied slowly with the mean wind speed. For a 10 m/sec mean wind this corresponds to a response distance of 1 cm as compared with 60 cm for the Vector Vane.

(b) Calibration

The three hot-film sensors of the probe were calibrated in the circular wind tunnel already mentioned with the flow at right angles to each of the sensors. As can be seen in Equation (4), the calibration of the hot-film sensors versus wind speed is not linear.

(c) Errors Involved and Practical Considerations

The hot-film sensor is directionally sensitive and errors are introduced in the measurements if the flow direction is not normal to the sensor. Champagne(5) found that the relationship between the actual mean velocity and the effective cooling velocity can be expressed as

$$V_c^2 = V^2\,(\sin^2 \alpha + K^2 \cos^2 \alpha) \qquad (5)$$

where V_c = effective cooling velocity past the sensor,

V = mean velocity,

K = a constant that depends upon the fluid and the wind speed, and

α is the angle the sensor makes with the mean wind direction.

$K \cos \alpha$ is a measure of the effectiveness of the velocity parallel to the sensor.

Serious errors can be encountered using this system when large variations in wind direction occur. For the time periods involved in this experiment, the flow was fairly steady and the direction did not change appreciably. Other factors affecting the hot-film system such as conduction to supports, temperature gradient along the sensor, finite length of the sensor, and presence of water spray are to be taken inot account in interpreting the results. The relative importance of these errors depends greatly on the problem studied. For atmospheric studies most of the above errors turn out to be negligible. In locations where water spray is present, it is not advisable to use hot-film sensors.

RESULTS

The wind data from the bivane and hot-film was recorded simultaneously on magnetic tape in analog form. The analog record was digitized and then recorded at 0.1 sec intervals. The digitized data was analyzed using a CDC 6600 computer.

Comparison of the vector wind is made instead of individual wind components to keep the comparison as realistic as possible. This is due to the fact that the three-dimensional hot-film sensor was designed mainly to measure the vector wind rather than the components.

The following values are compared:

(1) Mean wind speed

(2) Standard deviation of the fluctuations of wind speed

(3) Turbulence level

(4) Energy spectra

(5) Energy dissipation rate

Mean and Standard Deviation of the Wind Speed and Turbulence Level.

Table 1 shows the mean wind speed, standard deviation (σ) of the wind speed and the turbulence level which is defined as the ratio of the standard deviation to the mean wind speed. These values were computed for three successive ten-minute periods when the wind speeds showed a tendency toward stationarity.

Table 1

	Hot-Film			Vector Vane			Turb. Level
Data Set	Mean m/sec	σ m/sec	Turb. Level	Mean m/sec	σ m/sec	Turb. Level	V.V./h.f.
1	8.31	0.66	0.079	8.13	0.55	0.068	0.861
2	7.54	0.72	0.094	7.74	0.64	0.083	0.833
3	7.63	0.79	0.103	7.91	0.71	0.090	0.874

The mean wind speeds as measured by the two systems are nearly the same. The vector wind speeds computed for the second and third ten-minute periods for the hot-film are somewhat less than the corresponding values for the Vector Vane. This may be due to a slight change in horizontal wind direction during these periods.

As expected, the standard deviations of the wind fluctuations as measured by the hot-film sensor were larger due to its higher frequency response. The Vector Vane measurements under-estimated the standard deviations by about 10 to 16% as compared with those measured by the hot-film. Because of the substantial difference in the frequency responses of the two instruments, this error is relatively small and probably not important for many practical purposes. Turbulence level is considered an important parameter in characterizing atmospheric conditions in meteorological measurements and analyses. The turbulence levels for the Vector Vane were about 13 to 17% less than those for the hot-film.

Energy Spectra

Energy distribution at various frequencies is generally used by meteorologists to provide information on eddy size distribution. The vector wind data for consecutive ten-minute periods were analyzed to determine the energy spectra. The spectral density S(n) is defined by

$$\bar{v}^2 = \int_0^\infty S(n)\, dn = \int_0^\infty S(k)\, dk \qquad (6)$$

where v is the fluctuation of the wind from the mean, and the wave number k is defined as $2\pi n/V$. Reciprocal of k represents actual length scales.

A comparison of the spectral densities near the high frequency end of the spectrum is shown in Figure 3 and in wave number domain in Figure 4. The relative under-estimation of the spectral densities at higher frequencies by the Vector Vane as compared with the hot-film anemometer can be seen. At frequencies above about 1 hertz, the under-estimated spectral density starts becoming significant.

It is often convenient to express the frequencies normalized with the height of the instrument and the mean wind speed as nz/V. Equation (6) can be rewritten as

$$\bar{v}^2 = \int_0^\infty n\, S(n)\, d\ln n \qquad (7)$$

A graphical representation of $n\,S(n)$ versus $\log_{10} n$ has the advantage that the area under a segment of the curve represents the contribution to the energy in the corresponding log-frequency interval. Variation of normalized spectral density $nS(n)/\sigma^2$, is shown in Figure 5, where σ^2 is the variance obtained from Table 1. Normalized spectral densities obtained from the Vector Vane do not differ significantly for non-dimensional frequencies below one. An average mean wind speed was obtained from Table 1 for both instruments.

A graphical representation of the spectral densities estimated from the two instruments is shown in Figure 6. A maximum error curve has been drawn to show the maximum energy under-estimation by the Vector Vane as compared with the hot-film anemometer. Relative maximum error defined as the ratio of the difference in the spectral densities measured by the two instruments to that measured by hot-film is shown in Figure 7. The values expressed as a percentage were obtained from the maximum error envelope in Figure 6. The percentages have been computed with respect to the spectral density of hot-film and bivane and shown as separate curves. Thus, knowing the spectral density as estimated from bivane measurements, it will be possible to estimate the error involved as compared with the hot-film anemometer measurements. The percentage error has a tendency to increase with decrease in the spectral density which is associated with an increase in the cyclic frequency or radian wave number. The error becomes significant for cyclic frequencies of about one hertz.

Energy Dissipation Rate

An energy dissipation rate ε, obtained from Kolmogorov's hypothesis in the inertial subrange, is useful in determining the diffusive properties of turbulence. The approximate magnitude of error involved in the estimation of ε can be computed for the frequency range of interest. In the inertial subrange a relation of the form

$$S(k) = K^1\, \varepsilon^{2/3}\, k^{-5/3} \qquad (8)$$

has been found to be applicable where K^1 is the Kolmogorov constant with a value of about 0.5. From Equation (8) it can be seen that the error involved in the computation of the energy dissipation rate ε would be $r^{3/2}$ where r is the relative error in the estimation of the spectral density. Since the beginning of the inertial subrange depends to a certain extent on the distance to the ground(5), a rough estimation of the error involved can be made for the instruments compared here. Assuming that the inertial subrange exists over the frequencies studied, a maximum error of about 18% in ε will occur if it is computed from frequencies below 0.5 hertz. The error tends to increase at higher frequencies.

CONCLUSIONS

Comparisons of the two instruments were made in the atmosphere using data measured by the systems exposed to relatively steady turbulence conditions. From comparisons of the vector winds made in near neutral strong wind conditions, the following conclusions can be made.

(1) The Vector Vane measurements of the turbulence levels are in reasonable agreement with those of the hot-film anemometer, with errors varying from 10 to 16%.

(2) Mean wind speeds obtained from both instruments were approximately the same.

(3) The Vector Vane was found to under-estimate the spectral densities above about 0.5 hertz and the errors involved were found to become significant above one hertz.

(4) Errors involved in computing other parameters viz. energy dissipation rate, friction velocity, etc. from the spectral densities depend on frequency range used for computation.

(5) The Vector Vane has the advantages of simple operation and ruggedness and will give reasonable results at low frequencies. For high frequency turbulence studies, the hot-film sensor provides more accurate information. But, a three-dimensional hot-film probe of the type used in this study should align itself continuously with the mean direction of the wind for best results.

ACKNOWLEDGEMENT

The entire Meteorology Group was involved in various aspects of this study. The material used in this paper is part of the data being collected in a continuing program to study the diffusive properties of the ocean-air, land-ocean environment, sponsored by the Division of Biomedical and Environmental Research of the U. S. Atomic Energy Commission.

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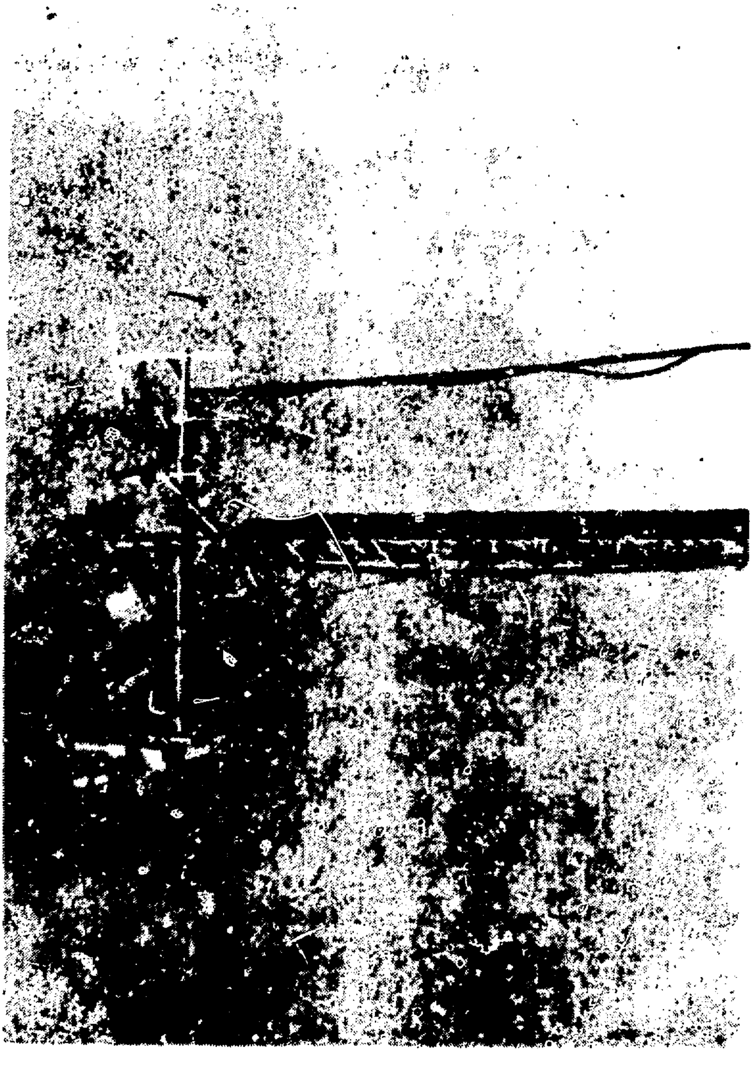

Fig 1

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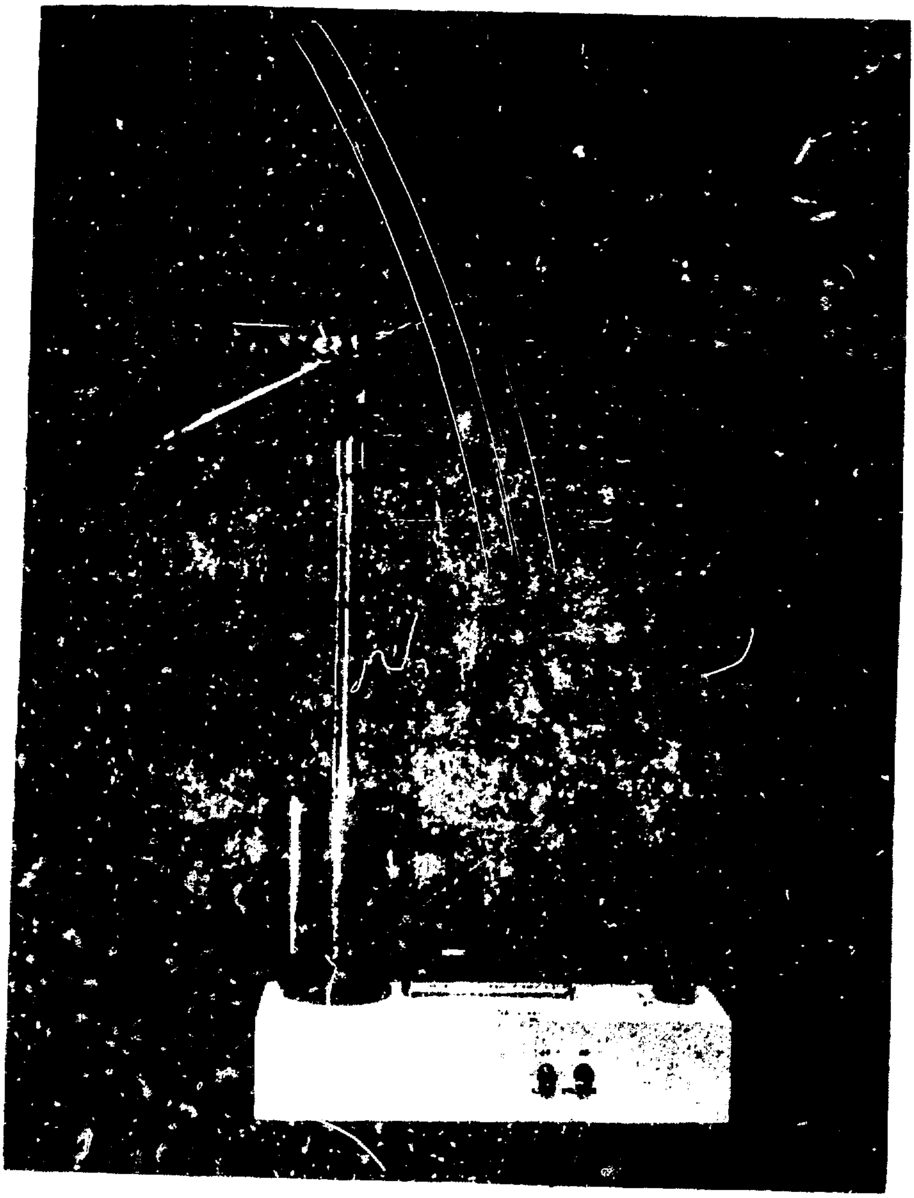

Fig 2a

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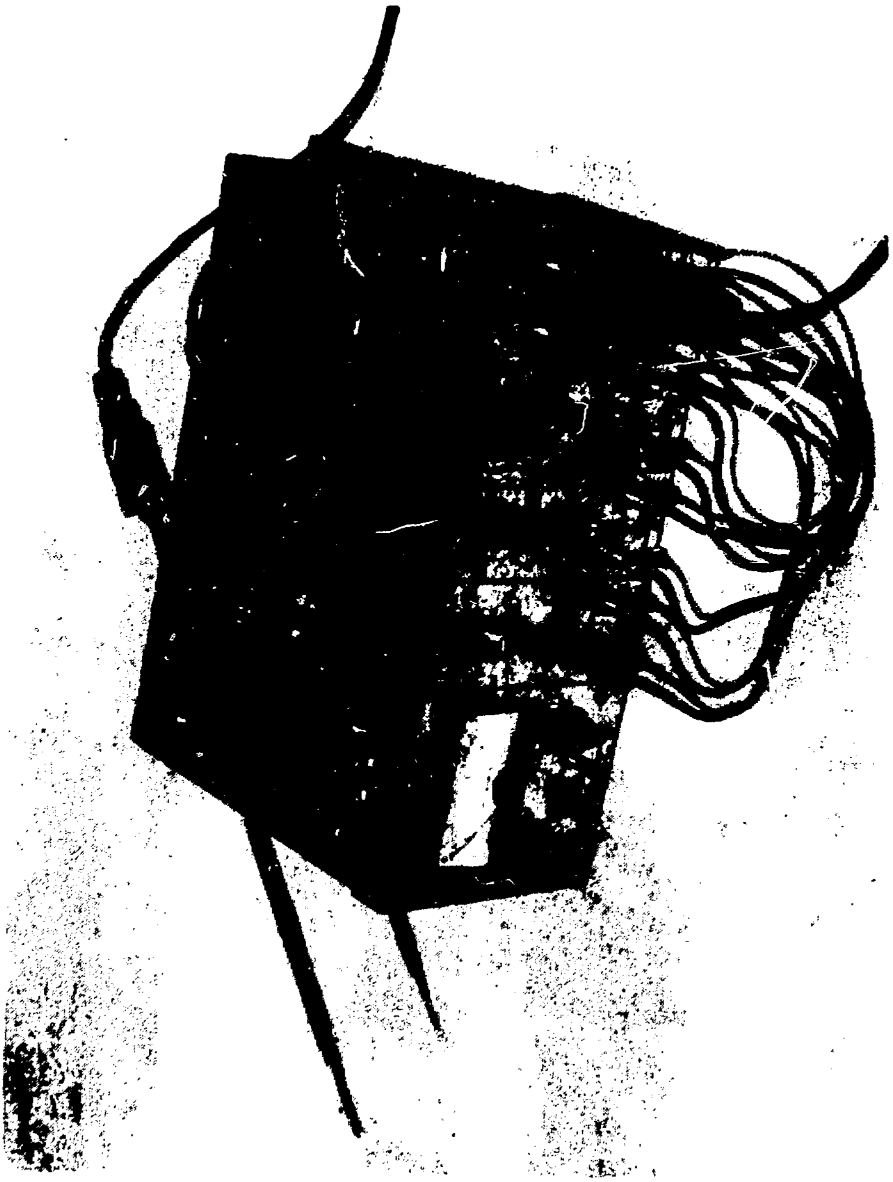

Fig 2b

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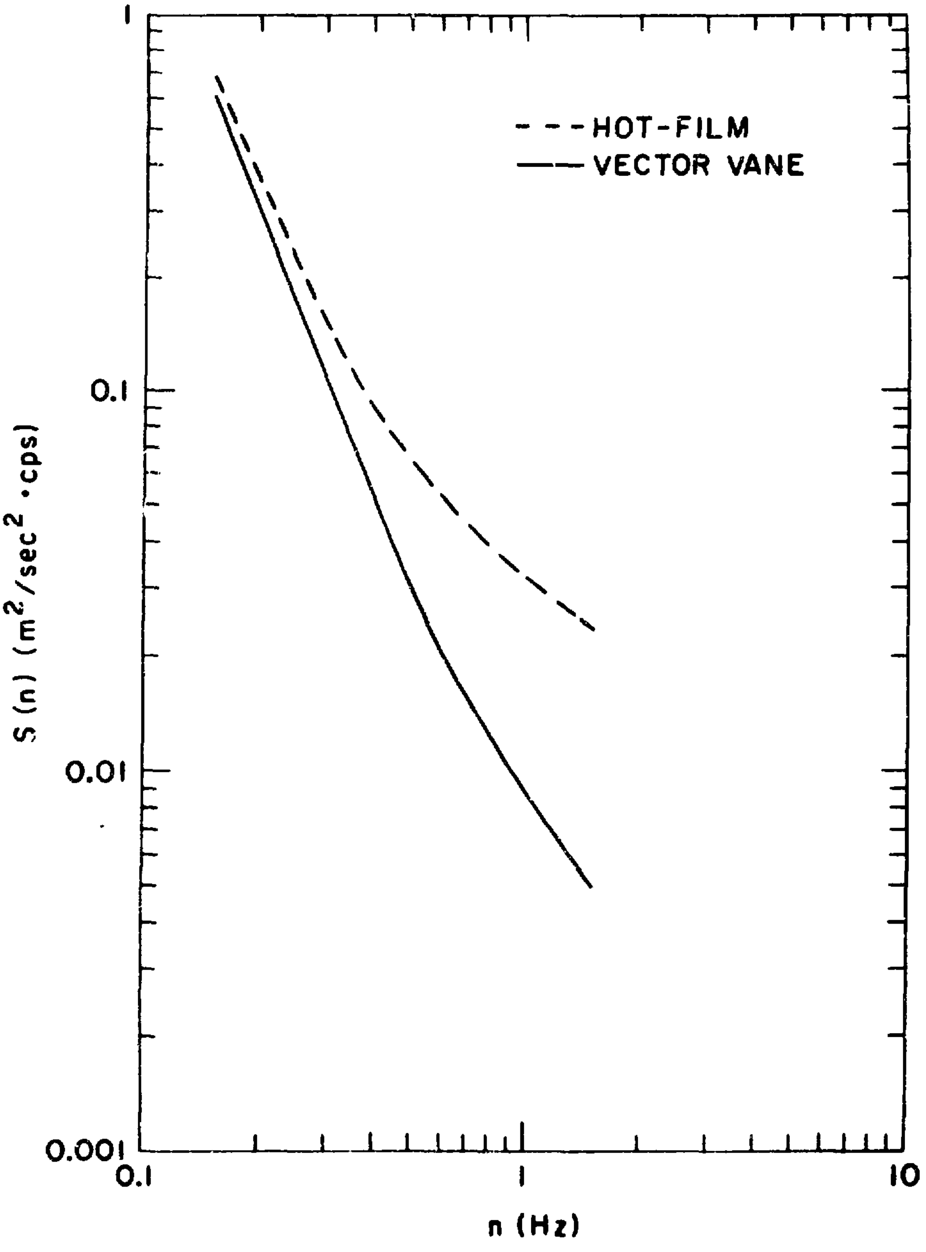

Fig. 3 COMPARISON OF SPECTRAL DENSITIES OF HOT-FILM AND VECTOR VANE IN THE FREQUENCY DOMAIN

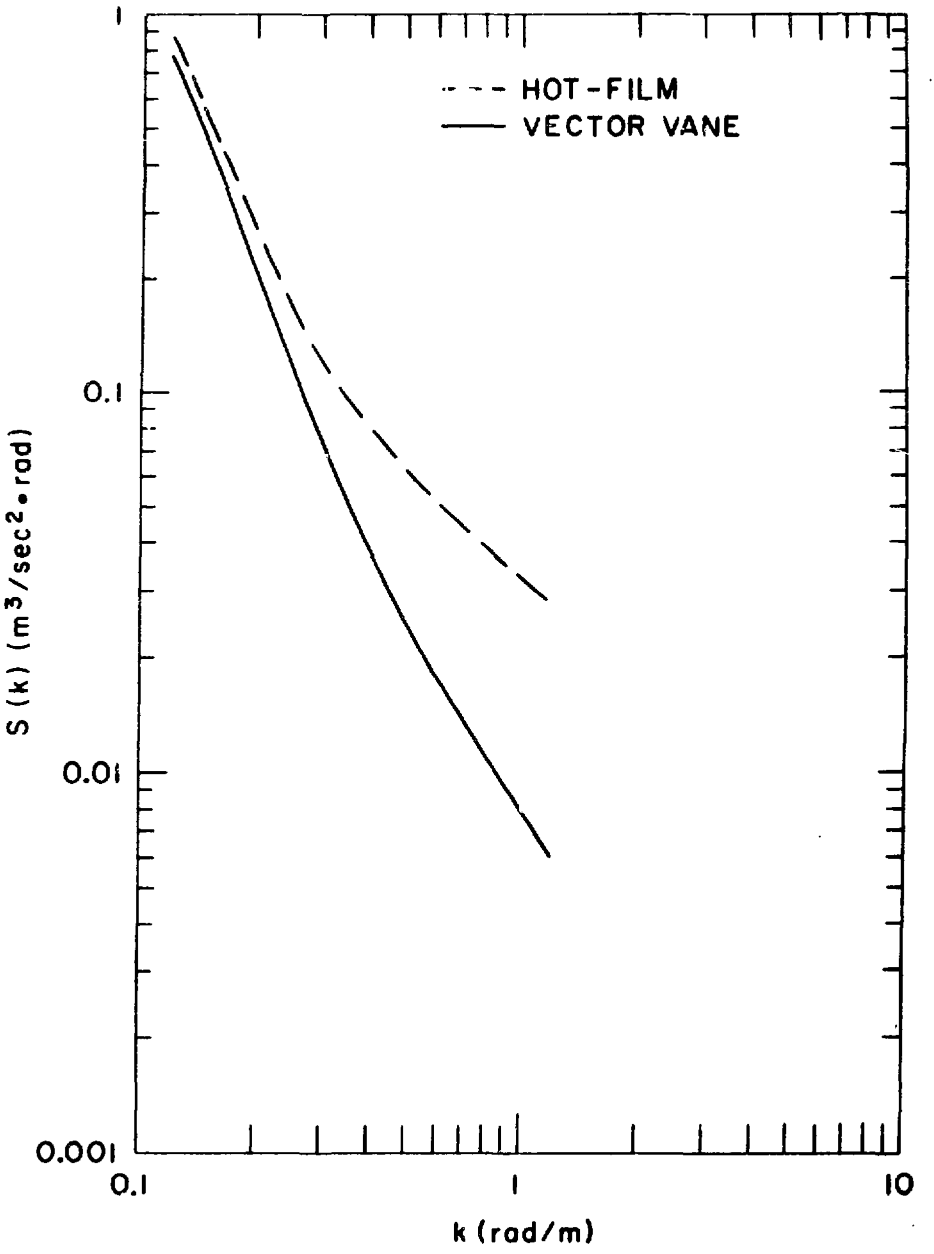

Fig. 4 COMPARISON OF SPECTRAL DENSITIES OF HOT-FILM AND VECTOR VANE IN THE WAVE NUMBER DOMAIN

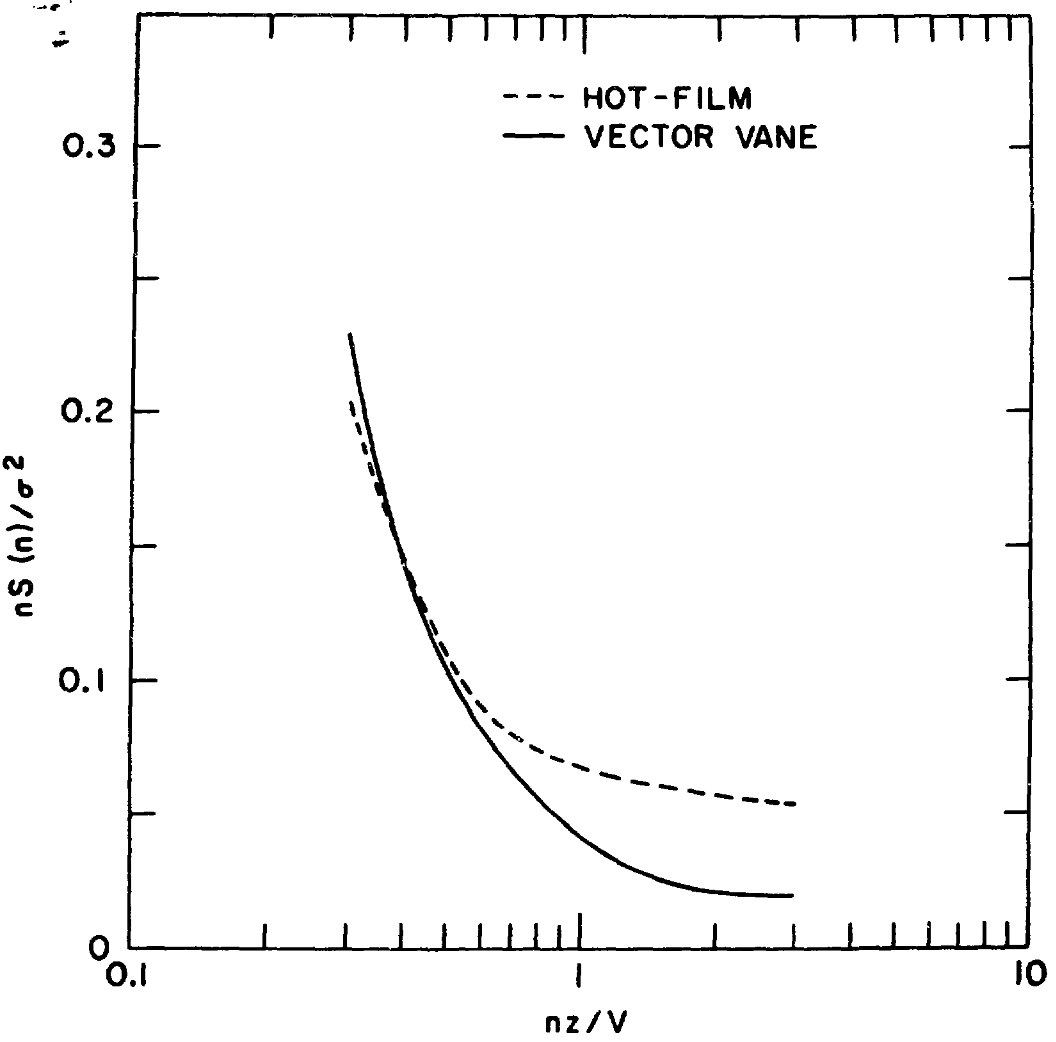

Fig. 5 NON-DIMENSIONAL ENERGY DISTRIBUTIONS FOR THE HOT-FILM AND THE VECTOR VANE

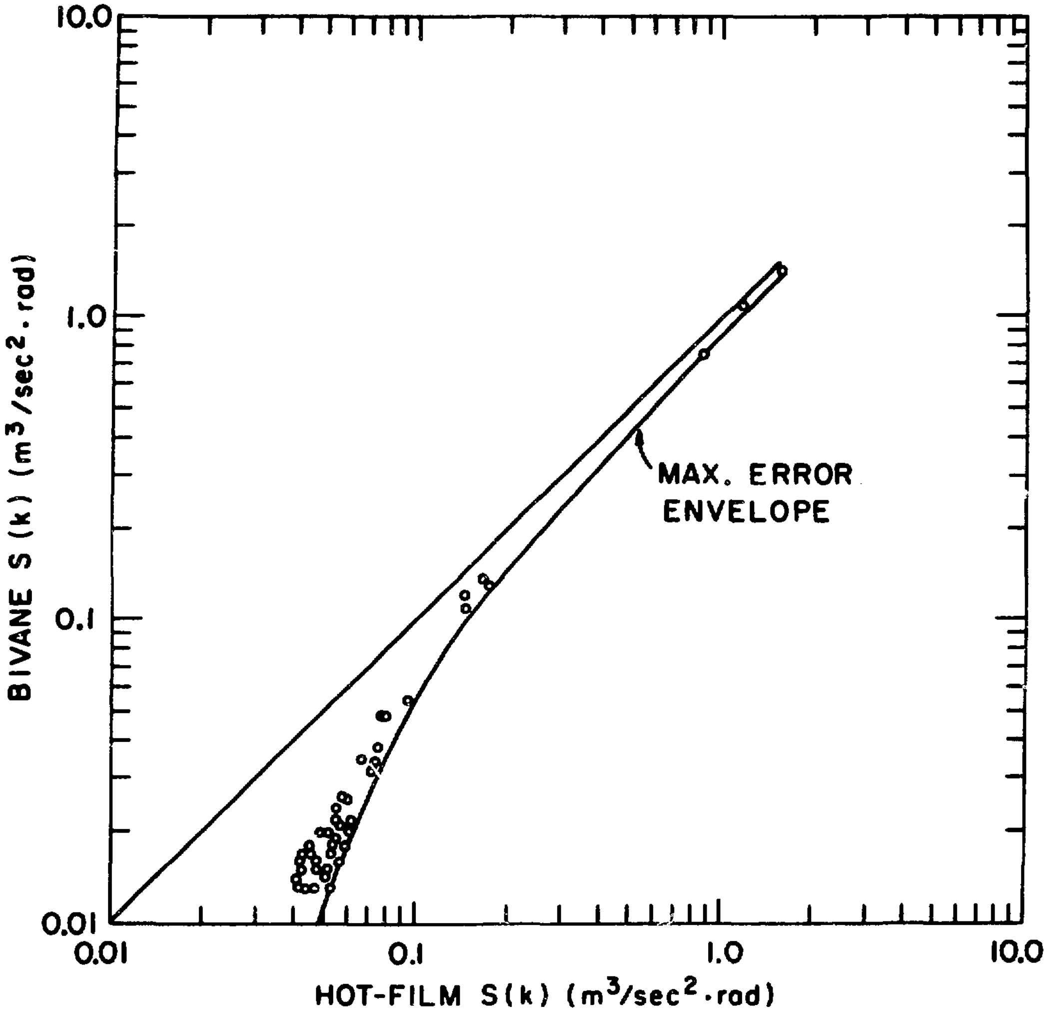

Fig. 6 SPECTRAL DENSITY OF THE VECTOR VANE VERSUS THAT OF HOT-FILM

Fig. 7 RELATIVE MAXIMUM ERROR AT DIFFERENT SPECTRAL DENSITIES