Some Response Characteristics of Parabolic Hot Films in Water

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Nomenclature

B, B' = constants
D = diameter of hot film sensing element
E = d.c. voltage
L = length of hot film sensing element
R_o = surface radius of curvature at film stagnation point.
U = local mean velocity
e = fluctuating voltage
f = frequency
fc = cutoff frequency
k = constant depending on film aspect ratio
ϵ = half peak-to-peak probe displacement
θ = angle between flow and a plane normal to the probe

TURBULENCE in liquids presents an important problem for many disciplines from chemical engineering to ocean physics, hydraulic engineering, and fluvial geomorphology. In such areas mean velocities are usually low (less than 5 msec^{-1}) and spectra of turbulence range over frequencies from about 300 Hz down to a scale determined by that of the experiment. The only instrument presently capable of measuring such a range in a nonlaboratory environment is the hot-film anemometer. The classic field experiment of Grant, Stewart, and Moilliet[7] used a conical hot film probe to test Kolmogorov's hypotheses, while more recent field measurements in hydraulics have been carried out by Holley.[8] The response of such an instrument is a subject of considerable concern, for no adequate theoretical model has been developed for its heat transfer characteristics.[12]

The frequency response of hot wires has been extensively studied since King's pioneering work (Davies and Fisher,[2] Champagne et al.,[1] and Sandborn.[17] Early work on hot films by Grant et al.[7] and Evans[4] tested the frequency response of conical hot films and found the response flat up to 200 Hz, then showing a tendency to rise with increasing frequency up to 1 kHz. However, the work of Fabula[5] showed the response to drop for glass cylinders, the drop being greater for the 5 mil than 2-mil-diam sensor. No other work appears to have been carried out at frequencies above 100 Hz.

Hot films have come under increasing scrutiny since the commencement of commercial manufacture of the probes. Liu[10] examined the response of a cylindrical hot film over the range 2–38 Hz and concluded that the response was essentially flat. More recent work of a similar nature was carried out by Rodriguez et al.,[15,16] in which probes of several different configurations were vibrated over a frequency range of 5–100 Hz in turbulent pipe flow, with a velocity range of 2–5 msec^{-1} in viscoelastic solutions. Responses were practically flat over the entire range but showed a tendency to rise at frequencies below 10 Hz which, it was claimed, was due to experimental error. Theoretical studies of the dynamic characteristics of hot films have been carried out by Rasmussen and Bellhouse,[14] based on a one-dimensional model of the backing material, while a comprehensive study of the frequency response of hot wires and films is given by Sandborn.[18]

The sensitivity to pitch and yaw of the probe has been studied in great detail for hot wires, where the use of angled wires to measure Reynolds stresses and other turbulence components is common (Sandborn[17] and DISA[3]). The sensitivity of hot films is neither clearly understood nor experimentally studied. One theoretical study was carried out by Friehe and Schwartz[6] for cylindrical hot films, while an experiment investigation was carried out by Sellin.[19]

Theory

A description of the heat transfer away from a hot film at low frequencies may be made using a simple, one-dimensional model with fluid on one side and the backing material of the probe on the other: a normalized heat-transfer function can be developed [Rasmussen and Bellhouse,[14] Eq. (15)]. However, for parabolic hot films such a theory must be used with great care. Fabula[5] applied Lighthill's[9] work on the response of heat transfer to fluctuations in freestream velocity to hot films in water flows where the Prandtl number is about 7. The application of this model requires that the hot film be confined to the neighborhood of the stagnation point and that heat transfer to the substrate can be considered separately. Fabula tabulated Prandtl number vs cutoff Stroudhal number for circular cylinders. For noncircular sensors the characteristic velocity gradient in the boundary layer around the probe, $B = B'U_o/D$ is replaced by $B = B'U/2R_o$ where R_o is the surface radius of curvature at the stagnation point. He thus hypothesized that the cutoff frequency would take the form

$$fc = \frac{B'}{3.6}\,\frac{U}{2R_0}\left(\frac{fcD}{U_0}\right)$$

In the case of parabolic films, B' is asserted to be 2. Cutoff frequencies vary with velocity, ranging from 60 Hz at a velocity of 0.3 msec^{-1} to 250 Hz at 1.45 msec^{-1}.

The heat transfer from a hot film depends both on the axial and normal components of flow. The cosine law

$$U/U_{\text{eff}} = \cos\theta$$

for the effective cooling velocity, U_{eff}, as a function of the angle θ between the flow and a plane normal to the probe, has been used as a basis for empirical correlation of directional sensitivity. Champagne et al.[1] used the function

$$U_{\text{eff}} = U(\cos^2\theta + k^2\sin^2\theta)^{1/2}$$

where $k = 0.2$ for $L/D = 200$, $k = 0$ for $L/D = 600$, and $25° < \theta < 60°$. Of greater suitability is the formula proposed by Friehe and Schwartz (1968)

$$U_{\text{eff}} = U[1 - k(1 - \cos^{1/2}\theta]^2$$

where $k = 1 - 2.2\,D/L$, $0° < \theta < 60°$ quoted for cylindrical hot films.

Experimental Procedure

Frequency response studies of three parabolic hot films were carried out in a water tunnel utilizing tap water at 21°C. The speed of the tunnel could be varied up to 2.4 msec^{-1}, but flows of less than 0.3 msec^{-1} were considered too unstable for the long-term measurements of frequency. The probe was vibrated in a horizontal direction and the rms value of its displacement measured. The frequency range of vibrations was from 6 to 500 Hz. The probes tested were Thermo-Systems Inc. quartz coated parabolas (TSI 1253 W), treated against NaCl corrosion. They were

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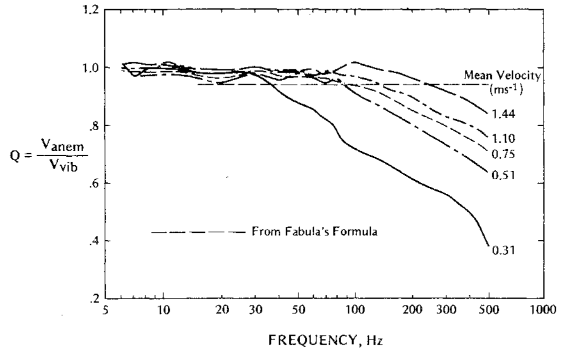

Fig. 1 Fluctuating velocity sensitivity, probe no. 1.

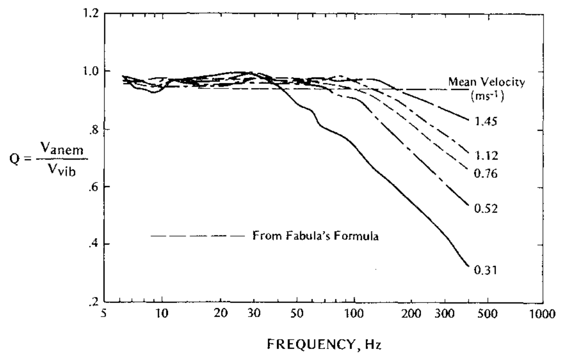

Fig. 2 Fluctuating velocity sensitivity, probe no. 2.

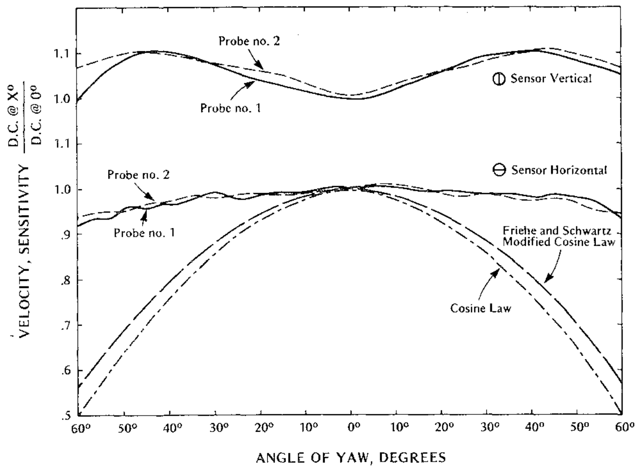

Fig. 3 Angular sensitivity of the probes.

operated by a TSI 1053 constant temperature anemometer at a nominal overheat of 20°C. Preliminary experiments were performed to obtain resistance vs temperature relationships for each probe. These were linear over the measured range from 3° to 47°C, and least-squares fit to the data yielded coefficient of determination in excess of 0.990.

The output from the anemometer was filtered to remove frequencies above 1 kHz and the output fed to a dual trace oscilloscope, one channel showing the probe velocity as a sinusoid, the other channel showing the vibrator displacement measured from the vibrator electronics. Below 10 Hz, the vibrator sinusoidal motion became slightly distorted, the signal showing a flattening of the peaks and thus setting a lower limit on the experimental frequencies. The upper limit was chosen as 500 Hz as preliminary spectra of Raichlen,[13] Rodriguez et al.,[16] and McQuivey[11] indicated that such a frequency was well above the Kolmogorov microscale in water. The rms voltage of the anemometer was recorded, as was the rms voltage of the vibrator which had been previously calibrated to yield probe amplitude. The probe was also monitored by an audio system which indicated when the probe was dirty or when resonances were introduced.

The measurement of angular sensitivity was also performed in the water tunnel, where background noise levels are very low: turbulence intensities were generally less than 0.01%. The probe was rotated so that the tip remained at the same point in the flow. The true mean velocity was measured with a Pitot tube.

Results

Frequency Response

The frequency response of three parabolic hot films was measured at five different velocities in the range 0.3–1.45 msec^{-1}. Calibration curves of the form $E^2 - E_o{}^2 = A + BU^n$ were drawn up with coefficient of determination of 0.990 and these were graphically differentiated to yield sensitivity curves. The data showed considerable departure from King's law which, when fitted, gave coefficients of determination of 0.95.

Figures 1 and 2 show the frequency response for two of the parabolas: the response of the third was in all respects identical. The actual velocity fluctuations U_{vib} were evaluated from knowledge of the probe displacement and frequency:

$$U_{vib} = 2\pi\epsilon f$$

where $\epsilon = \frac{1}{2}$ peak to peak displacement while the fluctuating velocity sensed by the probe was evaluated from

$$U_{anem} = e/(\partial E/\partial U)$$

and

$$Q = U_{anem}/U_{vib}$$

It may be seen that there are individual peculiarities for each probe, such as the dip in the curves at 9 Hz for all velocities for probe no. 2, but within experimental error the probe response may be considered flat for velocities greater than 0.50 msec^{-1} out to 100 Hz. The scatter around the horizontal is partly due to errors in calculating $\partial E/\partial U$. All the curves show a characteristic dropoff at higher frequencies, delayed for higher velocities. For work on ocean turbulence and river flows, this would appear to be relatively unimportant as the dissipation spectra apparently peak near 60 Hz. The dropoff at higher frequencies may have two causes. The first would be the feedback system of the anemometer bridge, but this would appear unlikely at such low frequencies. The second cause is the behavior in the boundary layer around the probe. The cutoff frequencies predicted from Fabula's model are also plotted in the figures and agree remarkably well with the experimental results, considering the assumptions made and that the model was originally developed for cylindrical sensors.

Angular Sensitivity

The response of the probe to pitch and yaw would appear to be a function of this particular probe shape, superimposed upon a general tendency for the response to drop off when yawed out of the flow, when the probe is horizontal. Figure 3 shows the response of the probes when they are horizontal, that is, when the leads are in the horizontal plane. The probes showed very little angular sensitivity. The slight differences between the two films is probably a function of the local variations in film thickness, of inhomogeneities in the quartz coating, or of the plastic shielding that covers the whole probe except for the film possibly causing variations in the boundary layer around the film. Also plotted on Fig. 3 are the cosine law and the model put forward by Friehe and Schwartz,[16]

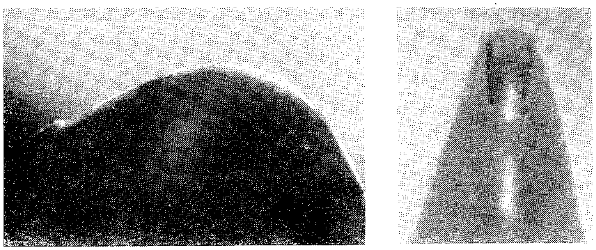

Fig. 4 Probe tip. Note the lip in the left-hand photo where the plastic coating shields the film, while in the right-hand photo, the coating is seen to be peeling away from the film.

which both drop off faster than the empirical results. A close fit to the Friehe-Schwartz model could only be obtained if their k-value were taken to be an order of magnitude smaller, thereby making a very small length to diameter ratio.

Figure 3 shows the angular sensitivity when the probe tip is vertical; that is, when the leads are in the vertical plane. The very unusual response would appear to be most readily explained in terms of the film being behind lips of plastic coating (Fig. 4): only when pitched out of head-on position does the stagnation point occur on the film.

Conclusions

The probe response for frequency is a function of mean velocity, while the cutoff frequency is partly determined by the boundary-layer behavior about the probe (hence by probe geometry). The angular sensitivity of parabolic hot films depends on the probe characteristics, the response to yaw being very flat. The pitch response appears to be influenced by shielding around the probe rather than by the position and shape of the probe tip. A need for further work with unshielded probes would seem to be indicated by this result.

References

[1]Champagne, F. H., Schleicher, C. A., and Wehrmann, O. H., "Turbulence Measurements with Inclined Hot Wires," *Journal of Fluid Mechanics*, Vol. 28, No. 1, April 1967, pp. 153–175.

[2]Davies, P. O. and Fisher, M. J., "Heat Transfer from Electrically Heated Wires," *Proceedings of the Royal Society of London*, Ser. A., Vol. 280, No. 1383, Aug. 1964, pp. 486–527.

[3]*DISA, Probe Manual*, Leaflet No. 2004, 1970.

[4]Evans, D. J., 1962, "An Instrument for the Measurement of Ocean Turbulence," TM 63-8, 1962, Canada DND, Pacific Naval Lab., Victoria, B.C., Canada.

[5]Fabula, A. C., "Operating Characteristics of Some Hot Film Velocity Sensors in Water," *Advances in Hot Wire Aenmometry*," edited by W. L. Melnik and J. R. Weske, Univ. of Maryland, College Park, Md., 1967.

[6]Friehe, C. A. and Schwartz, W. H., "Deviation from the Cosine Law for Yawed Cylindrical Anemometer Sensors," *Transactions of the ASME*, Vol. 35E, No. 4, Dec. 1968, pp. 655–662.

[7]Grant, H. L., Stewart, R. W., and Moilliet, A., "Turbulence Spectra from a Tidal Channel," *Journal of Fluid Mechanics*, Vol. 12, No. 1, Feb. 1962, pp. 241–268.

[8]Holley, E. R., "Turbulence Measurements near the Free Surface of an Open Channel Flow," *Water Resources Research*, Vol. 6, No. 3, June 1970, pp. 960–964.

[9]Lighthill, M. J., "The Response of Laminar Skin Friction and Heat Transfer to Fluctuations in the Free Stream Velocity," *Proceedings of the Royal Society of London*, Ser. A, Vol. 224, No. 1156, June 1954, pp. 1–23.

[10]Liu, C. L., "Characteristics of Hot Wire and Hot Film Sensors in Liquids," Ph.D. thesis, 1967, Purdue University, Lafayette, Ind.

[11]McQuivey, R. S., "Turbulence in a Hydrodynamically Rough and Smooth Open Channel Flow," Ph.D. thesis, 1967, Colorado State Univ., Fort Collins, Colo.

[12]Patterson, G. K. and Zakin, J. L., eds., "Turbulence Measurements in Liquids," *Proceedings of the Symposium on Turbulence Measurements in Liquids*, Dept. of Chemical Engineering, Univ. of Missouri-Rolla, Rolla, Mo., 1971.

[13]Raichlen, F., "Some Turbulence Measurements in Water," *Proceedings of the ASCE*, Vol. 93, No. EM2, April 1967, pp. 73–97.

[14]Rasmussen, C. G. and Bellhouse, B. J., "Low Frequency Characteristics of Hot Film Anemometers," *DISA Information*, Vol. 6, 1968, 1–6.

[15]Rodriguez, J. M., Patterson, G. K., and Zakin, J. L., "Frequency Response Studies for a Wedge Probe in Viscoelastic Fluids," *Proceedings of the Symposium on Turbulence Measurements in Liquids*, Dept. of Chemical Engineering, Univ. of Missouri-Rolla, Rolla, Mo., 1971.

[16]Rodriguez, J. M., Patterson, G. K., and Zakin, J. L., "Effects of Probe Geometry on Turbulence Measurements in Liquids Using Hot-Film Anemometry," *Journal of Hydronautics*, Vol. 4, No. 1, Jan. 1970, pp. 16–21.

[17]Sandborn, V. A., "Notes in Metrology," Rept. CER66VAS32, 1967, College of Engineering, Colorado State Univ., Fort Collins, Colo.

[18]Sandborn, V. A., *Resistance Temperature Transducers*, Metrology Press, Fort Collins, Colo., 1971.

[19]Sellin, R. H. J., "Some Experiments with the Hot Film Anemometer in Water," *Journal of Hydraulic Research*, Vol. 8, No. 1, January 1970, pp. 71–88.