14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Manipulation of Natural Frequency Separation to Improve Dynamic Response of Hot-Wire Probes

C. S. Anderson, S. E. Semercigil and Ö. F. Turan

School of the Built Environment – Mechanical Engineering
Victoria University of Technology
PO BOX 14428, MCMC Melbourne, Victoria, 8001 AUSTRALIA

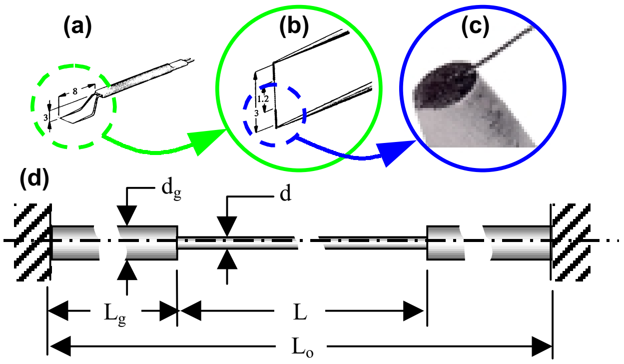
Abstract

The slender sensing wire of a hot-wire probe can resonate with large amplitudes in turbulent flow. This resonance can cause measurement inaccuracies since the wire is no longer stationary with respect to the flow. Once the wire begins to oscillate, any measurement taken is a combination of the flow velocity and the wire velocity, and for this reason, the resulting measurements can be inaccurate. Here, selected experimental results are shown which identify this inaccuracy.

The authors have previously investigated structural modifications to the profile of the sensing wire to reduce large amplitude oscillations. They have shown that geometries having close first and second natural frequencies have favorable vibration characteristics. Structural modifications to the wire geometry are suggested to reduce these inaccuracies. Experimental results are presented here supporting the new geometries.

Introduction

Hot-wire anemometry is still a powerful and practical technique for measuring mean and fluctuating fluid velocities and temperatures in turbulent flows. For research, teaching and industrial applications, it is popular due to being relatively inexpensive and easy to use. When used in the constant temperature anemometry (CTA) mode, the sensor of a hot-wire probe is kept at a temperature of about 300^o C during measurements. In Figure 1, the sensing wire is shown mounted between two prongs. For numerical modelling purposes, the hot-wire is represented as shown in Figure 1(d). The middle sensing wire has d and L, respectively, for diameter and length; whereas d_g, L_g and L_o represent the diameter and length of the thicker ends and the total length of the wire, respectively. Boundary conditions are taken to be built-in where the wire is rigidly connected to the prongs as shown in the electron microscope photograph in Figure 1(c).



(Dimensions are shown in mm)

Figure 1: Showing (a) hot-wire probe in entirety, (b) hot wire alone, (c) electron microscope photograph of wire and prong connection and (d) schematic diagram of the beam model used for numerical simulations. [3] (1993).

The cooling effect of the oncoming fluid on the sensing wire is interpreted as the velocity of the flow to be measured. The assumption is that the wire is stationary, and the velocity of the flow 'relative' to the wire can be assumed to be the 'absolute' velocity. However, due to its flexibility, the probe wire is susceptible to large amplitude resonance vibrations. As a result of these vibrations, the relative velocity can no longer represent a close indication of the absolute flow velocity.

The problem of wire vibration was first reported in [2,3]. Perry and Morrison investigated two types of wire vibration, namely, rotational vibration and skipping (or whirling) of the wire. However, the more predominant case of stream-wise transverse vibrations had not been investigated in detail before [4].

The earlier study presented in [4] reported measurement errors when large amplitude wire vibrations are expected. It suggested that hot wire dimensions must be chosen such that the resulting first natural frequency of the wire will be larger than the expected frequency content in the flow. One way to achieve a high first natural frequency of the wire is to use a short wire, which increases the dynamic rigidity. However, a short wire causes heat loss problems. Heat conduction creates non-uniform temperature along the wire, which in turn reduces sensitivity. This prominent problem is discussed in [5] and [6]. Hence, this condition may not be practically achievable. To reduce heat loss to the prongs, an acceptable sensitive length, L, has been defined as $L/d \geq 200$ [6] where d is the wire diameter. This definition was later modified to $160 \leq L/d \leq 310$ [7]. The upper limit is to minimise spatial averaging over the wire length.

When the first natural frequency is within the frequency range of excitation, accurate measurements are observed if the first and second natural frequencies of the probe wire are close numerically. A limited number of already existing favourable designs is identified in [4]. No effort was made to look at new designs with improved dynamic characteristics. In keeping with this finding, the objective here is to present geometric changes that can yield coincident first and second natural frequencies.

The authors previously presented numerical predictions, and later, scaled-up experimental verification of the predictions [8,9,10] Here, preliminary turbulence measurements are presented to verify the existence of the vibrating wire problem and to validate the suggested modifications.

Suggested Structural Modifications

This section briefly summarises the previous work by the authors. It is included here as background to the results presented in this paper. The authors have shown that if the first and second natural frequencies of a slender beam (or wire) are close together, the beam will be less susceptible to large amplitude vibration. This phenomenon relates to the mode shapes of the first and second natural frequencies. As shown in Figure 2, the first mode shape has an anti-node at the mid-span where the second mode shape exhibits a node. If these two mode shapes attempt to co-exist, then the node of the second mode suppresses the anti-node of the first mode. The end result is that the vibration amplitude is reduced.

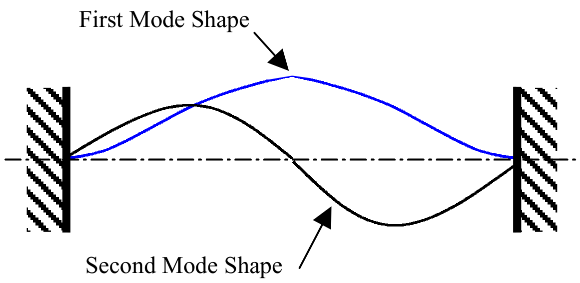


Figure 2. The first and second mode shapes of a slender beam between two built-in end supports.

The authors have shown that the first and second natural frequencies of the wire can be pushed close together by carefully selecting the plated end diameter and length, d_g and L_g, respectively, in relation to the sensitive diameter and length, d and L, respectively. In general, for a given sensitive diameter, d, the end diameter should be at least 5d. Also, the end length to sensitive length ratio, L_g/L, should be as large as possible, while still giving an acceptable L/d of between 160 and 310. The next section discusses experimental results obtained with three hot-wire probes to illustrate the effect of wire vibration and the success of the suggested structural modifications as a control technique.

Experimental Setup

Fully developed turbulent pipe flow measurements were conducted using the experimental setup shown in Figure 3. A throttled fan is capable of generating mean centreline velocities of 0 to 33m/s. The pipe is made from mild steel with a smooth interior surface and an internal diameter of 108mm. To ensure fully developed turbulent pipe flow conditions at the exit, the pipe is 18m long. The Reynolds number at the pipe exit is 230000, based on the centreline velocity.

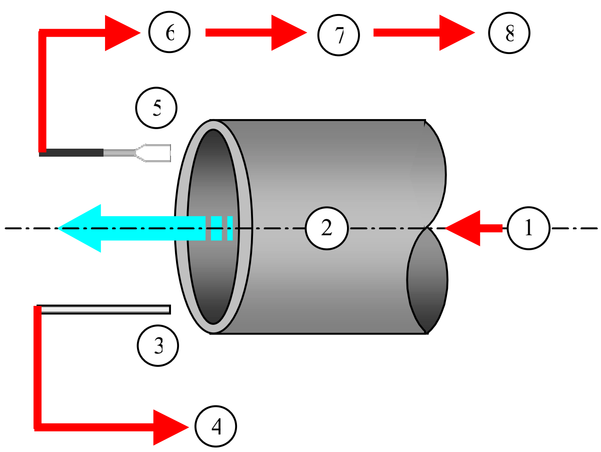


Figure 3. Schematic diagram of the experimental set-up.

1 Fan
2 Steel Pipe: L=18m, I.D. = 108mm
3 Pitot tube: I.D. = 1mm
4 Micromanometer: Furness Controls Limited FC012
5 Hot-wire Probe with 90 degree probe support and 4m cable
6 Dantec Streamline 90N10 Frame CTA Module 90C10
7 Keithley Metrabyte STA-U DAS58 Universal Screw Terminal Accessory Board
8 Pentium 166MHz Personal Computer with 64Meg RAM

The hot-wire probes were positioned at 13.2mm below the pipe wall and 2mm downstream of the pipe exit to enable wire observation during measurements. A 1mm diameter Pitot tube was mounted in the mirror image position directly below the hot-wire probe, as shown in Figure 3 for calibration purposes. Measurements were taken using the Dantec Constant Temperature Anemometer (CTA), Streamline, and the accompanying software, Streamware. The data were recorded on a desktop computer via a Metrabyte data acquisition board, DAS58, using a sampling frequency of 100kHz, for just over 5 seconds, giving a total of 524288 points. The sampling frequency was chosen following the observation that the frequency spectra had no significant amplitude after 35 to 40 kHz at sampling speeds of 100 and 200 kHz. Post processing was done using Matlab.

Separate measurements were taken using seven different probe geometries at the same position in the flow, three of which are discussed here. The first probe used was a Dantec 55P05, a standard boundary layer probe, with dimensions listed in Table 1. Table 1 also shows the dimensions of Probes 4, and 8, which were made in the laboratory for the purposes of this study.

Measurements in Fully Developed Pipe Flow

The mean velocity value was removed from the velocity trace of each probe before taking its fft (fast Fourier transform). Each power spectrum, $E_1(k_1)$ of longitudinal velocity fluctuations, u, was then scaled so that the area under the graph equalled the mean square velocity fluctuations, $\overline{u'^2} = \overline{u^2}$. The frequency axis of the power spectrum was converted into one-dimensional longitudinal wave number, k_1, as follows:

$$k_1 = \frac{2\pi}{U} f \tag{1}$$

where: f is the frequency of velocity fluctuations, and
U is the longitudinal mean velocity.

Wire response to high frequency, small-scale fluctuations can be seen clearly in a plot of dissipation spectra. The dissipation spectra $k_1^2E_1(k_1)$ measured with these three probes are plotted against one-dimensional longitudinal wave number, k_1 in Figure 4.

Firstly, Figure 4a shows the dissipation spectrum of a standard Dantec 55PO5 boundary layer probe with a sensitive length of L=1.10mm, d=5.75µm and dg=40µm. This plot represents a typical dissipation spectrum with the exception of isolated spikes. These spikes must be due to the electronic circuitry since they appear almost consistently in all spectra presented in Figure 4a to 4c.

Based on early L/d arguments alone, probe 4 would have been deemed acceptable, since it has an L/d inside the allowable range of 308 and a sensitive length of 0.77 mm. However, here, probe 4 is predicted to be extremely susceptible to large amplitude vibration, since it has its first natural frequency well separated from the second one. Inspection of the dissipation spectrum of probe 4, shown in Figure 4b, reveals a significant dip, which is believed to be due to wire resonance as expected. The dip occurs in the vicinity of k_1=3.5×10^3 m^{-1} corresponding to a frequency of about 17 kHz, close to the predicted first natural frequency of 11 kHz. The natural frequencies of the wires were calculated by solving the eigenvalue problem generated with 30 standard finite beam elements across the wire length. This method assumes perfectly rigid boundary conditions; whereas in practice, this is not the case. Therefore, it is not unreasonable to expect the numerically predicted natural frequency to differ slightly from the measured one.

The final probe geometry for discussion here is that of probe 8, which has an unacceptable L/d of 112 with L=0.56 mm. The dissipation spectrum measured with this probe, Figure 4c, demonstrates a smooth curve without any dips or peaks. Probe 8 was predicted to have a close first and second natural frequency with the third well separated. It also has its first natural frequency extremely high compared to the other probes tested. Numerically, it stood out to be the least susceptible to resonance in comparison with the other geometries listed in Table 1. Again, this expectation was confirmed by the measurements.

Conclusions

Preliminary measurements are presented from a fully developed turbulent pipe flow to test the predicted characteristics of hot-wire probes. Significant dips are obtained in the dissipation spectra measured with susceptible probes. These dips are likely due to the structural resonance of the probe wire. Wire dimensions can be chosen such that large amplitude resonance is discouraged by making the first natural frequency outside the excitable range, or by grouping the first and second natural frequencies of the wire as close as possible. Additional measurements are currently underway to further explore these preliminary findings.

References

[1]Dantec Electro Medical and Scientific Equipment Ltd *Probe Catalogue* Publication No. 2201 E (Denmark) 1982, 10.

[2]Perry, A.E. and Morrison, G.L., Errors caused by hot-wire filament vibration. *Journal of Physics E: Scientific Instruments*, 5, 1972, 1005-1008.

[3]Perry, A.E. and Morrison, G.L., Vibration of hot-wire anemometer filaments. *Journal of Fluid Mechanics*, 50, 1971, 815-925.

[4]Turan, Ö.F., Semercigil, S.E. and Chukkapalli, G., Effect of structural vibrations on hot-wire probe response. *Measurement Science and Technology*, 4, 1993, 1416-1425.

[5]Champagne, F.H., Turbulence measurements with inclined hot-wires. Ph.D. thesis, University of Washington, 1966.

[6]Comte-Bellot, G., Hot-wire anemometry. *Annual Review of Fluid Mechanics*, 8, 1976, 209-230.

[7]Turan, Ö.F., and Azad, R.S., Comparison of the zero-wire length dissipation technique with spectral corrections and the effect of high turbulence intensity. *Experimental Thermal Fluid Science,* 6, 1993, 292-308

[8]Anderson, C.S., Semercigil, S.E. and Turan, Ö.F., An investigation of the structural dynamics of hot-wire probes. Proceedings of the 13th Australasian Fluid Mechanics Conference, Melbourne, Australia, 1998, 75-78.

[9]Anderson, C.S., Semercigil, S.E. and Turan, Ö.F., Hot-wire geometry modifications to improve dynamic response, 3rd ASME/JSME Joint Engineering Conference, San Francisco, California (FEDSM'99) 1999, paper no. FEDSM99-5032.

[10]Anderson, C.S., Semercigil, S.E. and Turan, Ö.F., Local structural modifications for a better hot-wire probe design, 6th International Thermal Anemometry Symposium, Melbourne, Australia, 2001, Paper No. S285-3-P10.

	L_g [mm]	L [mm]	L_o [mm]	L_g/L	d_g [μm]	d [μm]	L/d	f_{n1} [kHz]	f_{n2} [kHz]	f_{n3} [kHz]	[m/s]	$\sqrt{\overline{u^2}}$ [m/s]
Dantec 55PO5	0.95 ±0.01	1.10	3.00	0.87 ±0.01	40	5.75	191.3	12.2	12.8	20.0	32.2	5.92
Probe 4	1.14 ±0.04	0.77	3.05	1.48 ±0.05	71	2.5	308	11.0	20.9	21.0	30.93	6.01
Probe 8	1.11 ±0.01	0.56	2.78	1.98 ±0.02	82	5	112	20.6	20.7	35.0	32.35	6.32

Table 1. Dimensions of the three selected probes. Mean and fluctuating velocity values as measured with these probes are given for completeness.

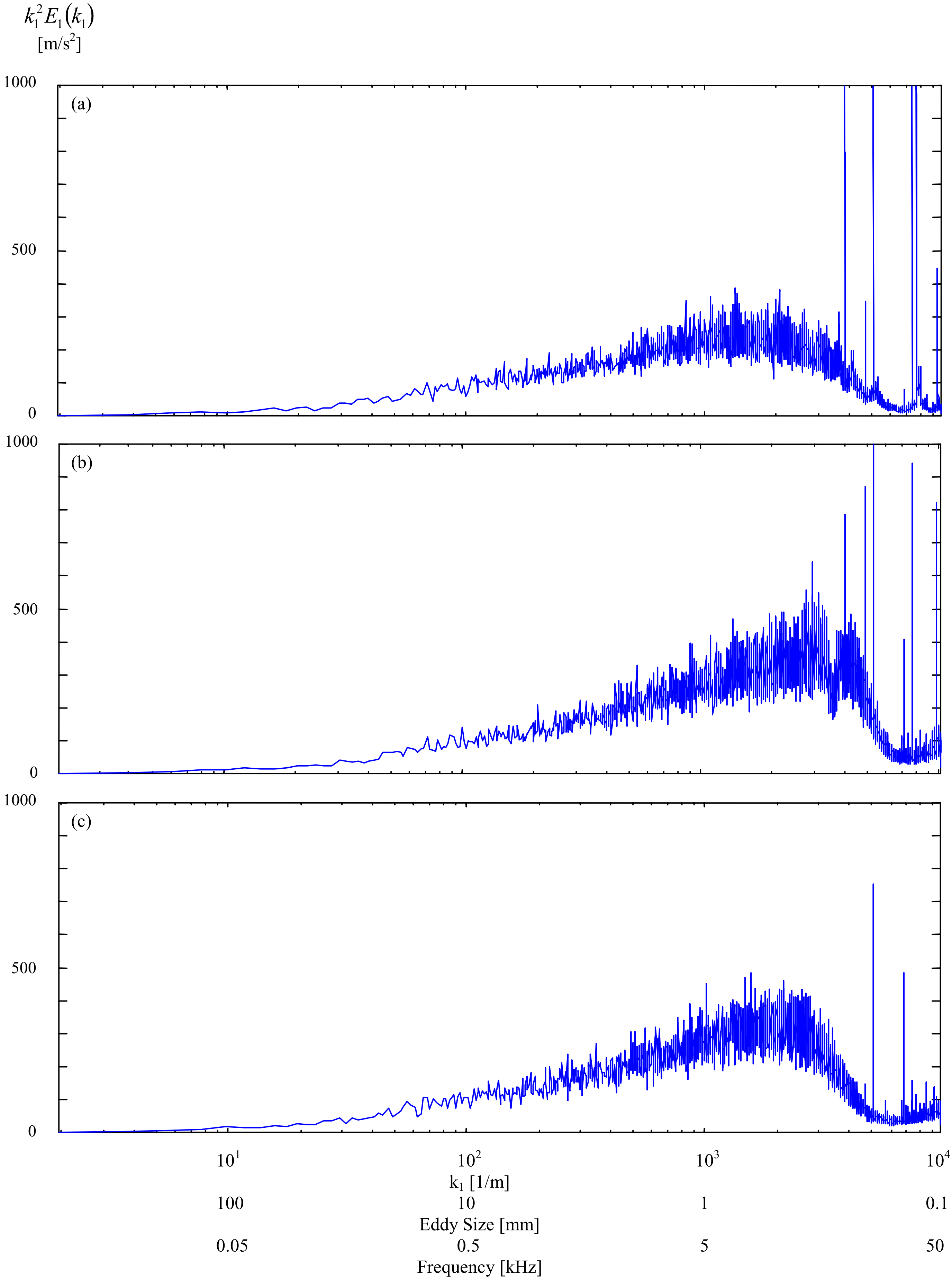


Figure 4. Dissipation spectra of the three probes discussed here, (a) Dantec 55PO5, (b) Probe 4 and (c) Probe 8.