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AN INVESTIGATION OF THE STRUCTURAL DYNAMICS OF HOT-WIRE PROBES

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ABSTRACT

Hot-wire probes are very slender structures, and as a result they are prone to excessive transverse oscillations during flow measurements. This structural vibration control problem may be approached from the point of view of suggesting geometric changes to locate the resonance frequencies of the structure in a favorable configuration. Sample results presented here indicate that significant improvements are possible. This paper represents a progress report of an ongoing research.

INTRODUCTION

Hot-wire anemometry is a powerful and practical technique for measuring mean and fluctuating velocities and temperature fluctuations in turbulent flows. It is relatively inexpensive and easy to use for research, teaching and industrial applications. For traditional isothermal applications in a laboratory environment, the sensor of a hot-wire probe is a thin wire, in the order of 2 to 5 microns in diameter. This thin wire is kept at a temperature of about 300° C during measurements, when used in constant temperature anemometry (CTA) mode. The cooling effect of the oncoming fluid is interpreted as the velocity of the flow to be measured. The underlying assumption of this interpretation 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 hot-wire probe 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 As a result of these vibrations, the relative velocity can no longer represent a close indication of the absolute flow velocity.

Since the hot-wire filament is essentially a slender beam which is subjected to fluctuating fluid forces, it is highly prone to structural vibrations. Structural vibrations can alter the relative flow velocity resulting in erroneous readings. Due to the inherent flexibility of the wires, several natural frequencies may fall in the forcing frequency range, since turbulence is a wide-band phenomenon. The problem of wire vibration was first observed by Perry and Morrison (1971, 1972). 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 the work of Turan et al. (1993).

The earlier study of two of the authors has indicated measurement errors when large amplitude wire vibrations are expected (Turan et al. 1993). This study has suggested that the filament of a hot-wire probe can be excited at its first or higher resonance modes. If the probe wire is excited in the first mode, the resulting vibration velocity is in-phase with the velocity fluctuations in the flow along the entire wire length. Hence, these in-phase oscillations may reduce the relative velocity between the wire and the flow, leading to smaller readings than the true absolute velocity of the flow. Therefore, 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. However, a short wire causes heat loss problems. Heat conduction creates non-uniform temperature along the wire, which reduces hot wire sensitivity. This prominent problem is discussed by Champagne (1966) and Comte-Bellot (1976). Hence, this condition may not be practically achievable. For cases when the first natural frequency is within the frequency range of excitation, the most accurate measurements have been observed when the first and second natural frequencies of the probe wire are close numerically. This last condition will be elaborated further in the next section.

The earlier investigation pointed out a limited number of already existing favorable designs. In this investigation, the reasons why different resonant modes affect the structural response differently are discussed. In addition, representative results from a new numerical work are presented in which geometric changes are suggested to reduce the susceptibility of a standard hot-wire probe to excessive vibrations.

The numerical model of the hot-wire probe used in this investigation is schematically shown in Figure 1. In this figure, the middle sensing wire has d and L for diameter and length, whereas dg, Lg and Lo represent the diameter and the length of the thicker ends and the total length of the wire, respectively. Boundary conditions are taken to be built-in where the connections are to the prongs.

Standard Euler-Bernoulli finite beam elements were used to obtain the mass and stiffness matrices. Ten elements were used for each of the three length sections. Once the matrices were obtained, the corresponding eigenvalue problem was solved to obtain the resonance frequencies. Promising cases were further analysed to compare their dynamic response after they were exposed to a uniformly distributed random white noise excitation. This random noise, covering at least twice as wide a frequency range presented in the next section, was generated once and used to excite all cases to maintain a consistent comparison base. Response of the hot-wire probe to this random excitation was obtained by direct integration of the matrix equations using the Newmark-β method. Numerical simulations were performed until the root-man square average of the response settled to a steady state value (typically in the order of several hundred fundamental periods of simulation) .

Although only numerical results are presented in this paper, experimental verification of these results are currently being planned with comparative wind tunnel measurements of the existing and the modified geometries.

FAVORABLE STRUCTURAL CHARACTERISTICS OF A HOT-WIRE PROBE

As an example, one of the existing hot-wire probe geometries, probe number 3 in Turan et al. (1993), will be investigated here. This probe had dg =30μm, d =5.75μm, Lg =0.91mm and Lo =3mm. These properties resulted in the first two natural frequencies to be 9227 Hz and 10271 Hz. This probe has already been reported to be a favorable probe in the earlier study.

The reason why this particular probe has been evaluated positively in the earlier work is related to the natural mode shapes of the first and the second resonances. The first resonance produces a mode shape similar to a half-sinusoid along the length of the probe with its largest amplitude in the mid-span. Keeping with the sinusoid analogy, the second mode shape is similar to a full-sinusoid with a zero amplitude (node) where the first mode has its largest amplitude. When the first two resonances are well separated, the overall response is overwhelmed by the more flexible first resonance mode. Hence, well separated resonance frequencies may lead to excessive structural vibration amplitudes. On the other hand, when the second resonance frequency is close to the first resonance frequency, the node of the second mode imposes a retarding effect on the mid-span response of the first mode. This retarding effect reduces the "apparent" flexibility of the first resonance mode, and seems to lead to a smaller overall response.

Following the argument presented in the previous paragraph, the probe investigated here should have favorable characteristics due to its ratio of the second to first resonance frequencies of 1.113. Therefore, it may be reasonable to expect that if the third and higher resonance frequencies could be manipulated to approach the first two, the structural properties should be enhanced further. The present investigation is to check the validity of this last assertion. Incidentally, the third mode shape is similar to a one-and-a-half sinusoid wave (with two nodes, approximately marking $1/3^{rd}$ of the length) and the fourth mode is similar to two full sinusoid waves (with three nodes, approximately marking $1/4^{rd}$ of the length).

RESULTS

Initial simulations (not given here due to lack of space) indicated a detrimental effect, if the third resonance frequency approaches to the first two. As mentioned earlier, the third resonance mode has two nodes approximately $1/3^{rd}$ length from each end, producing a local peak response in the middle where the second mode has a node. Having a peak response at the node of the second mode, reduces the retarding effect of the node of the second mode on the first mode. Therefore, structural changes should separate the third resonance frequency from the first two. In addition, moving the 4^{th} resonance frequency closer to the 3^{rd} resonance frequency seems to be helpful.

The sensing middle section of the wire is kept at its original dimensions for the results presented in Figure 2, to show the effect of varying the total length, Lo. Variation of Lo is the result of varying only the length of the end sections, Lg. The vertical axis represents the five resonance frequencies corresponding to the five curves given in an ascending order from the first to the fifth frequency. Figures 2(a), 2(b) and 2(c) correspond to diameter of the ends, dg, of 15 μm, 30 μm and 45 μm, respectively. A vertical line drawn at Lo = 3 mm in Figure 2(b) indicates the first five frequencies of the original state at the intersection points with the five curves.

There are two general trends in Figure 2. First, resonance frequencies increase as the diameter of the thick ends increases for all three frames. Secondly, in each frame, as Lo increases the natural frequencies decrease. The reason for both trends is the increase in the flexibility for smaller dg and longer Lg. The exception to these trends is when a particular mode shows insensitivity to the variation of L_o, such as those of the flat sections of the third resonance in Figures 2(b) and 2(c).

In each frame, as Lo decreases from the original value of 3mm, the first resonance frequency increases, as a result of increasing the overall stiffness as mentioned above. This is a desirable trend to avoid resonance in the fundamental mode. However, as Lo decreases, the separation between the first and second resonance frequencies also increases negating the desirable effect of the increased first resonance frequency. On the other hand, as Lo increases from the original value of 3 mm, the value of the first resonance frequency decreases but the gap between the first and the second resonances become smaller. Especially for the two larger diameters of 30 µm. and 45 µm. in Figure 2(b) 2(c), these two frequencies are almost coincident for Lo larger than 3.5 mm. In addition, the larger values of Lo have an added benefit of separating the third resonance frequency further from the first two. Again, this last trend is particularly true for the two larger diameters.

Seven representative Lo values (of 2mm, 2.5mm, 3mm, 3.5mm, 4mm, 4.5mm and 5mm) were selected from Figure 2, and subjected to a uniformly distributed excitation to obtain their dynamic response for comparison. Result shown in Figures 3(a), 3(b) and 3(c) are the root mean square (rms) displacement values obtained for different locations along the length of each probe for dg of 15 µm., 30 µm. and 45 µm.. A value of zero along the horizontal axis represents the middle of the wire. Hence, different lengths could be identified easily from their spread along the horizontal axis. The rms distribution marked (✡), with a flat middle portion and Lo = 5 mm, will be discussed later in this section.

Results presented for the smallest end diameter of 15 µm. in Figure 3(a) are significantly larger than those of the larger diameters. This trend could easily be related to the results presented in Figure 2(a) earlier where it is clearly demonstrated that the first two frequencies (in fact, all five of them shown in this figure) are well clear of each other to produce any desirable behaviour structurally.

As the total length increases, due to increasing Lg, the ends become more flexible and contribute more significantly to the dynamic response. As the contribution of the ends increase, the contribution of the sensitive wire decreases. This last trend is due to the suppression effect of the second mode on the first mode. As shown in Figures 2(b) and 2(c) earlier, large values of Lo can produce almost coincident frequencies of the first two modes and move the third one away from the first two.

The response of the original wire is marked with (+) in Figure 3(b). In this figure, the smallest peak response is obtained with Lo = 4.5 mm (•), and it is only 15% smaller than the response of the original wire. The increase of the diameter of the ends to 0.045 mm in Figure 2(c), results in the smallest response with the largest Lo = 5mm, and this response is again only 20% smaller than the original wire. Hence, although some useful trends could be observed, the overall gain which could be achieved is quite marginal if the sensitive wire is allowed to remain unchanged.

The case marked with (✡) in Figure 2 corresponds to Lo = 5mm and L/Lg = 3. For this case, the sensitive length is allowed to vary from its original L /Lg of 0.77, although the sensitive wire diameter is still kept at its original value. Hence, allowing the sensitive wire length to change produces significant reductions of better than 85% in the middle of the wire. It should be mentioned that this 85% attenuation does deteriorate for smaller L/Lg than 3.

CONCLUSIONS

Sample results from an ongoing extensive numerical study are presented here to investigate the possibility of improving structural characteristics of a hot wire probe. It is suggested that significant improvements are possible if the total length and the length of the sensitive wire are allowed to change. These results need to be checked experimentally and need to be evaluated for their practical value.

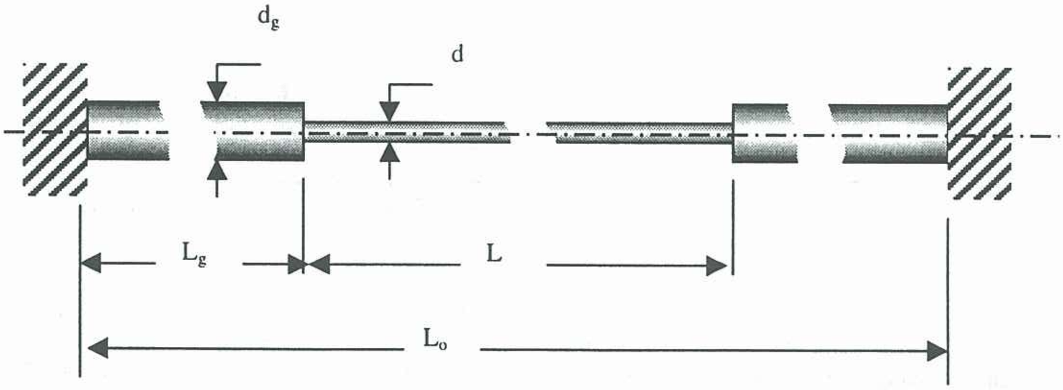

Figure 1. Schematic representation of the hot-wire model for numerical simulations.

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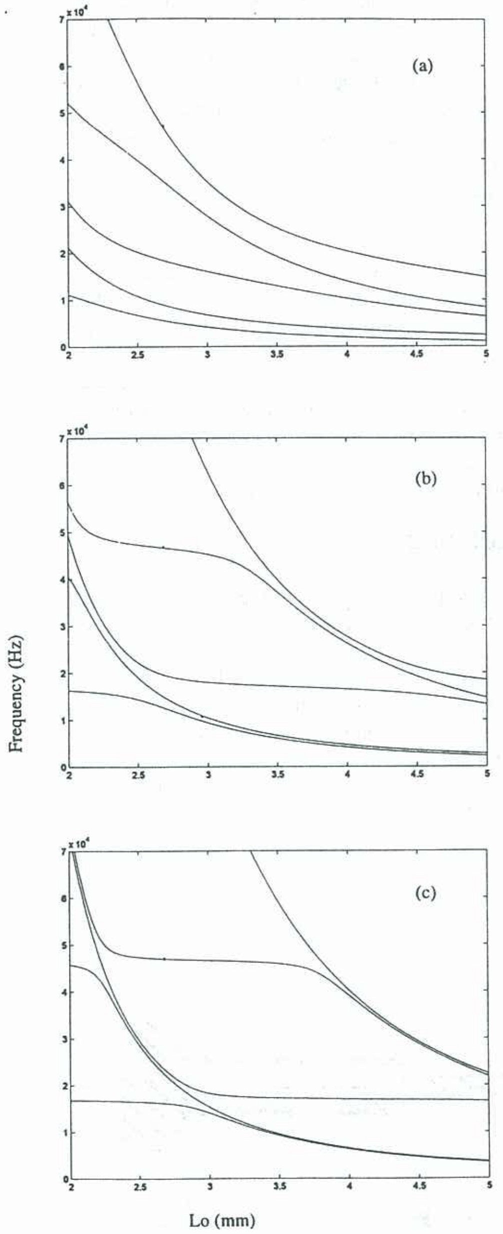

Figure 2. Variation of the first five natural frequencies with Lo and for dg of (a) 15 μm, (b) 30 μm and (c) 45 μm.

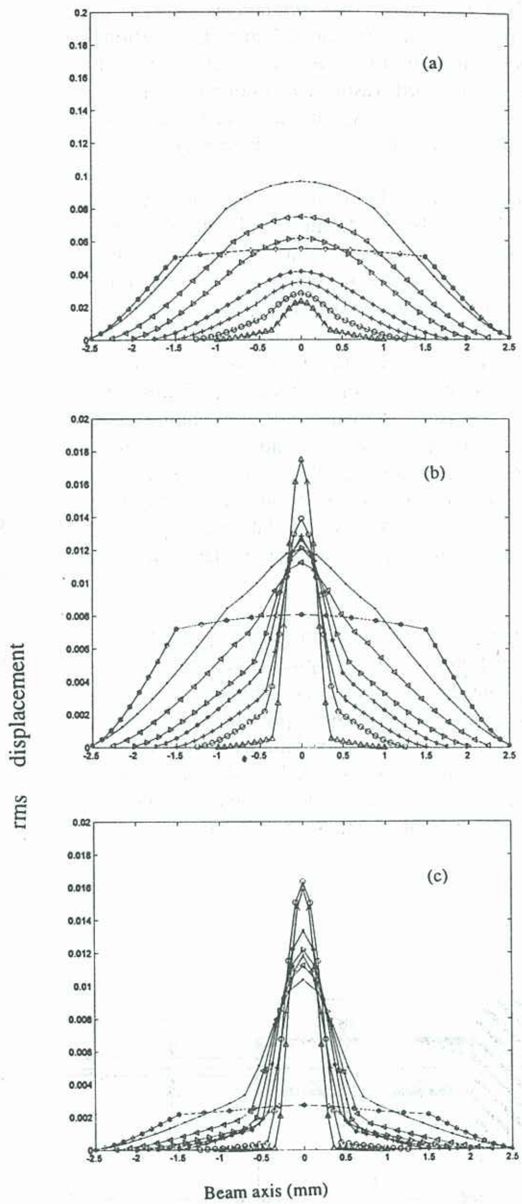

Figure 3. Variation of the rms displacement response (arbitrary units) for random white noise exciattion and for dg of (a) 15 μm, (b) 30 μm and (c) 45 μm.