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THE FREQUENCY RESPONSE OF HOT-WIRE ANEMOMETER SENSORS TO HEATING CURRENT FLUCTUATIONS

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Abstract—Frequency response measurements by the current injection technique of hot-wire anemometers at very low overheat ratios, show that for wires with substantial end conduction losses, a single time constant system response is not obtained. This is contrary to currently used theoretical models. A new model is presented which successfully simulates the measured frequency response characteristics. It is concluded that the traditional assumption of constancy of temperature at the wire ends under dynamic conditions is incorrect. Hot-wires with negligible end conduction losses were found to give the anticipated single time constant system response.

NOMENCLATURE

- A, cross-sectional area of hot-wire;
- a, constant in equation (8a);
- C_1, heat capacity of hot-wire;
- C_2, C_3, lumped heat capacity of transition region and bulk of wire attachment respectively;
- d, wire diameter;
- db, $20 \log_{10}$ (output/output at reference condition);
- F, a function defined by equation (7);
- h, instantaneous convection heat-transfer coefficient;
- $\bar{h}$, mean convection heat-transfer coefficient;
- h', fluctuation from the mean convection heat-transfer coefficient, $=h-\bar{h}$;
- I, instantaneous wire current;
- $\bar{I}$, mean wire current;
- I', fluctuation from mean wire current, $=I-\bar{I}$;
- j, $\sqrt{-1}$;
- K, constant defined by equation (8b)
- k_w thermal conductivity of hot-wire material;
- L, length of hot-wire;
- P, parameter defined by equation (4);
- Q, parameter defined by equation (4);
- q, heat generated by hot-wire;
- q_h, heat transfer by convection;
- q_k, heat transfer by conduction;
- q_1 or q_2, heat flow along branches shown in in Fig. 3;
- R, total resistance to heat transfer;
- R_{c1}, R_{c2}, resistance to heat transfer by conduction from one body to another;
- R_{e1}, R_{e2}, equivalent resistance defined as part of Fig. 4;
- R_E, mean wire resistance at the equilibrium temperature for zero heating current;
- R_w, total wire resistance;
- R'_w, fluctuation of total wire resistance;
- r_E, instantaneous wire resistivity at equilibrium temperature, T_E;
- $\bar{r}_E$, mean wire resistivity at equilibrium temperature, T_E;
- r'_E, $r_E-\bar{r}_E$;
- r_0, wire resistivity at a reference temperature;
- r_w, instantaneous wire resistivity at wire temperature;
- $\bar{r}_w$, mean wire resistivity at wire temperature;
- r'_w, $r_w-\bar{r}_w$;
- s, $=j\omega$;
- T_E, wire equilibrium temperature at zero heating current—at low subsonic speeds this is virtually identical to the fluid temperature;
- T_1, T_2, T_3, effective temperature of wire, transition region and bulk of end supports or plated section of wire respectively;
- t, time;
- x, co-ordinate along the wire, $x = 0$ being the centre of the wire;
- Z, Z_1, Z_2, impedances.

Greek symbols

- α, temperature coefficient of resistivity;
- γ, absolute magnitude of perturbation in the convective heat transfer coefficient;
- δ, damping coefficient in equation (8a);
- η, absolute magnitude of perturbation in r_E;
- π, $=3.1416$;
- τ, absolute magnitude of wire current perturbation;
- τ_1, τ_2, time constants of wire and transition region respectively;
- ϕ, phase angle;
- Ω, parameter defined by equation (4);
- ω, angular frequency;
- ω_n, characteristic or natural angular frequency;
- ω_1, ω_2, corner (roll-off) frequency of wire and transition region respectively.

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1. INTRODUCTION

THE RESPONSE characteristics of the small cylindrical element which is the heart of hot-wire anemometers, are amongst the most difficult to measure directly. Consequently even now, a full understanding of these characteristics cannot be claimed. Many of the more dominant ones are well documented in the literature such as Hinze [1] and Bradshaw [2].

Studies of the response characteristics generally commence with the partial differential heat balance equation which accounts for convection, conduction and storage of heat, radiation and thermoelectric effects being negligible. No evidence appears to invalidate this basic equation. The next step involves the selection of boundary conditions with which a solution either in closed form or by numerical methods can be obtained. The most generally used boundary condition is that the temperature of the wire ends equals that of its supports which in turn equals the wire equilibrium temperature at zero heating current which is often equal to the stream temperature. Some experimental evidence has been provided by Champagne *et al.* [3] showing that under some conditions, the temperature of the wire ends is above that of the stream and that of the major part of its supports. For the assessment of the fluctuating wire response, it is also assumed that the temperature of the wire ends remains constant. This assumption follows from the fact that the supports are massive compared with the wire. Solutions for these boundary conditions are presented in Kronauer [4] and Hinze [1] and show that even when significant conduction of heat to the end supports takes place, the frequency response of the wire is that of a single time constant system—a single pole—except at high wire temperatures where the wire response approaches that of a distributed system due to the high temperature gradient along the wire. The resultant deviations from a single time constant system are, however, small and before the development of closed loop hot-wire anemometer systems, was considered insufficient to warrant the use of open loop compensation networks more complex than a single zero. Direct experimental evidence of this behaviour is provided by Kidron [5] for a tungsten wire operated at a high wire temperature and low velocity.

Although the majority of hot-wire anemometer systems are now of the closed loop form which keep the mean wire temperature constant regardless of velocity, and hence no longer require the operator to measure the wire time constant, the frequency response characteristic to heating current fluctuations is still of interest for design purposes. It is also of vital importance in the measurement of stream temperature fluctuations when using constant current hot-wire anemometers. In this application, the frequency range of the measured quantity generally exceeds that of the transducer thus requiring the use of open loop compensation. Matching of the compensation network zero to the pole representing the wire is generally achieved by the square wave current injection technique pioneered by Kovasznay [6]. This method is relatively insensitive to errors and consequently gives an apparently good match. Recent attempts by the authors to do this with a sinusoid instead of a square wave showed that, for commonly used hot wires even at extremely low overheat ratios where the wire is no longer a distributed system within achievable measurement accuracy, a zero will not match the "pole" representing the hot wire. A re-examination of the heat-transfer characteristics of the wire shows that the assumption of constant temperature for the wire ends leads to this dilemma.

2. THEORETICAL RESPONSE WITH WIRE ENDS AT CONSTANT TEMPERATURE

The partial differential equation expressing the instantaneous heat balance at any point along the wire is given by equation (1), where for the operating conditions of interest in the present work, thermal radiation, thermoelectric effects and variations in wire thermal conductivity have been neglected.

$$\frac{I^2 r_w}{A} = \frac{C_1 A}{r_0 \alpha}\frac{\partial r_w}{\partial t} + \frac{h\pi d(r_w - r_E)}{r_0 \alpha} - \frac{k_w A}{r_0 \alpha}\frac{\partial^2 r_w}{\partial x^2} \quad (1)$$

where r_w is a function of x and t but only the case of h = constant along the wire is of interest. Considering the small perturbation response, time dependent components can be replaced by a mean component and a fluctuating one as follows

$$\begin{aligned} I &= \bar{I} + I' \\ r_w &= \overline{r_w} + r'_w \\ r_E &= \overline{r_E} + r'_E \\ h &= \bar{h} + h' \end{aligned} \quad (2)$$

where I', r'_E and h' are functions of time only but r'_w is a function of x and time. $\overline{r_w}$ is a function of x alone. Collecting first order terms gives the small perturbation response equation,

$$\frac{\bar{I}^2 r'_w}{A} + \frac{2\bar{I}\bar{r}I'}{A} = \frac{C_1 A}{r_0\alpha}\frac{\partial r'_w}{\partial t} + \frac{h'\pi d(\bar{r}_w - \bar{r}_E)}{r_0\alpha} + \frac{\bar{h}\pi d(r'_w - r'_E)}{r_0\alpha} - \frac{k_w A}{r_0\alpha}\frac{\partial^2 r'_w}{\partial x^2}. \quad (3)$$

When h varies with time and r_E and I are constant, let $h'/\bar{h} = \gamma \sin \omega t$ and introducing the following non-dimensional groups

$$P^2 = \frac{A\bar{h}\pi d}{\bar{I}^2 r_0 \alpha} - 1; \quad Q^2 = \frac{L^2 \bar{I}^2 r_0 \alpha}{k_w A^2} \quad (4)$$
$$\Omega = \frac{\omega C_1 A^2}{P^2 \bar{I}^2 r_0 \alpha}$$

the solution to equation (3) is given in exact as well as in symbolic form by Kronauer [4] for the boundary condition $r'_w = 0$ at $x = \pm L/2$. Symbolically,

$$R'_w = -\gamma \overline{R_E}\, \frac{1+P^2}{P^4} F \sin(\omega t - \phi) \quad (5)$$

where R'_w is the resultant fluctuation in wire resistance integrated over the length of the wire and F is a function of Ω and the product PQ. F and ϕ contain the frequency dependence of R'_w and it is easily shown for commonly used wires at low overheat ratios that a single pole system results to an accuracy of better than 5%.

The response to stream temperature fluctuations is obtained by setting I' and h' equal to zero and taking $r'_E = \eta \sin \omega t$. Applying the boundary condition $r'_w = 0$ at $x = \pm L/2$ results in a solution of equation (3) in symbolic form,

$$R'_w = \frac{L\eta}{A}\left(\frac{1+P^2}{P^2}\right) F \sin(\omega t - \phi). \tag{6}$$

For a wire sensitive only to temperature fluctuations, $\bar{I}$ is usually kept very low and d is small so that generally $PQ > 1$. Kronauer [4] shows that for $PQ > 20$, F and ϕ are given to within 2.8% and 1.1° respectively by equations (7)

$$F = \left(1 - \frac{2}{PQ}\right) \frac{1}{\left[1 + \left(\dfrac{\Omega}{1+(2/PQ)}\right)^2\right]^{1/2}}$$
$$\phi = \tan^{-1} \frac{\Omega}{1+(2/PQ)}. \tag{7}$$

Thus the response of the wire is again that of a single pole to within measurable accuracy.

3. APPLICATION OF THEORETICAL RESULTS TO A WIRE WITH ENDS AT CONSTANT TEMPERATURE

The solutions given in the previous section all indicate that the wire responds like a single time constant system. At high overheat ratios several doubts arise when using these solutions as h becomes temperature dependent and, therefore, will vary along the wire. Also, in view of the experimental evidence of Champagne *et al.* [3] the ends of the wire can no longer be assumed to be at the temperature of the fluid.

It is better, therefore, to concentrate on the response at low wire currents when the wire is operated essentially as a resistance thermometer. In this case the solutions of the previous section show that to an accuracy of better than 1%, the wire can be represented by a single pole system. Precise measurements to verify this do not appear to have been reported to date.

Measurements with a DISA 55M20 constant current bridge incorporating probe cable compensation (DISA 9055 M2381) and employing the set-up procedure as described by Bremhorst and Krebs [8] gave the result of Fig. 1 for a 5 μm dia. × 1.5 mm tungsten wire at a very low overheat ratio. The wire was soldered directly to its supports which were massive compared with the wires—certainly more massive than commercially produced ones. Significant differences which cannot be explained by experimental error are noted between this and a single pole system. At the 45° phase lag point the amplitude difference would give an error of 35% in spectral measurements.

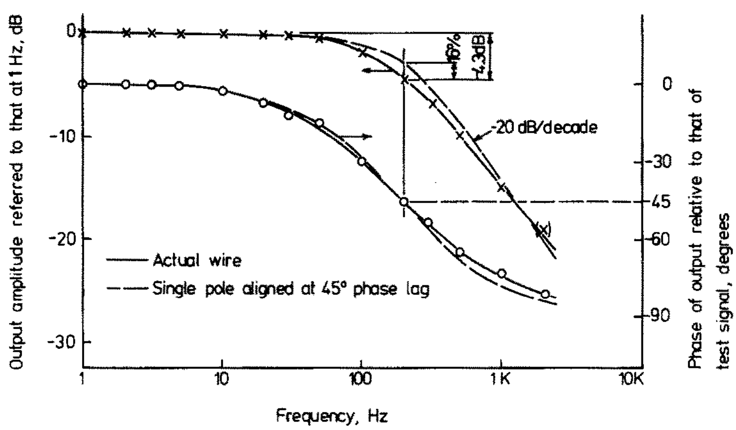


FIG. 1. Frequency response of 5 μm × 1.5 mm tungsten wire, for air velocity = 2.3 m/s, wire current = 8 mA and constant size test signal.

Finally, the wire's response to current fluctuations of the form $I'/\bar{I} = \tau \sin \omega t$ when h' and r'_E are zero is given by the sum of the responses to velocity and temperature fluctuations, that is, the sum of equations (5) and (6) but with $\gamma = -2\tau/(1+P^2)$ and $\eta = 2\tau \bar{r}_E/(1+P^2)$. For a wire operated at low $\bar{I}$, as is the case when measuring temperature fluctuations, $P^2 \gg 1$ so that the response is closely approximated by that to temperature fluctuations, that is, by equations (6) and (7) with the above substitution for η. Again it is a single pole system response.

4. RE-EXAMINATION OF THEORETICAL MODEL

The assumptions used in the derivation of the basic heat transfer equation, equation (1), and its perturbation form, equation (3), are considered valid and are consistent with, for example, Davies and Davis [7]. However, the form of the measured response of Fig. 1 suggests the interaction of two single pole systems where the second time constant can be attributed to a portion of the supports holding the wire. The new physical model of Fig. 2 is proposed.

The essential difference between this and previously

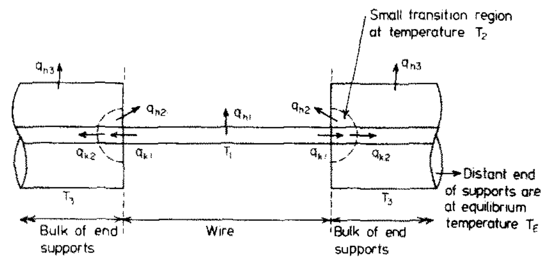
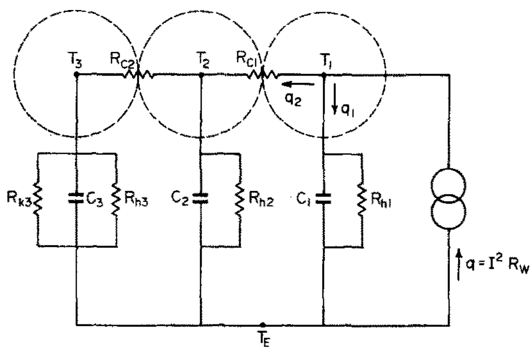


FIG. 2. New model of hot-wire anemometer.

used models is that a small transition region has been included where considerable crowding of the heat flux lines takes place. This section is not assumed to be at constant temperature. Figure 3 shows this new model as a lumped parameter network equivalent circuit for constant fluid temperature, T_E.



Note: $q_2 = q_{k1}$ of Fig. 2

FIG. 3. Lumped parameter network equivalent circuit of new hot-wire model for T_E = constant.

The end supports of the wire have a considerable thermal inertia so that T_3 will be essentially constant. Also, R_{k3} will be very small due to the high conductivity and large cross-section of the end supports so that a reasonable assumption for most cases of interest is that $T_3 = T_E$ giving the simplified model of Fig. 4, where

$$Z_1 = \frac{R_{e1}}{\tau_1 s + 1} \quad \text{and} \quad Z_2 = \frac{R_{e2}}{\tau_2 s + 1}$$

$$R_{e1} = R_{h1}$$

$$R_{e2} = \frac{R_{k2} R_{h2}}{R_{k2} + R_{h2}}$$

$$\tau_1 = R_{e1} C_1$$

$$\tau_2 = R_{e2} C_2$$

and

$$s = j\omega.$$

For current injection, the ratio T_1/q is of interest as this gives the system transfer function measured when observing the signal from the hot-wire unit and comparing it with the forcing function, q. This ratio is the impedance, Z, of the network of Fig. 4 and has the form given by equation (8a) which for certain combinations of "a" and "δ", will yield a higher than first order response in the frequency range of interest in turbulence measurements.

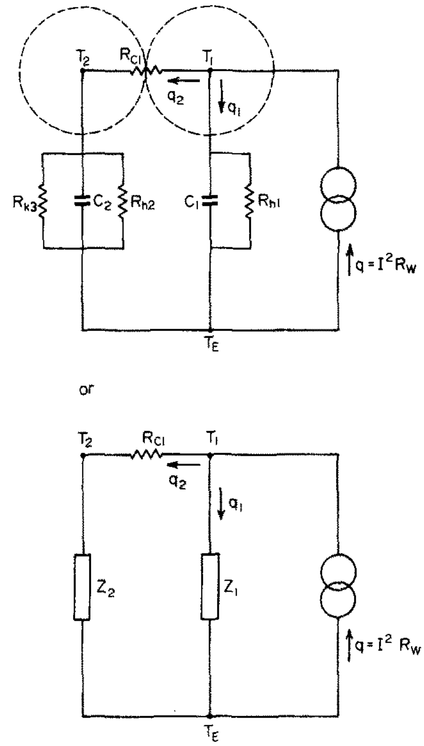


FIG. 4. Simplified lumped parameter network equivalent circuit of new hot-wire model for T_E = constant.

$$Z/K = \frac{as/\omega_n + 1}{\dfrac{s^2}{\omega_n^2} + 2\delta \dfrac{s}{\omega_n} + 1} \tag{8a}$$

where

$$K = \frac{R_{e1}(R_{c1} + R_{e2})}{(R_{e1} + R_{e2} + R_{c1})} \tag{8b}$$

$$a = \frac{R_{c1}}{R_{c1} + R_{e2}} \frac{\tau_2}{\tau_n}, \quad \tau_n = 1/\omega_n \tag{8c}$$

$$\omega_n^2 = \frac{R_{e1} + R_{e2} + R_{c1}}{R_{c1} \quad \tau_1 \quad \tau_2} \tag{8d}$$

$$2\delta = \frac{(R_{e2} + R_{c1})\tau_1/\tau_2 + (R_{e1} + R_{c1})}{[(R_{e1} + R_{e2} + R_{c1})R_{c1}\tau_1/\tau_2]^{1/2}}. \tag{8e}$$

Thus,

$$\frac{\tau_2}{\tau_n} \approx \left(\frac{R_{e1} + R_{e2} + R_{c1}}{R_{c1}}\right) \frac{1}{\tau_1/\tau_n}. \tag{9}$$

For an effectively infinite wire, $R_{c1} \to \infty$ and equation (8a) reduces to

$$Z/K = \frac{1}{\tau_1 s + 1} \quad \text{where} \quad K = R_{h1} \tag{10}$$

which is the already well known transfer function of an infinitely long wire—a single pole.

For effectively short wires, R_{c1} is finite. When half the heat generated by the wire is lost by conduction to the supports, $\bar{q}_1 = \bar{q}_2$ in Fig. 2 so that $R_{c1} + R_{e2} = R_{e1} = R$. The parameters in equation (8a) then become

$$K = R/2 \tag{11a}$$

$$a = \frac{R_{c1}}{R}\frac{\tau_2}{\tau_n} \tag{11b}$$

$$\omega_n^2 = \frac{2R}{R_{c1}\tau_1\tau_2} \tag{11c}$$

$$2\delta = \frac{\tau_1/\tau_2 + \left(1 + \frac{R_{c1}}{R}\right)}{\left[2\frac{R_{c1}}{R}\frac{\tau_1}{\tau_2}\right]}. \tag{11d}$$

Substitution of equations (11b) and (11c) in (11d) yields

$$\delta = \frac{1}{2a} + \frac{a}{4} + \frac{aR}{4R_{c1}}. \tag{12}$$

Since R_{c1} is extremely difficult to measure directly, equation (12) can be used for its indirect measurement by finding "δ" and "a" from a frequency response of such a wire. These values will also give an indirect measure of the corner frequencies of the wire and the portion of the end support in question. From equation (11b) follows

$$\frac{\omega_2}{\omega_n} = \frac{\tau_n}{\tau_2} = \frac{R_{c1}}{aR} \tag{13}$$

and substitution of this in equation (11c) yields,

$$\frac{\omega_1}{\omega_n} = \frac{a}{2}. \tag{14}$$

5. TEST RESULTS

In order to test the above theory, wires were tested at very low overheat ratios. The first significant result of the above theory is that the wire approaches a single pole as $R_{c1} \to \infty$. Such a condition cannot be obtained readily with tungsten wires because of their high thermal conductivity thus giving effectively low values of R_{c1}. Platinum–iridium is much better in this regard, Figs. 5(a)–(c) showing a typical set of results with the smallest diameter wire commercially available.

Since only very low overheat ratios were used, the result of Fig. 5(a) cannot be attributed to a buoyancy phenomenon which could perhaps be triggered by the pulsating heat input and consequent pulsating wire temperature. Also, the observed trends cannot be attributed to stray inductive effects as the bridge was compensated for these and balanced correctly at all times to frequencies above those reported. Because of the low overheat ratio, the traditional model for the hot wire with constant temperature at its ends predicts a single pole system. This is not the case for the result of Fig. 5(a) either for amplitude or phase. The same wire when subjected to an air stream to increase the convection loss, which effectively is the same as an increase in R_{c1}, gives almost the correct phase response but the amplitude response still differs significantly from that of a single pole. A difference remained even when the air velocity was increased further. Using the much longer wire of Fig. 5(c) at high velocity, simulated the case of a much higher value of R_{c1} and within experimental accuracy, a single pole response for both amplitude and phase is obtained. It was estimated that for this wire less than 5% of the total heat input is lost to the supports thus confirming that it is effectively an infinitely long wire.

These test results are, therefore, consistent with the new theoretical model proposed in the previous section. They also clearly show that the amplitude alone gives a misleading result, at least for this wire material, as any differences between it and that of a single pole may be argued to be within reasonable experimental accuracy. Together with the phase responses a much more sensitive test of the influence of the fluctuating end condition is obtained. Another case of a low value of R_{c1} was obtained with tungsten wire as already illustrated in Fig. 1.

As a final test, equation (8a) can be fitted to the test result of Fig. 1, since the heat loss to the ends is of the order of 50% of the total heat input. Two such attempts are shown in Fig. 6. The case of $\delta = a = 1.1$ gives a reasonable fit to the test result. Substituting these values in equation (12) yields $R/R_{c1} = 1.35$ and equations (13) and (14) give $\omega_1 = 94$ Hz and $\omega_2 = 115$ Hz. ω_1 is near the wire corner frequency which would usually be taken as the frequency at which the amplitude has dropped by 3 dB. Since resistance to conduction heat transfer in the support is much less than that to convection heat transfer from the wire ($R_{e2} \ll R_{e1}$) the result for ω_2 indicates that the volume of the transition section is larger than that of the wire. The result of $R/R_{c1} = 1.35$ appears a little high, however, since the measurements of Champagne *et al.* [3] indicate that at low overheat ratios, the mean temperature of the wire ends is very close to that of the fluid temperature consequently requiring R/R_{c1} to be close to unity.

The second case of $\delta = a = 1.15$ gives an even better fit but gives $R/R_{c1} = 1.48$. ω_1 and ω_2 are 98 Hz and 100 Hz respectively. This case is considered to be the best approximation with the remaining differences between the measured results and those of equation (8a) being due to the estimate of 50% heat loss to the ends to which case equations (11)–(14) apply, and approximating the transition region by a single pole. In view of the rapidly changing geometry this is considered to be an oversimplification which can be resolved only by the solution of the complete heat-transfer equations of this section. Such a study could even include the effect of crowding of the heating current flux lines. The accuracy of the measured points at 2 kHz and above also tends to be low as the signal is of similar size to that of the electronic noise. Furthermore, equation (12) from which R/R_{c1} is obtained is

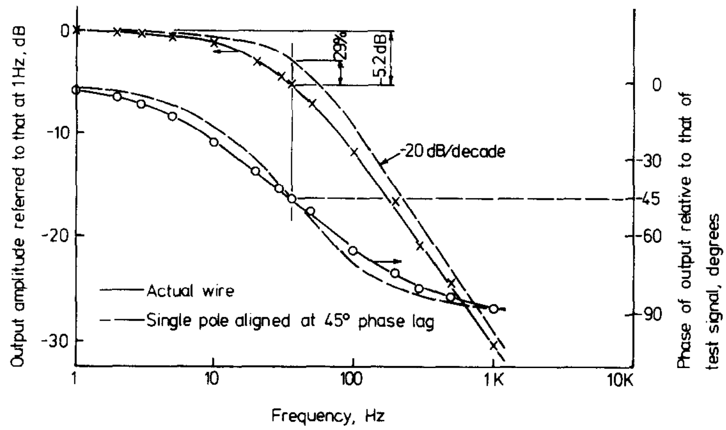


FIG. 5(a). Frequency response of 10 μm × 1.5 mm Pt–Ir wire in still air, wire current = 10 mA and constant size test signal.

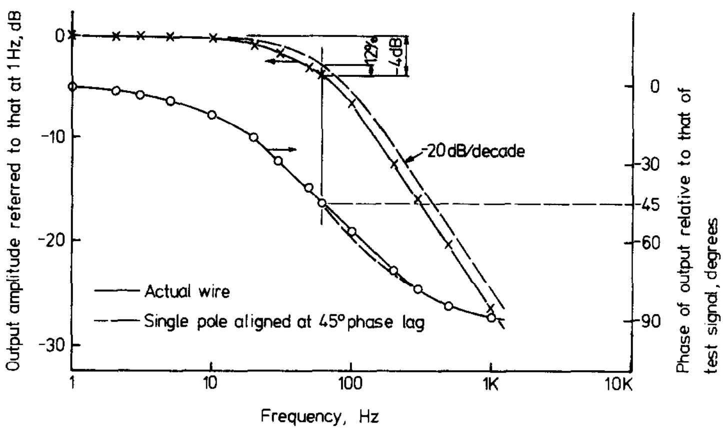


FIG. 5(b). Frequency response of 10 μm × 1.5 mm Pt–Ir wire for air velocity = 2.3 m/s, wire current = 10 mA and constant size test signal.

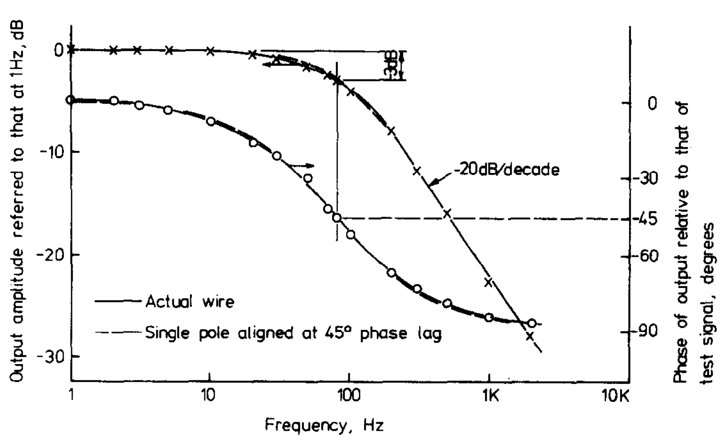


FIG. 5(c). Frequency response of 10 μm × 6 mm Pt–Ir wire for air velocity = 9 m/s, wire current = 10 mA and constant size test signal.

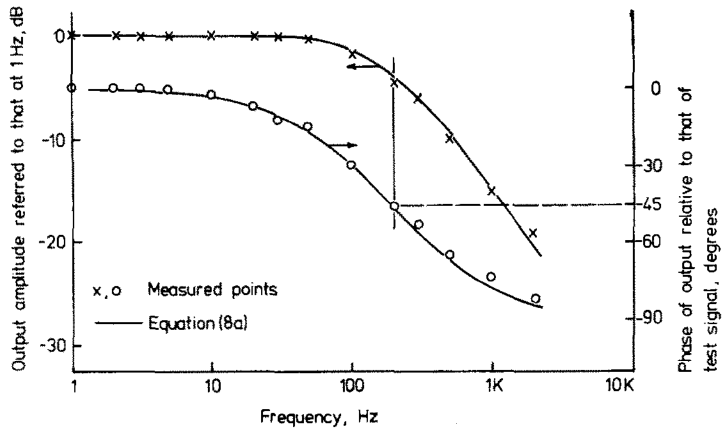


FIG. 6(a). Frequency response of Fig. 1 simulated by equation (8a) for $\delta = a = 1.1$ and $\omega_n = 170$ Hz.

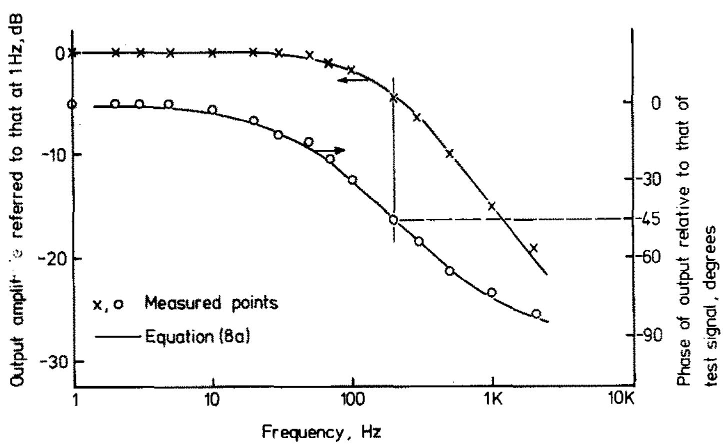


FIG. 6(b). Frequency response of Fig. 1 simulated by equation (8a) for $\delta = a = 1.15$ and $\omega_n = 170$ Hz.

very sensitive to small changes in "a" relative to "δ" so that the above results for R/R_{c1} are of comparatively low accuracy.

6. CONCLUSIONS

Commonly used hot-wires are made of tungsten or platinum wire with length/diameter ratios of less than 600 for which considerable heat conduction to the wire supports exists. It has been shown that in such cases the wire frequency response will differ significantly from that of a single pole even at very low overheat ratios. Use of open loop compensation with a single zero will not yield a flat frequency response. Only approximate compensation will be obtained, the setting achieved depending on whether a square wave or a sinusoid test signal is used.

A model has been proposed which is consistent with measured results and shows that the wire behaves like a single pole only when heat losses to its supports are small—a reasonable upper limit probably being of the order of 5%. The practical implication of this is that when using uncompensated wires or ones with open loop compensation, it is best to use effectively infinitely long wires such as 0.5–2 μm dia. platinum–iridium or platinum–rhodium wires with a length-to-diameter ratio of approximately 600.

For a wire with a constant end temperature, the frequency response to heating current fluctuations is similar to velocity or stream temperature fluctuations. This will still apply for the new end condition thus enabling the latter responses to be inferred from that to heating current fluctuations. When using closed loop (constant temperature) anemometers, this new end condition will not introduce an error but does give new insight for design purposes as it effectively introduces another pole into the bridge arm containing the wire, its holder and connection cable when using wires with significant heat losses to the supports.

For the purpose of describing the effects of the wire ends on the wire's frequency response, the simplified model of Fig. 4 is adequate. If phenomena attributable to distributed effects are to be investigated, a more complex model would be required. Such a model would be useful for the study of the wire's response under static relative to dynamic conditions for which case the ratio of heat lost by the wire to the fluid to the heat lost by end conduction (q_1/q_2 in Fig. 4) may not remain independent of frequency.

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REPONSE EN FREQUENCE DES ANEMOMETRES A FIL CHAUD AUX FLUCTUATIONS DU COURANT DE CHAUFFAGE

Résumé—Des mesures de réponse en fréquence par la technique d'injection de courant pour les anémomètres à fil chaud, à très faible surchauffe, montre que pour des fils ayant des pertes sensibles aux extrémités par conduction, on n'obtient pas une réponse à une seule constante de temps. Ceci est contraire aux modèles théoriques couramment utilisés. On présente un nouveau modèle qui simule avec succès les caractéristiques mesurées de la réponse en fréquence. On conclut que l'hypothèse habituelle d'une température constante aux extrémités du fil, sous des conditions dynamiques, est incorrecte. On trouve que des fils chauds avec des pertes par conduction négligeables donnent une réponse à une seule constante de temps.

DER FREQUENZGANG VON DRAHT-ANEMOMETER-SONDEN BEI HEIZSTROMSCHWANKUNGEN

Zusammenfassung—Frequenzgangmessungen mit Hilfe der Stromeinspeistechnik für Hitzdrahtanemometer mit kleinen Überhitzungsverhältnissen zeigen, daß das dynamische Verhalten von Hitzdrähten mit beträchtlichen Leitungsverlusten an den Enden nicht mit einer einzigen Zeitkonstanten beschrieben werden kann. Dies widerspricht den gegenwärtig verwendeten theoretischen Modellen. Es wird ein neues Modell vorgestellt, das den gemessenen Frequenzgang gut wiedergibt. Daraus wird der Schluß gezogen, daß die traditionelle Annahme einer konstanten Temperatur an den Drahtenden unter dynamischen Bedingungen nicht korrekt ist. Hitzdrähte mit vernachlässigbar kleinen Leitungsverlusten an den Enden zeigten das ursprünglich angenommene Verhalten mit einer einzigen Zeitkonstanten.

ЧАСТОТНАЯ ХАРАКТЕРИСТИКА ДАТЧИКОВ ТЕРМОАНЕМОМЕТРА ПРИ КОЛЕБАНИЯХ ТОКА НАГРЕВА

Аннотация — Измерение частотных характеристик термоанемометров при очень низких отношениях перегрева позволило установить, что для проволочек термоанемометра, имеющих значительные концевые потери за счет теплопроводности, нельзя получить характеристику с одной постоянной времени. Это противоречит используемым в настоящее время теоретическим моделям. Предложена новая модель, с помощью которой успешно моделируются измеряемые частотные характеристики. Сделан вывод об ошибочности традиционного допущения о постоянстве температуры на концах проволочки в динамическом режиме работы термоанемометра. Найдено, что для проволочек с пренебрежимо малыми концевыми потерями за счет теплопроводности можно получить необходимые характеристики с одной постоянной времени.