Operating Manual
for the
IIHR Hot-Wire and Hot-Film
Anemometers

By
PHILIP G. HUBBARD

Research Engineer
IOWA INSTITUTE OF HYDRAULIC RESEARCH

Published by the State University of Iowa
Iowa City
1957
Model IIHR, Type 3A Twin-Channel Hot-Wire Anemometer
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Background</td>
<td>1</td>
</tr>
<tr>
<td>General Description</td>
<td>1</td>
</tr>
<tr>
<td>Theory of Electrical Control</td>
<td>3</td>
</tr>
<tr>
<td>Practical Design Procedure</td>
<td>6</td>
</tr>
<tr>
<td>Design and Performance of Operating Circuits</td>
<td>8</td>
</tr>
<tr>
<td>Design of Sensing Elements</td>
<td>16</td>
</tr>
<tr>
<td>Construction Details</td>
<td>20</td>
</tr>
<tr>
<td>Operating Procedure</td>
<td>21</td>
</tr>
<tr>
<td>Calibration Techniques</td>
<td>23</td>
</tr>
<tr>
<td>Turbulence Computations</td>
<td>24</td>
</tr>
<tr>
<td>Trouble Shooting</td>
<td>26</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>29</td>
</tr>
<tr>
<td>References</td>
<td>29</td>
</tr>
<tr>
<td>Table of Symbols</td>
<td>30</td>
</tr>
</tbody>
</table>
OPERATING MANUAL
FOR THE
IIHR HOT-WIRE AND HOT-FILM ANEMOMETERS

HISTORICAL BACKGROUND

Most investigators trace the use of the hot-wire technique for measuring the instantaneous velocity of moving fluids to the definitive work by L. V. King in England which was published in 1914 [1, 2]. The possibility of using a temperature-sensitive wire to establish a relationship between fluid velocity and convective heat loss was not new, but King's careful measurements and analysis furnished a firm foundation which had been lacking up to that time. Thereafter, the method was used in several widely separated places [3, 4, 5] and was repeatedly modified. An important forward step was the use of electrical networks to compensate for the reduced sensitivity and phase lag which introduce errors in the response of the wire to higher-frequency fluctuations [6]. Most of the measurements made to date have used the constant-current method of operation with compensating networks similar to those discussed in the latter reference.

Within a few years after compensating networks were first suggested, a completely different technique for eliminating thermal lag was adopted and developed by several investigators [7, 8, 9]. In this method, the effects of thermal lag were minimized by using amplifiers to keep the resistance, and hence temperature, at a nearly constant value. The adoption of the constant-temperature technique at the Iowa Institute of Hydraulic Research in 1947 was entirely independent of these earlier works, however, as their existence was not known until an operating instrument using the principle had been completed [10].

GENERAL DESCRIPTION

Model IIHR anemometers are instruments designed for the specific purpose of measuring the instantaneous velocities of moving fluids, and are the result of extensive use of the hot-wire method by the staff of the Iowa Institute. The general designation IIHR includes several types, the common characteristics being operation on the constant-temperature principle and production of a signal directly proportional to the instantaneous velocity. In addition to the types using the conventional wire, an instrument has been developed with a thin film of platinum on a glass wedge.
as the sensing element [11]. Whether wire or film is used for the sensing element, the Model IIHR is a carefully-integrated system designed to meet the most exacting specifications without requiring an electronic specialist as operator. This has been accomplished by using modern control principles and circuits custom-built for the task, and combining them in such a way that automatic control and synchronized switches replace detailed procedures and an array of accessories.

Two primary factors control the design of anemometers depending upon the forced convection of heat: the deficiencies of the sensing element itself, and the nature of the statistical quantities necessary to describe turbulent flow. In order to assure a uniform response to all fluctuations over the entire range of magnitudes and frequencies found in turbulence, it is necessary to remove as sources of error the two outstanding defects of the sensing element: its thermal or time lag and its non-linear conversion of velocities to electrical signals. It is clear, then, that the compensation for lag should be compatible with linearity; it also should be automatic, so that any changes of thermal lag with time or velocity do not require a troublesome redetermination of its magnitude and consequent readjustment of the instrument. These advantages can be secured only by constant-temperature operation.

In compensating for thermal lag by the constant-temperature method, the hot wire is used as one arm of a Wheatstone bridge with fixed resistors in the other arms. Current is supplied to the bridge from the output of an amplifier in proper phase to cause a decrease in bridge current when the wire resistance is greater than the proper value for bridge balance. If the transconductance and phase shift of the amplifier are infinite and zero, respectively, the wire will remain at a constant resistance—and hence constant temperature—regardless of the rate at which heat is lost to the surroundings. An amplifier (or bridge) which is imperfect will, of course, permit some fluctuation in resistance and give incomplete compensation for thermal lag. The degree to which any particular system approximates the ideal can be shown by the transfer-function analysis commonly used in servo-mechanism design.

The linear relationship between velocity and electrical signal which is furnished by these instruments is obtained by amplifying the bridge voltage, which bears the usual fourth-root relationship to velocity, then applying the signal to the control grid of a tube in which the relationship between signal current and control voltage is the inverse of the bridge characteristic for a wire of the recommended size if operated at the correct overheating ratio. Both the reading of a panel meter and the voltage available at an output terminal connector are directly proportional to the plate current of this tube.

Root-mean-square values of the usual quantities associated with turbu-
lence measurement are obtained by blocking out the steady components of
the signal, then passing the deviations about this mean value through a
thermocouple type of milliammeter after appropriate amplification or attenu­
ation and impedance matching. Very little amplification is needed, because
of the high level (50 volts full scale) of the primary signal. It should be
noted that the r-m-s amplifier has been designed to have a linear range
which is several times the full-scale output in order to accommodate sharp
peaks without overloading. For observing the fluctuations in voltage with
an oscilloscope, recording, or performing other operations (for example,
spectrum analysis), a scope output jack has been provided on the panel.

THEORY OF ELECTRICAL CONTROL

As proposed originally by King and verified in many subsequent studies,
a wire with resistance $R$ and temperature coefficient $\alpha$ will obey the fol­
lowing law when immersed in a fluid moving at a velocity $U$ normal to
the wire:

\[ \frac{i^2 R \alpha}{a} = C_1 + C_2 \sqrt{U} \]

The coefficients $C_1$ and $C_2$ are constants for any particular wire, and $i$
the current required to maintain the resistance at $R$. At the temperature
of the fluid, the wire resistance would be $R_0$, and $a$ is the overheating ratio
$(R - R_0)/R_0$. The temperature coefficient $\alpha$ is assumed to be based on
the resistance at fluid temperature.

For a balanced bridge and perfect amplifier, $R$ is constant and the heat­
ing-current fluctuation $\Delta i^*$ due to a velocity fluctuation $\Delta U$ will be

\[ \Delta i^* = \frac{\partial i}{\partial U} \Delta U \]

The actual current fluctuation due to a velocity fluctuation $\Delta U$ for a prac­
tical control circuit will be $\Delta i$, and it is desired to find how closely $\Delta i$
approaches $\Delta i^*$.

As has already been pointed out, the control signal must be generated
from small changes in the resistance of the wire. Inasmuch as the resistance
depends on the heating current, the velocity, and the fluctuation frequency
$\omega/2\pi$ the incremental variation can be written as follows:

\[ \Delta R = \frac{1}{1 + j \omega M} \left[ \left( \frac{\partial R}{\partial i} \right) \Delta i + \left( \frac{\partial R}{\partial U} \right) \Delta U \right] \]

The parameter $M$ is a constant characterizing the way in which the wire
responds to fluctuations of various frequencies, and is ordinarily referred
to as the time constant [5]; $j$ is the imaginary operator $\sqrt{-1}$. If the
partial derivatives in the above equation are evaluated from King's law (other laws could be used, of course), then the incremental change in wire resistance is seen to be:

\[
\Delta R = \frac{2aR}{1 + joM} \left[ i - \frac{1}{i} \left( \frac{\partial i}{\partial U} \right) \Delta U \right]
\]

\[
= \frac{2aR}{i(1 + joM)} (\Delta i - \Delta i^*)
\]

This resistance variation gives rise in turn to an error voltage \( E_s \) across the wire:

\[
E_s = i\Delta R = \frac{2aR}{1 + joM} (\Delta i - \Delta i^*)
\]  \( (1) \)

If the control system of Fig. 1 is now considered, the error voltage \( E_r \) which appears at the input to the amplifier can be determined by simple network analysis with the following result:
If the bridge is in static balance, i.e., $R/R_1 = R_2/R_3$, then the relationship is much simpler:

$$\frac{E_r}{E_s} = \frac{1}{1 + R/R_1} \quad (2)$$

From Eqs. (1) and (2), $E_r$ can be expressed as

$$E_r = \left(\frac{2aR}{1 + j\omega M}\right) \left(\frac{\Delta i - \Delta i^*}{1 + R/R_1}\right) \quad (3)$$

The relationship between the incremental heating current and this error can be clarified by introducing the open-loop transconductance $g$ of the control amplifier:

$$g = \frac{\partial i_b}{\partial E_r} \quad (4)$$

where $i_b$ is the total bridge current $i(R + R_3)/R_3$. The transconductance $g$ will depend in general upon the frequency and possibly upon the average value of the bridge current in the case of a DC amplifier. Equations (3) and (4) can now be combined to yield the desired relationship showing the effectiveness of the control system:

$$\frac{\Delta i}{\Delta i^*} = \frac{1}{1 + K} $$

(7)

The relative response of the closed-loop system will be

$$\frac{\Delta i}{\Delta i^*} = \frac{1}{1 + K}$$

The open-loop transfer function $K$ defined in Eq. (6) is a measure of the degree to which nonlinearities are prevented from affecting the overall operation adversely. Its magnitude at zero frequency is commonly called the suppression ratio. The negative sign is introduced for convenience because an increase in wire resistance must cause a decrease in heating current and vice versa.

Although the transfer function has been derived as a relationship between ideal and actual heating currents, its numerical value can be measured more conveniently by opening the control loop inside the amplifier and measuring the output voltage $E_0$, which results from the introduction
of an error voltage $E$ (see Fig. 1c). It is important to note that $K$ is a measure of both the magnitude and the phase relationship of this open-loop response. This fact can be indicated mathematically by using complex algebra, for which purpose two new variables defined by the following equation are introduced:

$$K = \frac{E_v}{E} = G e^{i\phi}$$  \hspace{1cm} (8)

From the definition, it is evident that $G$ represents the magnitude and $\phi$ the phase angle of the transfer function. Equation (8) is, of course, the counterpart of Eq. (6) for open-loop operation. When the loop is closed for normal operation, then the transfer function for the entire system is represented by the following equation:

$$\frac{\Delta i}{\Delta i^*} = H e^{i\psi} = \frac{G e^{i\phi}}{1 + Ge^{i\phi}}$$  \hspace{1cm} (9)

The importance of this result is evident if it is emphasized that $H$ is the ratio of the output signal to the ideal signal, and $\psi$ is the angle by which the output lags behind the velocity fluctuation.

**Practical Design Procedure**

Two different performance criteria must be used in designing a practical circuit to control a wire operating under specified conditions: constancy of temperature over a large range of mean velocities, and uniformity of amplitude and phase response over the necessary frequency range. As the following analysis will show, the circuit requirements of these two factors may be in conflict, and a highly modified control amplifier must be designed to reconcile the conflict and assure stable electrical operation.

In the preceding section, it was stated that an imperfect control amplifier will permit some error in resistance of the wire (and hence in its temperature) as the ambient thermodynamic conditions vary, and the exact error will now be determined. As the velocity past the wire increases from zero to a maximum value, the heating current $i$ must likewise increase from a value $i_0$ to a maximum $i_v$ in order to maintain the wire at its proper resistance. Since the signal for this change is derived from the wire itself, an error $R_e$ in resistance must exist, causing an error $a_e$ in the overheating ratio:

$$a_e = \frac{R_e}{R_0}$$

This is equivalent to an error $T_e = a_e/\alpha$ in operating temperature. If the
variation in overheating ratio is to be restricted to a value \( \epsilon \), then the required transconductance \( g_n \) of the amplifier at zero frequency can be determined from Eqs. (3) and (4) by setting \( \omega = 0 \):

\[
g_n = \frac{i_M - i_n}{R_o} \left( 1 + \frac{R}{R_1} \right) \left( 1 + \frac{R}{R_2} \right)
\]

To determine the required transconductance at any other frequency, the following inverse relations, derived directly from Eq. (9) by equating real and imaginary components, can be used:

\[
\tan \phi = \frac{\sin \psi}{\cos \psi - H}
\]

\[
G = \frac{H}{(1 - 2H \cos \psi + H^2)^{\frac{1}{2}}}
\]

\[
\tan \psi = \frac{\sin \phi}{\cos \phi + G}
\]

\[
H = \frac{G}{(1 + 2G \cos \phi + G^2)^{\frac{1}{2}}}
\]

To determine the required open-loop parameters \( G \) and \( \phi \) at any frequency of fluctuation throughout the entire operating range, it is only necessary to specify the desired values of \( H \) and \( \psi \). As a practical matter, however, the critical values for a hot-wire circuit occur at the maximum frequency to be included, so that only this frequency need be considered. If, at the maximum frequency \( f_M \), values of \( H_n \) and \( \psi_M \) are specified, the corresponding values of \( G_n \) and \( \phi_M \) can be computed from Eqs. (11) and (12).

Some important properties of Eq. (9) relating to stability of operation should now be considered. Note that if \( \phi = \pi \) when \( G = 1 \), then \( H = \infty \), and the system will oscillate; this point is clearly to be avoided. A closer analysis will also show that values of \( H \) greater than unity will exist if \( G > 1 \) for \( 2\pi/3 < \phi < \pi \). This means that the system will respond abnormally to any signal falling within the frequency range for which this condition holds, and a distorted signal will result. If \( G = 1 \) when \( \phi = 2\pi/3 \), then the system is critically damped, and optimum performance (for the purposes of this design) will be achieved.

Three important required characteristics of the control circuit (\( G_n, G_M, \phi_M \)) can now be determined simply by substituting specified values of \( \epsilon, f_M, H_M, \) and \( \psi_M \) into Eqs. (10), (11), and (12). It is to be noted that the open-loop response \( G_o \) at zero frequency can be determined by combining Eqs. (6), (8), and (10):

http://ir.uiowa.edu/uisie/37
This completes the general analysis, and the designer is free to proceed in any of several possible directions beyond this point. It should be remarked, however, that the performance of a system can best be analyzed through Eqs. (13) and (14) once the actual circuits have been constructed. Another factor of extreme practical importance is the fact that the open-loop transfer function will be drastically affected by the time constant $M$ of the wire. For example, a system employing an amplifier which has no frequency error whatever will exhibit an open-loop response in which $\phi$ is essentially equal to $\pi/2$ at practical values of $f_M$. By making judicious use of phase-shifting networks within the amplifier, a large degree of control can be exercised over the system response.

**Design and Performance of Operating Circuits**

With the preceding analysis as a guide, two basically different control circuits have been developed: Type A for use with fine wires operated in air, and Type C (carrier) for the heavier wires operated in either air or water. A Model IIHR system includes either type of control circuit together with all necessary power supplies, analyzing circuits, and accessories for producing useful quantitative information.

In the Type A circuit, direct current is used to heat the wire, and the control amplifier is direct-coupled throughout. The use of direct current is advantageous because the bridge and amplifier need to operate over a frequency range which is only slightly greater than the range of frequencies to be measured in the turbulent fluctuations, and the response can be readily extended to any upper frequency limit of practical importance. Disadvantages are the need for highly regulated power supplies and carefully selected tubes at critical points, and very inefficient operation of the power stage because of the poor impedance match between vacuum tube and the low-impedance bridge.

The Type 3A control amplifier for use with 0.00014-inch tungsten wire operated at an overheating ratio of 0.8 (approximately 210°C above air temperature) is presented in Fig. 2, and its regulated power supply is shown in Fig. 3. As may be seen in the curves of Figs. 4, 5, and 6, the response of this circuit is adequate for reproducing turbulent fluctuations up to at least 10 kilocycles. The improved operation at the higher mean velocity is due to the increase in the transconductance of the power tube with increasing cathode current, and to the reduction of the time constant $M$ as the dissipation of heat by forced convection increases (see Reference [5] for a discussion of the manner in which the time constant varies with various parameters).
Fig. 2. CIRCUIT FOR TYPE 3A CONTROL AMPLIFIER AND LINEARIZING STAGE
Fig. 3. Regulated Power Supply for Type 3A Amplifier
Fig. 4. Low-frequency Response of Type 3A Control System

Fig. 5. High-frequency Response of 3A System at Low Mean Velocity

Fig. 6. High-frequency Response of 3A System at High Mean Velocity
Fig. 7. Root-Mean-Square Analyzer Circuit Diagram
Although, as these curves show, the control and linearizing circuits produce a signal which is a true representation of all frequency components from zero to about ten kilocycles, the range of frequencies in the final measurements will also depend upon the capabilities of the analyzing equipment. For this reason, careful attention has been given to the design of analyzing circuits which will include all the frequency components of interest; the circuit for an analyzer which covers the band from about ten cycles per second to beyond ten kilocycles is presented in Fig. 7, and its operating characteristic is shown in Fig. 8. The selector switch permits this analyzer to measure the root-mean-square values of the following quantities ordinarily used in turbulence measurements: (a) the deviation about the mean of the signal from either of two wires, (b) the instantaneous sum of the two deviations, (c) the instantaneous difference, and (d) time derivatives of any of the preceding.

![Relative Frequency Response of RMS Analyzer](http://ir.uiowa.edu/uisie/37)

A typical mean-velocity calibration for the Type A anemometer is presented in Fig. 9, and it can be seen that the desired proportionality between mean velocity and output signal has been attained for most of the velocity range. Only at quite low speeds is the deviation important; if, however,
Fig. 10. Circuit for Type C Control Amplifier and Linearizing Stage
linear operation in this range is important, the operating point can be adjusted to give an essentially linear characteristic over the range from 0 to 15 fps.

Operating circuits for the hot-film anemometer are similar to the Type A circuits, the principal differences being associated with the requirement of more heating current and the more complex thermal-lag characteristics [11].

For many measurements, such as those in water and large-scale or low-velocity air systems, the frequency range of interest is much lower and the use of larger-diameter wire is feasible. Since the fine tungsten wire is quite fragile and the fabrication procedure is rather tedious, the use of larger wire is advisable wherever possible. Several problems are immediately evident when this is considered, however. For example, the resistance of the wire will be less, and the required heating power will be much greater, so that the inefficient operation of the power stage in the Type A control circuit becomes a major drawback. Furthermore, the relative noise level at the input to the control circuit will be higher, again because of the impedance mismatch. Both of these problems can be overcome by using alternating current to heat the wire so that proper impedance matching can be accomplished with the aid of transformers. This is the basic principle underlying the development of the Type C (carrier) control amplifier.

The Type C control circuit of Fig. 10 is designed for operation with 0.001” wires of platinum, nickel, or Hytemco (an alloy of nickel and iron) in either air or water. In order to obtain the necessary control over the loop-response characteristic, the error-modulated signal is converted to fluctuating DC and passed through a selective filter, and then used to control the output of the power stage. Two different carrier frequencies can be used depending upon the range of frequencies desired in measuring turbulent fluctuations: 10 kilocycles for fluctuations up to 1000 cycles, and 35 kilocycles for fluctuations up to 5000 cycles. The response curves for this circuit are presented in Figs. 11 and 12.

![Fig. 11. Relative Frequency Response of Type C System in Air](http://ir.uiowa.edu/uisie/37)
Factors to be considered in selecting the material for the sensitive wire are strength, resistance to corrosion, sensitivity to changes in velocity, and, for very small wires, ductility. In the construction of a sensitive-film probe, of course, mechanical support and form are provided by the base material of glass or quartz so that strength and ductility become unimportant, but capability of being deposited as a thin film on an electrical non-conductor is the critical requirement. When the constant-temperature method is used, the time constant is a secondary consideration. Information on most of these characteristics is readily available, and the best combination of properties for any particular set of conditions can be determined with relatively little trouble. However, the manner in which the properties of the material affect the velocity sensitivity is less obvious.

As has been stated earlier, velocity fluctuations can generate a signal only by changing the temperature, and hence resistance, of the sensing element. Since the equilibrium or steady-state relationship between temperature and velocity is a function of fluid properties and operating temperatures but is not dependent on the properties of the sensing-element material, the problem can be reduced to the determination of the voltage $E_s$ which results from a given temperature change $\Delta T$:

$$E_s = i \Delta R = iR\alpha \Delta T$$

$R$ is, of course, the resistance and $\alpha$ the temperature coefficient of the sensing element. In the case of a hot-film element, the resistance can be adjusted independently of the exposed area or resistivity by simply changing the thickness of the film. The heating current $i$ depends upon this resistance as well as upon the exposed area and operating temperature differential, and therefore can also be adjusted to a desired level by controlling the film thickness. Because the product $iR$ can be adjusted in this way to any practical value regardless of the resistivity, it follows that only
the temperature coefficient need be considered in determining the relative sensitivities of various materials for use as films.

If the material is to be used as a wire, however, the product $iR$ cannot be adjusted independently of the resistivity, and the above equation must be modified to determine the applicable law:

$$E_x = iR\alpha \Delta T = i \left( \frac{4lr}{\pi d^2} \right) \alpha \Delta T$$

In this relationship, $r$ is the resistivity of the wire material, $l$ is the length and $d$ the diameter of the wire. Inasmuch as the power dissipation $W$ is not dependent on the properties of the wire material, this expression can be reduced to a more useful form by the following substitution:

$$i = \sqrt{\frac{W}{R}} = \sqrt{\frac{\pi d^2 W}{4rl}}$$

Combination of the above equations leads to this final relationship in which $a$ is the overheating ratio:

$$E_x = \left[ \frac{4W/l}{\pi d^2} \right]^{\frac{1}{2}} \frac{r\alpha \Delta T}{\sqrt{r(1 + a)}}$$

For a given wire size, fluid, and operating temperature, the quantity in brackets is constant, and the voltage generated by a change in velocity (and hence in temperature) is related to the temperature change as follows:

$$\frac{E_x}{\Delta T} = \left( \text{constant} \right) \left[ \frac{ra^2}{1 + a} \right]^{\frac{1}{2}}$$

From this result, it is apparent that the product $ra^2$ or some power thereof should be considered as the basic criterion of sensitivity when selecting wire material; the greater this product, the more sensitive to velocity the wire will be.

After a careful study of the properties of metals as listed in available literature, the following have been chosen as having the desired characteristics of availability in small sizes, resistance to corrosion, strength, and velocity sensitivity. From the properties listed, the material best suited to particular circumstances can be chosen.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength</th>
<th>$\alpha \sqrt{r}$ (ohms/CMF)$^{\frac{1}{3}}$ (°C)$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>135,000</td>
<td>0.0408</td>
</tr>
<tr>
<td>Platinum</td>
<td>50,000</td>
<td>0.0293</td>
</tr>
<tr>
<td>Tungsten</td>
<td>500,000</td>
<td>0.0175</td>
</tr>
<tr>
<td>Hytemco*</td>
<td>150,000</td>
<td>0.0494</td>
</tr>
</tbody>
</table>

*Special Driver-Harris alloy
On the basis of this information, it appears that tungsten would be a good choice for wires wherever great strength is important, such as in high-velocity flow where the dynamic loading is high, or in fine-scale measurements where the linear dimensions of the wire must be very small. Where strength is not critically important, then the Hytemco alloy appears to be a good choice. It is recommended for use with the IIHR instruments wherever a wire of 0.001-inch diameter is feasible.

In designing hot-wire probes, special attention should be given to making the wire supports rigid, and the insulating material should have low moisture and temperature expansion properties. Bakelite and ceramics are superior to most plastics for this purpose. The supports should be about 1/8-inch apart at the tips, and should be tapered in order to avoid disturbing the flow. Some typical probes for general use are illustrated in Fig. 13.

![Typical Probes for Supporting Wires](http://ir.uiowa.edu/uisie/37)

All wires are fastened to the supports with soft solder, but the tungsten must first be plated with copper (silver could be used), because tungsten cannot be soft-soldered. This plating is usually built up until it is several
Design of Sensing Elements

The wire for Type A probes has a resistance of 2400 ohms per foot, so that the length of the active portion in normal use is 0.025 inch, and the diameter is approximately 0.00014 inch. As already mentioned, the wire for Type C probes is 0.001 inch in diameter, has a resistance of 120 ohms per foot at room temperature, and is used in nominal lengths of 0.1 inch. The Sigmund Cohn Company, Mt. Vernon, New York, can supply both types in specified sizes.

Hot-film probes are made by depositing platinum on a glass or quartz base of the desired form. This process usually consists of applying a special paint which can be obtained from Hanovia Chemical and Manufacturing Company, Ceramic Division, East Newark, N. J. After application, the painted surface is fired in an open flame or electric furnace to drive off the volatile components and leave a uniform film of metal. This process is repeated until a film of the desired resistance is obtained.

The glass support is prepared for the film by grinding, drawing, or otherwise forming it to the desired shape and dimensions. Wires for the electrical connections are imbedded in the glass so that the platinum coating is the only metal exposed to the fluid. A wedge-type probe is illustrated in the drawing of Fig. 14. Other possible forms are cylindrical or even a selected small spot on a flow boundary.

In making probes, extreme care must be exercised to eliminate sharp edges where the film is to be applied, because surface tension will cause the film to thin out at such points when the metal liquifies during the firing.
The heating effect of the current is then concentrated at these points during operation, and burnout occurs. It has also been found that the film adheres better if the glass surface is not polished too highly, probably because the difference in the coefficients of expansion of hard glass and platinum leads to excessive stress in the film if the surface is plane. In general, the hot-film probes are much more difficult to construct than are hot wires, even where plating of the wire is necessary.

Fig. 15. Type CAW Hot-Wire Anemometer System

Fig. 16. Type AL Hot-Film Anemometer System

**Construction Details**

Several major factors have been taken into account in the arrangement of components on the front panels of the assembled instruments (Figs. 15 and 16) and on the chassis supporting the operating components. For example, the controlling factor in locating the panel controls was logical arrangement from the operator's viewpoint. Meters are placed at or slightly below the eye level of a seated operator, and the controls affecting the indication of meters are placed where the connection will be apparent. The
cable connecting probes to the cabinet is long enough to reach any part of the wind tunnels or flumes normally used, but no longer than necessary, because the inductance of the cable is an undesirable part of the bridge impedance and hence should be kept to a minimum.

Behind the panels, major emphasis has been placed on ease of checking for proper operation and freedom from spurious indications due to environmental factors. Routine checks can be made from the rear of the cabinet without removing anything, and any one of the three major components can be removed from the front if detailed checking becomes necessary. The RMS Analyzer is completely independent from the rest of the components so that it can be used to analyze the signals from any type of pickup device.

Even though the Type A power supplies have been designed so that they do not introduce undesirable hum or noise into the system, precautions must be taken to prevent the introduction of extraneous signals from two other sources: slow drift from changes in ambient temperature or humidity, and noise in the turbulence spectrum due to microphonics or vibration-induced effects. The first problem is solved by blowing the warm air from the power supplies up through and around the bridge components and control amplifier. This air then passes out through the louvers on the side and rear of the relay rack. Because the vibrations near a wind tunnel may be quite pronounced, the control and linearizing amplifier chassis are suspended from soft coil springs which isolate them from all but the slowest and least offensive torsional and translational vibrations. For further flexibility and for use in trouble-shooting, these components are made individually removable and interchangeable.

Operating Procedure

All of the controls referred to in this section are located on the panels of either the power supply or the control and RMS units.

To place the Type A instrument in operation:

1. Be sure the Power-Supply switch is OFF, then connect the cables:
   (1) line cords to supply voltages as labelled, (2) the two inter-chassis power cables at the rear, (3) the probe cable to the WIRE CABLE socket, and (4) the fan cord to the socket provided on the power supply.
2. Before turning anything on, check the mechanical zeros of all meters, and adjust them if necessary.
3. Check to see that the OPR switch is in position T (for test). *Failure to do this may result in a burned-out wire.*
4. Place the probe in the region where measurements will take place.
5. Turn on the MAIN Power-Supply switch and the switch for whichever channel or channels are to be used. After the warmup
transients are over, use the DC BAL control to adjust the DC meter to approximately mid-scale.

6. Turn GALV switch to 1 or 2 as desired.

7. Set RESISTANCE control to 5 (this is the wire resistance for which the bridge will be in balance).

8. Etch wire with nitric acid until galvanometer balances at zero; if slightly shorter or longer wires are used, measure their resistance by adjusting the RESISTANCE control until galvanometer balances, then note reading of RESISTANCE control. Wash excess acid off of wire with water.

9. Set RESISTANCE control to 1.8 times value for galvanometer balance in step 8 (normally 9 ohms).

10. Turn OPR switch to 0. Wire is now in operation.

11. With wire in still air, bring panel meter to zero reading.

12. Place wire in air moving at 100 fps. Adjust meter reading $I$ to full scale by using METER SET. Check the bridge balance by noting indication of galvanometer; if not in perfect balance, readjust with DC BAL.

13. Reduce velocity to zero or cover the probe tip with a cap. If copper has been completely removed from the working length and the wire is straight, then the meter indication should be no greater than 0.05 MA. Furthermore, the slope of current vs velocity should be constant between this and the full-scale value. The curvature is affected by the overheating ratio. (See section on Trouble Shooting.)

14. If velocities greater than 100 fps are to be measured, place the probe in the region of maximum velocity and use the METER SET control to set $I$ to full scale. The slope of the calibration line will be constant for a wire which satisfies the conditions of step 13 above, but will have to be determined by comparison with a standard pitot at several velocities in the range of interest. (See following section on Calibration Techniques.)

15. Before measuring turbulence, turn GALV switch to center position. Failure to do this will increase noise level. It may be switched back in at any time to check bridge balance, however.

16. In order to avoid burning out the wire when shutting down, be sure to return OPR switch to T before turning off power supply.

To place the Type C instrument in operation:

1. Proceed as in steps 1 through 4 above.

2. Turn POWER on, and adjust the RESISTANCE control for a minimum reading on the panel meter. The indication of the RESISTANCE microdial will be proportional to the resistance of the sensitive wire at the temperature of the fluid.
3. Set the RESISTANCE dial to 1.2 (for water) or 2.0 (for air) times the value obtained in step 2.

4. Turn the control switch to OPERATE. This closes the control loop and the circuit automatically adjusts the wire resistance to its operating value.

5. Place the wire in fluid moving at the maximum mean velocity to be measured. Then use the RANGE control to bring the meter to full-scale deflection.

Special Note for crossed wires

In calibrating the crossed-wire probe, a linear relationship between $U$ and $I$ will be obtained when $I$ is approximately 70% of the corresponding value for a wire perpendicular to the stream. Since the sensitivity near a 45° inclination is approximately proportional to the sine of the angle, it is quite important that the angles $\Theta$ should be equal. This can be assured by adjusting the alignment of the probe until $I_1$ and $I_2$ (readings of the two panel meters) are equal.

Calibration Techniques

As noted in the following section, all turbulence computations are based on the slope $A$ of the $I$ vs $U$ curve, and hence it is essential to define this slope with an accuracy comparable to that which is expected in the results. To obtain this curve, a steady flow of fluid over the operating velocity range and a reliable instrument for measuring its velocity are necessary. A properly designed pitot tube is recommended for use as a standard. The pitot tube and the hot-wire probe are simply mounted side by side in a region where the velocity has been measured and proved uniform. Care must be exercised, of course, to assure that the pitot and probe are separated by sufficient distance to prevent either one from disturbing the flow past the other. Simultaneous readings of the mean current $I$ and velocity $U$ are taken and plotted, and the slope is measured directly from this curve:

$$A = \frac{\Delta U}{\Delta I}$$

If the curve is not a straight line, a trial-and-error manipulation of overheating ratio and meter setting will make it so with very little difficulty.

Because there is no equivalent of the pitot to compare with in the case of turbulent fluctuations, an indirect method not connected with flow must be used to calibrate the rms circuits. Since the basis of the calibration must be the mean velocity $U$ and its magnitude is indicated by the current $I$, any method must use $I$ as the standard of comparison. The voltage supplied to the rms circuits is developed by passing $I$ through a total resistance
of 50,000 ohms. By definition, the amplification constant $BF$ used in the following section is the ratio of two currents

$$BF = \frac{(I - \bar{I})^2}{I_T}$$

where $I - \bar{I}$ is the instantaneous deviation of the signal current $I$ from its mean value $\bar{I}$, and $I_T$ is the indication of the thermal meter.

For convenience in performing this calibration, a standard signal derived from an internal voltage source has been provided. When the CAL switch is pressed, exactly 0.5 volt is supplied to the metering circuit. If the multiplier switch is turned to position 1, the thermal meter will indicate a value $I_T$. The calibration constant $B$ is defined as

$$B = \frac{0.01}{I_T}$$

Note: Use the GAIN control to adjust the meter to full-scale deflection. Then $B = 0.002$. When the multiplier selector is turned to positions 2, 4, etc., the number indicated thereon is the factor $F$ already referred to.

To calibrate the differentiating circuit, a pure sine-wave voltage of variable frequency must be applied to one of the inputs and the indication of the thermal meter noted. The frequency of the voltage must be adjusted until the meter reading is identical for either position of the DIFFER­ENTIATOR switch. This will occur at a frequency $f_0$, and the circuit constant $D$ is

$$D = 2\pi f_0 B$$

The circuit is initially adjusted so that $f_0 = 3000$ cps, and can be readjusted to this value by means of the differentiator adjustment control on the chassis.

**Turbulence Computations**

1. Single wire normal to the flow: The mean velocity $U$ and the intensity of turbulence $u' = [u^2]^{\frac{1}{2}}$ are obtained from the meter readings $I$ and $I_T$ with the aid of calibration constants $A$, $B$, and $F$:

$$U = A\bar{I}$$

$$u' = A[(I - \bar{I})^2]^{\frac{1}{2}} = ABF I_T$$

2. Crossed-wire measurements: When the wire is mounted so that its axis is not normal to the flow, then it becomes sensitive to transverse fluc-
tations in velocity, and deviations in the signal current $I$ represent the following:

$$A(I - ar{I}) = u \sin \Theta + v \cos \Theta$$

where $\Theta$ = angle between the wire and the mean flow direction, $u$ is the fluctuation in the direction of the mean flow, and $v$ is the velocity fluctuation normal to $u$ in the plane of the wire. This characteristic can be used in several possible ways. Signals from two wires mounted at opposite angles $\Theta$ (wire 1) and minus $\Theta$ (wire 2) and operated simultaneously by the two control amplifiers can be combined or measured individually through use of the SELECTOR:

Position 1 — the reading $I_{T_1}$ on the thermal meter is related to the fluctuations by

$$ABFI_{T_1} = [u^2 \sin^2 \Theta + v^2 \cos^2 \Theta + 2 uv \sin \Theta \cos \Theta]^{\frac{1}{2}}$$

Position 2 — the signal $I_{T_2}$ represents

$$ABFI_{T_2} = [u^2 \sin^2 \Theta + v^2 \cos^2 \Theta - 2 uv \sin \Theta \cos \Theta]^{\frac{1}{2}}$$

Position A — deviations in the signal current are added instantaneously; the thermal meter reading $I_{T_A}$ represents

$$ABFI_{T_A} = 2 u' \sin \Theta$$

Position B — signals are subtracted simultaneously, and the reading $I_{TB}$ represents

$$ABFI_{TB} = 2 v' \cos \Theta$$

From these four readings, the following statistical quantities describing the flow can be obtained:

$$u' = \frac{ABF}{2 \sin \Theta} I_{T_A}$$

$$v' = \frac{ABF}{2 \cos \Theta} I_{TB}$$

$$uv = \frac{A^2 B^2 F^2}{4 \sin \Theta \cos \Theta} (I_{T_1}^2 - I_{T_2}^2)$$

3. **Correlation Measurements:** If two parallel wires are separated by a distance $s$ and placed so that their axes lie in a plane perpendicular to the
mean velocity, then their signals are combined by the SELECTOR to yield the following:

$$ABFI_{T1} = u'_1$$

$$ABFI_{T2} = u'_2$$

$$ABFI_{TA} = (u_1^2 + 2u_1u_2 + u_2^2)^{1/2}$$

$$ABFI_{TB} = (u_1^2 - 2u_1u_2 + u_2^2)^{1/2}$$

and the correlation function $g(s)$ is found as follows:

$$g(s) = \frac{u_1u_2}{u'_1u'_2} = \frac{1}{4} \frac{I_{TA}^2 - I_{TB}^2}{I_{TA}^2 + I_{TB}^2}$$

If the turbulence is homogenous, then $u'_1 = u'_2$ and

$$g(s) = \frac{I_{TA}^2 - I_{TB}^2}{I_{TA}^2 + I_{TB}^2}$$

4. **Dissipation-length Measurements:** The dissipation length defined by the relationship

$$\frac{1}{\lambda^2} = \frac{1}{u^2} \left( \frac{\partial u}{\partial x} \right)^2$$

can be found with aid of the differentiating circuit if the following assumption is permitted:

$$\frac{d}{dx} = \frac{1}{U} \frac{d}{dt}$$

If a single wire is placed normal to the flow, the fluctuations $(I - \bar{I})$ in its signal can be differentiated with respect to time before being measured by the thermal meter, which will give a reading $I_{m}$. Utilizing the relationship that $u^2 = (ABFI_r)^2$, $\lambda$ can be computed from the following equation:

$$\frac{1}{\lambda^2} = \left( \frac{D}{UBF} \right)^2 \left( \frac{I_{m}}{I_r} \right)^2$$

**Trouble Shooting**

Until the operator has had considerable experience in using a hot-wire anemometer, difficulties may plague his efforts, and there may be an appreciable delay between the times when work starts and results begin to come
The avoidance of these difficulties and simplification of the operating procedure have been primary objectives in the present design, and it is hoped that all of the major and most of the minor annoyances have been removed. This hope is supported by experience with several different operators at the Iowa Institute, most of whom had no previous experience with either electronic instruments or turbulence measurements.

Pitfalls which have been removed in the design, but of which the operator should be aware, include unstable operation due to tungsten wires which are operating, or have been operated, at overheating ratios of 1.0 or higher. If a wire is inadvertently operated at too high a temperature, destroy it. At the normal ratio of 0.8, wires have been used for months with no instability or detectable change of calibration. There is no danger of exceeding the allowable temperature due to a sudden reduction of velocity, however, because of the automatic control used.

If a wire breaks, this fact will quickly be indicated by the panel meter going completely off scale and refusing to return. Some difficulty will also be experienced in getting the bridge to balance. Simply turn off the power at the power unit until a new wire can be installed. In order to protect the galvanometer, do not switch it on when a broken wire is suspected.

In the event that a new wire does not conform to the regular operating curves within reasonable limits, check the fit of the probe in the socket, inspect the soldering of the wire to the probe, and make sure that there is no copper left on the active length. A microscope is a useful accessory in the inspection of the wire. If the wire appears to be blue instead of metallic white in color, it may have been overheated. A reddish color, of course, indicates incomplete removal of copper. If an old wire fails to follow its usual calibration, it may have become dirty and can be cleaned by washing in carbon tetrachloride. Bent wires should not be used. Small deviations from a strictly linear characteristic can be corrected by a slight adjustment of overheating ratio; some experimenting with different overheating ratios and the resultant curves is recommended for familiarization with their interrelationship.

Wherever possible, the substitution technique is a valuable aid in trouble shooting. If it is not known whether a particular difficulty has its source in the probe, the cable connections, the bridge, or the electronic circuit, then each of these elements can be replaced in turn with an alternate until proper operation is restored. This can be done completely, of course, only if at least two channels are available. The plug-in construction of the Type A control and linearizing amplifier is a great aid in using this method of trouble shooting.

If the static calibration is satisfactory but the noise level is unduly high, cover the probe so that no fluctuations of air speed can affect it. If the noise still persists, view it with an oscilloscope to determine its nature be-
fore further investigation. If the attenuator has no effect on the magnitude of the noise, then the trouble is in the output stage, and a competent technician should be able to find the source with the aid of the complete circuit diagram. Noise from the control amplifier will decrease with decreasing meter indication because of the non-linearity of the bridge amplifier, and should normally appear completely random in the absence of turbulence.

With regard to noise, it is important to secure the probe firmly to its traversing mechanism or whatever mount is used, and the probe should be so constructed that it will not permit the tips or the wire to vibrate. Vibration of the wire itself cannot be distinguished from fluctuations in velocity, except that vibrations may be more regular in form.

Correct output voltages for the power supplies are indicated in the circuit diagrams, and these can be checked periodically. Since the stability of the Type A hot-wire control circuits depends on the supply voltages, specially designed regulators are employed to give very high stability and very low noise in the output (total hum and noise in the B+ is 50 microvolts). All tubes, transformers, etc., in the power supply are operated at very conservative values and should give reliable operation for a long time. Controls for readjusting the supply voltages are clearly marked and can be used to compensate for changes due to normal aging of parts.

Because the hot-wire anemometer is naturally sensitive to the temperature as well as the velocity of the fluid, any change of fluid temperature after calibration will necessitate a resetting of the operating point for mean velocity. For normal changes in temperature, a single-point check is adequate, and the METER SET control can be used to adjust $I$.

**Basic Adjustments**

Only the controls used in normal everyday operation are located on the panels, and some of the basic controls accessible only when the instrument is removed from the rack may need occasional readjustment. The potentiometer located on the plug-in chassis on the control amplifier, for example, is used to adjust the DC level at which the 12AU6 bias-control tube operates. This control should be set so that the voltage on pin 2 of the 50C5 is zero when the voltage on pin 8 of the 12AX7 is 110 volts.

The adjustments on the power-supply chassis are used to set the regulated outputs to +250 volts (terminal 11 on the chassis connector at the rear of the plug-in unit) and —140 volts (on terminal 10 of the same connector).

The calibration signal for the RMS ANALYZER is obtained by chopping the 60-cycle supply voltage to obtain a pseudo-square-wave voltage with magnitude independent of the line voltage. To check this, a signal at any convenient audio frequency having a root-mean-square magnitude of exactly 0.5 volt should be supplied to the input. The panel-meter indication
should not change when the CAL switch is pressed. If it does, then the CAL ADJ control on the chassis can be adjusted to equalize the two indications.

ACKNOWLEDGMENTS

All phases of the work described herein have been carried out under the general supervision of Dr. Hunter Rouse, Director of the Institute, as part of a general program to develop instruments for use in fluid mechanics research. Complete financial support was provided initially (1946) by the Bureau of Ships under contract NObs-24084 and subsequently by the Office of Naval Research under contracts N7onr-495 and N8onr-500.

Valuable assistance in the design and evaluation of the instruments has been rendered by Messrs. E. G. Peterson, W. D. Baines, and S. C. Ling, Research Associates. Illustrations for the bulletin are primarily the work of Professor D. E. Metzler, Research Engineer, and Mr. K. C. Peng, Research Assistant.

REFERENCES


http://ir.uiowa.edu/uisie/37
**TABLE OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Slope of the mean-velocity calibration line, fps/milliampere</td>
</tr>
<tr>
<td>a</td>
<td>Overheating ratio of an operating wire</td>
</tr>
<tr>
<td>a_e</td>
<td>Error in overheating ratio</td>
</tr>
<tr>
<td>B</td>
<td>Basic calibration constant of the RMS Analyzer</td>
</tr>
<tr>
<td>C_i</td>
<td>Heat-dissipation constant for a hot wire at zero fluid velocity, watts/°C</td>
</tr>
<tr>
<td>C_s</td>
<td>Convective heat-dissipation constant, watts/°C/fps^{1/2}</td>
</tr>
<tr>
<td>d</td>
<td>Diameter of hot wire</td>
</tr>
<tr>
<td>D</td>
<td>Differentiating circuit constant, sec^{-1}</td>
</tr>
<tr>
<td>E_i</td>
<td>Output response of an open-loop control amplifier, volts</td>
</tr>
<tr>
<td>E_r</td>
<td>Input test signal to an open-loop control amplifier, volts</td>
</tr>
<tr>
<td>E_s</td>
<td>Signal across an operating hot wire, volts</td>
</tr>
<tr>
<td>E_r</td>
<td>Error signal at output of the control bridge, volts</td>
</tr>
<tr>
<td>F</td>
<td>Multiplying factor for RMS Analyzer sensitivity control</td>
</tr>
<tr>
<td>f</td>
<td>Frequency of velocity fluctuations, sec^{-1}</td>
</tr>
<tr>
<td>f_u</td>
<td>Frequency at which differentiating circuit has unity gain, sec^{-1}</td>
</tr>
<tr>
<td>f_m</td>
<td>Maximum fluctuation frequency to be measured, sec^{-1}</td>
</tr>
<tr>
<td>G</td>
<td>Open-loop amplification of control amplifier</td>
</tr>
<tr>
<td>G_0</td>
<td>Open-loop amplification at zero frequency</td>
</tr>
<tr>
<td>G_m</td>
<td>Open-loop amplification at maximum fluctuation frequency</td>
</tr>
<tr>
<td>g_o</td>
<td>Transconductance of control amplifier, mhos</td>
</tr>
<tr>
<td>H</td>
<td>Closed-loop characteristic of control amplifier</td>
</tr>
<tr>
<td>H_m</td>
<td>Closed-loop response at maximum fluctuation frequency</td>
</tr>
<tr>
<td>I</td>
<td>Signal current indication of main panel meter, milliamperes</td>
</tr>
<tr>
<td>I_1</td>
<td>Signal current corresponding to wire number 1</td>
</tr>
<tr>
<td>I_2</td>
<td>Signal current corresponding to wire number 2</td>
</tr>
<tr>
<td>I_T</td>
<td>Signal current indication of RMS Analyzer panel meter, milliamperes</td>
</tr>
<tr>
<td>I_{T_1}</td>
<td>Indication of RMS Analyzer for selector in position 1</td>
</tr>
<tr>
<td>I_{T_2}</td>
<td>Indication of RMS Analyzer for selector in position 2</td>
</tr>
<tr>
<td>I_{T_A}</td>
<td>Indication of RMS Analyzer for selector in position A</td>
</tr>
<tr>
<td>I_{T_B}</td>
<td>Indication of RMS Analyzer for selector in position B</td>
</tr>
<tr>
<td>I_{T_D}</td>
<td>Indication of RMS Analyzer with differentiator on</td>
</tr>
<tr>
<td>i</td>
<td>Heating current through hot wire, amperes</td>
</tr>
<tr>
<td>i_o</td>
<td>Heating current at zero velocity, amperes</td>
</tr>
<tr>
<td>i_m</td>
<td>Heating current at maximum velocity, amperes</td>
</tr>
<tr>
<td>j</td>
<td>Imaginary operator, $\sqrt{-1}$</td>
</tr>
<tr>
<td>K</td>
<td>Open-loop transfer function of control amplifier</td>
</tr>
<tr>
<td>M</td>
<td>Time constant of hot wire, seconds</td>
</tr>
<tr>
<td>r</td>
<td>Resistivity of wire material</td>
</tr>
<tr>
<td>R</td>
<td>Resistance of sensitive wire, ohms</td>
</tr>
<tr>
<td>R_0</td>
<td>Wire resistance at the temperature of the fluid, ohms</td>
</tr>
<tr>
<td>R_a, R_b, R_c</td>
<td>Resistances of control-bridge arms, ohms</td>
</tr>
<tr>
<td>R_e</td>
<td>Error in wire resistance, ohms</td>
</tr>
<tr>
<td>s</td>
<td>Distance separating wires for correlation measurements, feet</td>
</tr>
<tr>
<td>t</td>
<td>Time, seconds</td>
</tr>
<tr>
<td>U</td>
<td>Mean velocity past wire, feet per second</td>
</tr>
<tr>
<td>u</td>
<td>Deviation of longitudinal component of instantaneous velocity from mean, fps</td>
</tr>
<tr>
<td>v</td>
<td>Instantaneous magnitude of transverse component of velocity, fps</td>
</tr>
<tr>
<td>W</td>
<td>Power dissipated by hot wire, watts</td>
</tr>
<tr>
<td>x</td>
<td>Longitudinal distance coordinate, feet</td>
</tr>
<tr>
<td>Z</td>
<td>Input impedance of control amplifier, ohms</td>
</tr>
</tbody>
</table>

http://ir.uiowa.edu/uisie/37
Table of Symbols

\( \alpha \) Temperature coefficient of resistance, \(^{\circ}\text{C}^{-1}\)

\( \varepsilon \) Maximum permissible error in overheating ratio

\( \theta \) Angle between hot wire and direction of mean flow

\( \lambda \) Dissipation length, feet

\( \Phi \) Phase-shift angle of open-loop control amplifier

\( \Phi_{op} \) Open-loop phase angle at maximum fluctuation frequency

\( \Psi \) Phase-shift angle of closed loop control amplifier

\( \Psi_{cl} \) Closed-loop phase angle at maximum fluctuation frequency

\( \omega \) \(2\pi\) times fluctuation frequency

A bar (—) denotes the temporal mean of the quantity beneath it

A prime (’) denotes the root-mean-square of the associated quantity
COLLEGE OF ENGINEERING
STATE UNIVERSITY OF IOWA

Complete undergraduate courses are offered in Chemical, Civil, Commercial, Electrical, and Mechanical Engineering, as well as graduate courses in these fields and in Mechanics and Hydraulics. For detailed information, application may be made to T. H. McCarrel, Registrar.

IOWA INSTITUTE OF HYDRAULIC RESEARCH

The Institute was organized to coordinate the talents and facilities available at the State University of Iowa for the investigation of problems in the fields of fluid mechanics, hydrology, and hydraulic engineering. Through this medium the University has cooperated with government agencies, technical societies, and industrial concerns throughout the country. Correspondence regarding the services of the Institute should be addressed to Hunter Rouse, Director.
STUDIES IN ENGINEERING


Bulletin 33. "Third Decade of Hydraulics at the State University of Iowa," edited by M. C. Boyer, 1949. 84 pages, 8 figures, price $0.50.


http://ir.uiowa.edu/uisie/37