NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

TECHNICAL NOTE

No. 990

MEASUREMENT OF THE ARITHMETIC MEAN VELOCITY OF A

PULSATING FLOW OF HIGH VELOCITY BY THE HOT-WIRE METHOD

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FOR REFERENCE

NACA

Washington
April 1946

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SUMMARY

The report deals with an experimental method of measuring both the arithmetic mean velocity and the instantaneous velocity of pulsating flow and with the instruments developed for this purpose.

A circuit for a hot-wire anemometer applicable to the measurement of fluctuating flow is described. The principal elements of the circuit are a Wheatstone bridge, one branch of which is the hot wire, and an electronic amplifier and a current regulator for the bridge current which in combination maintain the bridge balanced. Hence the hot wire is kept at practically constant resistance and temperature, and the time lag caused by thermal inertia of the wire is therby reduced.

Through the addition of a nonlinear amplifier stage the reading of the instrument has been rendered proportional to the velocity.

A discussion of static and dynamic response of the circuit and of directional characteristics of the hot wire is given. Calculated characteristics are related to the results of calibration tests.

Hot-wire measurements of mean velocity and of the velocity profile of instantaneous velocities were obtained at the outlet of a rotating axial flow blade grid and correlated with measurements obtained with a pitot tube.

INTRODUCTION

Frequently it is necessary to determine the mean velocity in a stream of fluctuating velocity. If the direction of flow remains constant, the mean velocity may be determined from pitot tube measurements, provided the magnitude and character of the deviations from mean velocity are known. If, however, both the velocity and the direction of flow vary over a considerable range, for example, at the outlet of blade rows or compressor impellers, conventional methods of aerodynamic measurement fail to give accurate results.

It was for the purpose of developing a satisfactory method of measurement in instances similar to that cited that a program of investigation of the hot-wire technique was undertaken at Case School of Applied Science. This work was carried out under the auspices of the National Advisory Committee for Aeronautics, which also provided funds. Of necessity the measurement of instantaneous velocity profiles has been included in the program. Because of repeated delay in the delivery of testing equipment it was not possible to extend the investigation to velocities of the order of sound velocities, as intended. Instead the analysis of the instrument characteristics has been developed in detail, which should simplify further work in the high-velocity region.

The laboratory work and the calculation were carried out by Mr. R. J. Carleton and Mrs. F. Scott Rodgers, research assistants at Case School of Applied Science.

THE HOT-WIRE INSTRUMENT

The Component Parts

The hot-wire instrument consists of the following component elements shown schematically in figure 1:

(a) A Wheatstone bridge, one branch of which is formed by the hot wire

(b) A regulating circuit for the bridge current, including a battery or power supply and an electronic valve

(c) An electronic direct-current amplifier operated by slight variations of the unbalance of the bridge and controlling the current regulator

In addition to the above-mentioned three components
which constitute the basic circuit, an additional element
also shown in figure 1 may be provided; namely,

(d) A nonlinear amplifier stage; this stage is required
only if instrument characteristics other than
those resulting from the heat transfer charac-
teristics of the hot wire are desired and makes
it possible, in combination with the basic cir-
cuit, to obtain readings proportional to the
wind velocity past the hot wire.

Principle of Operation

If certain dynamic effects discussed later are neglected,
the operation of the basic circuit can be explained as follows:
The circuit is assumed to be operating at a given condition of
equilibrium. Then a disturbance, such as may be produced by
a change of velocity past the hot wire occurs, causing a vari-
ation of resistance of the hot wire and consequently a varia-
tion of potential between points (2) and (4) of the bridge
(fig. 1). This electric impulse is transmitted and amplified
by the amplifier stages. A variation of the potential between
grid and cathode of the current-regulating tubes and a corre-
sponding variation of the hot wire current is the result. The
resistance of the hot wire is thereby varied in such a way as
to counteract the original disturbance, and a new condition
of equilibrium is established. By proper choice of the ampli-
fication ratio of the amplifier it is possible, within certain
limits imposed by tube characteristics and stability of the
circuit, to make the difference between the hot-wire resist-
ance of the original and the new position of equilibrium very
small. The hot wire consequently operates essentially at con-
stant resistance - that is, at constant temperature.

In addition to the reduction of fluctuation of hot-wire
resistance, there is a corresponding reduction of the time lag
of response to variation of the condition of operation, pro-
vided the effect of capacitances in the circuit is also kept
small. This provision is necessary because the magnitude of
the time lag depends both upon the residual thermal inertia
of the wire and upon the effect of such capacitances.

Hot wire readings with the basic circuit are obtained by
measuring directly the heating current or by measuring a quan-
tity proportional to it, such as the grid voltage of the cur-
rent-regulator tubes, with respect to the ground.

In order to obtain a reading linear with velocity, use is made of an additional amplifier stage, item d of the preceding section, operated in a range of its characteristics, in which the exponent of the variation of plate current with grid potential, expressed in exponential form, is equal to the reciprocal of the exponent relating variations of heating current and of velocity past the hot wire. Tubes, such as those listed in tables I and II, were found to have a suitable range in which stable operation may be obtained. When adjusted for linearity between reading and velocity, the circuit may be expected to measure the mean velocity of fluctuating rectilinear flow.

The Circuit

(a) _Features of design of the hot-wire circuit_.- Circuit diagrams and circuit constants of the hot-wire instrument are given for two versions of the instrument: namely,

    (a) For battery operation, figure 2 and table I

    (b) For operation from 110-V alternating-current supply, figure 3 and table II

The two circuits are alike except for deviations necessitated by the different forms of power supply.

The bridge was designed with a view to keeping the input impedance of the amplifier low and to obtain a temperature adjustment which would stay constant over a sufficiently long period. The adjustable air condenser was provided to effect close balance of the bridge for alternating current, and a second condenser in the grid-leak circuit of the amplifier to compensate for the effect of interelectrode capacitance in the amplifier.

The design of the nonlinear stage was governed by the desirability of having one terminal of the output (i.e., the ground connection of the cathode-ray oscilloscope) at ground potential.

From operating experience with both versions of the hot-wire instrument it was concluded that the battery-operated instrument as designed has a lower time lag than the alternating-current supplied instrument.

It was found, however, to require frequent adjustment of bridge balance to counteract voltage drop of the batteries. Short effect, which is of negligible magnitude with fresh batteries, increases rapidly with age of the batteries to an

order of magnitude equal to that of the signal. With the
alternating-current-supplied instrument it was possible to
maintain bridge adjustment indefinitely once all tubes had
reached their equilibrium temperature; however, it has a higher
time lag and an alternating-current hum which precluded the
investigation of the high-frequency fluctuation of small am-
plitude.

(b) Design of power packs.- The power packs (fig. 4)
were designed to meet the following requirements:

(a) Maximum insensitivity of output voltage to
variations of input voltage

(b) Minimum alternating-current ripple

(c) Minimum time lag of response to variations
of load

These requirements were established after an investigation of
the effect of power pack characteristics upon operation of the
hot-wire instrument. They were found to be more exacting than
those ordinarily applied to power-pack characteristics and
therefore necessitated the development of special circuits.

The basic design of all three power-pack circuits is iden-
tical. Each power-pack consists of the following elements:

Main auxiliary transformers

Rectifier tube

Filter

Constant-current device, consisting of an electronic
tube and associated elements, such as a voltage reg-
ulator tube for the screen circuit

Voltage-regulator-tube circuit parallel to the output

Difference of output capacity and of the location of
ground connection resulted in certain differences in the de-
sign of the circuit, among them the following. The current-
regulator-supply power pack has four voltage-regulator tubes
in parallel capable of supplying a total of 100 milliamperes
output. The resistors placed in series with these tubes in-
sure firing of all tubes as the power pack is energized and
approximate equality of current through each at any load con-
dition. A separate screen supply for the current-regulator
tube was provided, the voltage of which is independent of the
output within closer limits than that of the plate supply of
the current regulator.

The circuit of the power pack for the screen and plate
supply of the direct-current amplifier differs from that for
the grid leak, apart from differences of the values of cer-
tain circuit constants, by a condenser C_7 (fig. 4). This
condenser serves to eliminate a ripple, and also decreases
the time lag of response to variation of output.

The relay in the current regulator supply was found neces-
sary to protect the screen leak VR tube during the warming-
up period of the power packs. Dynamic response of the power
packs constant current to variation of load was tested by con-
necting valve, a current amplifier circuit controlled by a
square wave generator to the output and measuring the time lag.
In all cases the time constant (see sec. on Response to Fluctu-
ations of Velocity) was found to be less than 1×10^{-6} second.

ANALYSIS OF OPERATING CHARACTERISTICS

List of Symbols

A	tube in hot-wire circuit for battery-operated hot-wire instrument
B	filament switch in circuit for battery-operated hot-wire instrument
C	equivalent capacitance in circuit for battery-operated hot-wire instrument
C_D	drag coefficient
c	constant in King's equation (2)
c_p	specific heat
D_1	milliammeter in circuit for battery-operated hot-wire instrument
D_2	microammeter in circuit for battery-operated hot-wire instrument
d	diameter of wire
E	steady flow voltage
e	instantaneous voltage
f_1, f_2, f_3	non-dimensional ratios of heating current to velocity
G	galvanometer in hot-wire circuit

g'_m	over-all transconductance of circuit
$(g'_m)_{cr}$	transconductance of current regulator value
H	quantity of heat
i	instantaneous heating current
i_0	heating current at zero air velocity
$j = \sqrt{-1}$	
$K = \dfrac{\Delta\Omega/\Omega}{\Delta l/l}$	strain sensitivity of wire
k	constant in King's equation (2)
l	length of wire
M	time constant, sec
m	mass of hot wire
$n = \dfrac{\omega}{2\pi}$	frequency
R	instantaneous resistance of hot wire
$\bar{R}$	mean ohmic resistance of hot wire
R_a	resistance of hot wire at temperature of ambient air
R_0	resistance of heated wire at zero velocity
S	power supply terminal
s	maximum sag of wire
T	temperature of wire
T_0	air temperature
t	time
V	velocity, ft/sec
Z	impedance of hot wire
α	temperature coefficient of resistivity
σ	tensile stress
θ	angle of incidence
$\varphi, \varphi_1, \varphi_2$	over-all phase lag of simple harmonic signal, of hot wire, and of amplifier, respectively

μ'   amplifier gain

ρ mass density, lb sec^2/ft^4

ω angular velocity

Ω resistance, ohms

Subscript

cr   current regulator value

Strength of Hot Wires at High Velocities

In testing hot wires of platinum in air streams of high velocity the observation was made that new wires, which were soft-soldered taut between their supporting prongs acquired a slight sag from exposure to a stream of 200 and even 150 feet per second velocity. As this could not be ascribed to failure of the solder joints, it was inferred that the wire was stretched. Further increase in velocity would increase sag until whipping of the wire occurred, which then would lead to breakage. Platinum wire of a length-diameter ratio l/d = 1000 would fail consistently at velocities exceeding 300 feet per second. No stretching of tungsten wire was observed after exposure to velocities from 500 to 800 feet per second.

(a) Equation for strength characteristics of hot wires. In order to establish a general relationship for the strength characteristic of the hot wires, it is assumed that breakage of the wire occurs as the aerodynamic drag causes the tensile stress in the wire to exceed the safe maximum limit for the metal. Let it be assumed further that the curves of the wire under load are similar — that is, that the ratio of sag p, to length l, is constant. The following relation may be established by the approximation of the curve by a parabola:

$$c_D \frac{\rho V^2}{2} ld \frac{l}{8p} = \sigma \frac{\pi d^2}{4}$$

hence

$$\sigma = \frac{1}{2\pi} c_D \frac{\rho V^2}{2} \left| \frac{l}{d} \right| \frac{l}{p} \tag{1}$$

(b) Maximum permissible length of hot wire.- Equation (1) may be used to calculate the maximum permissible length of a hot wire. To this end the following values have been assumed:

    1. Reynolds numbers for hot wires cover the range from 10 to 50.

    2. Corresponding drag coefficients are from 3.0 to 1.2.

3. Calculations were carried out for $C_D = 1.0$; if desired,
results may readily be corrected for any given value
of C_D.

4. In the absence of specific information it was assumed
that a sag equal to $1/100$ of the length of the wire
constitutes an acceptable operating condition, and
calculations have been carried out for this value,
$l/p = 100$.

The limiting velocity for safe operation of the hot wire in
respect to breakage was defined as the velocity of an air stream
of standard sea-level density producing a tensile stress in the
wire equal to the yield stress of the material. The tensile
strength of fine wires varies a great deal as a result of the
drawing process and the subsequent annealing of the wires for
purposes of aging before its use. The figures given in the fol-
lowing table are believed to represent average values.

TENSILE STRESS AND STRAIN PROPERTIES OF HOT WIRES

Material	Ultimate tensile strength (psi)	Yield strength (psi)	Modulus of elasticity (psi)
Platinum	20,000 to 30,000 annealed 53,000 hard drawn	as low as 5000 annealed	24.2×10^6 drawn
Tungsten	215,000 swaged rod 0.3 inch diameter 590,000 hard drawn wire 0.0014 inch diameter	500,000 hard drawn wire 0.0014 inch diameter	51.4×10^6 drawn wire

On the basis of the data of this table, curves have been
plotted in figure 5 giving maximum operating velocities versus
length-diameter ratio for various yield stresses. These data
lead to the conclusion that platinum wire may be used at rela-
tively low velocities; whereas tungsten wire is applicable for
very high air velocities.

(c) Strain sensitivity.- It is known that the electric
resistance of metal wires increases as the wire is subjected
to strain. The strain sensitivity is defined as the ratio:

$$\frac{\text{Unit resistance change}}{\text{Unit strain change}} = \frac{\Delta\Omega/\Omega}{\Delta l/l} = K$$

(See reference 3.)   This strain sensitivity forms the basis
of strain measurements by means of wire strain gages.   In ref-
erence 3 the values are given for the above ratio for strain
gage wire; namely,

$$K = 2.15 \text{ for cupronickel wire}$$

$$K = 3.6 \text{ for isoelastic wire}$$

Since corresponding values for tungsten wire were not
discovered in the literature, a simple test was made for the
purpose of identifying strain sensitivity and of establishing
its order of magnitude for this material.

A tungsten wire of 0.0011 centimeter diameter was sub-
jected to tensile loads.   At the same time a constant current
of 20 milliamperes was passed through the wire and the voltage
drop was measured.   The temperature of the wire was but slight-
ly in excess of room temperature.   No tests were conducted at
normal operating temperatures of hot wires.   The tungsten wire
was subjected to tensile stress of from 200,000 to 400,000
pounds per square inch.   The strain sensitivity was calculated
to be $K = 1.7$.

The calculated percentage variation of tungsten wire for
an assumed change of tensile stress of 200,000 pounds per
square inch, based on the measured strain sensitivity is 0.57
percent.

Strain sensitivity will affect the heating current of a
hot wire exposed to a high velocity air stream.   From King's
equation (see sec. on Static Response Characteristics of Hot
Wires at Constant-Resistance Operation)   it is seen that an
increase of the tension in the hot wire due to the impact of
the air causes an increase of its resistance R and for a
self-balancing bridge circuit a corresponding decrease of the
heating current.   This deviation from King's equation is shown
schematically in a graph of the square of the heating current
versus the square root of velocity (fig. 6).   This effect may
be as high as 1 milliampere and appears to make itself felt
in calibration curves.   (See fig. 12, curve C).   The effect
of strain sensitivity may be minimized by reducing the
length-diameter ratio of the hot wire.   Use may be made of
the graph (fig. 5) in conjunction with the data of the pre-

ceding table on Tensile Stress and Strain Properties of Hot
Wires in selecting a satisfactory length—diameter ratio.

(d) Method of mounting tungsten wire.— Hot wires of
platinum and nickel were mounted on their supporting prongs
by soft—soldering. This resulted in a connection which from
calibration tests appeared to be satisfactory both in regard
to mechanical strength of the connection and in regard to
its electrical resistance within the range of velocities for
which these wires are applicable. The ranges of velocities
are limited by the tensile strength of the hot wire itself.

Considerably more difficulty was encountered in attempt—
ing to mount hot wires of tungsten. Two methods of mounting
tungsten wire were investigated; namely, the spot—welding
method, and a special method described hereafter permitting
soft—soldering of the hot wire.

The welding of tungsten wire was done by a very simple
welding device in which the current and the fusion time
could be controlled only very crudely. As a consequence,
the prongs or the tungsten wire would burn and the probabil—
ity of obtaining two satisfactory welds and a taut wire was
low. It is believed, however, that neat welds could be ob—
tained with a welding device allowing careful control of the
conditions. However, since such a unit was not available,
this possibility was not pursued further.

A second method of mounting tungsten wire was developed
as a result of extended experimental investigation, in the
course of which more than fifty wires were mounted and subse—
quently tested in an airstream of up to 600 foot—per—second
velocity. It was recognized that a hot—wire connection to
be satisfactory for use in high—velocity air streams, must
have two discrete properties; namely, it must have adequate
strength and its electrical resistance preferably should be
negligible compared with the resistance of the hot wire, or
alternatively, it should be low and constant.

When attempting to soft—solder tungsten wire it was
found that soft—solder does not readily adhere to tungsten.
This condition appeared to be aggravated for certain samples
of tungsten wire which were believed to have acquired a coat
of tungsten oxide.

A method of obtaining a satisfactory connection between
tungsten wire and its prongs which takes account of the fore—
going considerations is described with reference to figure 7

by enumerating the various steps of the technique of mounting
a tungsten wire of 0.00061 centimeter diameter:

1. Pickling of the tungsten wire in hot aqua regia solu-
tion to remove the tungsten oxide. Duration of the process,
1/2 to 2 hours.

2. Plating of the wire in an electrolytic bath of rhodium.
A voltage of 1½ volts was applied to the electrodes for 30
seconds (figs. 7a and 7b).

3. Mounting of the tungsten wire between u-shape copper
wire shown in figure 7c. The u-shape wire is to be twisted
several times to wind the tungsten wire around the copper
wire after insertion of the latter into the hollow prongs.
Proper tension of the tungsten wire may be established con-
veniently by this method. The tungsten wire is then pushed
into a notch at the rim of the supporting prongs.

4. Soft-soldering of the u-shape wire and the tungsten
wire into the prong.

5. Removing of the rhodium from the hot wire outside the
solder joint by immersion into an aqua regia solution. It is
found that the solder is attacked much more slowly by the acid
than the rhodium, and no harm is done to the solder connection.

6. Microscopic inspection of the solder joint and of the
hot wire.

Tungsten wires mounted by this method were found to be
suitable for measurements in high velocity streams both in re-
gard to strength of the mounting and in regard to its elec-
trical resistance. The photograph of a hot-wire holder
(fig. 8) shows the proportions for a wire of 0.5 centimeter
length.

Static Response Characteristics of Hot Wires

at Constant-Resistance Operation

If constant resistance of the hot wire, or zero rate of
increase of heat energy in the wire, $dH/dt = 0$, is assumed,
the balance of energies supplied to, and dissipated by, the
hot wire may be expressed by King's equation (references 1
and 2).

$$3.4 \, i^2 = \frac{T-T_0}{R}(k+c\sqrt{V}) \tag{2}$$

Of interest is the variation of heating current with veloc-
ity at constant hot wire and ambient air temperature,
$T-T_0$ = constant, in which case it may be assumed that
both k and c also remain constant.

The variation of heating current with unit variation of
velocity may then be calculated from equation (1), using new

constants $k' = \frac{T-T_0}{3.4R} k$ and $c' = \frac{T-T_0}{3.4R} c$

$$f_1 = \frac{di}{dV} = \frac{1}{4V} \frac{c'\sqrt{V}}{\sqrt{k'+c'\sqrt{V}}} \tag{3}$$

The variation of heating current for 1-percent varia-
tion of velocity is

$$f_2 = \frac{1}{100} \frac{di}{\frac{dV}{V}} = \frac{1}{400} \frac{c'\sqrt{V}}{\sqrt{k'+c'\sqrt{V}}} \tag{4}$$

Finally, the percentage of variation of heating current
for 1-percent variation of velocity is

$$f_3 = \frac{\frac{(di)}{i}}{\frac{(dV)}{V}} = \frac{1}{4} \frac{c\sqrt{V}}{k+c\sqrt{V}} \tag{5}$$

The functional relations according to equations (3) to (5)
have been plotted in figure 9 for $k = 10$ and $c = 1$. It
follows that the accuracy of hot-wire readings, contrary to
general belief, at high velocities is inherently superior to
that at low velocities, at least for constant-resistance op-
eration considered here.

Response to Fluctuations of Velocity

Lag of response of the circuit to variations of velocity
may be caused by (1) lag of response of the hot wire, result-
ing in lag of the input signal of the amplifier and (2) by lag

of the amplifier and current regulator tube, resulting in
lag of the heating current with respect to the input signal
of the amplifier.

The time lag may be expressed by the angle of phase lag
of a simple harmonic signal. Let the angle of phase lag of
the hot wire be φ_1, and of the amplifier φ_2. Then the
over-all phase lag is

$$\varphi = \varphi_1 + \varphi_2$$

(a) Phase lag of the hot wire.— Considering first the re-
sponse of the hot wire it is recalled that the resistance of
the hot wire does not remain precisely constant. Its varia-
tions are related to variations of heating current by the
equation

$$i = i_0 \left[1 - g'_m (R - R_a) \right] \qquad (6)$$

Proportional changes of the temperature and the heat content
of the hot wire take place. The latter induces a heat-trans-
fer process requiring time, which is the cause of the time-
lag of response. This time lag has been expressed by Dryden
and Kuethe for constant-resistance operation (reference 2) in
the following form

$$M = \frac{4.2 \, m \, c_p (\overline{R} - R_a)}{i^2 R_a R_0 \, \alpha} \; \frac{1}{1 + g'_m \frac{(\overline{R} - R_a) \overline{R}}{R_a}} \qquad (7)$$

For values of the transconductance obtainable with the basic
circuit

$$2 g'_m \frac{(\overline{R} - R_a) R}{R_a} >> 1 \qquad (8)$$

hence equation (7) may be simplified to read

$$M = \frac{4.2 \, m \, c_p}{2 i^2 \, g'_m \overline{R} \, R_0 \, \alpha} \qquad (9)$$

The phase lag, φ_1, of the hot-wire response to a simple
harmonic variation of frequency $n = \frac{\omega}{2\pi}$ may then be calcu-
lated

$$\varphi_1 = \tan^{-1}(-M 2 \pi n) = \tan^{-1}(-M\omega) \qquad (10)$$

When expressing the time constant in terms of the ohmic re-
sistance $\overline{R}$ and the equivalent capacitance C of the hot
wire, $M = \overline{R}C$ (fig. 10),

$$\varphi_1 = \tan^{-1}(-\overline{R}\omega C) \qquad\qquad (11)$$

The minus sign in equations (10) and (11) indicates that the
current lags.

It is seen from equation (9) that the time lag of the
hot wire decreases as the over-all transconductance of the
circuit increases.

(b) Phase lag of the amplifier.— The amplifier stages
are resistance—coupled, and the only source of phase lag there-
fore is the interelectrode capacitances of the amplifier
tubes. As their effect may be reduced to a negligible amount
by a small compensating condenser shown in figures 2
and 3, the amplifier operates at practically zero phase lag
in the range of frequencies encountered.

(c) Dynamic characteristics of circuit response.— In
conjunction with the design of the hot—wire circuit, calcula-
tions of the response to velocity fluctuations were made and
the results are shown in figure 11, in the form of curves of
angle of phase lag versus amplifier gain μ' for simple
harmonic variations of hot wire resistance of various fre-
quencies. In these calculations the transconductance of the
current-regulator valve was assumed to have the constant value
$(g'_m)_{cr} = 0.005$. The phase lag of the amplifier was assumed
to be zero.

The calculations were carried through for two different
hot wires for which data is given in the following table:

Type of wire	Platinum wire	Tungsten Wire
Diameter $d =$	0.00025 centimeter	0.00061 centimeter
length $l =$	0.635 centimeter	0.635 centimeter
$l/d =$	2,540	1,040
Current at zero velocity $i_o =$	10×10^{-3} ampere	20×10^{-3} ampere
Time lag at $g'_m = 50$	$M = 0.0238 \times 10^{-6}$ second	$M = 11.35 \times 10^{-6}$ second

The following conclusions may be derived from inspection
of figure 11.

1. The residual thermal inertia of the hot wire is the
principal factor in determining hot-wire response. For maxi-
mum response to fluctuations of velocity of high frequency it
is desirable to use as thin a hot wire as can be handled.

2. For a given hot wire there exists an optimum gain of
the amplifier in regard to phase lag and tube noise. Ampli-
fier gain and hot-wire characteristics should be matched for
best response of the circuit. (See sec. d.)

3. Development of the hot-wire circuit for response to
high-frequency oscillations call for high amplifier gain and
for compensation of the phase lag of the amplifier, which
may easily be accomplished over a wide band of frequencies by
conventional technique.

(d) Limits of response.- Increase of over-all transcon-
ductance decreases the time lag according to equation (9).
It likewise decreases the variation of hot-wire resistance
$(R - R_0)$ for a given velocity variation according to equa-
tions (6) and (2) and thereby the magnitude of the input sig-
nal of the amplifier, which varies inversely to the amplifier
gain. There exists a definite lower limit of input signal
and consequently of amplifier gain, established by the magni-
tude of the tube noise of the first amplifier tube. As the
input signal is reduced to the order of magnitude of the tube
noise it can no longer be discerned readily nor be analyzed
correctly. This limit is reached as the input signal is re-
duced to less than 10 microvolts and is approached in the
design of hot-wire circuits. (See curves e and f of fig.
11.)

Interference from tube noise can be reduced by the fol-
lowing measures:

(a) Operation of the hot wire at high temperature

(b) Choice of a tube of low noise level for the first
amplifier stage

(c) Low amplifier gain

(d) It is to be noted that, all other things equal,
tube noise affects the readings less at higher
velocities than at low velocity

CALIBRATION

A number of calibration tests were performed to estab-
lish the characteristics of the instrument experimentally.

Static Calibration

Calibration tests for static response included measure-
ments of the equilibrium conditions of various states of op-
eration without regard to transient phenomena.

(a) _Variation of heating current with velocity_.— The
static response of the circuit to variations of velocity past
the hot wire was tested by measurement of the heating current
required to maintain the hot wire at constant temperature.
To this end the hot wire was supplied with a heating current,
i_o, at zero airspeed by adjustment of the variable bridge
resistor and then balanced. Once adjusted this balance was
maintained automatically at all speeds except for the small
unbalance necessary to induce compensating action. Typical
calibration curves are given in figure 12, in which the
square of the heating current, i_o, has been plotted against
the square root of the velocity, $\sqrt{V}$, for one value of i_o
each for three different hot wires. The platinum wire was
tested to 340 feet per second, the highest velocity it was
believed capable of sustaining without suffering permanent
strain, the other wires to the maximum airspeed obtainable
with the test equipment. At first the hot wire was placed
in the stream from a nozzle placed on discharge side of the
blower (an aircraft-type supercharger). This was found to
be unsatisfactory, however, because of large disturbances of
hot-wire readings which soon were traced to temperature lami-
nation in the air stream originating in the blower. After
placing the nozzle on inlet side of the blower these disturb-
ances vanished and the results of figure 12 were obtained
without further difficulty.

It is seen that the curve for platinum deviates from a
straight line at a velocity of 150 feet per second. The devi-
ation from straight line in the $i^2 - \sqrt{V}$ diagram is caused
by strain of the wire. Strain effects depend on factors not
readily controlled, such as the sag of the wire, and should
therefore be looked for especially in hot-wire calibration,
since the occurrence of strain probably establishes an upper

limit for the velocity range for which a hot wire may be ap-
plied. In the case of the nickel wire and the tungsten wire,
strain effects did not become apparent within the range of
velocities tested.

(b) Linearity of instrument reading with velocity.— It
was found that the variation of plate current of the non-
linear stage could be adjusted readily so as to be linear
with the variation of wind velocity past the hot wire. This
is effected by adjustment of the screen voltage of the non-
linear stage. It may be done without the use of an air jet
by reading the variation of plate current which takes place
as successively various currents $(i - i_o)$ related to the wind
velocities by the heating current—velocity characteristic of
the hot wire are impressed upon the current supply terminals
of the Wheatstone bridge to flow in opposite direction to
the heating current i_o. Linearity, which may be thus estab-
lished readily over all but the first tenth of the range of
velocities, may be checked in the air stream. Results of a
calibration test are given in figure 13.

(c) Directional characteristics.— Hot—wire readings of
the instrument with linear characteristic taken at constant
velocity but varying angle of incidence θ between direction
of flow and hot wire are plotted in figure 14. The figure
also shows in dot—and—dash lines the $\sqrt{\sin^2 \theta}$ curve, and it
is seen that the calibration curve displaced a few degrees
follows this $\sqrt{\sin^2 \theta}$ curve with reasonable approximation,
except in the range from 0° to 6° angle of incidence. It
can be stated that the hot—wire instrument measures the com-
ponent of velocity in the transverse plane of the wire.

Calibration for Response to Fluctuations of High

Frequency and Large Amplitude

(a) Theory of square—wave testing.— The theory of the
square—wave method is based upon the mathematics of the unit
function of Fourier's series (references 4 and 5). The theory
and application of square—wave testing of alternating current
and electronic circuits has been discussed in reference 6.

With reference to its application to hot—wire response,
it may safely be assumed that interference between states of

operation which are more than half a period of the square
wave apart are of no concern. For this reason the theory may
be confined to the study of the instantaneous change from one
condition to another condition, where both the initial and
the final conditions are maintained constant over an indefi-
nite period. This change is represented graphically by curve
a of figure 15.

Equivalent circuit.- The characteristics of the hot-wire
circuit are represented by the equivalent electrical circuit
(fig. 16). A decrease of velocity past the hot wire corre-
sponds to an increase of current through the equivalent cir-
cuit. The resistance R and the capacitance C represent
the resistance of the hot wire and its residual thermal iner-
tia as well as the reduced capacitance of the circuit. Vari-
ations of the resistance of the hot wire, which in a circuit
with automatically balanced bridge are small, are not taken
into account in the equivalent circuit.

Suddenly applied voltage.- The instantaneous application
of a voltage is described by the function:

$$e_1 = \int_{\omega=0}^{\omega=\infty} \frac{E}{\pi\omega} \sin(\omega t) \, d\omega$$

Let the resistance R_1 (fig. 16) be of such magnitude
that the effect upon the current i through the circuit of
the combined impedance

$$Z = \frac{R}{1 + \omega^2 C^2 R^2} - \frac{j\omega C R^2}{1 + \omega^2 C^2 R^2}$$

of the resistance R and the capacitance C acting in paral-
lel may be neglected. In that case the equation for the cur-
rent is:

$$i = \frac{E_1}{R_1} \int_{\omega=0}^{\omega=\infty} \frac{1}{\pi\omega} \sin(\omega t) \, d\omega$$

and the potential across the resistance R or capacitance C:

$$e = \frac{E_1}{R_1} R \left[\frac{1}{\pi} \int_{\omega=0}^{\omega=\infty} \frac{1}{\omega} \frac{\sin(\omega t)\, d\omega}{1+\omega^2 C^2 R^2} - \frac{1}{\pi} \int_{\omega=0}^{\omega=\infty} \frac{CR}{1+\omega^2 C^2 R^2} \cos(\omega t)\, d\omega \right]$$

where $\cos(\omega t)$ has been substituted for $j \sin(\omega t)$.

The first integral in brackets is of the form

$$\frac{1}{x(1+x^2)} \sin(mx)\, dx$$

as will be seen when substituting

$$x = \omega R C$$

$$m = \frac{t}{RC}$$

its value is (reference 7, item 445)

$$\pi - \frac{\pi}{2} e^{-t/RC}$$

The second integral in brackets is of the form

$$\int_0^\infty \frac{1}{1+x^2} \cos(mx)\, dx$$

x and m denoting the same quantities as above. The value of this integral is (reference 7, No. 263, p. 27)

$$\frac{\pi}{2} e^{\frac{-t}{RC}}$$

When substituting these values, the function $e = f(t)$ becomes

$$e = \frac{E_1}{R_1} R \left[1 - e^{\frac{-t}{RC}} \right]$$

This relation is represented by curve b, figure 15,

Geometrical representation of the time constant.- The quantity RC has been recognized as the time lag M. (See sec. on Response to Fluctuations of Velocity.) This quantity may be related to the response curve of an instantaneous change, curve b of figure 15, in two distinct ways, as shown below:

1. Differentiate the equation for e of the preceding paragraph with respect to time at t = 0

$$\left(\frac{de}{dt}\right)_{t=0} = \left(\frac{E_1}{R_1} \times \frac{R}{RC} \times e^{\frac{-t}{RC}}\right)_{t=0}$$

where $E = \dfrac{E_i}{R_1} R_1$, the voltage of the final state

when rearranging: $M = RC = \dfrac{E}{\left(\dfrac{de}{dt}\right)_{t=0}}$ which is

represented by the distance 1-2 in figure 15.

2. Calculate the ordinate of the response curve, curve b of figure 15, for the time t = RC = M

$$(e)_{t=RC} = E(1-e^{-1}) = 0.632 E$$

where, $E = \dfrac{E_1}{R_1} R$, as above.

From this it follows that the time constant M may be obtained as the horizontal distance from the start of the response curve to the ordinate e = 0.632 E.

Response to noninstantaneous changes.- The first geometrical construction for M is identical to the construction applied to the response curve of a harmonic disturbance. (See reference 2, p. 12.) It may be concluded from this that the time constant may be obtained by either geometrical construction even in cases where the original impulse is not instantaneous, provided the curve of the applied voltage is known and compensated for by a corresponding horizontal displacement of the response curve.

The relations established in this section derived for a simple electrical circuit may be applied to the calibration

of a hot—wire circuit as it has been shown in the section on
Response to Fluctuations of Velocity, that the combined char-
acteristics of a hot wire and its circuit may be expressed
through an ohmic resistance and an equivalent capacitance op-
erating in parallel.

(b) Calibrating device for square—wave testing of the
hot wire.— Changes of operating condition of the hot wire ap-
proximating those of square waves are produced by oscillating
the hot wire at right angles to an air jet. The hot wire is
arranged in such a manner that at the midpoint of its stroke,
consequently at its maximum velocity, it enters the air jet
simultaneously over its entire length. The axis of the wire,
the direction of the air jet, and the direction of motion of
the wire are at right angles with respect to each other. The
mechanism of the calibrating device is shown in figure 17,
which is believed to be self—explanatory. It operates at a
stroke of 4⅛ inches and at a frequency of 30 to 60 cycles per
second. The velocity of the air stream may be varied from 0
to 400 feet per second.

In using the calibrating device, account must be taken
of the fringe layer separating the free jet from the surround-
ing stagnant air. It should be reduced to minimum thickness
by removing the boundary layer of the nozzle (see fig. 17)
and by traversing the jet close to the throat of the nozzle.
Correction must be made for the remaining fringe layer in
evaluating the calibration records.

A sample oscillograph obtained with the square—wave cali-
brating device from a circuit with considerable time lag is
shown in figure 18.

Measurements of the time lag of the hot—wire instrument
with battery supply and with a tungsten wire of 0.00061 centi-
meter diameter and 0.80 centimeter length, carefully adjusted
for maximum response indicate that in this case M is of the
order of 10×10^{-8} second. Precise measurements, however,
were not possible, chiefly because of the disturbing effect
of the fringe layer upon the measurement. Further development
of the square—wave testing device is necessary to achieve
higher speeds of the hot wire as it enters the air stream and
thereby higher precision of measurement of small time lags.

MEASUREMENT OF MEAN VELOCITY OF AN AIR STREAM

The hot-wire instrument as described in the preceding
paragraphs was used for measuring the mean velocity in two
distinct cases, namely; (1) In a flow of varying velocity
but of uniform direction in which, moreover, both the mean
velocity and the character of the fluctuations could be ascer-
tained precisely. (2) In a flow of cyclicly varying velocity
and direction in which other measuring devices are not pre-
sumed to give precise results.

Measurement of Rectilinear Flow

The hot wire was mounted on a shaking device oscillating
at from 30 to 60 cycles per second through a stroke of 6
inches in an air stream parallel to the direction of flow.
The air stream was produced by a nozzle of 8 inches diameter,
its velocity could be varied from 0 to 400 feet per second.

The tests then consisted of shaking the wire at various
frequencies and at various velocities of the air stream,
while at the same time observing the cathode ray oscilloscope
and taking readings of the nonlinear stage.

The readings of the mean velocity confirmed the antici-
pation as it remained the same whether or not the hot wire
was shaken, except in case the airspeed of the jet was less
than the maximum speed of the shaker motion.

The oscillograph observation was less conclusive than
the mean readings since it is difficult to detect slight devi-
ation from a sine curve. Distinct indication, however, was ob-
tained from the oscillograph as soon as the direction of rela-
tive velocity reverses — that is, the case referred to above
when the instrument ceased to read the mean velocity.

Measurements of a Field of Flow of Varying

Velocity and Direction

An investigation was made of the possibility of measur-
ing the mean axial velocity, as well as the instantaneous
axial-velocity components at the discharge of a rotating blade
row. A rotating axial-flow blade grid of 36-inch tip diameter

20-inch hub diameter, consisting of 12 blades of 7-inch chord
and 8-inch span, rotating at from 600 to 1000 rpm, was avail-
able (reference 8). Directly downstream of this grid and ro-
tating with it was mounted a pitot tube by means of which wake
traverses could be measured while the grid was in operation.

Hot-wire measurements were obtained on this blade grid
by placing a stationary hot wire at midspan radius of the
blades approximately 1 inch axially downstream of the trail-
ing edges such that the hot wire was directed in the plane of
rotation tangential to a circle concentric to the axis of ro-
tation. The hot-wire instrument might then be expected, ac-
cording to the section Directional characteristics, to give
readings of the axial velocity components. The instantaneous
reading was made visible on the screen of a cathode-ray os-
cilloscope. To this purpose the sweep circuit of the oscillo-
scope was synchronized with the rotation of the rotating grid
by photocell circuit such that the velocity pattern of only
one-blade interval appeared on the screen. An oscillograph
thus obtained at midspan for 700 rpm and 120 feet per second
mean axial velocity is shown in figure 19. At the same time,
mean readings of the hot-wire instrument were taken.

The oscilloscope was evaluated from the known calibration
characteristics of the hot-wire instrument and the deflection-
voltage ratio of the oscilloscope, yielding the variation from
mean of the instantaneous axial velocity and in conjunction
with the mean reading of the instantaneous velocity.

Corresponding pitot tube measurements of a wake traverse
relative to the rotating grid were evaluated to give a profile
of instantaneous axial velocities. In this case variations
of direction of the relative velocity which were not measured
had to be disregarded. The profiles of the axial-velocity
components obtained from hot-wire readings and from pitot tube
readings in the rotating system, shown in figure 20, show rea-
sonably good correlation.

CONCLUSIONS

The investigation has shown that hot-wire circuits of the
type described, operating at essentially constant resistance
of the hot wire, respond to fluctuations of velocity at very
small time lag.

It is possible, by means of a suitably adjusted amplifier
stage, to obtain instrument readings proportional to the veloc-

ity of a flow of fluctuating velocity and of constant direction.

Directional calibration of the hot-wire instrument with linear reading reveals that within a wide range of variations of direction it is possible to obtain readings of the velocity component normal to the hot wire, from which it is concluded that in flow of varying velocity and direction the mean velocity component normal to the hot wire may be measured.

At high velocities both the strength and the strain sensitivity of hot wires must be considered. It appears that in this respect tungsten wire is most suitable. Suggestions are made for mounting tungsten wires.

Aerodynamics Laboratory,
    Case School of Applied Science,
        Cleveland, Ohio, December 13, 1944.

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TABLE I.- CIRCUIT CONSTANTS, BATTERY-OPERATED INSTRUMENT

R_1	2,000 ohms	A_1 and A_2	ILN5 tubes
R_2	5,000 ohms	A_3	ISA6 GT tube
R_3	30 ohms	A_4	1 to 4 IS4 tubes in parallel
R_4	100,000 ohms		
R_5	500,000 ohms	B_1	filament switch on R_5
R_6	10,000 ohms	B_2	filament switch on R_{13}
R_7	3 megohms		
R_8	10 megohms	B_3	filament switch on R_3
R_9	600,000 ohms	S_2 and S_5	+180 volts to ground
R_{10}	3 megohms	S_1 and S_4	+90 volts to ground
R_{11}	1 megohms	S_5	ground
R_{12}	5 megohms	S_7	-90 volts to ground
R_{13}	500,000 ohms	S_3 and S_6	-180 volts to ground
R_{14}	5 megohms	G	galvanometer
R_{15}	100,000 ohms	D_1	(0 to 75) milli-ammeter
		D_2	(0 to 100) micro-ammeter

TABLE II.- CIRCUIT CONSTANTS, ALTERNATING-

CURRENT SUPPLIED INSTRUMENT

R_1	2,000 ohms	G	(0 to 100) milliammeter
R_2	5,000 ohms	D_1	(0 to 100) microammeter
R_3	30 ohms	D_2	galvanometer
R_4	1,500 ohms		
R_5	500,000 ohms	C_1	0 to 100 mmf
R_6	1.2 megohms	C_2	0 to 30 mmf
R_7	3 megohms		
R_8	500,000 ohms	A_1, A_2, A_3	6AC7 tubes
R_9	1.2 megohms	A_4	6-Y-6 tube
R_{10}	200,000 ohms	A_5	1/4-watt neon bulb
R_{11}	1.8 megohms		
R_{12}	100,000 ohms	B_1	switch on R_4 control
R_{13}	50,000 ohms		For supply voltages at points
R_{14}	50,000 ohms		S_1 to S_7, see figure 4.
R_{15}	1.2 megohms		
R_{16}	1,000 ohms	$(S_8 - S_9)$	6 volts d.c.

TABLE III.- POWER SUPPLY

A_1	Thordarson, T-13312 or equivalent.
A_2	Utah, 660 or equivalent
A_3	Thordarson, T-19P54 or equivalent
A_4	filament transformer, 5 volts 2A
$(L_1 - L_2)$	shielded filter choke 20 hy 50 MA
$(L_3 - L_4)$	shielded filter choke 15 hy 200 MA
C_1, C_2, C_3, C_4, C_5	electrolytic condenser 20 MFD 450 volts
C_6	16 MFD
R_1	400 ohms, 1/2 watt
R_2 and R_5	6000 ohms, 1/2 watt
R_3 and R_6	100 ohms, 10 watts
R_4	2000 ohms, 2 watts
R_7	1000 ohms, 50 watt, with adjustable tap
R_8	1000 ohms, 1/2 watt
$R_9, R_{10}, R_{11}, R_{12}$	700 ohms, 1 watt
R_{13}	75 ohms, with adjustable tap
R_{14}	7500 ohms, 1 watt

HOT WIRE CIRCUIT

WITH VERY SMALL TIME LAG

CIRCUIT ELEMENTS   SCHEMATIC

BRIDGE BALANCE
GALVANOMETER

REGULATION OF BRIDGE BALANCE

ADJUSTMENT OF RANGE
AND LINEARITY

READING LINEAR
WITH
VELOCITY

G

D.C.- A.C. AMPLIFIER

GRID   OUTPUT

CATHODE

(GROUND)   (GROUND)

GRID

CATH

GRD GRD

A

HOT WIRE

REGULATION OF
HOT WIRE
HEATING
CURRENT &.e.
HOT WIRE
TEMPERATURE

CATHODE RAY
OSCILLOGRAPH

NONLINEAR
AMPLIFIER STAGE

A ← HEATING CURRENT

PLATE
GRID
CATH

← CURRENT REGULATOR VALVE

FIGURE 1.- COMPONENTS OF THE HOT WIRE INSTRUMENT, SCHEMATIC.

Fig. 1
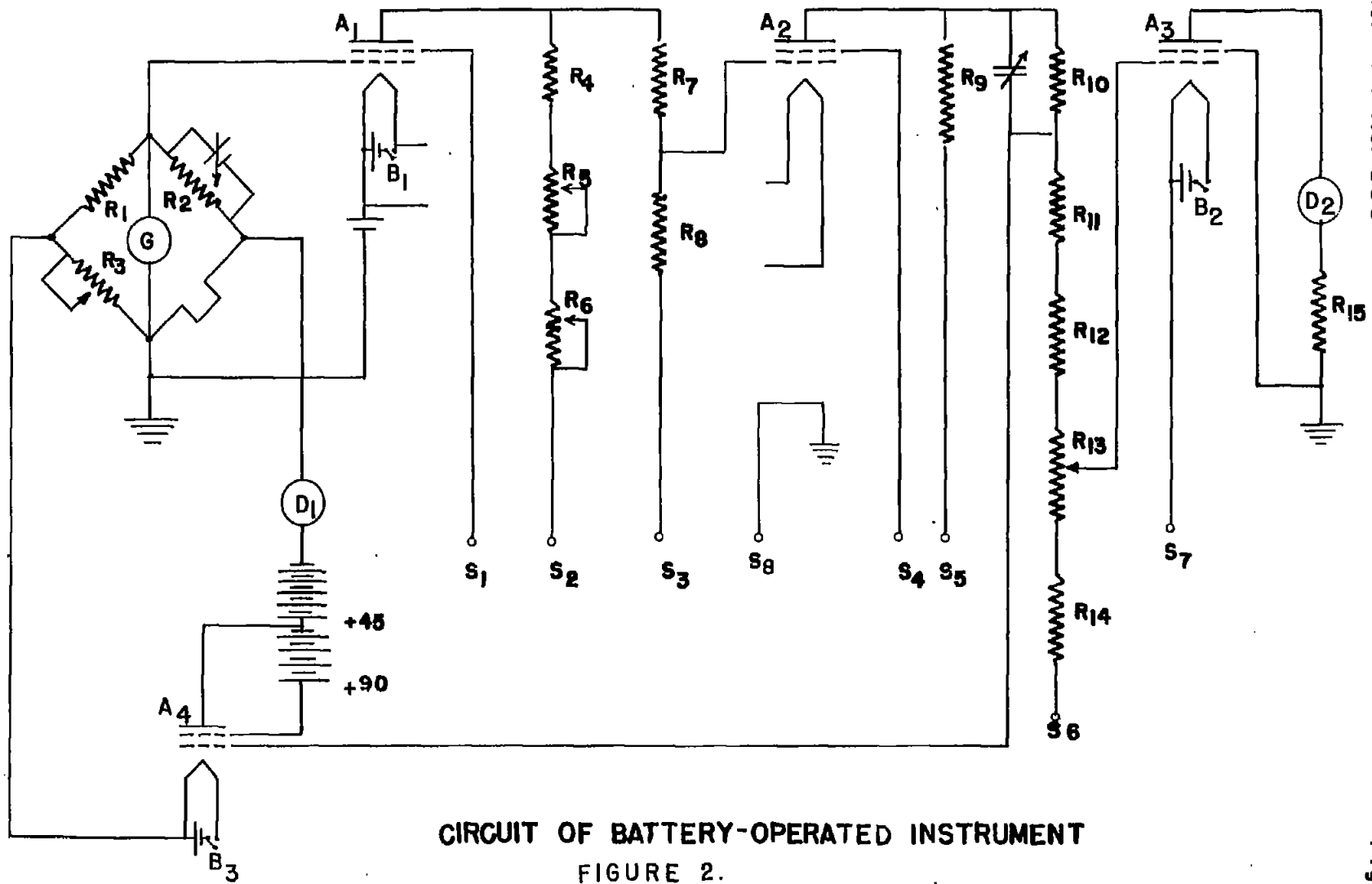
CIRCUIT OF BATTERY-OPERATED INSTRUMENT
FIGURE 2.

Fig. 2

Fig. 3
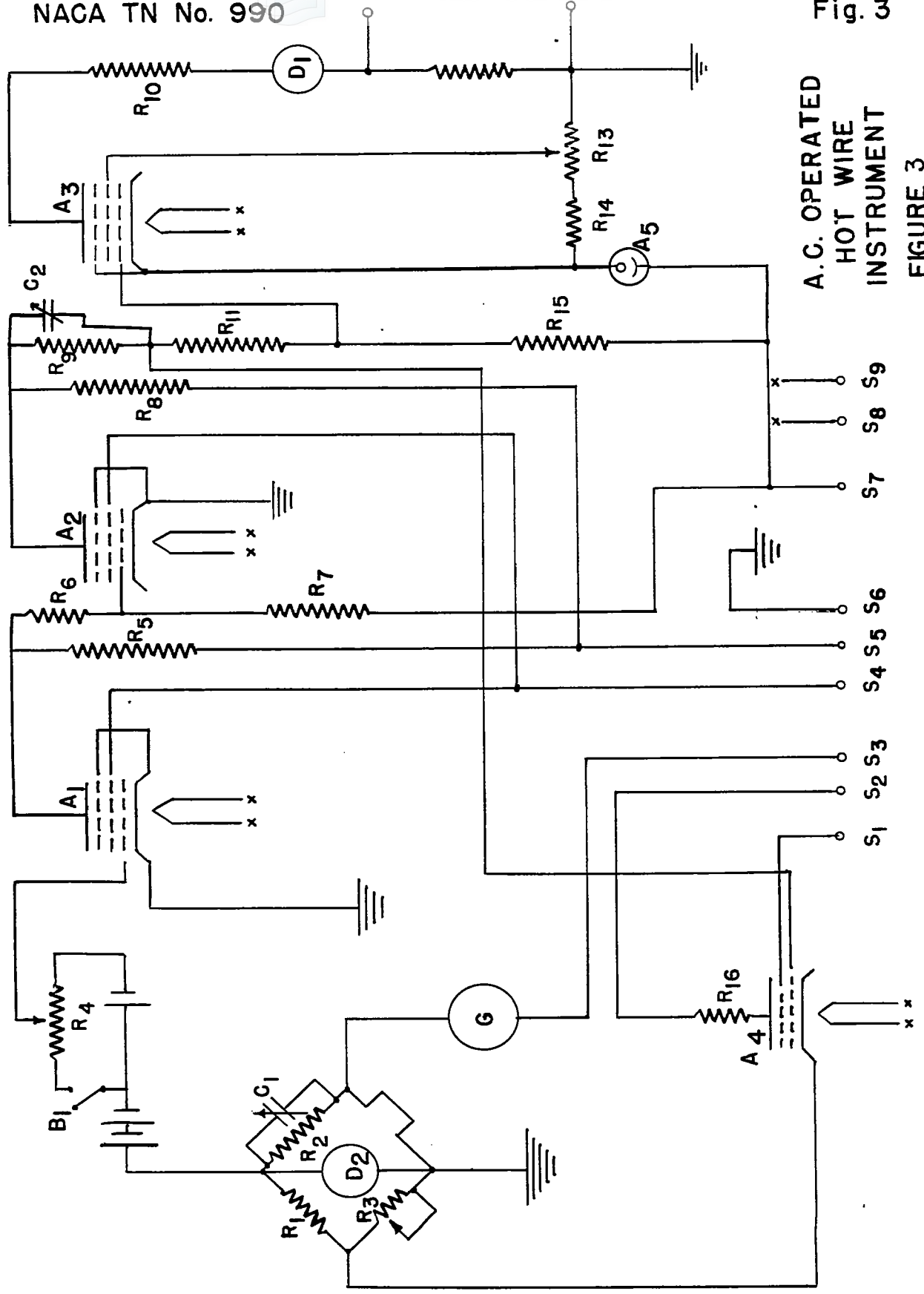
A.C. OPERATED
HOT WIRE
INSTRUMENT
FIGURE 3

Fig. 4
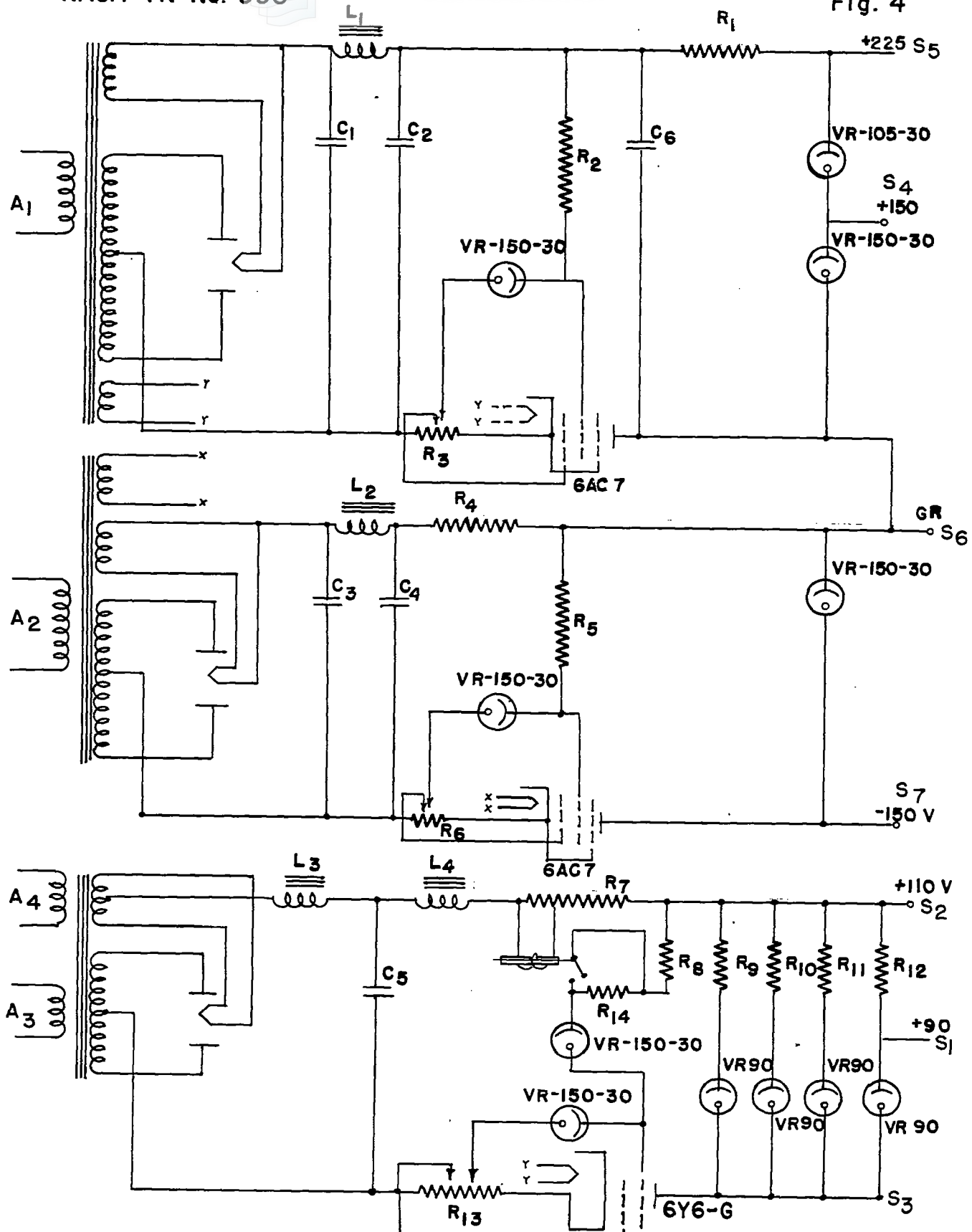
FIGURE 4.- CIRCUIT OF POWER PACKS FOR A.C. SUPPLIED INSTRUMENT.

MAXIMUM OPERATING VELOCITY OF HOT WIRES

EQUATION

$$V = \sqrt{\frac{2\pi}{C_D} \cdot \frac{2}{\rho_o} \cdot \frac{S}{\ell}} \sqrt{\frac{d}{\ell}} \sqrt{\sigma}$$

PLOTTED FOR $C_D = 1.0$

$\rho_o = .00238 \dfrac{LB.\,SEC.^2}{FT.^4}$

$\dfrac{\ell}{S} = 100$

WHERE S = SAG OF WIRE

500,000

200,000

100,000

50,000

TENSILE STRESS

10,000 LB/SQ. IN.

INDICATED AIR SPEED, FT/SEC

LENGTH/DIAMETER RATIO OF HOT WIRE

FIGURE 5

NACA TN No. 990

Fig. 5
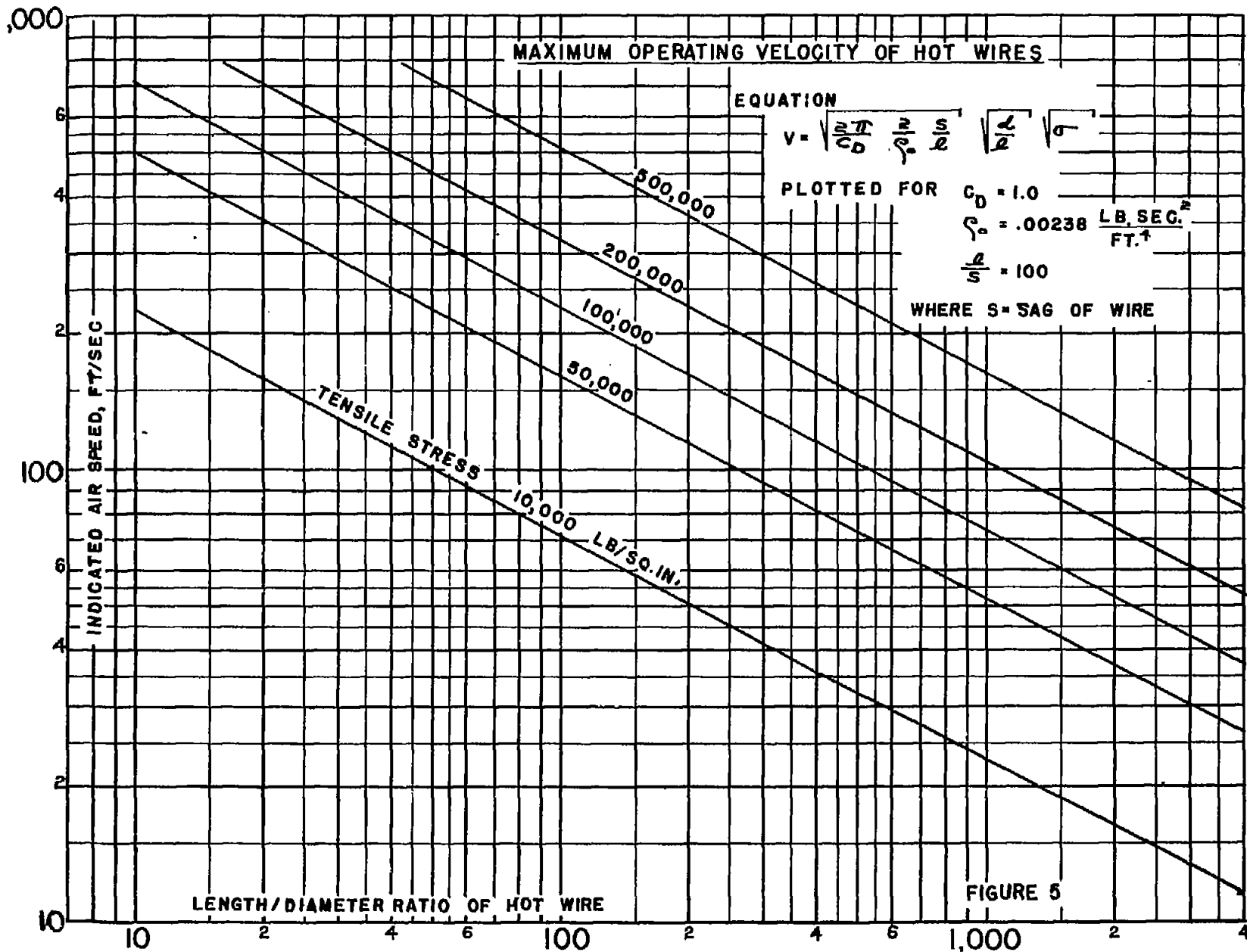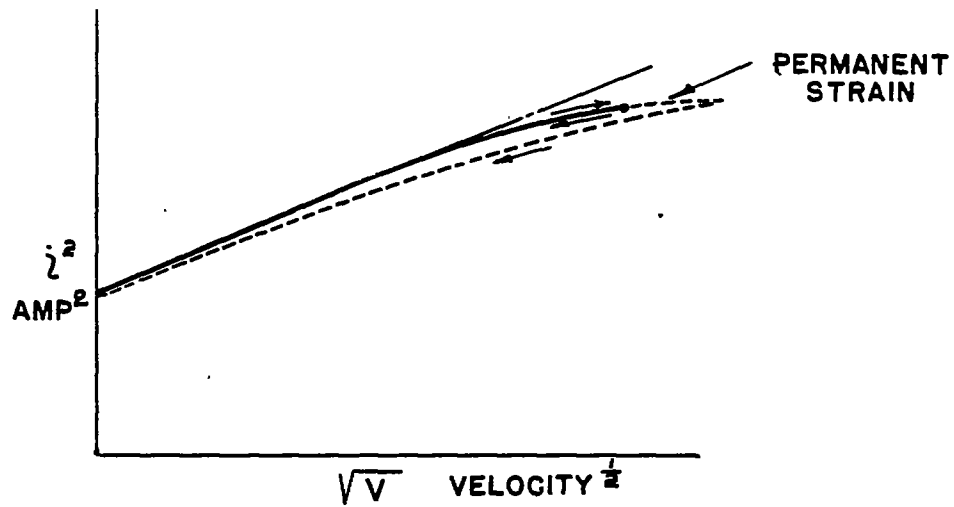
DEVIATION FROM KING'S EQUATION
AS A RESULT OF STRAIN SENSITIVITY

FIGURE 6
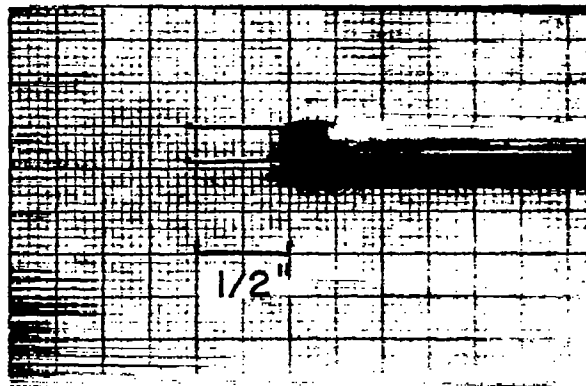
HOT WIRE HOLDER FOR TUNGSTEN WIRE

.FIGURE 8

METHOD OF MOUNTING TUNGSTEN WIRE
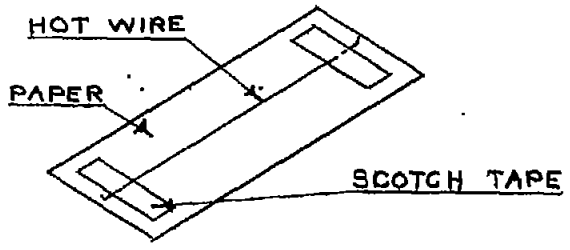
(a) HOT WIRE PREPARED FOR ELECTROPLATING
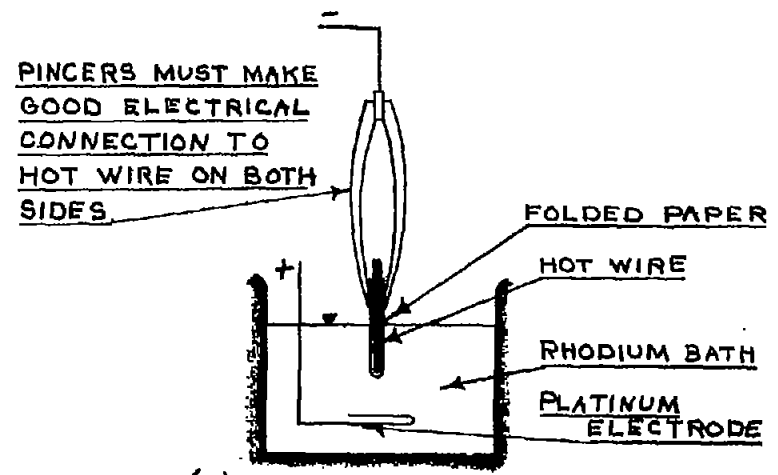
(b) ELECTROPLATING
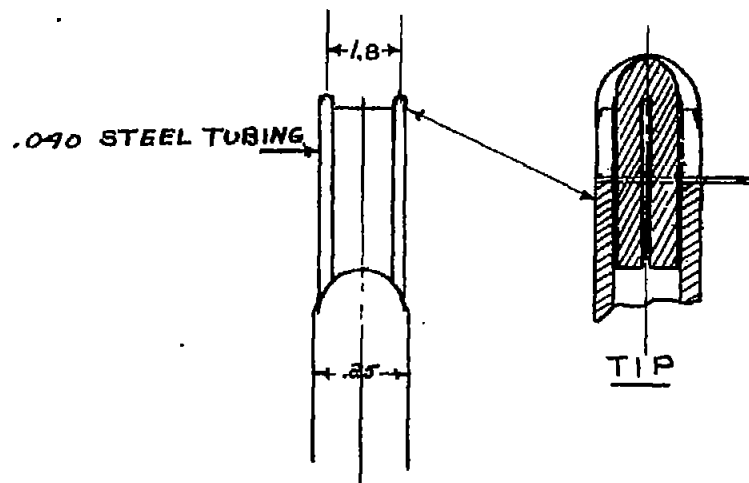
(d) MOUNTED TUNGSTEN HOT WIRE, AFTER SOLDERING
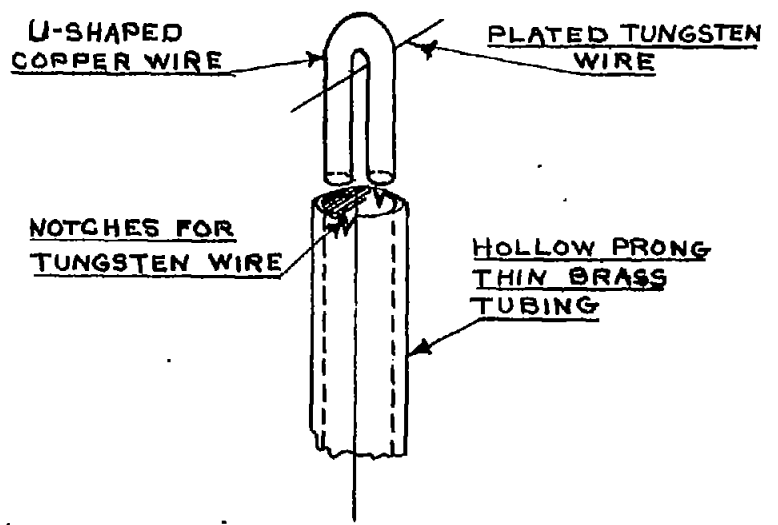
(c) EXPLODED MAGNIFIED VIEW OF CONNECTION TO PRONG

Figure 7.

Fig. 7
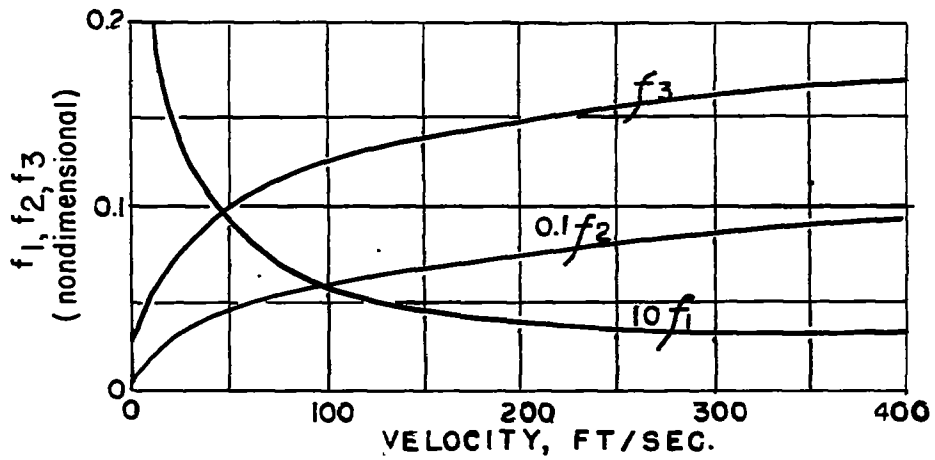
STATIC RESPONSE CHARACTERISTICS OF HOT WIRES
AT CONSTANT RESISTANCE OPERATION

FIGURE 9
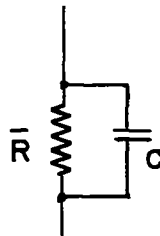
ELECTRICAL EQUIVALENT OF THE
HOT WIRE

FIGURE 10

LEGEND

Curve (a), for Pt wire at 5000 cycles, 1/d = 2540,
          .00025 cm dia
Curve (b), for Pt wire at 10000 cycles, 1/d = 2540,
          .00025 cm dia
Curve (c), for W wire at 5000 cycles, 1/d = 1040,
          .00061 cm dia
Curve (d), for W wire at 10000 cycles, 1/d = 1040,
          .00061 cm dia

Upper limit for μ' for 10 percent maximum noise in the
reading of a 1 percent velocity variation at mean operat-
ing conditions.

Curve (e), for Pt wire, .00025 cm dia
Curve (f), for W wire, .00061 cm dia
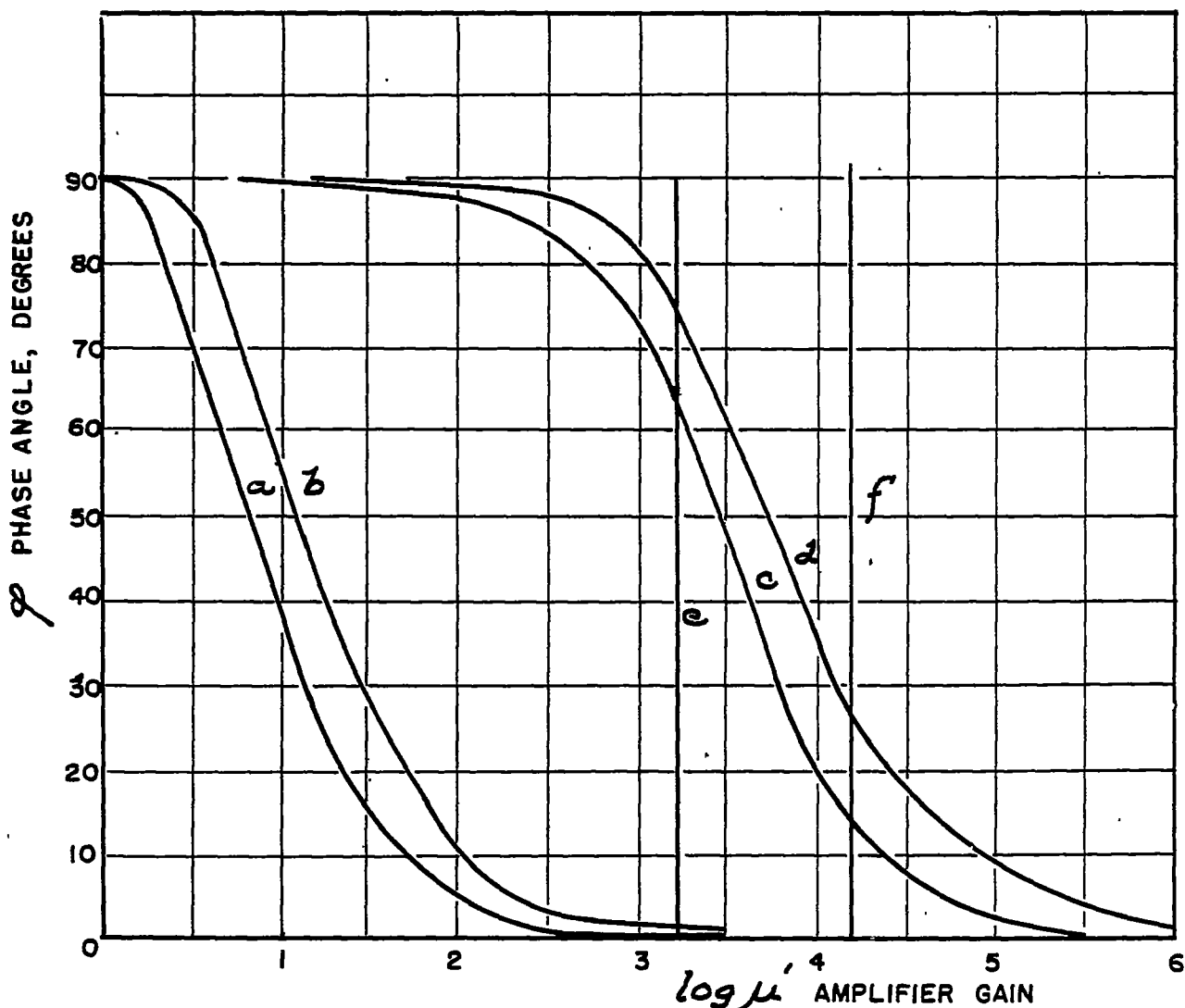
DYNAMIC CHARACTERISTICS OF CIRCUIT RESPONSE

FIGURE II
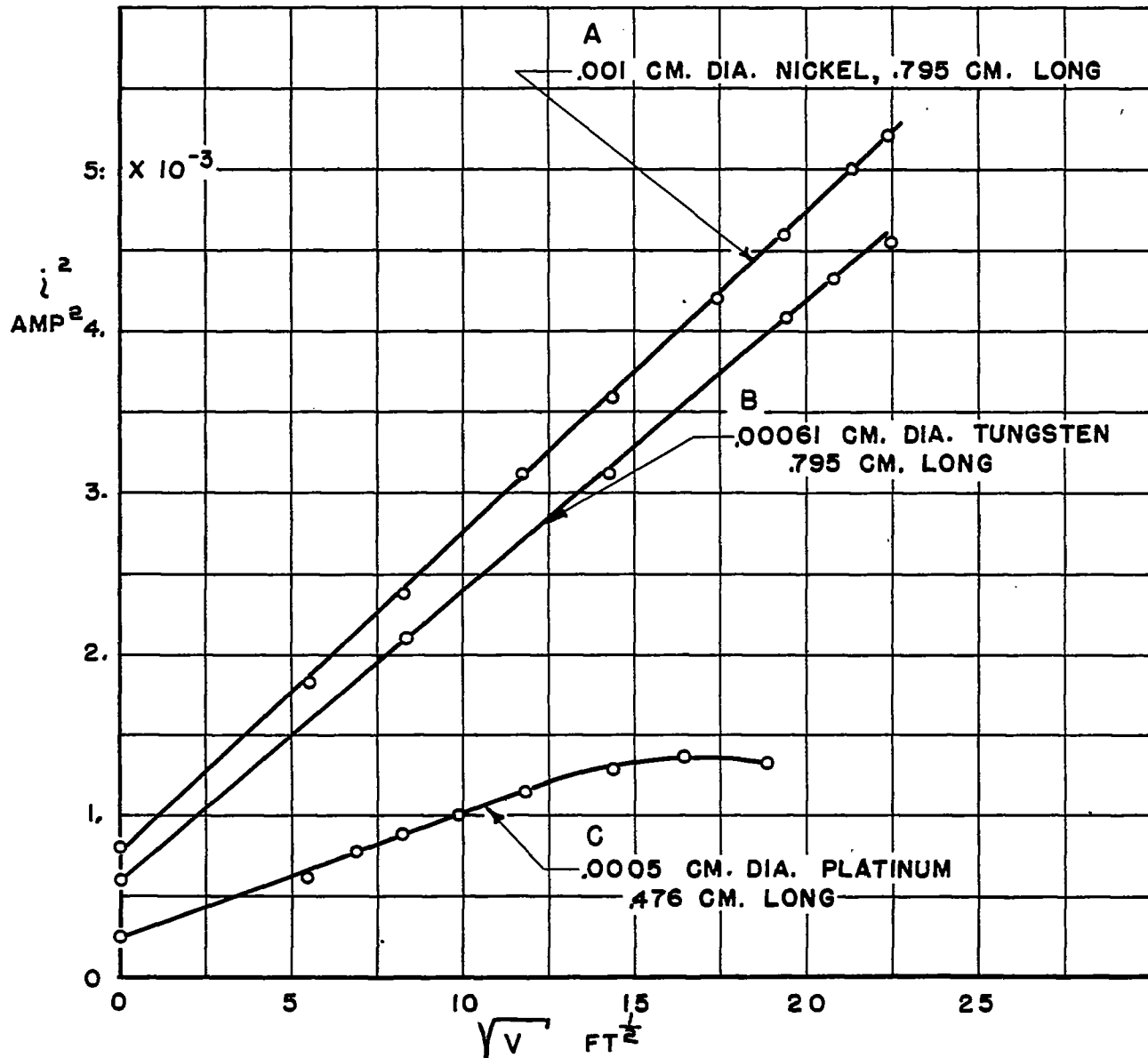
VARIATION OF HEATING CURRENT WITH VELOCITY

FIGURE 12
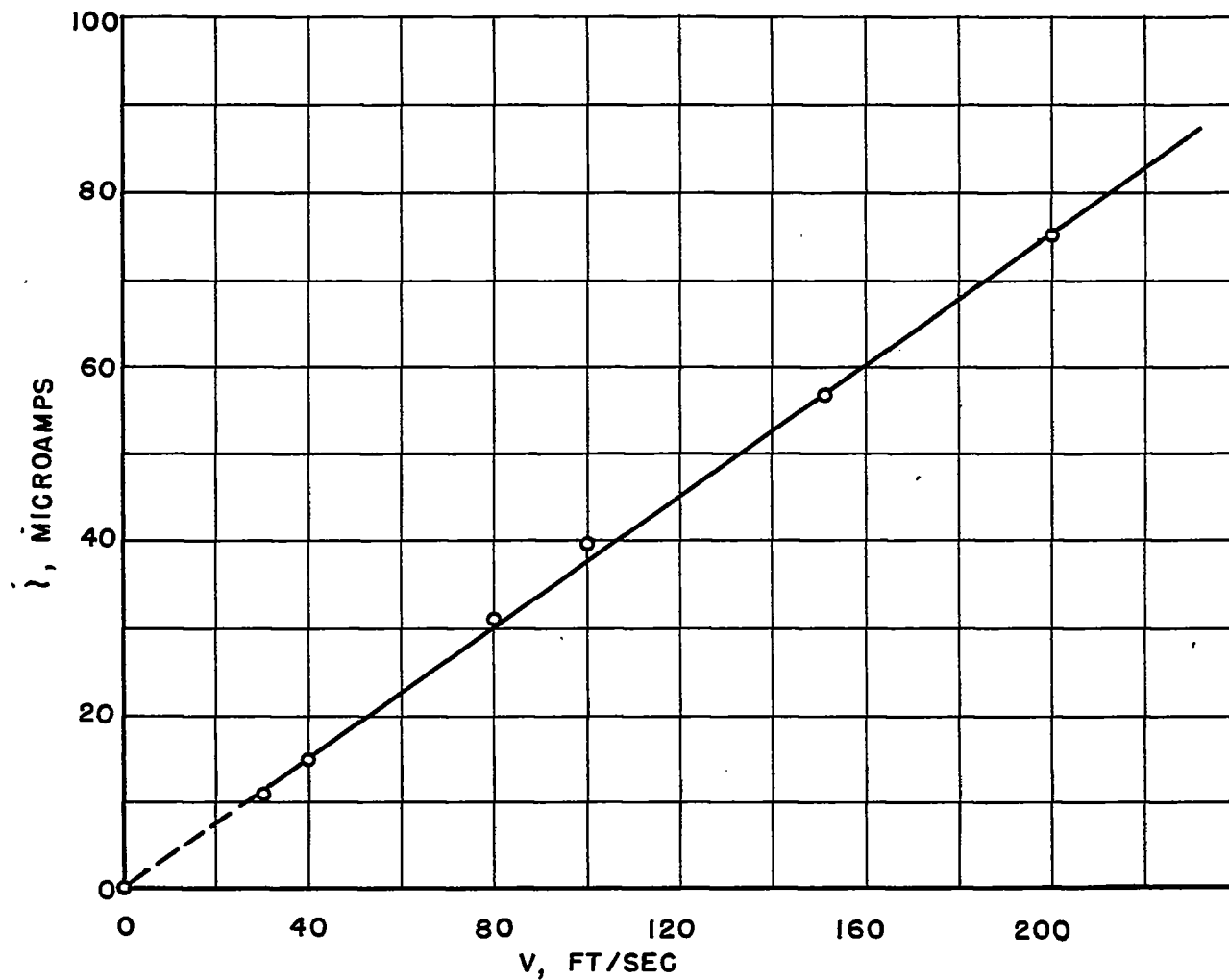
CALIBRATION FOR LINEARITY OF READING WITH VELOCITY

FIGURE 13
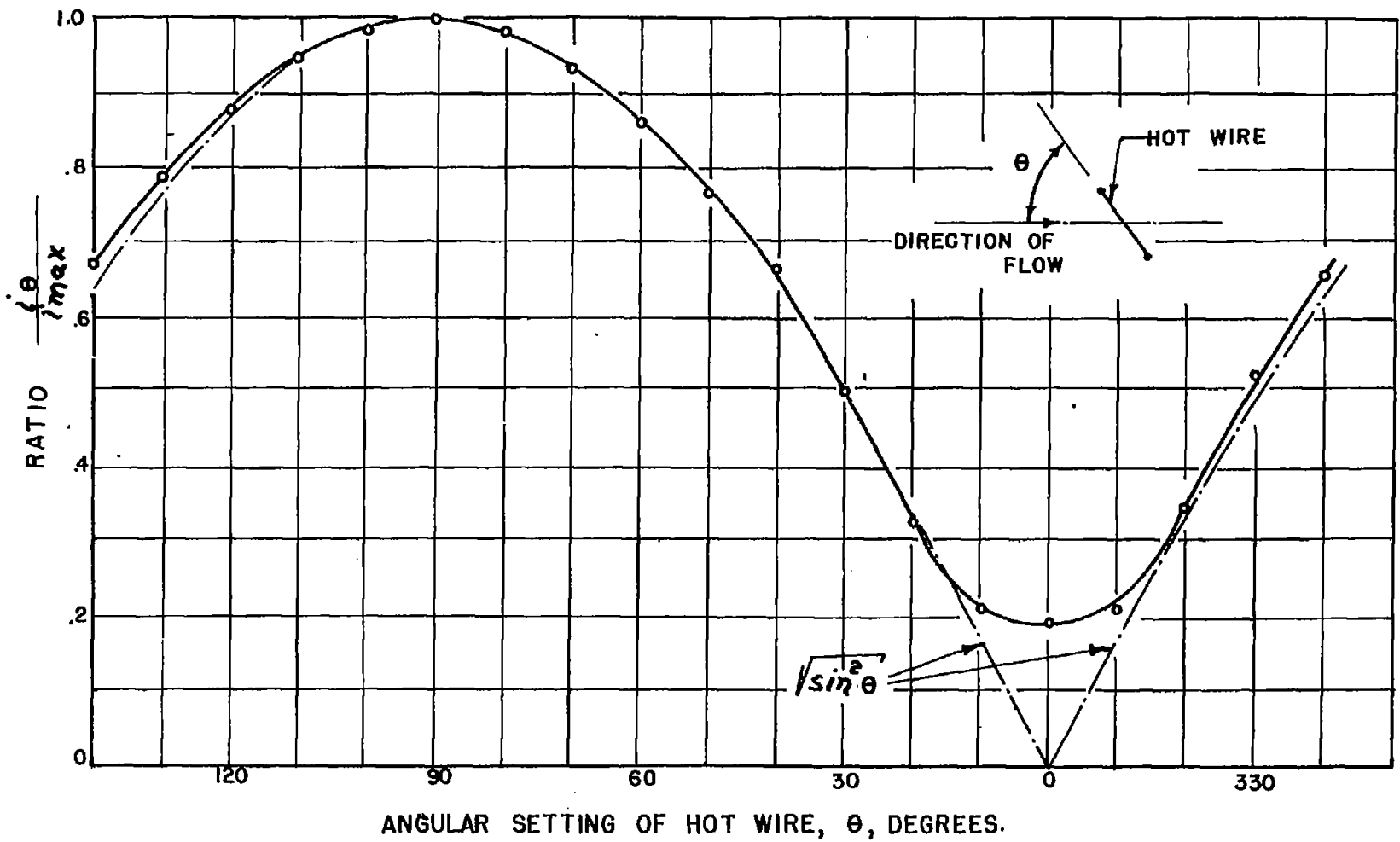
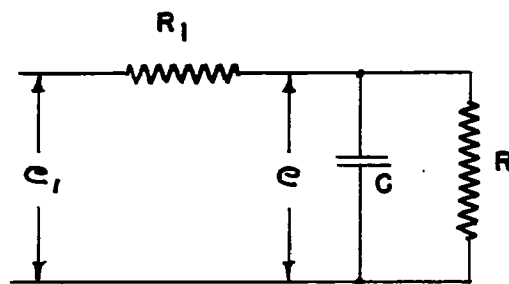DIRECTIONAL CHARACTERISTICS OF HOT WIRE AT CONSTANT RESISTANCE

FIGURE 14
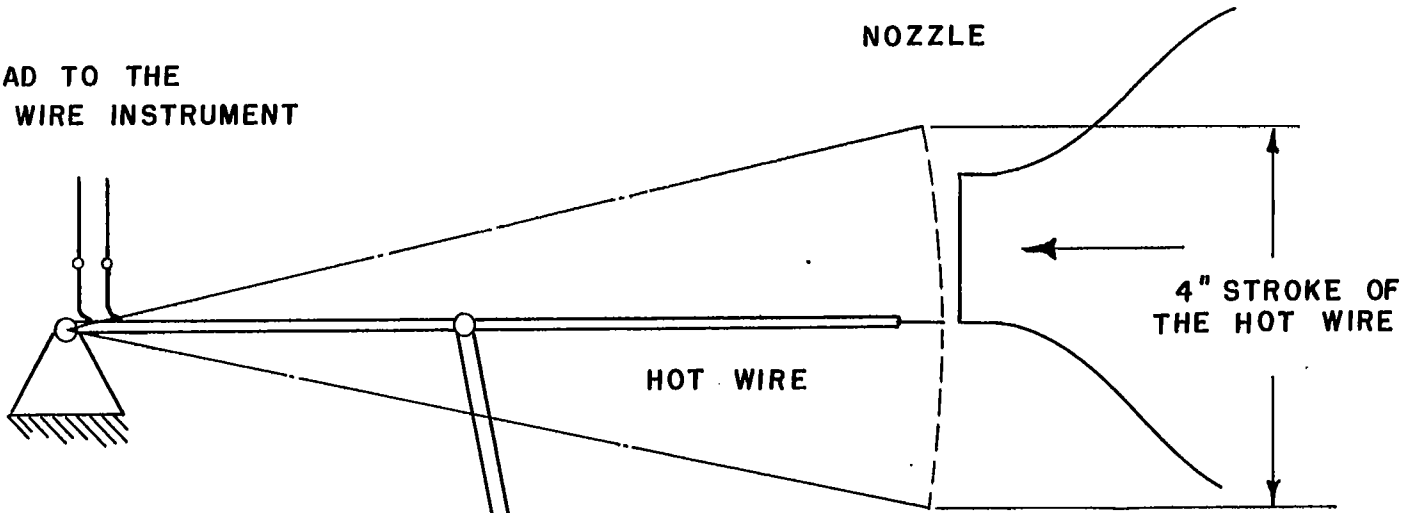
Fig. 14
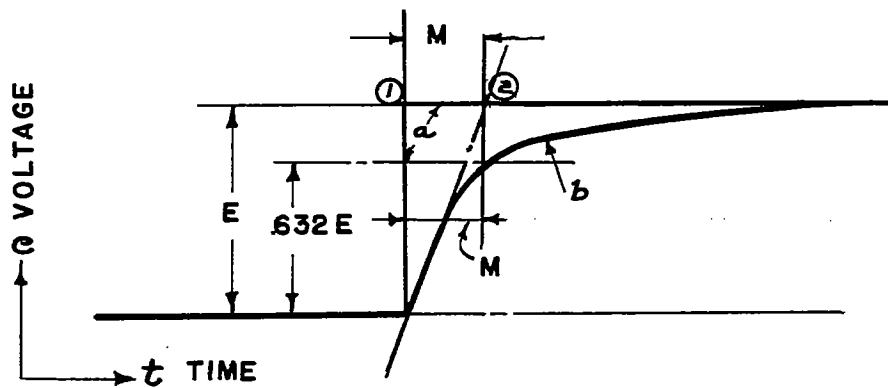
RESPONSE TO AN INSTANTANEOUS CHANGE
OF VELOCITY

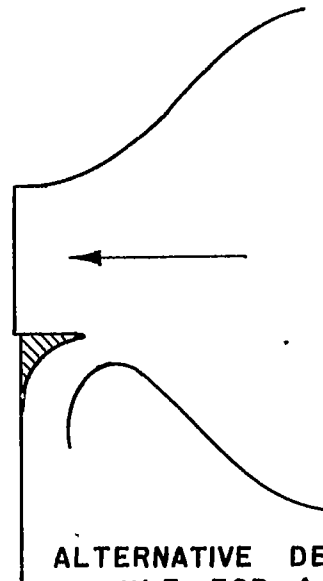FIGURE 15

EQUIVALENT CIRCUIT

FIGURE 16

NOZZLE

LEAD TO THE
HOT WIRE INSTRUMENT

4" STROKE OF
THE HOT WIRE

HOT WIRE

CALIBRATING DEVICE FOR HOT WIRE RESPONSE
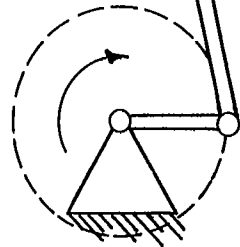
FIGURE 17

ALTERNATIVE DESIGN OF THE
NOZZLE FOR A VERY THIN
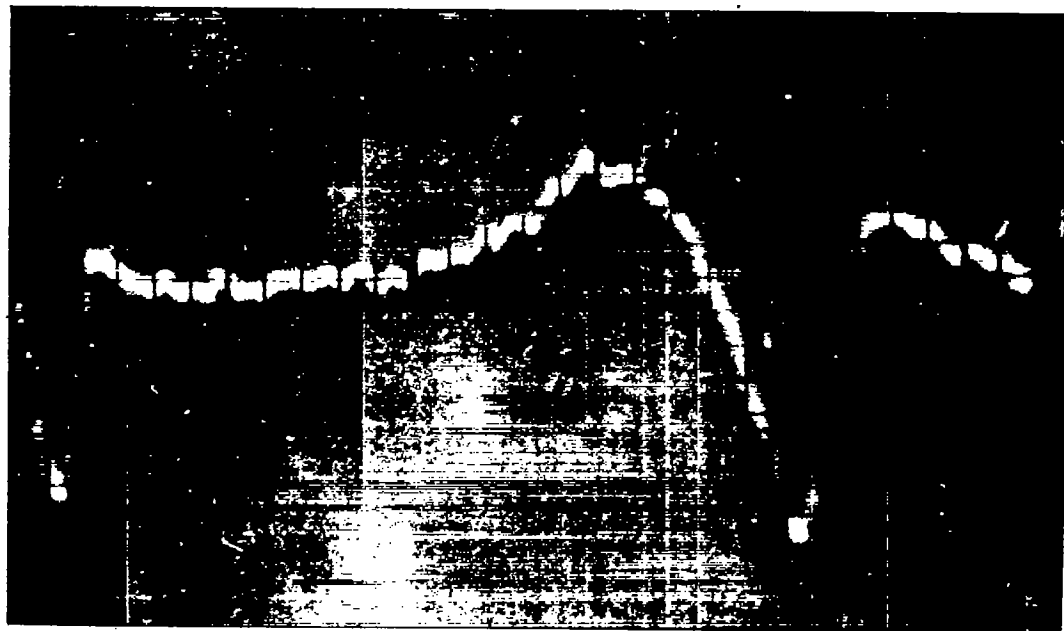TRANSITION LAYER OF THE JET

Fig. 17

FIGURE 18.- OSCILLOGRAPH OF SQUARE
WAVE CALIBRATION.

FIGURE 19.- INSTANTANEOUS VELOCITY PROFILE.

OSCILLOGRAPH OBTAINED BY HOT WIRE METHOD

PROFILE OF AXIAL VELOCITY COMPONENTS CALCULATED FROM PITOT TUBE TRAVERSE IN THE ROTATING SYSTEM

VELOCITY, FT/SEC

COMPARISON OF AXIAL VELOCITY PROFILES DOWNSTREAM OF A ROTATING GRID OBTAINED WITH A STATIONARY HOT WIRE AND WITH A ROTATING PITOT TUBE RESPECTIVELY

DISTANCE ALONG THE CIRCUMFERENCE IN DEGREES

FIGURE 20