1976-12

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Journal of Fluids Engineering, December 1976
http://hdl.handle.net/10945/40177

A Simple Linearized Hot-Wire Anemometer

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The circuit and application of an inexpensive simple linearized hot wire anemometer especially suited to turbulence research in incompressible media is described. Special features of the design are very high stability, simple bridge adjustment, and a linearizer having an adjustable exponent and very high transfer function accuracy. Measured frequency response is in excess of 100 kilohertz for the bridge and 7.5 kilohertz for the linearizer.

Introduction

Although the hot-wire anemometer has been in common use in fluid mechanics research for more than fifty years it is only in the last twenty-five years that the advances in solid state electronics have allowed its exploitation to the fullest extent in the form of a linearized constant temperature instrument. Many of the earlier designs of solid state instruments have been rendered obsolete by the recent rapid advances in integrated circuit technology. The present work describes a user oriented design which has evolved in the laboratories of the Naval Postgraduate School and the Max-Planck-Institut fur Stromungsforschung. The circuit employs readily obtainable components and may be contained on a single 4-1/2 × 5 in. circuit board, exclusive of its power supplies. The entire instrument may be constructed for about 500 dollars per channel. For the research worker employing a number of channels this is a welcome alternative to the purchase of commercial instruments.

The Bridge Circuit

A prime requisite, especially when engaged in multi-channel not wire measurements, is a simple, stable and easily adjusted hot wire bridge circuit free of spurious oscillations which may destroy the fine wires employed in turbulence research. The bridge circuit described here has been developed over a number of years and while of course similar in principle to others, [1],[1] embodies some unique user oriented features which enable *in situ* measurement of wire cold resistance which, coupled with a directly calibrated wire resistance control, allows the user to apply any desired overheat ratio directly. Details of the circuit are shown in Fig. 1. The power transistor specified is capable of handling collector currents of 2 amps and hence may be used to drive hot film sensors. For high current applications a suitable heat sink such as the Thermolog 6056 or Wakefield 207 should be used. The two 50 ohm resistors and the 1000 ohm resistor of the bridge circuit must have very low thermal coefficients of resistance in order to insure thermal stability. The IRC MEC-T9[2] or an equivalent should be used for the 50 ohm resistors and the IRC MEC-T9 or equivalent or the 1000 ohm resistance. These are factory selected deposited film units having a temperature coefficient of 0 ± 25ppm/°C and have proven entirely satisfactory. The adjustable arm of the bridge must also be carefully selected. The Bourns Infinitron[3] Model 3501S-1-102 with a suitable turns counting dial has proven satisfactory. Typical thermal drift is less than one percent per hour in non air conditioned laboratories. Power supplies for the bridge must be especially well regulated; 200 ma units are adequate for hot wire applications but should be replaced with higher current units for hot film operation.

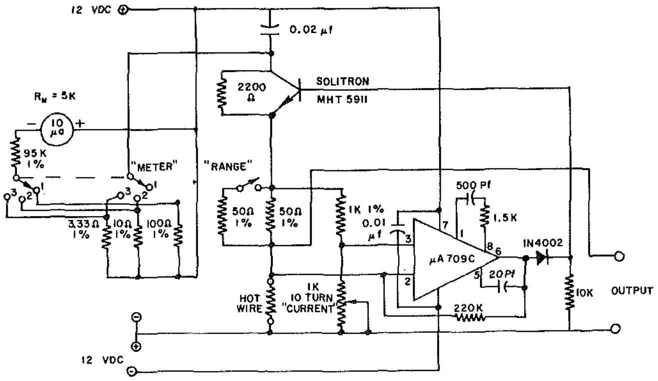

Fig. 1 Constant temperature hot-wire anemometer bridge

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[1] Numbers in brackets designate References at end of paper.

Contributed by the Fluids Engineering Division for presentation at the Applied Mechanics/Bioengineering/Fluids Engineering Summer Conference, Yale University, New Haven, Conn., June 15-17, 1977, of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received at ASME Headquarters September 21, 1976.

[2] Available from International Resistance Corp., 1136 N. LaBrea Ave., Los Angeles, California.

[3] Available from Bourns, Inc., Trimpot Division 1200 Columbia Ave., Riverside, Calif.

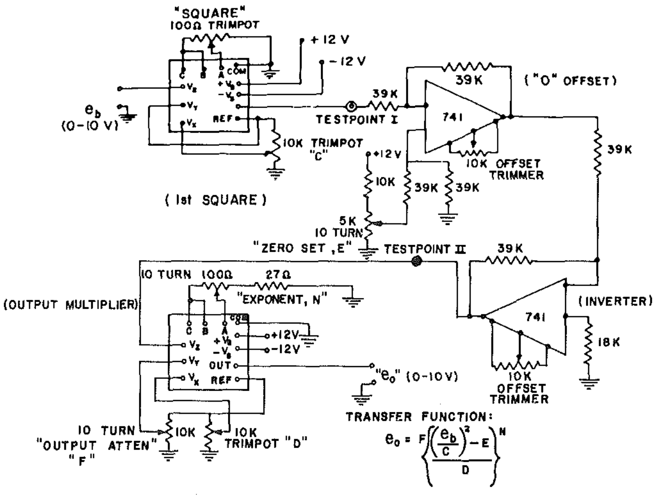

Fig. 2 Linearizer

The 2200 ohm resistor used to bypass the power transistor provides an indicated bridge current of 4.5 ma with no hot wire sensor in the circuit and 5.0 ma with a wire of 10 ohms when the "current" control is set at its minimum value. It is this small current which permits direct determination of sensor "Cold" resistance detailed below, although not with sufficient accuracy to allow the sensor to be used as a resistance thermometer. Typical bridge output voltages with a 10 ohm sensor are 0.4 volts with zero velocity and 0.6 volts at 30 meters/sec in air at 20°C.

The Linearizer Circuit

Although King's law:

$$I^2R = A + B\sqrt{U}, \tag{1}$$

the theoretical relationship between hot wire joulian heat loss and the local velocity, adequately describes the relationship between heat loss and velocity for many applications, it has been shown by the careful measurements of Collis and Williams, [2], that at low Reynolds numbers a more general form:

$$I^2R = A + B(U)^{\frac{1}{N}} \tag{2}$$

better describes the relationship. Values of N are of order 2 and depend on both the sensor geometry and the Reynolds number of the flow. In boundary layer measurements it is important that provision for adjustment of the exponent, N, be made if maximum accuracy is to be insured, particularly in the critical wall layers where local Reynolds numbers are low

In the usual case of constant temperature operation, the sensor resistance, R, is maintained at a constant value and a voltage, e_b, is derived from the hot wire bridge which is proportional to wire current, I. If an output voltage, e_0, proportional to velocity, U, is to be produced, the necessary transfer function may be obtained by inversion of equation (2):

$$e_0 = \left\{\frac{e_b^2R - A}{B}\right\}^N \tag{3}$$

A circuit having a transfer function corresponding to equation (3) is shown in Fig. 2. The heart of this circuit is the newly developed "logarithmic function modules"[4] consisting of three logarithmic amplifiers whose outputs are proportionally summed and fed to an exponential amplifier. The transfer function of these unit may be written:

$$e_0 = e_y\left(\frac{e_x}{e_z}\right)^M \tag{4}$$

In order to obtain the greatest accuracy it is necessary that the quantity in parentheses be of order one. Because of the logarithmic nature of the transfer function such units are restricted to operation on positive inputs.

With the form of equation (4) in mind equation (3) may be recast into:

$$e_0 = e_{y2}\left\{\frac{e_{y1}\left[\frac{e_b}{e_{x1}}\right]^M - A}{e_{x2}}\right\}^N$$

$$= F\left\{\frac{\left[\frac{e_b}{C}\right]^2 - E}{D}\right\}^N \tag{5}$$

where we have set $M = 2$. The quantity "F," termed the "Output Attenuator" in Fig. 2 allows the output to be scaled to any convenient value up to 10 volts. The quantity "E," termed "Zero Set," permits the output to be set to zero corresponding to zero fluid velocity. Quantities "C" and "D," identified in Fig. 2, allow the function generators to be adjusted for a given range of input voltage, e_b, to insure the quantities in parentheses in equation (4) are of order of magnitude one for maximum accuracy. These adjustments are typically altered only when the type of sensor is changed and not when a sensor is replaced with another of similar construction. The quantity, "N" termed "Exponent" in Fig. 2 is adjustable over the range 1–5. The details of these adjustments are given below.

Although high quality components should naturally be employed in any instrument designed to produce high quality measurements, there appear to be no critical parts in the linearizer requiring special selection.

Operation

Hot-wire or hot-film "cold" resistance may be determined directly by connecting the sensor to the circuit with the "Current" control at its minimum resistance setting. Measured current should be about 5 milliamps for a 10 ohm sensor. As the current control is advanced no increase in current will be observed until the bridge first comes into balance. The value of the "cold" resistance is proportional to the reading of the 1 kilohm current setting potentiometer at the point of first increase in current. This reading may then be multiplied by the safe resistance ratio for the sensor material and the resulting value set on the dial of the current control. Alternatively a safe "no flow" current may be determined for a particular sensor configuration and this value set directly by means of the appropriate range of the meter circuit.

Having adjusted the bridge, the linearizer may be calibrated. With the sensor in a no flow environment, preferably covered, and the "Output Attenuator" at maximum gain, the "Zero Set" control is adjusted for zero output from the instrument. This adjustment must be made from the direction of positive voltage as the logarithmic modules do not admit negative voltages.

Next, the "exponent" may be set. This may be done either by direct calibration of the sensor over the range of interest and selection of an appropriate exponent from the local slope of the

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[4] Intech model A-733, Intech Inc., 1220 Doleman Ave., Santa Clara, Calif.

[5] An open circuit is indicated by a current of about 4.5 milliamps.

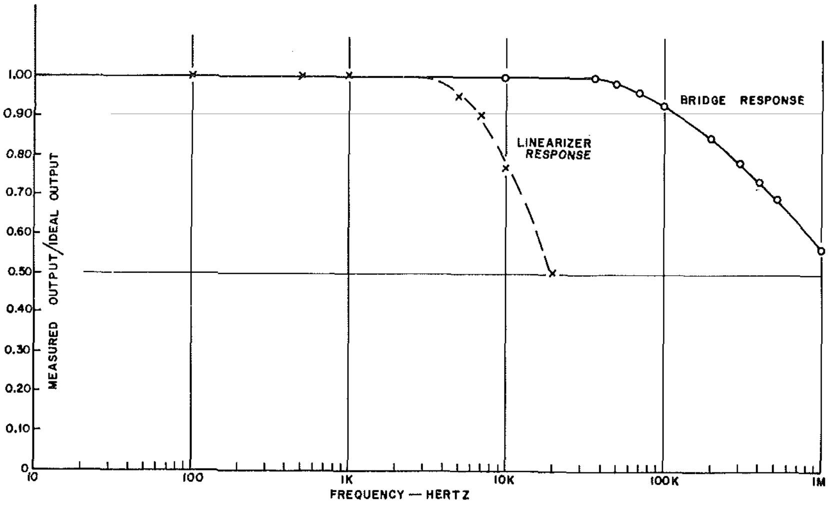

Fig. 3 Measured frequency response

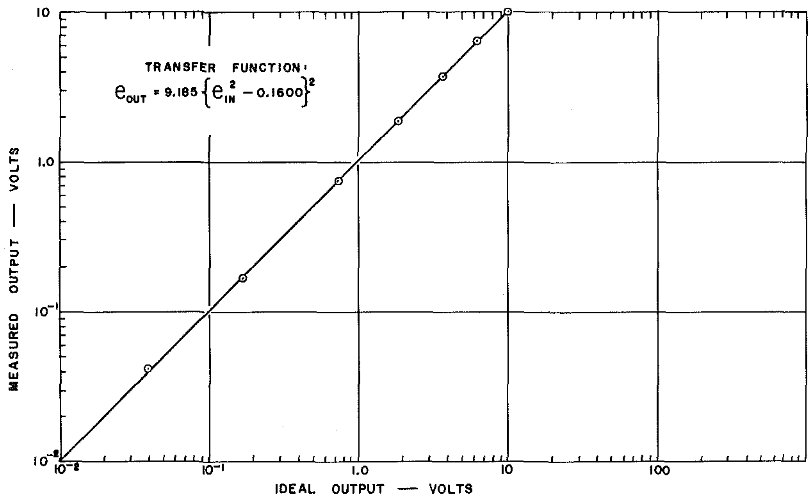

Fig. 4 Measured linearizer transfer function accuracy

resulting calibration plot or by a simple, though less accurate, two point fit over the velocity range of interest.

A two-point fit may be obtained by measuring two velocities, U_1, and U_2, corresponding to output voltages e_1, and e_2 with the known initial exponent N_i. Equation (5) may be solved simultaneously for both cases yielding:

$$N = \frac{N_i \ln\left(\dfrac{U_1}{U_2}\right)}{\ln\left(\dfrac{e_1}{e_2}\right)} \tag{6}$$

where N is the exponent of the transfer function passing through both calibration points as well as the origin.

The amplitude of the output may be scaled to a convenient level by the "Output Attenuator" potentiometer. Output voltages up to ten volts may be obtained.

Performance

The circuit frequency response has been measured with a 0.00015 in. tungsten hot-wire in an air flow of approximately 10 meters per second. A small signal, representing a turbulence intensity of about 0.1 percent of the mean velocity, was injected directly across the hot-wire probe. The results are shown in Fig. 3. While the bridge circuit has a frequency response above 100 kilohertz the linearizer response is limited by and is essentially the same as that of the logarithmic function modules. Nevertheless the overall response of 7.5 kilohertz is more than adequate for most turbulence research.

Measured signal to noise ratio is better than 10^6 and permits easy resolution of turbulence intensities of 0.01 percent. At maximum gain with an exponent of 2.0, RMS noise is less than 10 μ V.

The measured transfer function accuracy over three decades of output is shown in Fig. 4. The values of the constants are representative of typical operating values. Additional data over five decades of output show accuracies of better than 1 percent.[6]

Fig. 5 reports the overall instrument performance. The exponent in this case was determined from equation (6) and the

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[6] Contrary to common practice in electrical engineering "accuracy" as used here means actual error divided by true value, not full scale value.

data of the "Set Points." The maximum measured error between these set points was 0.4 percent at $U/U_{MAX} = 0.89$.

The remaining two points plotted had no measurable error. The error in the lower velocity portion of the curve is traceable principally to the change in the exponent, N, of equation (3) at lower Reynolds numbers.

Acknowledgment

The author takes this opportunity to thank his many colleagues whose help contributed to the evolution of the design.

References

1 Freymuth, Peter, "Feedback Control Theory for Constant Temperature Hot-Wire Anemometers," *Review of Scientific Instruments*, Vol. 38, No. 5, May 1967, p. 677.

2 Collis, D. C., and Williams, M. J., "Two Dimensional Convection from Heated Wires at Low Reynolds Numbers," *Journal of Fluid Mechanics*, Vol. 6, 1959, p. 357.

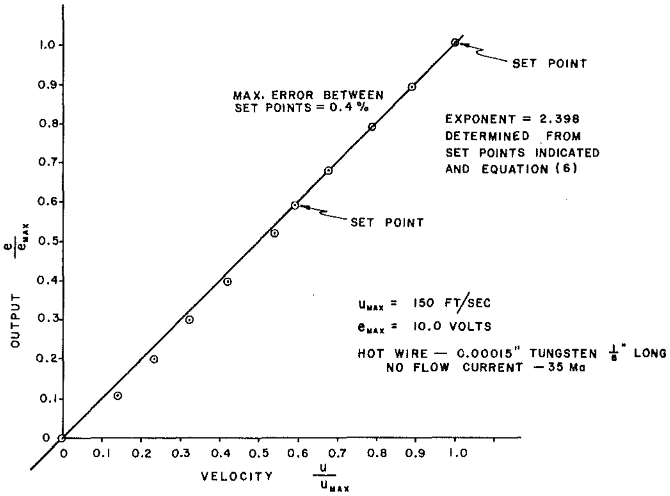

Fig. 5 Measured accuracy

APPENDIX

Initial Alignment and Calibration

The bridge circuit requires no initial adjustment; however, it may be useful to calibrate the ten turn "Current" dial. The theoretical calibration may be obtained from the bridge ratio, 40:1 with the "Range" switch closed and 20:1 with the switch open. However since the multi-turn potentiometers may not have precision overall resistances the exact values may be obtained by substituting a precision resistor of about ten ohms for the hot-wire in the bridge and measuring its cold resistance following the procedure outlined above.

Initial alignment of the linearizer requires an adjustable voltage source and a digital voltmeter. It is also necessary to know the maximum expected input to the linearizer from the bridge circuit, e_{bMAX}, corresponding to the greater anticipated velocity. "V_x" in the first squaring stage, (see Fig. 2), should be adjusted with the potentiometer, "C", to a value about ten percent greater than e_{bMAX} and this value noted. V_y in the first stage should be accurately measured and a potential of about 2.0 volts applied to the input, V_z. Using these measured voltages and $M = 2.0$ in equation (4), the "Square" potentiometer in the first squaring stage should be adjusted to produce the calculated value of e_0 measured at "Test Point I." A second value of V_z, may be used to insure that the exponent has been adjusted to produce an exact square function. Anticipated transfer function accuracy is of the order of 0.25 percent.

The "O offset" and "inverter" stages must have their offset trim adjusted. This may be accomplished by removing the "first squaring" module and grounding "Test Point I." The "Zero Set" potentiometer is set to the "ground" end and the output of the "O offset" stage is monitored with a voltmeter. The "offset trim" for this stage is adjusted to make the output zero corresponding to zero input. This having been done the voltmeter may be connected to, "Test Point II," and the "offset trim" of the "inverter," stage adjusted for zero output. Before adjusting the "Output Multiplier" stage the two 741 Amplifiers should be removed from their sockets, preserving their identity.

Adjustment of the "Output Multiplier" stage should begin with calibration of the ten turn "Exponent" dial. V_x should be set to about 10 volts by means of potentiometer, "*D*," and (V_y) also set to 10 volts by means of the "Output Attenuation" potentiometer. A potential of about 8 volts may be fed into "Test Point II, (V_z), and equation (4) used to calibrate the "Exponent" dial. The range of the exponent, "N," in equation (4) is 1–5, however the range 1.5–3.0 probably encompasses most cases of practical interest. The relationship between dial reading and the exponent "N" is nearly linear and may be plotted for reference.

Finally the scale of the "Output Multiplier" stage may be adjusted. To do this replace the "First Squaring" function module and both 741 operational amplifiers. A voltage, e_{b0}, corresponding to hot-wire current with a zero fluid velocity is set on the input and the "zero set" potentiometer adjusted to produce a zero voltage at "Test Point II." Next the maximum expected bridge voltage, e_{bMAX}, is introduced and the voltage produced at "Test Point II" measured. Potentiometer "*D*" is adjusted to produce a voltage 5-10 percent greater at V_x of the "Output Multiplier" stage. Obviously adjustment of the scale of the output stage may be readily accomplished with an actual hot-wire *in situ*.

These preliminary adjustments are necessary only once. In general none of them need be repeated when sensors are replaced with similar units. When a change in sensor type is made it is only necessary to adjust the scaling potentiometers, "*C*," and "*D*."