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HOT FILM and HOT WIRE ANEMOMETRY

THEORY AND APPLICATION

BULLETIN TB5

THERMO-SYSTEMS INC.

2500 CLEVELAND AVENUE NORTH • SAINT PAUL, MINNESOTA 55113

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1.0 INTRODUCTION

The hot wire anemometer has been used for many years as a research tool in fluid mechanics. Recently, the application of anemometry has expanded greatly due to better equipment and more interest in details of fluid flow.

In this paper hot wire anemometry will refer to the use of a small, electrically heated element exposed to a fluid medium for the purpose of measuring a property of that medium. Normally, the property being measured is the velocity. Since these elements are sensitive to heat transfer between the element and its environment, temperature and composition changes can also be sensed.

Figure 1 shows a hot wire anemometer probe. Typical dimensions of the wire sensor are 0.00015 to 0.0002 inches (0.0038 to 0.005 mm) in diameter and 0.040 to 0.080 inches (1.0 to 2.0 mm) long. This is the type of hot wire that has been used for such measurements as turbulence levels in wind tunnels, flow patterns around models and blade wakes in radial compressors. The film type of sensor is shown in Figure 2. The basic hot film concept was introduced over ten years ago (16,19) and this type of sensor has been replacing the hot wire for many applications in recent years. More detailed descriptions of film sensors and a comparison between hot wires and films will be discussed later.

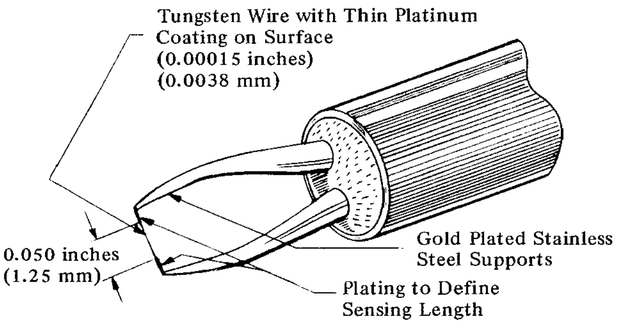


Figure 1: Tungsten Hot Wire Sensor and Support Needles-0.00015" Dia. (0.0038 mm)

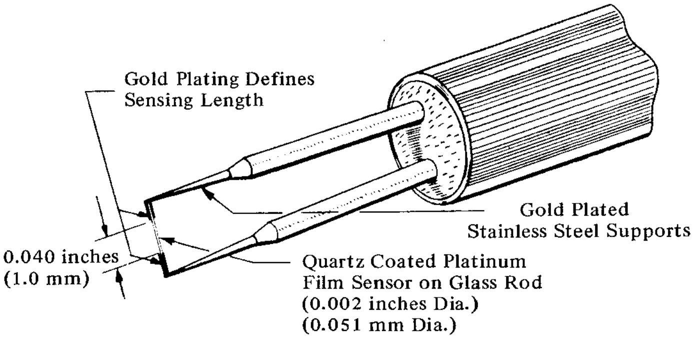


Figure 2: Cylindrical Hot Film Sensor and Support Needles-0.002" Dia. (0.051 mm)

A very important part of high frequency anemometry is the electronic circuit. It supplies a controlled amount of electrical current to heat the sensor and provides frequency compensation for the sensor. A very fine hot wire by itself cannot respond to changes in fluid velocity at frequencies above about 500 Hz. With electronic compensation this response can be increased to values of 300 to 500 KHz. The traditional, constant current type of anemometer operates by taking the voltage signal caused by wire resistance changes and compensates for frequency lag with a non-linear amplifier. The constant temperature control system, while certainly not a recent innovation, has gained rapidly in acceptance during the last few years. It operates by utilizing a feedback controlled bridge circuit to maintain the sensor at constant temperature. Transistor circuitry has aided development of the constant temperature system, permitting full utilization of its many practical advantages.

In addition to the increasing use of film type sensors and constant temperature compensating circuitry, better accessory equipment such as true rms meters, correlators, and other signal conditioning, indicating, and recording equipment have made anemometry more practical. The end result is that it is now possible to get reliable measurements in a wide variety of fluid flow systems, including electrically conductive liquids such as water. Thermo-Systems' continued research and development programs have greatly enhanced the state-of-the-art in anemometry.

$R = R_o(1 + \alpha t)$ t = temp.
R_o = resistance at 0°C
α = temperature coefficient of resistance

2.0 PROBES

2.1 HOT WIRE SENSORS

A hot wire type sensor must have two characteristics to make it a useful device:

A. A high temperature coefficient of resistance

B. An electrical resistance such that it can be easily heated with an electrical current at practical voltage and current levels.

The most common wire materials are tungsten, platinum and a platinum-iridium alloy. Tungsten wires are strong and have a high temperature coefficient of resistance, (0.004/°C). However, they cannot be used at high temperatures in many gases because of poor oxidation resistance. Platinum has good oxidation resistance, has a good temperature coefficient (0.003/°C), but is very weak, particularly at high temperatures. The platinum-iridium wire is a compromise between tungsten and platinum with good oxidation resistance, and more strength than platinum, but it has a low temperature coefficient of resistance (0.00085/°C). The temperature coefficient of resistance is an important property of a hot wire sensor since the obtainable signal to noise ratio with a given system is directly proportional to the temperature coefficient of the sensor. Tungsten is presently the more popular hot wire material. A thin platinum coating is usually applied to improve bond with the plated ends and the support needles.

2.2 HOT FILM SENSORS

The hot film sensor is essentially a conducting film on a ceramic substrate. The sensor shown in Figure 2 is a quartz rod with a platinum film on the surface. Gold plating on the ends of the rod isolates the sensitive area and provides a heavy metal contact for fastening the sensor to the supports. When compared with hot wires the cylindrical hot film sensor has the following advantages:

A. Better frequency response (when electronically controlled) than a hot wire of the same diameter because the sensitive part of the sensor is distributed on the surface rather than including the entire cross section as with a wire.

B. Lower heat conduction to the supports (end loss) for a given length to diameter ratio due to the low thermal conductivity of the substrate material. A shorter sensing length can thus be used.

C. More flexibility in sensor configuration. Wedge, conical, parabolic and flat surface shapes are available.

D. Less susceptible to fouling and easier to clean. A thin quartz coating on the surface resists accumulation of foreign material. Fouling tends to be a direct function of size.

The metal film thickness on a typical film sensor is less than 1000 Angstrom units, causing the physical strength and the effective thermal conductivity to be determined almost entirely by the substrate material. Most films are platinum due to its good oxidation resistance and the resulting long term stability. The low strength of platinum is not important since it is supported by the quartz rod. The ruggedness and stability of film sensors have led to their use for many measurements that have previously been very difficult with the more fragile and less stable hot wires.

Even though film sensors have basic advantages, hot wire sensors give superior performance for some applications. The diameter of a cylindrical film sensor is typically 0.001 inches (0.025 mm) or larger. When compared with the dimensions of a hot wire this is quite large. In addition, the film sensor generally has a lower temperature coefficient of resistance. Therefore, in applications requiring maximum frequency response, minimum noise level and very close proximity to a surface, the tungsten hot wire sensor is superior.

In comparing Figures 1 and 2 note that the supports for the two sensor types are different. The film sensor has low elasticity and must be supported on relatively flexible supports in order to withstand dynamic loads. The hot wire must be supported on rigid supports to limit movement that could break the wire. Although both the cylindrical film sensors and the hot wire will take high dynamic loading in flow streams, the film sensors will withstand much greater abuse from impact of solid particles in the fluid. Film sensors in shapes other than cylindrical (Figures 4 through 6) will withstand much greater loads, such as in high speed liquids or two-phase flows.

2.3 PROBE SHAPES

In the comparison of hot wire and hot film probes the discussion was limited to cylindrical shapes. In addition to the cylindrical shape, hot films have been made on cones, wedges, parabolas, hemispheres, and flat surfaces. Thermo-Systems also makes cylindrical film sensors that are cantilever mounted. This is done by making the cylindrical film sensor from a quartz tube and running one of the electrical leads through the inside of the tube. Figure 3 shows an example of a single ended sensor. This is an important modification for fluidic applications since they can be made very small and inserted into very small channels. Also, for omni-directional measurements (e.g., meteorology applications when the vertical flow can be ignored), it permits unobstructed flow from all directions.

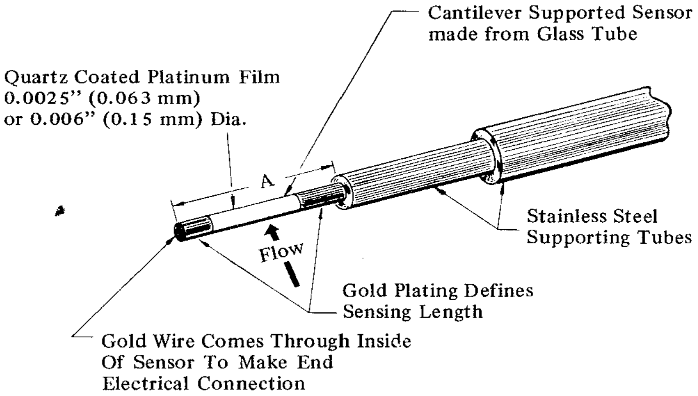


Figure 3: Single Ended Type Sensor

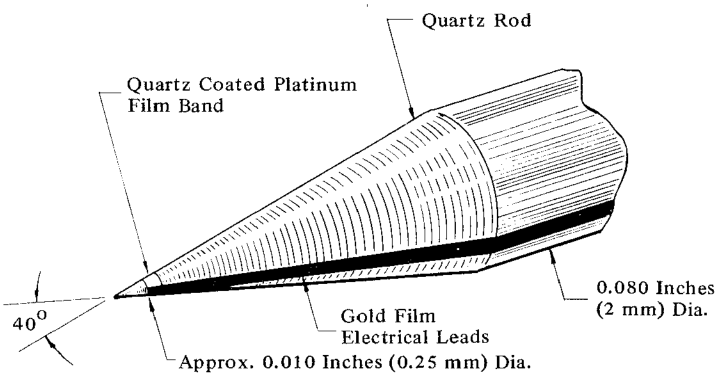


Figure 4: Hot Film Cone Probe

A cone shaped sensor is shown in Figure 4. This sensor is used primarily in water applications where its shape is particularly valuable in preventing lint and other fibrous impurities from getting entangled with the sensor. The cone can be used in relatively contaminated water, while cylindrical sensors are more applicable when the water has been filtered. Figure 5 shows a flush mounted probe which has been used for sensing the presence of flow with no obstruction in the fluid passage, detecting whether the boundary layer is laminar or turbulent, and measurements of shear stress at the wall. It makes a very rugged probe when compared with other anemometer type sensors.

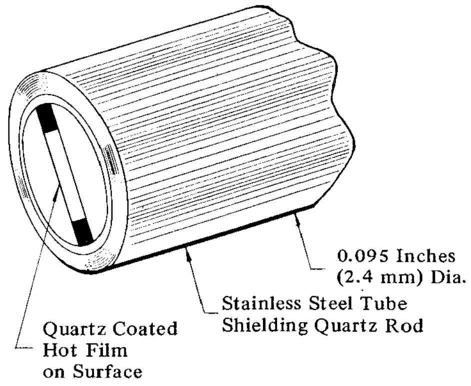


Figure 5: Hot Film Flush Mounted Probe

The wedge shaped probe shown in Figure 6 has been used for both gaseous and liquid applications. It is somewhat better than cylindrical sensors when used in contaminated water and

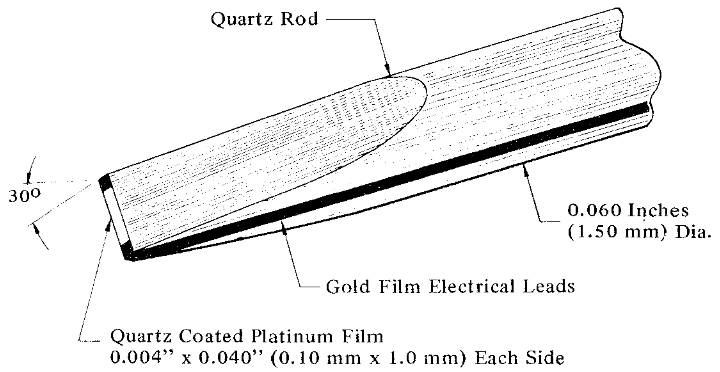


Figure 6: Hot Film Wedge Probe

is certainly stronger than cylindrical sensors for use in very high velocity air or water where there is a large load on the sensor due to fluid forces. Relative merits of each sensor type are given in TSI Bulletin N16-2.

2.4 CALIBRATION CHARACTERISTICS

Figure 7 shows a typical velocity calibration curve for a film sensor 0.002 inches (0.051 mm) in diameter in an air stream. The calibration curve is non-linear, with maximum sensitivity at low velocities, decreasing toward high velocities. The disadvantages of a non-linear output in terms of convenient reading and recording are well known. A significant advantage of the non-linear output characteristic is the ability to make measurements over a wide range of flow velocities while maintaining a nearly constant "percent of reading" accuracy. Measurements from a few feet per minute to supersonic velocities can be made with no change in either the sensor or the scale range.

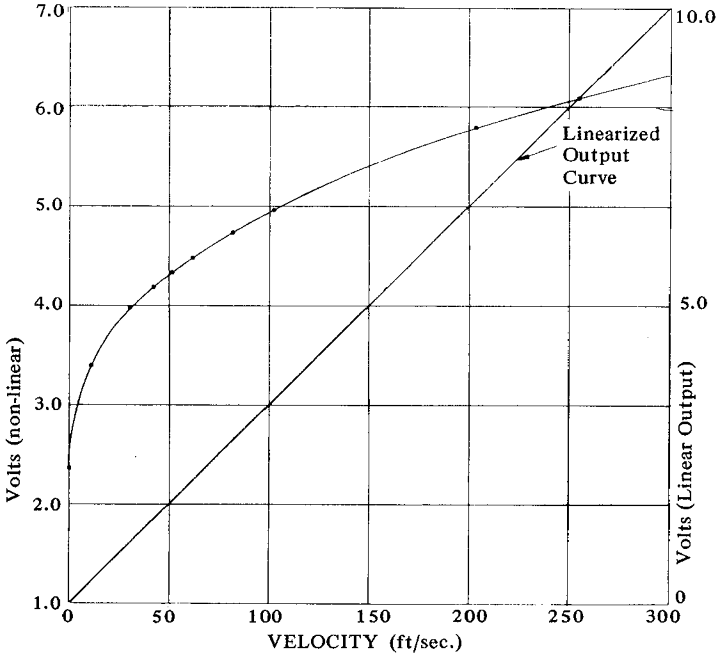


Figure 7: Calibration for a 0.002 inch (0.051 mm) Dia. Hot Film Sensor in Atmospheric Air. 0 – 300 ft/sec (0 – 91m/sec.)

The basic bridge output signal is a voltage which is related to flow approximately as follows:

$$E^2 \sim \left[A + B \left(\rho V \right)^{\frac{1}{n}} \right] (t_s - t_e) \qquad (1)$$

where A, B are constants depending on fluid properties, ρ = fluid density, V = velocity, n = exponent that varies with range and fluid (usually about 2), t_s = sensor operating temperature (hot), and t_e = fluid or environmental temperature (cold). This illustrates the non-linearity of the anemometer output as well as the relationship with density, velocity and temperature. Although the basic variable is mass flow, velocity is indicated whenever density is constant. The hot wire has been used to measure temperature, velocity, mass flow, thermal conductivity, pressure, basic heat transfer and mass fractions because of the many variables that can be sensed. For the same reason care must be taken to isolate or control all the variables that are not of interest when measuring a single variable. Temperature compensation is of particular importance when measuring velocity or mass flow.

Most hot wire anemometer data can be taken with the basic non-linear output, but linearizing circuits are becoming "standard" additions to the system because:

A. Accuracy of turbulence measurements can be increased by using a linearizer when large scale fluctuations (>10%) are present.

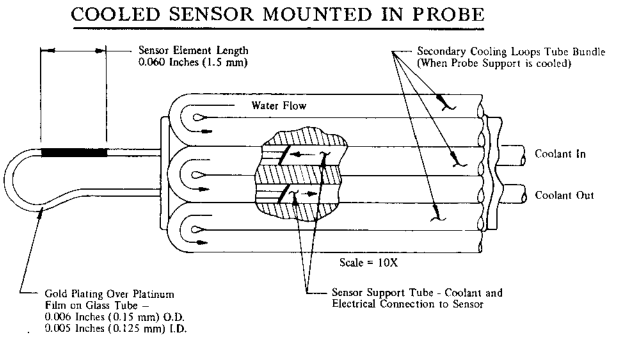
B. The convenience of making mean flow measurements is increased with a voltage output linear with flow.

These two reasons are justification for the increasing popularity of linearizing circuits. Some accuracy is lost when going through any signal conditioning circuit, so for highest accuracy it is sometimes advisable to use the non-linear output. Thermo-Systems' recent introduction of linearizers that match actual calibration curves rather than relying on empirical heat transfer relationships has greatly improved linearizing accuracy. Whether linearized or non-linearized, the sensitivity at low velocities, the large dynamic range, and the small size of the sensors all have an important influence in making anemometers a significant tool for measuring both mean and transient phenomena.

2.5 COOLED SENSORS

As indicated by its name the cooled sensor is primarily applicable to measurements in high temperature gases. The normal wire or hot film is limited by the maximum operating temperature of the sensor. Since heat transfer is relied on for the actual measurement, a non-cooled sensor must be operated at a temperature actually higher than the environmental temperature. The cooled sensor circumvents this problem by adding an internal heat sink so that its surface is actually below the temperature of the environment. In this manner it is possible to expose sensors to very high temperature environments, the only limitation being the maximum cooling rate that can be applied to the sensor.

In actual practice the cooled sensors are made tubular and the cooling is accomplished by passing the cooling fluid through the interior of the sensor. The only sensor size available is 0.006 inches (0.15mm) in diameter by approximately 0.050 inches (1.5mm) long. The sensor is mounted in tubes which serve as both the electrical connection and the plumbing


COOLED SENSOR MOUNTED IN PROBE

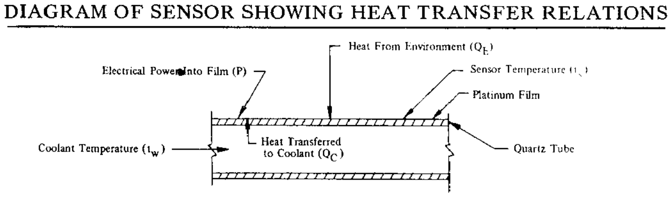


DIAGRAM OF SENSOR SHOWING HEAT TRANSFER RELATIONS

$Q_C = U_C (t_s - t_w) = \text{Constant}$

U_C = Heat Transfer Coefficient, BTU/hr – °F

$Q_C = P + Q_E$

Q_E = Heat Transfer From Environment to Sensor

Since $P > 0$,

$Q_C > Q_E$ For Proper Operation

Figure 8: Cooled Probe And Fundamental Heat Transfer Relation

connection for the cooling. The body of the probe must also be cooled. Figure 8 shows the tip of a typical cooled probe and the basic heat transfer relation which governs the cooled sensor.

Although the ability to withstand high temperature environments is the primary property of cooled sensors, they are also useful in applications where it is necessary to have high frequency response at low velocities. This ability comes from the fact that the closed loop gain of the constant temperature anemometer depends on the actual electrical power input to the sensor. In low velocity or low density environments this power for a normal hot wire or hot film is very low. With the cooled film it is possible to keep this power quite high because of the heat transfer from the sensor to the interior coolant. This enables the cooled sensor to react very quickly to a sudden shock or some other transient flow.

3.0 CONTROL CIRCUITS

The previous sections have been primarily concerned with the sensitive element itself. In successfully using an anemometer for a specific fluid mechanics measurement the selection of a sensor is of primary importance. However, this sensor must be controlled with an electronic circuit and some basic knowledge of its function and operation is important.

3.1 CONSTANT CURRENT ANEMOMETER

The two basic types of circuitry used with hot wire type sensors are constant current and constant temperature. The electrical schematic of a constant current system is shown in Figure 9. As implied by the name, the current to the sensor is maintained essentially constant by using a large resistor in series with the sensor. The current is selected so the sensor is operated at the desired temperature in the environment of interest. If the heat transfer between the environment and the sensor increases (due, for example, to an increase in the velocity) the sensor will tend to cool with a resulting decrease in its resistance. With a constant current in the sensor the decrease in resistance will cause a decrease of voltage at the terminal between the sensor and the dropping resistor. An amplifier is used to pick up this change in voltage and amplify it to useful signal levels for recording or monitoring. If the velocity change takes place very rapidly the response of the sensor will lag the actual change in velocity due to its own thermal inertia. To compensate for this the amplifier connected to the sensor is given a non-linear characteristic with frequency. By carefully matching the frequency characteristic of the amplifier to that of the sensor a flat frequency response is possible out to several hundred KHz (Figure 9 shows the basic scheme).

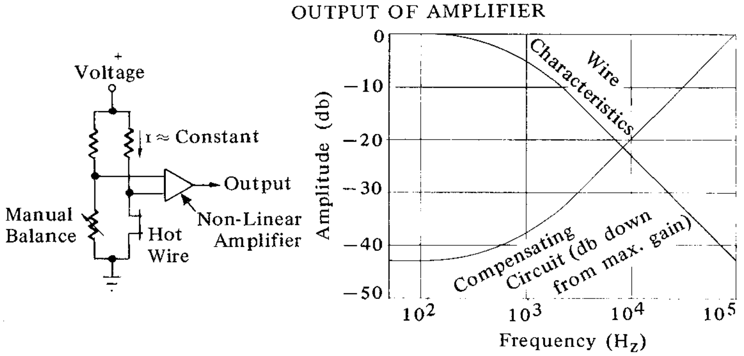

OUTPUT OF AMPLIFIER

Figure 9: Schematic of Constant Current System

The major drawback of the constant current system is that the frequency response of a sensor depends not only on sensor characteristics but also on flow characteristics. The response depends on both the thermal capacity of the sensor and the heat transfer coefficient between the sensor and its environment. Since the sensor response changes with changes in flow (changing the heat transfer coefficient), the frequency compensation of the amplifier must be readjusted whenever the mean flow changes. This is not practical for fast changes. Therefore, the constant current type of compensation is most applicable where the fluctuations in velocity are small compared with the mean velocity. Constant current operation is desirable for temperature measurements when a very small current flows through the sensor essentially keeping it in equilibrium with the fluid. Thermo-Systems' general purpose anemometers are equipped with a circuit to accomplish this, but no compensating network is included for high frequency response.

3.2 CONSTANT TEMPERATURE ANEMOMETER

The constant temperature type of compensating circuitry overcomes the primary disadvantage just mentioned in the constant current system by using a feedback loop. Figure 10 depicts a constant temperature system. As the velocity past the sensor increases the sensor will tend to cool with a resulting decrease in the resistance. This resistance decrease will cause the voltage to decrease changing the input to the amplifier. The phase of the amplifier is such that this decrease in voltage will cause an increase in the output of the amplifier to increase the current through the sensor. If the amplifier has a sufficient gain, it will tend to keep its inputs very close to the balanced condition. Therefore, any change in the sensor resistance will be immediately corrected by an increase or decrease in the current through the sensor.

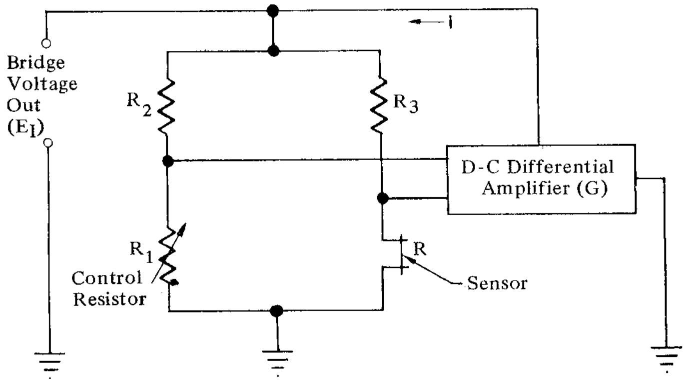


Figure 10: Schematic of Constant Temperature System

The output of the constant temperature system is the voltage output of the amplifier which in turn is the voltage required to drive the necessary current through the sensor. Since with the feedback control the resistances in the bridge are constant, the voltage across the bridge is directly proportional to the current through the sensor and power is equal to the current squared times the resistance ($P=I^2R$). Therefore, the square of the voltage measured on top of the bridge is directly proportional to the instantaneous heat transfer between the sensor and its environment. No matching of compensation curves is required since the feedback makes the matching automatic.

3.3 COMPARISON OF ANEMOMETER SYSTEMS

When comparing anemometer circuits the basic performance parameters of noise level and frequency response must be considered. This is particularly true for measurements of high frequency components in turbulence. Regardless of the type of compensation, the amplifier must increase its compensation for response lag in the sensor as the frequency increases. Also, the amplitude of flow fluctuations usually decreases at high frequencies. Therefore, when making measurements near the performance limits of an anemometer, both the noise level and the frequency response are important. In the past the constant current system has had lower noise levels and higher frequency response than the constant temperature system. One of the reasons for this has been the use of transformer coupling for impedance matching between the sensor and the amplifier input. The use of transistor inputs has considerably reduced this advantage, and the best present day constant temperature systems are comparable to the maximum performance of constant current systems in both noise level and frequency response.

In addition to noise level and frequency response such things as convenience in operation and the flexibility of the system are important practical considerations. Here the constant temperature system has a clear advantage. Several other basic advantages of constant temperature anemometers include:

A. Constant temperature systems are compatible with film type sensors while constant current systems are not due to the complex frequency response characteristics of films.

B. The operation of a sensor at constant temperature prevents sensor burn-out when the cooling velocity past the sensor is suddenly decreased.

C. Constant temperature operation is a more practical approach for measurements in liquids where large changes in sensor cooling occur when velocity changes.

D. Linearizing is possible. With a constant current system it is not feasible.

E. The constant temperature system can be temperature compensated.

F. The constant temperature system gives a direct DC output. With a constant current system, the measurement of mean levels is typically made by manually balancing a built-in bridge, the lower frequency limit of the amplifier system generally being around 2 Hz.

For these reasons, plus the inability of the constant current system to measure large fluctuations under most circumstances, the constant temperature system has essentially replaced the constant current type. It should be pointed out that regardless of the compensation used the resolution of the anemometer is very high when compared to most types of instrumentation. For example the measurement of 0.02 percent turbulence levels is quite feasible with either system in a 10 KHz bandwidth.

When comparing constant temperature systems it is important to compare the three basic design variables of frequency response, background noise level and power output.

4.0 OPERATING A SENSOR

The optimum sensor type and mounting configuration must be established as a first step. As indicated in Section 2.0 there are a large variety of probe types available. Thermo-Systems also offers in-line mass flowmeters that utilize a film sensor inside a tube where a built-in venturi controls the flow pattern. Refer to Bulletin N16-2 for Hot Wire and Hot Film probes, Bulletin 1350 for Mass Flowmeters and Bulletin C26 for Cooled probes.

To operate a sensor it is necessary to determine and set the proper operating temperature for the application, turn the anemometers on and proceed to calibrate and/or take measurements.

4.1 SENSOR OPERATING TEMPERATURE

With hot film and hot wire sensors in room temperature air the normal operating temperature ranges from 300-500° F. For a hot film sensor this calls for an operating resistance about 1.5 times the sensor resistance at ambient temperature. This is the overheat ratio or ratio of hot to cold resistance. The relationship between overheat and operating temperature is as follows:

$$R_H/R_C = 1 + \alpha_C (t_s - t_e) \qquad (2)$$

where R_H=operating (hot) resistance of sensor; R_C=resistance of sensor at environmental (cold) temperature; α_C=temperature coefficient of resistance for the sensor material referenced to temperature, t_e; t_s = sensor operating temperature; and t_e = environmental (fluid) temperature. For a platinum film sensor $\alpha_C = 0.0026/^{\circ}C$ while for a tungsten hot wire $\alpha_C = 0.004/^{\circ}C$. When an accurate determination of sensor temperature is required, an actual temperature vs. resistance curve should be plotted for the specific sensor of interest. For most work with anemometers the sensor is calibrated and knowledge of the exact operating temperature is not important so long as conditions can be repeated. When heat transfer equations are relied upon for reducing data, either because of the lack of a calibration curve or because the number of variables does not permit simple reduction of data by reference to a calibration curve, the actual temperature is an important parameter.

In practice the operating temperature is set by inserting the correct resistance in the bridge leg opposite the sensor. This is either a single fixed resistor preselected to match the probe, a temperature compensating winding or a resistance decade that can be varied to select the desired operating resistance. This resistor is R_1 in Figure 10.

4.2 TEMPERATURE COMPENSATION

Whenever the temperature of the flow medium is varying between calibration and measurement or during measurements, the influence of temperature on the anemometer output must be considered. There are several approaches for temperature correction including: (a) measuring temperature separately and correcting the data either by referring to a family of calibration curves taken at different temperatures or by using the theoretical equations for heat transfer; (b) placing a temperature sensitive resistor in the flow stream with the active probe and letting the resistance change regulate the output to automatically compensate for temperature; and (c) to correct for high frequency temperature changes, using two active sensors operated at two different temperatures and differencing the outputs to get a flow signal independent of temperature.

The first method is straight forward. Corrections are generally small because there is a large temperature difference between the fluid and the sensor. For example, if the sensor is at 470° and the fluid at 70°, a 4° change represents about a 1% error. The other two methods will be briefly discussed.

4.2.1 AUTOMATIC TEMPERATURE COMPENSATION

A temperature sensitive resistor of the correct value and temperature coefficient is installed in the bridge opposite the sensor. This is mounted in the flow stream near the velocity probe. Its resistance will vary with temperature forcing the velocity sensor to vary a corresponding amount. These are adjusted to keep the anemometer output constant for a given flow rate over a range of temperatures. In the simplest case, the temperature compensating winding must have enough surface area to stay in equilibrium with the fluid temperature and as a result the winding is rather large and cannot compensate for fast temperature changes. Thermo-Systems offers these in the Model 1300 Probe series. For work in very small areas or for steep temperature gradients the Model 1025 Temperature Compensator is used. This utilizes a second closely spaced hot wire or hot film sensor that senses temperature near the velocity sensor and corrects the anemometer using a transfer bridge.

4.2.2 CORRECTION FOR FAST CHANGES IN TEMPERATURE

If two sensors are operated at different surface temperatures the following equations can be written to indicate the output relationship:

$$P_1 = \left[A + B\,(\rho V)^{\frac{1}{n}}\right](t_{s_1} - t_e)$$

$$P_2 = \left[A + B\,(\rho V)^{\frac{1}{n}}\right](t_{s_2} - t_e)$$

and $$P_1 - P_2 = \left[A + B\,(\rho V)^{\frac{1}{n}}\right](t_{s_1} - t_{s_2}) \qquad (3)$$

where P = electrical power dissipated in sensor (proportional to bridge output squared) and the remaining terms correspond to Equation (1) for the two sensors. Figure 11 shows the typical hookup of equipment.

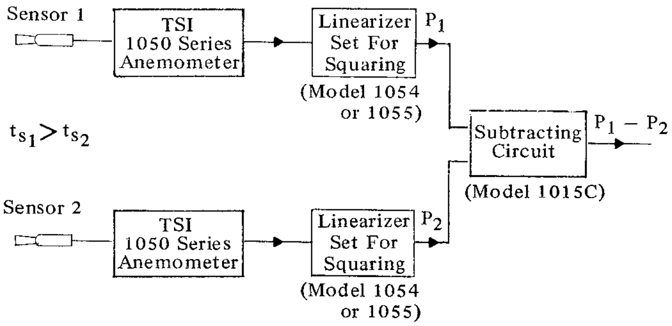


Figure 11: Setup For Measuring Flow In Presence of Fast Temperature Changes

4.3 FREQUENCY RESPONSE

The closed loop frequency response of a constant temperature anemometer depends on several factors including the thermal properties of the sensor and the fluid, the overheat ratio, the temperature coefficient of the sensor, the fluid velocity, the gain of the amplifier, the resistance of the bridge and the bandwidth of the amplifier. Since it is very difficult to generate a fluctuating flow or temperature of known amplitude at very high frequencies, frequency response specifications for anemometers tend to be vague. Several different methods of measurement and interpretation are in current use. A common method is to introduce an electrical square wave on one side of the bridge and to observe the output on an oscilloscope. Square wave generators are built into most general purpose anemometers for this purpose. Frequency response can be varied by adjusting the effective gain-bandwidth product of the bridge and amplifier system. Figure 12 shows the response of a 0.0002 inch (0.0038 mm) diameter tungsten hot wire at 300 fps in air to a square wave test pulse when using a TSI Model 1053A Anemometer while Figure 13 shows the response using the 1:1 bridge on the TSI Model 1050 Anemometer. Response time is measured as the time, τ, from the beginning of the upward pulse to a point on the way down equal to 3% of the total pulse height. Thermo-Systems offers the fastest responding anemometers available.

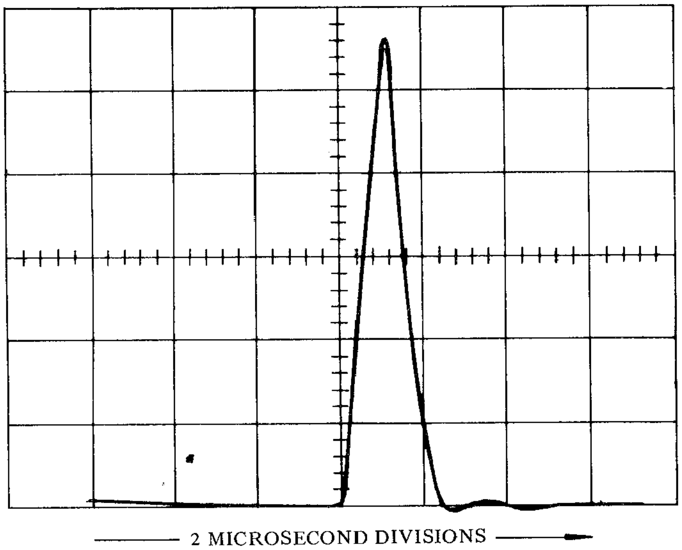


Figure 12: Square Wave Test Signal with Model 1053A Anemometer (or Model 1050 on 5:1 Bridge) on a 0.0002" Diameter (5 micron) Tungsten Hot Wire in Air

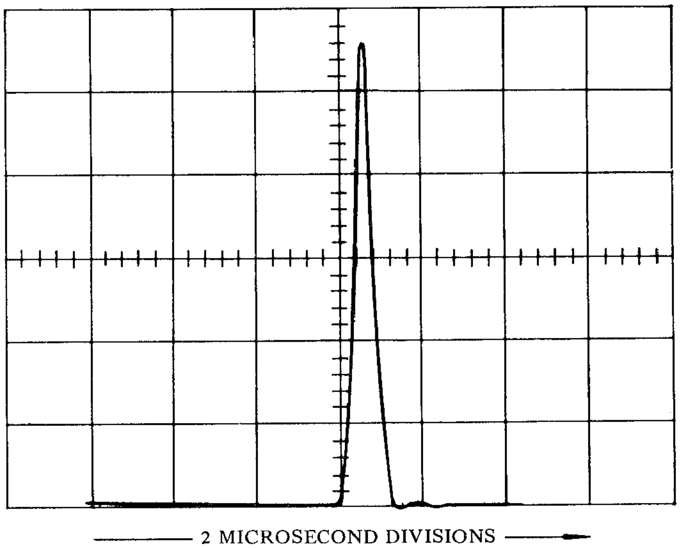


Figure 13: Square Wave Test Signal with Model 1050 Anemometer (1:1 Bridge) on a 0.0002" Diameter (5 micron) Tungsten Hot Wire in Air

The interpretation of the time, τ , in terms of frequency response is somewhat controversial, but according to the thorough investigations of Freymuth (7) they are related as follows:

$f = \frac{1}{1.5\tau}$ = frequency in Hz at which closed loop response is attenuated 3 db. Figure 13 would indicate response of about 550 KHz by this method.

In comparing anemometers it is very important that noise level be investigated as well as frequency response as in turbulence measurements the higher frequency signals often have the lowest amplitude and can be hidden by the electronic background noise of the anemometer.

5.0 LINEARIZING

The non-linearity of an anemometer when measuring velocity has already been discussed. The usual relationship between the electrical power to the sensor and the velocity past the sensor was given in Equation 1 as follows:

$$E^2 \sim \left[A+B(\rho V)^{\frac{1}{n}}\right](t_s - t_e) \qquad (1)$$

The original work done by King (12) indicated that n = 2, giving the typical fourth power relationship between velocity and the voltage on the anemometer bridge. In practice even cylindrical sensors do not follow King's Law precisely. As shown by Collis and Williams (3) the exponent for even very long wires is 0.48 for the lower velocity ranges and 0.51 for the higher velocity ranges. As indicated, King's Law would give the exponent as 0.5. For sensors of finite length such as used with anemometers, the variation in exponent is greater. In addition, cones, wedges and parabolic shaped sensors vary considerably from the 0.5 exponent. If the purpose of linearizing is only to increase the accuracy of turbulence measurements then the use of a power or variable exponent relation in the linearizer is often adequate. However, if the anemometer is being used to make accurate mean value measurements in a flow stream the use of a King's Law relation, or for that matter any fixed exponent curve, is clearly inadequate.

The approach used by Thermo-Systems to circumvent this problem is to set up the linearizing function to match an actual calibration curve for a specific type of sensor, fluid and flow range. The sensors are then made very reproducible so they can be interchanged without having to change the linearizing function for a given sensor type. By this technique it is possible to measure mean flow velocity to accuracies of 2% of reading or better over a 100 – 1 linearized range. When fluid, type of sensor or flow range are changed the linearizing function can be changed by the user. This approach essentially provides a universal linearizer as it can linearize non-analytic curves as well as curves with fixed exponent.

Linearizing is often a convenience for readout rather than an absolute necessity for making measurements. However, in many applications this convenience in readout makes the difference between a practical application of anemometry and one that is impractical.

6.0 READOUT AND SIGNAL CONDITIONING EQUIPMENT

An anemometer system can be furnished with adequate readout equipment to make itself sufficient for mean flow and turbulence measurements. It is useful to discuss the output equipment that is used for various studies.

6.1 DC MEASUREMENTS

A. *VOLTMETER* – A basic DC voltmeter is furnished with the anemometer for measurements of mean quantities. An accurate zero suppression circuit (as included in the TSI Model 1057 Signal Conditioner) increases reading accuracy by subtracting a precise DC voltage allowing a very sensitive meter scale to measure the remainder. Accuracies of 0.1% are then possible. A digital voltmeter should be employed for highest accuracy. To improve on the DC meter accuracy a 0.01% electronic digital voltmeter should be used. The servo-driven digital voltmeters sometimes offered as anemometer accessories are usually not this accurate.

B. *SUM AND DIFFERENCE CIRCUIT* – For an "X" probe with two sensors, the instantaneous velocity components are proportional to the sum and difference of the signals from the two linearized anemometers. This is useful for directional work but the sum and difference circuits must be capable of handling DC signals as well as AC. Thermo-Systems' Model 1015C Correlator is applicable for this.

C. *RECORDERS* – Almost any strip chart, oscillographic or tape recorder can be used on the output of the anemometer. Since the anemometer is capable of high speed measurements a high response recorder is often recommended.

D. *ANALOG AND DIGITAL COMPUTERS* – For computing vectors, angles, some correlations, phase shift, etc., an external analog device (in addition to a sum and difference circuit) is sometimes utilized. It is also becoming popular to digitize the anemometer output and analyze data in a digital computer.

6.2 AC MEASUREMENTS

A. *RMS VOLTMETER* – The most common addition to any anemometer system is a true RMS voltmeter to measure the root mean square average of flow fluctuations to get turbulence measurements. Recently, Thermo-Systems introduced an RMS meter optimally designed for mechanical type measurements. The Model 1060 RMS Voltmeter has frequency response down to 0.1 Hz, recordable 0 - 10V output for both mean square and RMS, averaging times to 100 seconds and very high crest factors.

B. *OUTPUT FILTERS* – When working with signals with a very wide frequency bandwidth it is convenient to eliminate signals not in the frequency range of interest. Also, some spectrum analysis can be done by bandpassing over the range of frequencies encountered. The Model 1057 Signal Conditioner contains precise, fast cutoff filters for both high and low pass filtering.

C. *OUTPUT AMPLIFIERS* – When recorders do not have adequate sensitivity and/or when very low level fluctuations are present a calibrated, low noise amplifier (such as included in the Model 1057 Signal Conditioner) can be very useful.

D. *CORRELATION* – With a fluctuating signal it is common to correlate one signal with another with respect to location, direction, time, etc. A sum and difference correlator (such as TSI Model 1015C) feeding its output into a true RMS voltmeter can measure the cross-correlation functions for any two random signals. The Model 1015C also includes circuits to directly read Reynold's shear stress and microscale of turbulence.

For autocorrelation measurements a time delay system must be incorporated. This can be a two-tape head magnetic tape system (such as offered by Ampex), electronically (such as like Princeton Applied Researchs' Model 100) or by electromagnetic means.

E. *SPECTRAL ANALYZER* – For spectral analysis of turbulence, this type of instrument is a common addition. Spectral densities and probability densities can be obtained by variable bandpass filters, a good commercial spectrum analyzer or by autocorrelation.

F. *RECORDERS* – For high frequency signals an FM tape recorder is the best known method of recording. This allows for later analysis in a digital computer or other data handling equipment. A high speed oscillograph is also common but these are limited to frequencies on the order of 5 to 10 KHz.

7.0 APPLICATIONS

7.1 MEAN VELOCITY MEASUREMENTS

A. *CALIBRATION*

For any mean velocity measurement a calibration curve must first be obtained. Once a calibration curve has been established for a specific type of sensor, good accuracy can be achieved with a second matched sensor by taking only two calibration points. The linearizing circuit discussed previously makes use of this fact, allowing calibrations to be made with just zero flow and a full scale point. Velocity readings are then taken directly on a linear meter scale. For the non-linear case a voltage is read on the meter and referred to the calibration curve to get velocity. For precision and for non-matched sensors accuracy increases with the number of data points taken.

Temperature changes must either be corrected for or automatically compensated out as outlined in part 4.2

Apparatus for Calibration – For work in gases at velocities above 30 ft/sec calibration can be made by referencing to a pitot tube or the pressure difference across a nozzle in the throat of which the sensor is located. For very high velocities compressibility ef-

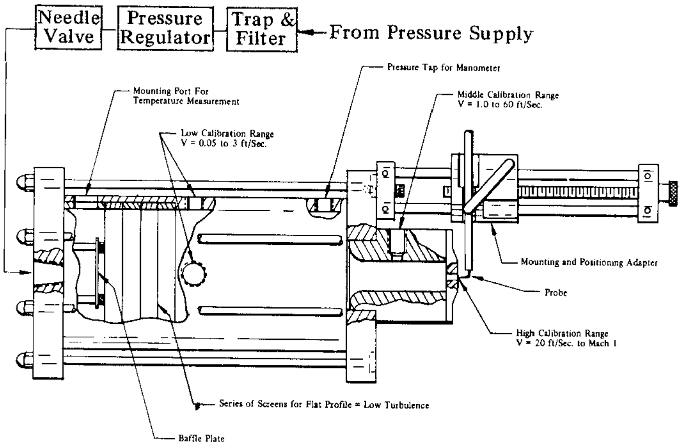


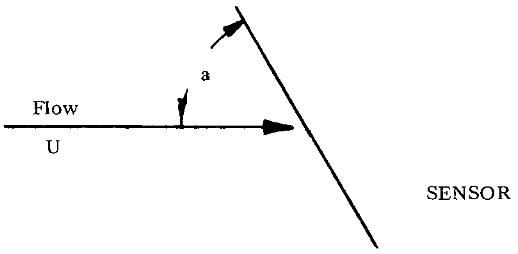
Figure 14: Calibrator For Hot Wire and Hot Film Probes

fects must be considered. For very low velocities a laminar flow tube or timing of a tracer is used. TSI offers a calibrator (Model 1125) that has three locations cascaded in area, each with a controlled velocity profile to cover a very wide velocity range from about 0.05 ft/sec to Mach 1. This is shown schematically in Figure 14. Temperature compensated probes can be purchased with calibration curves if desired.

In liquids calibrations can be accomplished by towing the probe through a channel, or running the probe in a flow nozzle. With an adapter kit the Model 1125 Calibrator can also be used in liquids.

B. *DIRECTIONAL SENSITIVITY*

If the flow direction is not normal to a cylindrical sensor the resulting data is affected. The relationship between actual mean velocity and the "effective cooling velocity" past the sensor generally follows a sine law for small angles, where $V = U \sin a$. A more accurate relationship which holds for much larger angles is that due to Champagne (2). Figure 15 shows this relationship.



$$V^2 = U^2 (\sin^2 a + k^2 \cos^2 a)$$

U = mean velocity
V = effective cooling velocity past sensor
$k \cos a$ = effectiveness of velocity parallel to sensor

Figure 15: Direction Sensitivity for Cylindrical Sensor

This angular relationship is very useful when two mutually perpendicular sensors are operated each at about 45° to the main flow to indicate the components of velocity parallel and perpendicular to the flow direction. The sum and difference of the two signals are proportional to the two components (if linearized).

C. *STABILITY*

For a mean flow measurement to be useful it must maintain its calibration over long time periods. Hot wires are notoriously troublesome in this regard due to their small size making them susceptible to picking up small contaminants, corroding on the surface, strain gage effects and/or easily breaking. They are also difficult to clean. The larger hot film sensor has been a great improvement in this regard. The effects of surface contamination tend to be a function of sensor size and a quartz coating on the sensor surface prevents corrosion and erosion. Hence, the hot film is far superior for mean measurements. Figure 16 shows some data points taken with a 0.002 inch diameter, cylindrical, quartz coated hot film sensor during a one-week period when it was continuously exposed to atmospheric conditions (in St. Paul) without cleaning. As can be seen, there was no significant change in calibration.

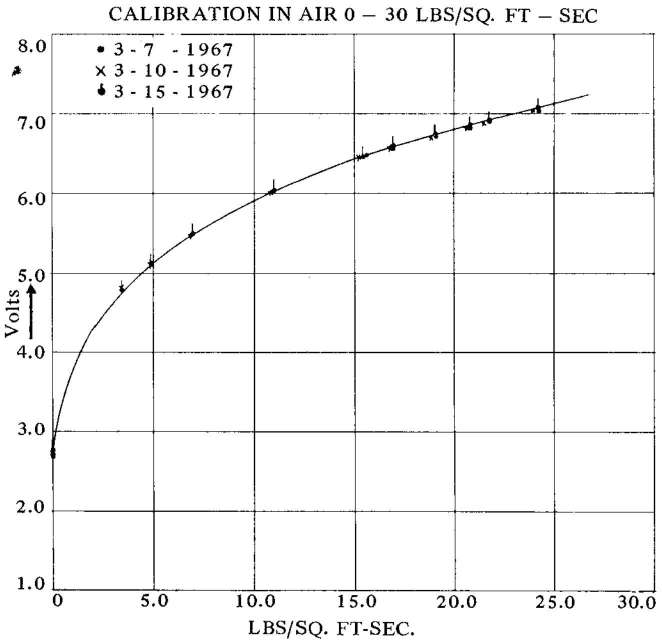


Figure 16: Repeatability of Quartz Coated Hot Film Sensor in Atmospheric Air

Stability in liquids can be a more difficult problem due to "lint" type particles, gas bubbles and electrical conductivity. Liquid considerations are covered in more detail in another bulletin.

7.2 TOTAL FLOW MEASUREMENTS

For measuring total flow in a duct or pipe there are two basic approaches. The cross-section can be broken into equal areas with measurements taken in each of the areas and averaged, or the velocity profile can be controlled or known at the point of measurement such that a single data point can be taken.

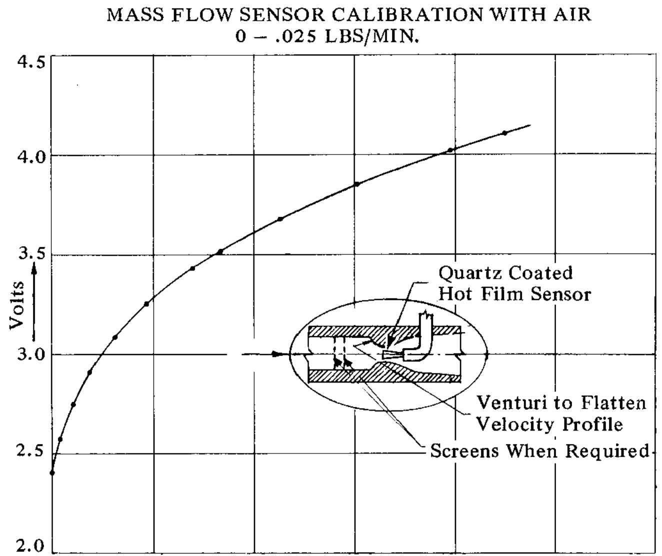


Figure 17: Sketch of Mass Flowmeter and Calibration Curve

Thermo-Systems builds a series of In-Line Mass Flowmeters that maintain a flat velocity profile at the sensor location and are calibrated to measure total mass flow. Figure 17 shows a typical calibration curve and schematic diagram of the measuring section. Besides having high frequency response these mass flowmeters cover an unusually wide flow range in a given device (1000 to 1) and have low pressure drop.

7.3 INSTANTANEOUS MEASUREMENTS

Most instantaneous measurements are used to obtain turbulence data and turbulence correlations with respect to velocity. The detail of an instantaneous signal is sometimes interesting in itself rather than its root mean square average as the signal may not be random, but have some pattern. A great deal of information in addition to turbulence levels can be obtained depending on the nature of the project and the variables to be considered. Fluctuations in heat flux, temperature, composition and pressure can also be measured and/or correlated with other variables. Only measurements in turbulent flows will be considered here to avoid prohibitive detail.

A. MEASUREMENTS WITH ONE SENSOR

The following terminology will be used in the discussion:

U = Instantaneous velocity
$\bar{U}$ = Average (mean) velocity
u = Fluctuating portion of the velocity
u' = Root mean square average of the fluctuating velocity – turbulence

(1) Turbulence In Mean Flow Direction

With the sensor oriented perpendicular to the mean velocity the turbulence in the mean flow direction, u', is obtained by connecting a true RMS voltmeter (Model 1060) to the anemometer output. For a linearized system a proportionality factor is applied to convert from voltage to velocity. On a non-linear system, the conversion is made by determining the slope of the calibration curve at the point of measurement. If the turbulence is large scale a "distortion" error is introduced in the non-linear system due to the uncertainty in selecting the correct slope.

(2) Turbulence Intensity in Mean Flow Direction

The ratio of turbulence to the mean velocity, $u'/\bar{U}$, is defined as turbulence intensity. Turbulence is indicated by the RMS meter and the mean velocity on the anemometer meter. It can be obtained without a calibration curve if a functional relation between heat transfer and velocity is assumed for the sensor.

(3) Microscale of Turbulence

The microscale can be defined as $\lambda = \bar{U}\ \tau\ u'/y$ where $y = \tau \sqrt{\overline{(\frac{du}{dt})^2}}$. The value of y is found by passing the output signal through a differentiating circuit with a time constant of value, τ, and from there to an RMS voltmeter. Microscale is related to the size of the smallest eddies in the turbulence field which become dissipated due to viscosity effects. The Model 1015C Correlator includes a differentiating circuit for microscale measurements with a true RMS voltmeter.

(4) Spectrum of Turbulence

Analysis of the total range of frequencies in a turbulence signal to determine the relative amount of energy or probability density vs. frequency can further indicate the properties of a turbulent flow.

The turbulence spectrum is obtained by passing the instantaneous anemometer output through a variable, narrow band filter. For precision work a high quality wave analyzer such as Hewlett-Packards' Model 302A or General Radio Type 1900A should be used. The energy spectrum can also be calculated from the autocorrelation function. (The TSI Model 1057 Signal Conditioner & Model 1060 True RMS Voltmeter can be used for spectral analysis. The filters in the Model 1057 roll off at 12 db per octave with a sharp corner so the amplitude at the corner is within 5% of the full amplitude.)

(5) Autocorrelation Function

Autocorrelations are made by comparing a signal with itself delayed in time to determine a correlation function or any harmonic relationship. This requires the use of a time delay apparatus plus a cross-correlating instrument that can obtain the correlation function $\overline{u_t \cdot u_{t-\Delta t}}$ after the time delay (this could also be written in normalized form as $\overline{u_t \cdot u_{t-\Delta t}}/u'^2$. Autocorrelators such as the Princeton Applied Research Model 100 and Honeywell Model 9410 can be used. Magnetic tape or drum systems with moveable heads or variable time delay networks can also be used in conjunction with the TSI Model 1015C Correlator and Model 1060 RMS Voltmeter. TSI can offer Ampex tape systems with moveable heads. A tape system has the advantage of a permanent record while the PAR Model 100 gives the most direct reading of correlation.

(6) Integral Scale (macroscale)

The integral scale of turbulence is calculated from the correlation function. With an autocorrelation function, R(t), the integral scale is $\int_0^\infty R(t)\,dt$. The integral scale is related to the size of the largest eddies in the turbulence field. A similar relationship can be found for space correlation curves obtained with two sensors as discussed in the following sections.

B. MEASUREMENTS WITH TWO SENSORS

In the discussion that follows it will be assumed that turbulence intensities are low so the usual assumptions regarding neglect of higher order terms can be made. A later paragraph briefly describes a method for large scale turbulence. Also, velocity fluctuations in the longitudinal, transverse and vertical directions will be designated as u, v and w respectively.

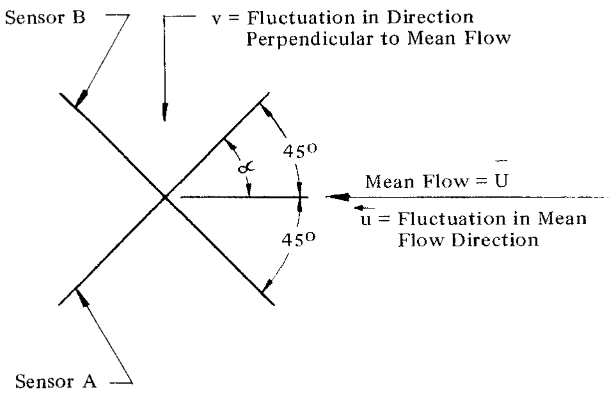


Figure 18: Standard X-Array Configuration

(1) *Two Sensors In An "X" Configuration*

Figure 18 shows the two-sensor orientation. With this arrangement the turbulence in two perpendicular directions and the directional correlation (Reynolds' stress) can be measured. Assuming that the effective cooling velocity follows a sine law (as discussed under 7.lb) and that the two sensors are 45° to the mean flow, their output voltages will be related by:

$$A = s_A\ (u+v)$$

$$B = s_B\ (u-v)$$

where s = proportionality constant, A and B are output voltages. Hence also, if the two signals are adjusted so $s_A = s_B = s$ then:

$$u = \frac{1}{2s}\ (A+B)$$

$$v = \frac{1}{2s}\ (A-B)$$

and

$$u' = \frac{1}{2s} \sqrt{\overline{(A+B)^2}}$$

$$v' = \frac{1}{2s} \sqrt{\overline{(A-B)^2}}$$

$$\overline{uv} = \frac{1}{4s^2} \left(\overline{A^2} - \overline{B^2}\right)$$

These quantities can also be written in the normalized form. The equipment needed to make these measurements is shown in Figure 19. The TSI Model 1015C Correlator combined with the 1060 RMS meter will directly read the u', v' and $\overline{uv}$ values. It is no longer necessary to obtain two correlators to get a direct reading of $\overline{uv}$.

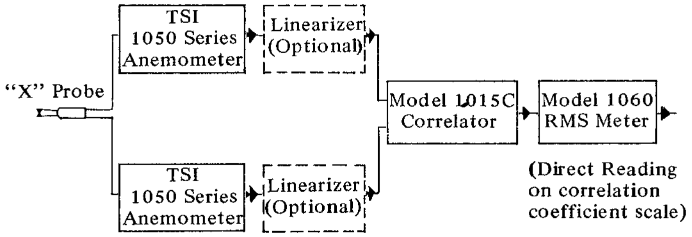


Figure 19: Setup for Measuring u', v', $\overline{uv}$

The "X" probe can be oriented in different planes to obtain u', v', w', $\overline{uv}$, $\overline{uw}$ and $\overline{vw}$ quantities.

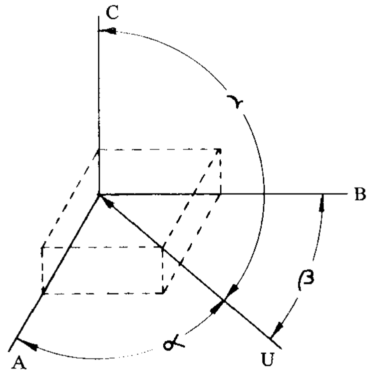
(2) *Two Parallel Sensors*

Two sensors located at points A and B in the flow stream are perpendicular to and in the mean flow path. A correlation between the two signals, $\overline{u_A u_B}$, can be read directly using the Model 1015C Correlator and Model 1060 RMS meter combination. The same procedure would be used to correlate the signals from two sensors located at any two points or to correlate a velocity signal with a temperature, pressure or other signal to determine relationship. For instance there might be a vibration in one part of a system that correlates with a velocity fluctuation in another part. A variable time delay device is convenient if there could be a strong relationship between two random signals after placing them on the same time base.

C. *LARGE SCALE TURBULENCE*

In many applications of anemometers to fluid mechanics problems the assumption of small scale fluctuations is not valid. Large fluctuations cause errors in the reduction of transient data and in the mean flow readings. This is true even if the system is linearized due to the higher order terms that are being neglected. See references (23) and (24).

The following technique circumvents the problems briefly referred to above. It does not rely on higher order terms being insignificant. The procedure is to determine the instantaneous velocity vector rather than the individual components.



$$V_A^2 = U^2\ (\sin^2\alpha + k^2 \cos^2\alpha)$$

$$V_B^2 = U^2\ (\sin^2\beta + k^2 \cos^2\beta)$$

$$V_C^2 = U^2\ (\sin^2\gamma + k^2 \cos^2\gamma)$$

$$U^2 = \frac{V_A^2 + V_B^2 + V_C^2}{2 + k^2}$$

Figure 20: Direction Sensitivity Using Three Mutually Perpendicular Sensors

First, it is necessary to obtain a relationship between the effective cooling velocity and the actual mean velocity that is more accurate than the normal sine law.

The relationship suggested by Champagne (2) shown in Figure 20 satisfies this requirement as it takes into consideration the residual velocity sensitivity when the velocity vector is parallel to the sensor. This effect is due to the finite length of the sensor and the resulting non-uniformities in the temperature of the sensor. The actual value of k (Figure 15) depends on the sensor type and the length to diameter ratio.

If three mutually perpendicular sensors are exposed to the environment the resulting configuration and equations are given in Figure 20. As shown by the last equation the actual mean velocity can be calculated from the sum of the squares of the three effective cooling velocities past the three sensors. Once the mean velocity has been determined, it is relatively simple to get back to the three previous equations and calculate the three angles. This data now gives the actual instantaneous velocity vector (both magnitude and direction). It is necessary, of course, to know which octant the velocity vector is in, since identical readings can be obtained from any of the eight possible octants. It is possible to make meaningful measurements at fluctuation levels up to 50% of the mean velocity. With the addition of an octant indicating sensor and an analog device to convert the velocity vector into the desired components this becomes a very powerful technique for micro-meteorological measurements as well as boundary layer and reversal type flow. In contrast, the accuracy of the usual data reduction techniques suffers considerably for velocity fluctuations over 20% of the mean value.

7.4 TEMPERATURE MEASUREMENTS – ASPIRATING PROBE

In the previous discussion it has been assumed that velocity is the parameter of interest. Composition has been assumed constant and if the temperature varied it was either corrected for by a compensating type probe or the resulting data was corrected for the temperature change. It is useful to consider a hot wire type device for measuring temperature and/or composition.

The primary problem in measuring temperature or composition directly with a hot wire is the fact that in almost all cases velocity is varying also. It is possible to separate temperature and velocity variations by the use of two sensors operating at two different temperatures as discussed in part 4.2. This is a useful technique that has been applied but the data reduction procedures are necessarily more complicated with a resulting loss in accuracy. It is also possible to use the sensor as a resistance thermometer (constant current) at low overheat and most general purpose anemometers are equipped for this. However, frequency response is only as good as the uncompensated sensor unless a separate compensating network is also used. Hence, the need for a fast temperature measuring probe.

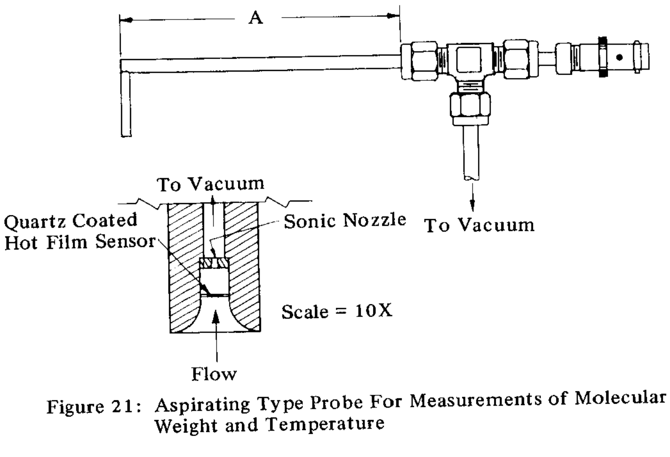


Figure 21: Aspirating Type Probe For Measurements of Molecular Weight and Temperature

Figure 21 shows an Aspirating type probe. In this probe the gas that passes the sensor is actually removed from the stream by the use of a vacuum pump. Sonic velocity is maintained through an orifice just down stream from the sensor. In this manner, the velocity past the sensor is nearly independent of the environment velocity and depends only on the temperature and composition of the stream. Therefore, in a constant composition stream this probe becomes a high frequency temperature measuring device. Its frequency response is as great as the compensated sensor being used. Alternately, when the temperature is constant but the composition is varying this probe can be used for measuring composition. For composition measurements it is possible to determine percentages in a two phase gas mixture when the gases have sufficiently different heat transfer properties so the sensor can differentiate them. For example carbon dioxide and air are very difficult to differentiate while a mixture of helium in air gives a very substantial signal. This probe is primarily applicable to velocities below 300 ft/sec. since at high velocities the affect of density changes at the sensor due to velocity fluctuations becomes more predominate.

7.5 OTHER APPLICATIONS

The thermal anemometer has been and can be applied to a large number of measuring problems. Since each is an involved subject in itself discussions on Supersonic Flow, Special Considerations for Liquid Flow, Pressure Measurements and Measurements in Hot Gases are being covered in additional bulletins.

8.0 SUMMARY

The increased application of anemometer equipment in recent years has led to more reliable and versatile instrumentation. In particular both the constant temperature system and film type sensors have found wider markets and applications as the equipment has been improved and the varieties available increased.

The use of constant temperature systems and film type sensors has made routine measurements of mean velocity, mass flow, and turbulence levels very feasible. With linearization and temperature compensation the systems are very easy to use and very little calibration is required. Also the variety of equipment presently available permits one to choose a system as simple or as complex as required for the specific application. The extremely wide velocity range and the high frequency response with anemometer type equipment will no doubt lead to its continuing acceptance for measurements in more fields in both industry and universities.

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