SONIC ANEMOMETER
FOR HARSH ENVIRONMENTS

H. D. Collins

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by

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SONIC ANEMOMETER FOR HARSH ENVIRONMENTS

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INTRODUCTION

The sonic anemometer is based on the transmission of acoustical waves traveling in opposite direction over a well-defined path, and the determination of the resulting phase between the two waves caused by the wind velocity parallel to the path.

The instrument was developed for the purpose of obtaining very low wind velocities (in the order of 1 cm/sec) in an environment of extreme temperature, moisture, and pressure (120 °C, saturated steam, and 70 psi). An instrument of this type, utilizing the basic concept of sound waves traveling over a well-defined path, seemed very attractive because of the following characteristics: excellent sensitivity, fast response time, and the ability to withstand the adverse environment of the medium.

The final results of the wind tunnel calibration indicated the instrument was capable of determining wind velocities in the order of 0.1 cm/sec.

SUMMARY AND CONCLUSIONS

The anemometer has excellent sensitivity and performance over the desired velocity range under normal atmospheric conditions. The instrument, after calibration in the wind tunnel, was subjected to high temperatures, pressures, and steam. The results of the pressure chamber tests on the array indicate that degradation of the received amplitude signal occurs progressively with the increase in temperature, pressure, and moisture. The dc resistances across the terminals of the transducers decreased considerably, and indicate that

insulation is still a major problem. The effects of temperature on the array show that it is responsible for part of the signal attenuation.

The results of these tests indicate the anemometer with the same transducers is capable, under atmospheric conditions, of operating to approximately 100 °C. In the pressure chamber and steam environment with the present transducers, the anemometer is capable of operating to approximately 70 °C. More comprehensive environmental tests will have to be performed to evaluate the factors contributing to the degradation of the signal amplitudes of the transducers. Insulation breakdown seems to be the major problem, and if this can be solved, the anemometer should be capable of operation in the extreme environment.

DISCUSSION

THEORY OF THE SONIC ANEMOMETER

The principle of the sonic anemometer is based on the accurate measurement of the velocity of sound over a given path. The velocity of a sound wave can be given by:

$$C = 20.067 [T(1 + 0.3192 e/p)]^{1/2} \quad (1)$$

where C is the velocity, T is the absolute temperature, e is the vapor pressure, and p is the pressure of the medium.

Because the sound wave is propagated in the medium, the wind will affect the apparent speed of the sound at a fixed point. Suppose the wind V has a component W in the direction from T₁ to R₁ in Figure 1. This figure illustrates the effect of the wind on the sound ray vectors. The sketch shows the transducers oriented for measuring the horizontal velocity components of the wind. The sound wave front traveling from

T_1 to R_1 will have a velocity of $W + C \cos \alpha$, where $\sin \alpha = u/c$ and u is the wind component perpendicular to d .

FIGURE 1. Vector Diagram Illustrating Principle of Anemometer Operation

The transit time is then:

$$t_1 = \frac{d}{W + C \cos \alpha} \quad (2)$$

Similarly, the transit time t_2 of the sound wave front traveling from T_2 to R_2 is:

$$t_2 = \frac{d}{C \cos \alpha - W} \quad (3)$$

The difference in transit times of the two sound wave fronts traveling in opposite directions is:

$$t_2 - t_1 = \frac{2dW}{C^2 - V^2} \quad (4)$$

because $C^2 \cos^2 \alpha = C^2 - u^2$, where u is the velocity component normal to the path d and $V^2 = W^2 + u^2$, where V is the vector

sum of the wind velocity. The assumptions are that the inhomogeneities in the air are larger than the wave length of the sound wave, and that the sound traveling in each direction follows the same path.

If the instantaneous sound velocity (C) is much greater than the wind velocity (V), then the following approximation can be used:

$$t_2 - t_1 \simeq \frac{2dW}{C^2},$$

and if the sonic velocity C is known or constant, then W the wind velocity component parallel to d is given by:

$$W \simeq C^2 \frac{(t_2 - t_1)}{2d}. \quad (5)$$

If the sonic velocity is not a constant over the desired sampling interval, then either a direct continuous measurement of C is required, or T , e , and p must be known, and C calculated from Equation (1).

The phase difference between the two sound wave fronts traveling in opposite directions between T_1 and R_1 is proportional to the difference in transit times ($t_2 - t_1$), and hence, to the wind velocity component parallel to d . The following relationship exists:

$$\omega(t_2 - t_1) = \phi_2 - \phi_1 \quad (6)$$

where $\omega = 2\pi f$,

f = frequency in hertz,

ϕ_2 = phase of the sound wave front traveling from T_2 to R_2 ,

ϕ_1 = phase of the sound wave front traveling from T_1 to R_1 .

The wind velocity component parallel to d is then given by:

$$W \simeq C^2 \frac{(t_2 - t_1)}{2d} = C^2 \frac{(\theta_2 - \theta_1)}{4\pi fd} \quad (7)$$

Equation (7) shows that the component of wind velocity W varies directly as the phase difference between the two sound wave fronts and can be calculated if $\theta_2 - \theta_1$, f and C are known.

DESCRIPTION OF THE SONIC ANEMOMETER

An array consisting of two sound wave transmitters (T_1 and T_2) and two receivers (R_1 and R_2) is arranged such that T_1 opposes R_1 , and T_2 opposes R_2 , and their separation being the distance d as shown in Figure 2. The distance between T_1 and R_2 , and T_2 and R_1 , is much less than the distance d . The difference in transit times (or the phase difference) of the two sound waves traveling in opposite directions is proportional to the component of wind velocity parallel to d . Figure 2 is a block diagram of the basic units required for the measurement and readout of a single component of wind velocity. A 25 kHz sine wave oscillator drives the two lead-zirconate-titanate transmitters T_1 and T_2 . The opposing receivers R_1 and R_2 detect the incoming signals. The signals are then amplified by the high gain saturating amplifiers. The negative portion of the signals are then differentiated and trigger the one-shot multivibrators which function as phase detectors and variable time delays. Each multivibrator will then produce a pulse whose time and length correspond to the phase and the time delay respectively. The time delay is required to allow adequate time between the two pulses for starting and stopping a bi-stable multivibrator over the required wind velocity range of the instrument. The two positive pulses are then differentiated and the negative spikes coupled directly to a bi-stable multivibrator. The difference in arrival times of the two spikes contains the phase and time delay information,

FIGURE 2. Block Diagram of the Single Axis Sonic Anemometer

and acts as start and stop signals for the bi-stable multivibrator. The output generated by the bi-stable multivibrator is then a positive pulse whose width in time contains the wind velocity information. The width of the pulse controls the integration time of the time-to-analog converter. The converter produces a pulse whose amplitude is proportional to the width of the bi-stable multivibrator pulse. Thus, the wind velocity component parallel to d is a function of the amplitude of the converter pulse. The pulses are then averaged, and a direct readout or chart recording of the uncompensated wind velocity is produced. The wind velocity is then corrected for changes in the sound velocity of the medium due to the variations of temperature and humidity.

CIRCUITS OF THE SONIC ANEMOMETER

The basic circuits used in the sonic anemometer will be self-explanatory to the reader knowledgeable in electronics. Figure 3 is a block diagram of the various circuits used in the sonic anemometer, and Figure 4 is the associated waveforms. Four transducers are necessary to make up one axis of the array; two receivers and two transmitters. The transducers are 25 kHz lead-zirconate-titanate ceramics fabricated in the bimorph mode. Approximately 50 ft of RG 178 teflon extruded coaxial cable connect each of the transmitters to a 25 kHz power oscillator.

Figure 5 is the circuit diagram of the Wien-bridge oscillator and the power amplifier. The power amplifier supplied 1.5 W to drive all four transmitters. Each of the receiving transducers also have the same length of cable and connect into the input of high gain amplifiers. The input signal is approximately 60 mV in amplitude and the amplifiers are driven into saturation. The amplifier output signal is a 6 V, 25 kHz² wave. Figure 6 is the circuit diagram of the amplifier.

FIGURE 3. Block Diagram of the Basic Circuits of the Sonic Anemometer

Output signals of the PZT4 receivers.
Horizontal scale: 20 $\mu\text{sec}/\text{cm}$
Vertical scale: 0.05 V/cm

Output signals of the high gain amplifiers.
Horizontal scale: 20 $\mu\text{sec}/\text{cm}$
Vertical scale: 5 V/cm

Output signals of the differentiators.
Horizontal scale: 60 $\mu\text{sec}/\text{cm}$
Vertical scale: 2 V/cm

Output signals from the time delays.
Horizontal scale: 10 $\mu\text{sec}/\text{cm}$
Vertical scale: 10 V/cm

Phase comparator output signals.
Horizontal scale: 10 $\mu\text{sec}/\text{cm}$
Vertical scale: 10 V/cm

Time-to-analog converter output signal.
Horizontal scale: 10 $\mu\text{sec}/\text{cm}$
Vertical scale: 0.2 V/cm

FIGURE 4. Waveforms of the Instrument (Refer to Figure 3 for circuit locations identified by circled numbers)

FIGURE 5. 25 kHz Wien-bridge Oscillator and Power Amplifier, Schematic Circuit Diagrams

FIGURE 6. High Gain Amplifier, Schematic Circuit Diagram

The square wave is differentiated and the negative spike is coupled through IN4149 silicon diodes to the input of the mono-stable multivibrator. Each axis has two multivibrators that act as phase detectors and time delays. Figure 7 is the circuit diagram of the mono-stable multivibrator. The 10 V positive square wave outputs of the multivibrators are then differentiated, and the negative spikes are coupled through a pair of IN4149 silicon diodes into the bi-stable multivibrator. One channel acts as a start signal and the other as a stop signal for the bi-stable multivibrator. This multivibrator produces a 15 V output square wave that contains the phase information between the two negative spikes. Figure 8 is the circuit diagram of the bi-stable multivibrator.

FIGURE 7. Mono-stable Multivibrator, Schematic Circuit Diagram

FIGURE 8. Bi-stable Multivibrator, Schematic Circuit Diagram

The width-in-time of the bi-stable pulse, controls the integration time of the "time-to-analog converter." The variable amplitude of the converter is proportional to the phase difference of the two received signals. The amplitude of each integrated pulse is held for 20 μ sec and is then reset to zero. Figure 9 is the circuit diagram of the "time-to-analog converter" and the Darlington emitter follower while Figure 10 is a circuit diagram of the reset multivibrator (mono). The output signal of the converter is a series of square pulses separated 15 μ sec in time. The output of the converter is directly connected to the Darlington emitter follower. The output of the emitter follower is then available to drive a chart recorder. The average of the train of converter pulses is then proportional to the uncompensated wind velocity component, parallel to the transmission path.

FIGURE 9. Time-to-Analog Converter, Schematic Circuit Diagram

FIGURE 10. Reset Multivibrator (Mono), Schematic Circuit Diagram

The array of the four transducers and their associated electronics is shown in Figure 11. Figure 12 is the receiving section electronics for the sonic anemometer. It contains the two channels for measuring wind velocities in two directions. Figure 13 is the power oscillator, receiving section, and the power supply. Figure 14 is a simplified schematic of the type of transducer used in the sonic anemometer.

CALIBRATION OF THE SONIC ANEMOMETER

The instrument was calibrated at 25 °C and atmospheric pressure. Figure 15 shows the calibration curves for one axis of the instrument. The wind velocity was measured in both directions for the instrument. The variations of velocity versus output voltage were linear from approximately 0.1 to 50 cm/sec. The sensitivity was 26 mV/cm/sec, and this could be increased at the expense of decreasing the velocity range of the instrument. The instrument was compensated at a temperature of 25 °C, atmospheric pressure, and zero steam pressure; therefore, at other values of these parameters there are errors in the wind velocity measurement. If we let V_1 be the scale reading of the anemometer at T_1 , P_1 ; and e_1 and V_2 the reading at T_2 , P_2 , and E_2 (where T_1 , p_1 and e_1 are the values when the instrument was calibrated); then the reading V_2 can be corrected for the variations in temperature, pressure, and steam air mixture. We obtain the following relationships:

$$V_1 = \frac{C_1^2 \Delta t}{2d}$$

$$V_2 = \frac{C_2^2 \Delta t}{2d}$$

$$\frac{V_1}{V_2} = \frac{C_1^2}{C_2^2}$$

Neg. 0671552-2

FIGURE 11. Array of the Four Transducers and Associated Equipment

Neg. 0671552-1

FIGURE 12. Display of the Main Chassis Electronics

17

Neg. 0671552-4

FIGURE 13. Display of the Sonic Anemometer Equipment

BNWL-604

[Ceramic material supplied by Clevite Corporation and transducer fabricated in Puerto Rico by Euphonics Corporation.]

FIGURE 14. *Diagram of PZT4 Transducer Construction*

FIGURE 15. *Calibration Curves for the Sonic Anemometer*

then

$$V_2 = \left(\frac{C_1}{C_2} \right)^2 V_1$$

let

$$\left(\frac{C_1}{C_2} \right)^2 = \gamma$$

then

$$V_2 = \gamma V_1$$

γ is the correction coefficient for the calibration curve of the instrument. If the temperature, pressure, and steam air mixture is given, the sound velocity can be found using the set of curves in Figure 16. The ratio γ can then be calculated and the wind velocity measurement corrected.

FIGURE 16. Acoustic Velocity in Steam-Air Mixtures

TRANSDUCER ENVIRONMENT TEST

Tests were conducted to determine if the ultrasonic transducers (Figure 14) would function at temperatures to 120 °C in extremely humid atmospheres without major modifications. A tank that could be purged with a controlled amount of steam was used to elevate the temperature and provide the humid atmosphere. Also, a laboratory setup was used to test the effects of heat alone. Results show that the transducers would not function in a humid atmosphere above approximately 70 °C, but would function to 120 °C in normal ambient laboratory humidity.

The transducer array was placed into the test tank that had acoustic padding inside to reduce reflections. Both transmit transducers were driven with the same power oscillator, and the signal from the receiver transducers were monitored on a dual trace oscilloscope.

On the initial run, failure occurred at about 70 °C. After disassembly it was found that the polyethylene dielectric of the RG62/U cable had melted allowing the center conductor to come in contact with the shield. This cable was replaced with RG180/U which has teflon dielectric and insulation that withstand temperatures to 200 °C.

The next run gave the following results:

Temperature, °C	T1 & R2 Received Sig. 1, mV	T3 & R4 Received Sig. 2, mV
25	114	120
40	72	100
50	40	40
55	35	20
60	25	20
70	20	no sig.

Before exposure to the steam, the dc resistance across the transducers was approximately infinite, but at 70 °C the resistances were as follows: T1 = 8K and R2 = 70K, T3 = 25K and R4 = 150K. It is apparent that the moisture across the transducer does have an adverse effect on the performance of the transducers. While the transducers were being held at 70 °C in the above run, the frequency of the power oscillator was varied to see if the transducers had changed resonate frequency due to the change in temperature. Only a very small increase in signal amplitude was noticed. The tank was then vented to laboratory atmosphere and allowed to cool. The transducer signals recovered to their original value. Because a change in frequency made a slight change in signal amplitude, it was decided to monitor the frequency and change the frequency to peak the received signal at each temperature. The results follow:

Temperature, °C	Receive 1, mV	Freq. 1, Hz	Receive 2, mV	Freq. 2, Hz
25	100	25335	114	25415
35	85	25268	100	25333
40	50	25116	70	25106
45	--	--	40	25121
50	50	24915	--	--
55	35	25003	35	24824
60	30	24583	--	--
70	10	24540	12	24581

It can be seen that even with a change of 150 to 200 Hz in resonate frequency, the attenuation of the received signal in the previous run was much like that in the run above, which was frequency compensated.

We thought at this point that the transducer failure was due to moisture lowering the impedance across the transducer to the extent of greatly reducing its efficiency.

The ceramic material is a lead-zirconate-titanate built by Clevite Corporation. The maximum operating temperatures of Clevite's ceramics range from 125 to 250 °C, so one would not expect too much degradation below 125 °C. An experiment was set up in the laboratory to see the effect of temperature. Two brass cylinders were devised which had nichrome heaters wrapped around them. A transducer, with a thermocouple placed approximately 1/8 in. from the back of the ceramic material, was placed inside of each cylinder. One transducer was driven with a power oscillator and the other was monitored on an oscilloscope. The temperature was raised on the cylinders simultaneously, and the following data were recorded:

Temperature, °C	Received Amplitude, mV
35	70
75	60
80	50
85	40
100	40
105	30
110	25
115	20
120	10
130	--

Note that the reduction of signal from 35 to 75 °C is only about 14%, where it had been approximately 90% reduction in the humid atmospheric tests. At approximately 120 °C, the plastic support failed and the transducers became misaligned.

It appears that the transducers will function without any modification up to at least 100 °C in a dry atmosphere; but before operation in a steam atmosphere, they would have to undergo considerable modification. A new mount for the ceramic, and methods of moistureproofing the transducer material, should be considered.

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