TECHNICAL NOTE

Constant Voltage Anemometer

Description

The Constant Voltage Anemometer (CVA) is a new type of hot-wire anemometer specifically designed for high-performance flow measurements. The CVA enables real-time measurement of fluctuating velocity and temperature in air and gases without the need for careful tuning of its frequency response. The CVA principle of operation allows for an almost constant bandwidth operation even when the flow and sensor conditions are varied. Because of its high frequency response and low noise characteristics, CVA is especially suitable for turbulent flows with large frequency content and/or low turbulent intensity.

Hot-wire anemometers are widely used in fluid mechanics for measuring the mean and fluctuating components in a fluid flow. The anemometer operates on the relationship of fluid velocity to the convective heat transfer from a heated wire to the surrounding fluid.

Turbulence measurement plays a key role in determining the extent of momentum, heat and mass transfer in fluid flows. Understanding turbulence is critical for the proper design and evaluation of vehicles, engines, compressors and pumps in a variety of fluid regimes. Hot-wire anemometers are frequently used for accurate measurement of turbulence.

Features

- High frequency response (>450 kHz), without tuning
- Real-time continuous output signal
- Operates with commercial or in-house probes
- In-situ temperature correction without additional probe
- Ensured circuit stability regardless of probe cable length
- Long probe cable length (up to 100 m) without deterioration of frequency response
- Low noise level
- Easy-to-use hardware/software compensation techniques for wire thermal inertia

Applications

- Velocity and turbulence measurement using single/multiple sensors in isothermal and non-isothermal flow
- Measurement of velocity and temperature fluctuations
- Measurement of high-speed compressible turbulent flows
- Measurement of transitional and turbulent boundary layers

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Introduction

The constant voltage anemometer is designed for the measurement of velocity and temperature fluctuations in air and gases. It operates in combination with a hot-wire sensor which is placed in the flow under investigation. Convective heat transfer between the wire and the flow results in a change of the wire resistance, which is converted to an output voltage by the CVA circuit. Thus, analysis of the output voltage ultimately provides a way to monitor and analyze the characteristics of the flow.

1. Basic CVA Circuit

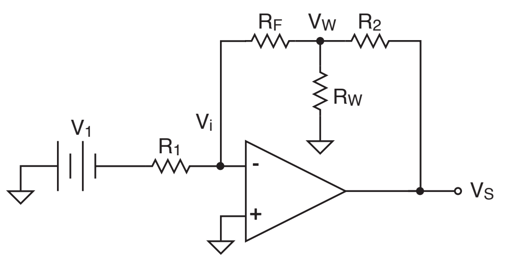
The basic CVA circuit is shown in Figure 1. It is an inverting operational amplifier circuit with the hot-wire of resistance R_w connected within the feedback loop. Analysis of the circuit shows that the wire voltage V_w is given by:

Equation 1

$$V_w = \frac{R_F}{R_1} V_1$$

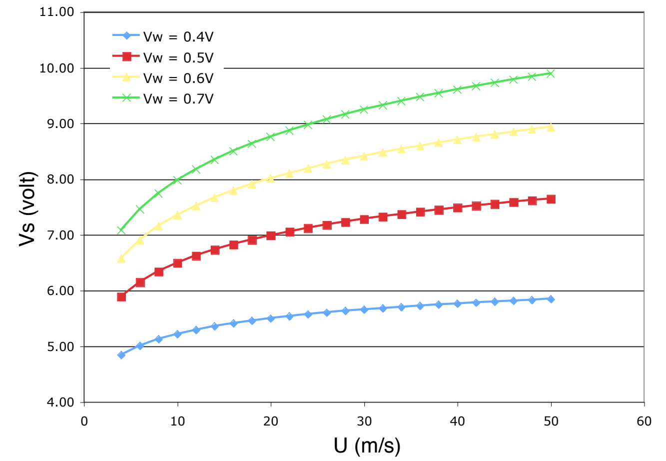
where R_F and R_1 are fixed resistors and V_1 is a variable voltage source. Consequently, the wire voltage V_w can be controlled by the user through the variation of V_1. The wire voltage V_w is not a function of the wire resistance R_w, so that the wire effectively operates in a constant voltage mode.

Figure 1: Basic CVA circuit



In practice, a hot-wire sensor is connected to the CVA with a BNC cable. Contrary to other types of anemometers, the cable length does not affect the stability of the circuit, so that very long connecting cables can be used. Any type of commercial or self-made hot-wire can be used with the CVA as long as the wire resistance stays in the specified range of R_w. The output voltage V_s can be recorded with a standard data acquisition system via a BNC connector.

Figure 2: CVA output versus flow velocity



Because the wire voltage V_w is held constant, any change of wire resistance will result in a current change in the wire, the path for which is only through the resistor R_2 of the circuit. Working out the circuit equations leads to the following expression for the output voltage V_s, which is taken at the operational amplifier output:

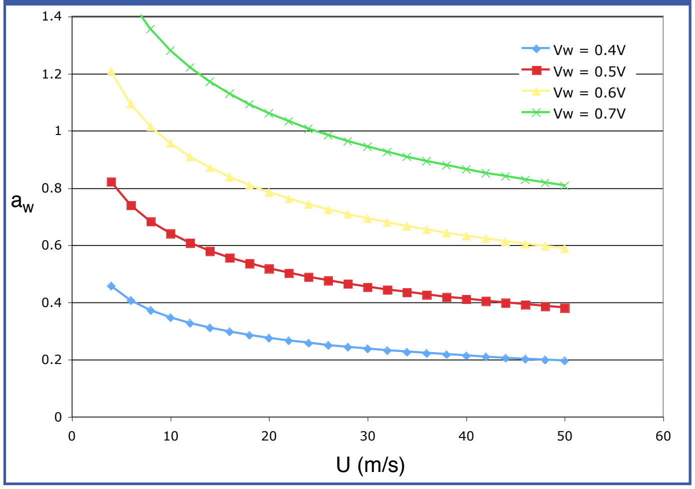
Equation 2

$$V_s = \left(1 + \frac{R_2}{R_F} + \frac{R_2}{R_w}\right) V_w$$

It is clear from Eq. 2 that the output voltage V_s depends on both the wire resistance R_w and the chosen wire voltage V_w. A finite value of V_w will heat the wire and increase its resistance R_w through the Joule effect. When the wire is placed in the flow, any change in fluid velocity or temperature will result in a change of R_w through heat transfer. Ultimately, the resistance change of the wire will lead to a change in the output voltage V_s that can be measured.

For example, Fig. 2 shows a typical variation of CVA output voltage for a standard hot-wire placed in a air stream. With increasing velocity, the wire temperature T_w and hence its resistance R_w decrease due to increased cooling, and this leads to an increase in the output voltage V_s, in accordance with Eq. 2. In practice, a calibration curve similar to Fig. 2 is obtained for each type of sensor. This calibration curve is a relationship between the fluid velocity and the output voltage that can be used for subsequent flow velocity measurements.

Figure 3: Overheat ratio versus flow velocity



The choice of wire voltage V_w will depend on the type of measurements to be performed. An important parameter that characterizes the response of hot-wires is the wire overheat ratio a_w, which is defined by:

Equation 3

$$a_w = \frac{R_w - R_a}{R_a}$$

where R_w and R_a are respectively the heated and unheated resistance of the wire. At high overheat (typically $0.3 < a_w < 1.0$), the wire is mostly sensitive to velocity fluctuations, while at low overheat (typically $0 < a_w < 0.3$), the wire is mostly sensitive to temperature fluctuations. With the CVA, the wire overheat changes freely when the velocity is varied but the range of a_w variation is directly linked to the choice of V_w.

Figure 3 shows the variation of wire overheat corresponding to the calibration data of Fig. 2. In the range of velocity defined by 10m/s < U < 40m/s, a value of V_w = 0.6V will result in an overheat range of $0.6 < a_w < 1.0$, which is well suited for velocity fluctuation measurements.

In contrast to a Constant Temperature Anemometer (CTA), the CVA does not suffer from a highly non-linear response at low overheat allowing temperature fluctuation measurements at very low values of V_w.

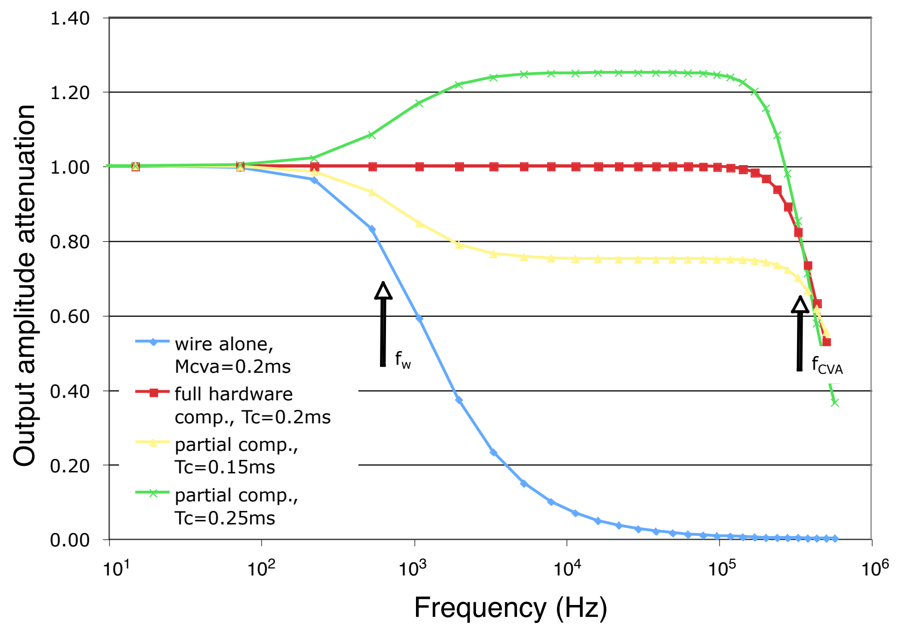
2. Compensation of thermal inertia

At high frequencies, the response of hot-wire sensors deteriorates because of thermal inertia. In practice, this means the fluctuations measured by the wire are attenuated above $f_w = 1/(2\pi M_{CVA})$, where M_{CVA} is the wire time-constant under constant voltage operation. To perform satisfactory measurements at frequencies above f_w, it is therefore necessary to compensate for the wire thermal inertia. In the CVA, this is accomplished by a specific compensation network that selectively amplifies the fluctuations attenuated by the hot-wire, thus recovering the original signal. The compensation network features a variable compensation time-constant T_c that can be set by the user for the specific sensor and conditions encountered. The compensation network is inherently stable and its effectiveness is not dependent on cable capacitance or cable inductance effects.

In practice, there are two possible ways to compensate the wire thermal inertia:

- In the "full hardware compensation method," the time constant T_c is set equal to M_{CVA}. This ensures that the frequency response of the system is flat up to the cut-off frequency f_{CVA}. In this case, the calibration curve can be directly used for fluctuations of frequencies up to f_{CVA} without any post-processing.
- In the "partial compensation method," the time constant T_c is set to a fixed value that can be different from M_{CVA}. In this case, there is a step in the frequency response of the system. To perform quantitative measurements at high frequencies, it is then necessary to use post-processing to eliminate the step and retrieve the fully compensated signal.

Figure 4: CVA compensation of hot-wire thermal lag



The different methods of compensation are illustrated in Fig. 4. In this example, a hot-wire sensor of time constant M_{CVA} = 0.2ms is chosen. This value of M_{CVA} leads to a significant attenuation of the wire signal above several hundred Hertz (f_w~800Hz). When T_c is set to 0.2ms, the system is fully compensated and the frequency response of the CVA output is flat up to the cut-off frequency f_{CVA}. When T_c is set at 0.15ms, the system is undercompensated and there is a step down in the frequency response. Finally, when T_c is set at 0.25ms, the system is overcompensated and there is a step up in the frequency response.

For frequencies lower than the cut-off frequency f_{CVA}, the conclusions are:

- frequency response of the CVA is flat, when $T_c = M_{CVA}$
- there is a step down in the frequency response, when $T_c < M_{CVA}$
- there is a step up in the frequency response, when $T_c > M_{CVA}$.

From this conclusion it would seem that the best solution is to use full hardware compensation all the time since no post-processing is required to retrieve the original signal. The partial compensation method, however, provides several advantages over the full hardware compensation:

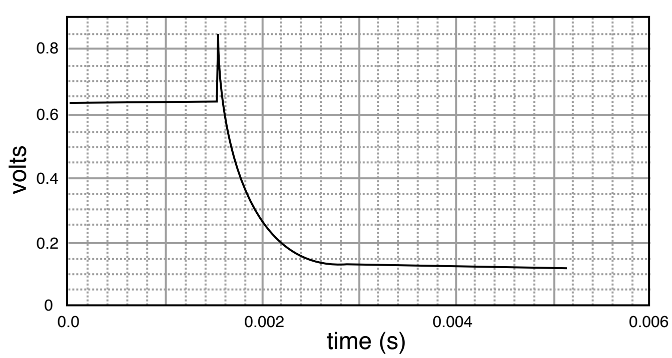
- The wire time constant M_{CVA} usually depends on the mean flow conditions and the chosen wire voltage V_w. Whenever one of these parameters is modified, the full hardware compensation method requires the user to modify T_c in accordance with the change of M_{CVA}. While this is not a problem in itself, a frequent modification of T_c can affect the productivity of the measurements.
- The anemometer cut-off frequency f_{CVA} is a function of T_c. To perform measurements with a constant bandwidth, it is therefore advisable to use a constant value of T_c for all flow conditions.
- The post-processing algorithm required to retrieve the original signal after partial compensation of M_{CVA} is very easy to implement in the data processing routine, as will be shown below.

3. Partial compensation post-processing

It was shown in the last section that operating the CVA with partial compensation of hot-wire thermal lag and post-processing the signal is an effective method for productive measurements of high-frequency flow fluctuations. This requires a way to accurately measure the hot-wire time constant M_{CVA} under in-situ flow conditions.

The CVA features a specific circuit for measurement of M_{CVA} using an electrical square wave test. When

Figure 5: Typical wire square wave response



the sensor is placed in the flow, the square wave signal is injected in the wire and the output signal is recorded. M_{CVA} can be retrieved from this signal, either directly on an averaging oscilloscope of later through processing of the square wave output. This is illustrated in Fig. 5, which shows a typical hot-wire square wave response. The signal is an exponential decay that is characteristic of first order systems like hot-wire sensors. The time constant M_{CVA} can directly be determined as the time taken to reach the 63% of the final value.

If $T_c \neq M_{CVA}$, the original signal can be retrieved through post-processing of the raw data acquired using partial compensation. This is done by an inversion of the step function described in Fig. 4. If $V_{s,raw}$ is the raw signal acquired with a compensation setting of T_c, the corrected signal $V_{s,corr}$ is obtained using the following equation written in the frequency domain:

Equation 4

$$V_{s,corr}(j\omega) = \left[\frac{1 + j\omega M_{CVA}}{1 + j\omega T_c}\right] V_{s,raw}(j\omega)$$

where j is the imaginary unit and ω is the angular frequency. This equation can easily be implemented in the data analysis software to retrieve the corrected signal. Evidently, when $T_c = M_{CVA}$, $V_{s,corr} = V_{s,raw}$ and the system is fully hardware compensated. When measurements are performed at angular frequencies much higher than $1/M_{CVA}$ and $1/T_c$, Eq. 4 reduces to:

Equation 5

$$V_{s,corr}(j\omega) = \frac{M_{CVA}}{T_c} V_{s,raw}(j\omega)$$

and the post-processing algorithm is reduced to a simple multiplication in the frequency domain.

In contrast to a Constant Current Anemometer (CCA), a wire subjected to constant voltage always has a smaller time constant. The CVA circuit is less demanding in gain and the bandwidth is substantially larger. Indeed, it can be shown that

Equation 6

$$M_{CVA} = \frac{M_{CCA}}{1 + 2a_w}$$

4. Measurement with fluid temperature drifts

The constant voltage hot-wire anemometer is particularly suited for the measurement of turbulence in flows with temperature drifts or non-isothermal flows. Because of its unique capability to measure in situ resistance of the hot-wire both heated as well as unheated, measurements in presence of temperature drifts can be performed without the need for an auxiliary probe.

To take advantage of this capability, a new calibration scheme has been developed for the CVA. Instead of directly relating the output voltage with the fluid velocity, the new measurement is the ratio of the power dissipated by the wire and the difference between heated and cold resistance that is related to velocity. This new quantity, defined by PDR, has been shown to be only dependent on the velocity, even when temperature fluctuations are present:

Equation 7

$$PDR = \frac{P_w}{R_w - R_a} = f(U)$$

In this definition of PDR, f(U) is a function of the flow velocity only, R_w is the resistance of the heated wire, R_a the resistance of the same wire unheated, and P_w is the power dissipated by the wire, $P_w = V_w^2/R_w$.

This new quantity is advantageous compared to the conventional relationship between anemometer output voltage E and velocity, as the latter is usually a relationship that depends on the temperature. Indeed, the conventional calibration formula reads:

Equation 8

$$E = f(U, T_a)$$

where E is the anemometer output voltage, U is the flow velocity, and T_a is the fluid temperature. Since E depends both on U and T_a, the calibration curve can only be used if the measurements are performed at

Figure 6: Velocity calibration at different T_a

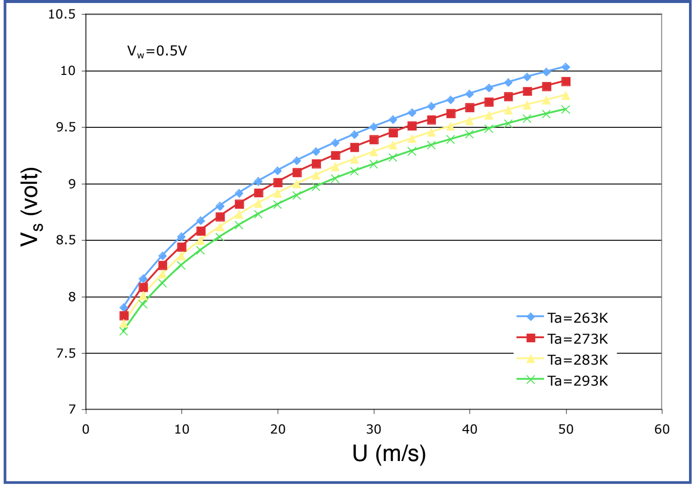
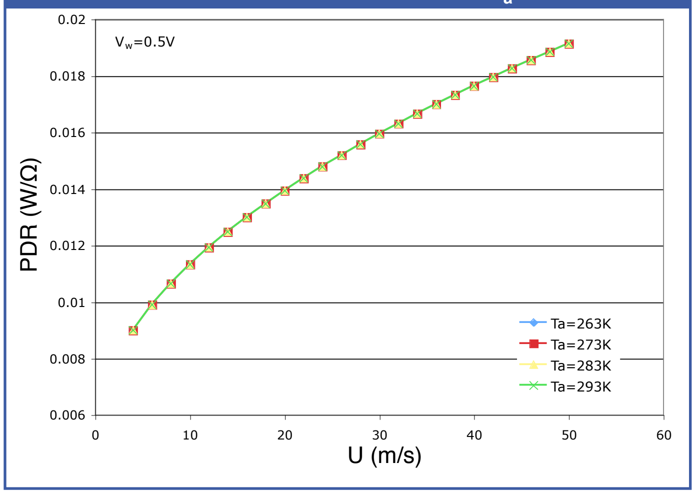


Figure 7: PDR output at different T_a



the same calibration temperature. When this is not the case, as in most realistic environments, a correction method has to be employed.

With the new PDR calibration scheme, only one calibration curve is needed, even if the calibration temperature is significantly different than the measurement temperature. Indeed, with the CVA, both R_w and R_a can be measured in situ, so that PDR is a known quantity (the wire voltage V_w is held constant by the circuit).

Figure 6 shows a typical set of calibration curves obtained for different fluid temperatures T_a with a commercial hot-wire sensor. It is clear that T_a has an influence on the CVA output voltage, exactly like on the output of other types of hot-wire anemometers. In Figure 7, the quantity PDR is calculated using the calibration data of Fig. 6. It can be seen that all the calibration data falls into one unique calibration curve. Thus, this calibration curve can be used for quantitative measurements at different fluid temperatures and the use of an auxiliary temperature probe is therefore unnecessary with the CVA.

Conclusion

This technical note describes a high-performance hot-wire anemometer with the ability to make reliable turbulence measurements with high signal-to-noise ratio at large bandwidths (> 450 kHz). The anemometer is easy to operate and setup, without the conventional cable management issues. The system has the ability to use both hardware and software compensation techniques to significantly increase productivity. Finally, it has been shown that turbulence can be measured even under changing ambient temperature without any additional temperature probe.

With its superior performance over today's conventional anemometers, Tao Systems' CVA has the potential to advance fast into existing and new fluid measurement applications.

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