High-Speed Temperature Measurement

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Abstract. In certain applications where temperature changes rapidly, e.g., compressor cylinder or explosion chamber, it is necessary to obtain temperature data with a sample rate high enough to register the change, i.e., the temperature probe response time must be very low. Type E coaxial thermocouples with response time in the range of μs can be an example of such a temperature probe. This paper describes several approaches for high-frequency temperature data obtained using coaxial thermocouples. Individual approaches are described together, as well as their shortcomings. Furthermore, the possible method of data evaluation is discussed.

1 Introduction

Fast response thermocouples are used in wind tunnels, explosion chambers, and other cases where the temperature change is sudden [1,2]. They are robust and offer better longevity in these types of environments compared to thin-film thermometers that are also sometimes used [3]. Regardless of the application, they must always be connected to hardware capable of acquiring signals at a high sample rate to be able to register the change. In day-to-day instances, the thermocouples would be connected to modules designed specifically for them, that is, with built-in cold junction compensation (CJC). However, their low sample rate (up to 100 S/s) makes them unusable in the applications described in this paper. For this reason, oscilloscopes are often used [3]. They offer a very high sample rate (in the range of GHz) and an adjustable range, meaning that with a low bit rate analog-to-digital converter (ADC) they do not produce very noisy data even when measuring low voltage coming from a thermocouple. On the other hand, they seem to be more prone to picking up noise from their surroundings. Newer versions of voltage modules seem to produce promising results; nevertheless, in research they are barely used. In this research, several NI voltage modules were considered. Module 9222 appeared to be the best option due to its high sample rate (up to 500 kS/s), but 16 bits with ±10 V range made the ADC noise higher than the signal itself. The best results were achieved with the 24-bit ±5 V module NI 9234 with IEPE (Integrated Electronics PiezoElectric Signal Conditioning) turned off paired with a signal amplifier.

2 Materials and Methods

2.1 Experimental setup

For this paper, an experimental setup (Fig. 1.) has been built. It consists of a water supply, two water boilers, a three-way valve, and a temperature measurement set-up. Two tanks, one with hot water and the other with cold water, provide 2 L/s of water. A three-way valve periodically switches between the two tanks, serving as a source of temperature that varies over time. The valve is controlled by a computer with LabVIEW software installed to make the switch every 5 seconds.

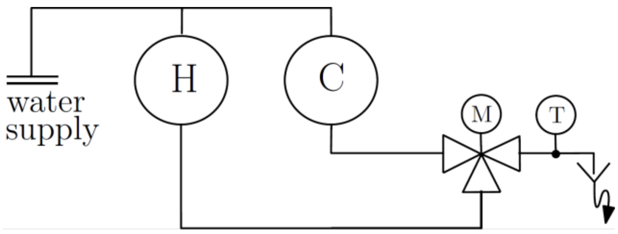

Fig. 1. Experimental setup

The temperature measurement setup consists of two Müller MT 19 type E coaxial thermocouples (Chromel - Constantan) from Dr. Müller Instruments. The probe is 26 mm long and is equipped with M2 thread on its 1.9 mm outer diameter. The thermocouple offers a response time of 3 μs and a sensitivity of 60 μV/K. Because the two metals are insulated one from another by a very thin layer of nonconductive material, the thermocouple joint is formed only at the tip of the probe by lightly sanding it with sand paper.

The first thermocouple is attached to the pipe surface and the other one is placed inside a zero point thermostat with a constant temperature of 0 ° C. The two are connected differentially. The voltage generated by the thermocouples is amplified and collected by the data acquisition system (DAS) (Fig. 2). This type of differential connection compensates for the lack of cold junction compensation, which is usually necessary when using thermocouples [1].

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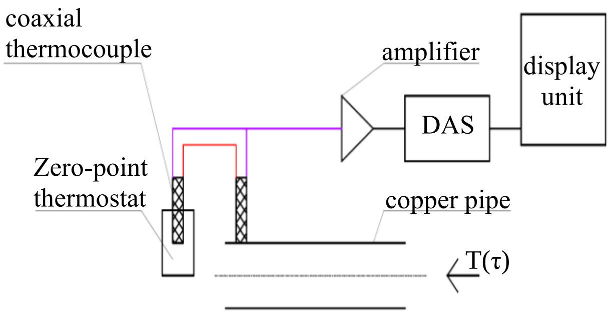

Fig. 2. Temperature measuring setup

2.2 Data acquisition

In this paper, two types of DAS were used. Both were voltage modules made by National Instruments. The ±10 V module NI 9222 with 16-bit ADC and a maximum sample rate of 500 Ks/s was compared with a NI 9234 module that offers a sampling rate of 50 kS/s, a 24-bit ADC, and a measuring range of ±5 V. Because it is made primarily for sound and vibration, it has built-in IEPE that had to be turned off. For data acquisition, a virtual instrument (VI) was made using LabVIEW 2020 software because it works well together with the NI module line. For both modules, data were collected at a sample rate of 11.8 kS/s.

Because thermocouples produce such a low voltage (hundreds of µVs), it can be helpful to amplify the signal [1,5].

The amplifier amplifies only the core signal, thus increasing the signal-to-noise ratio, making the signal more readable. Although in theory it is true, practical use shows that the amplifier itself can be a source of noise that can sometimes be even higher than the noise from the ADC (Fig. 6.) [1], making the amplifier redundant or even harmful. This noise can be present, especially when powering the amplifier with an alternating current (AC) system. Powering it with a direct current (DC) system in the form of a battery pack or a laboratory power supply can solve the problem.

It is also necessary to properly shield the amplifier to ensure it does not pick up any noise from its surroundings.

In this work, the Müller Voltage Amplifier MVA 10 was used. Its advantage is the ability to switch between ×200 and ×2000 gain, however, in this study, only the ×200 option was used. The VI was altered when reading the amplified data so that it divides them by gain before writing them into a file.

2.3. Data Processing

2.3.1 Smoothing

As a tool to make noisy data more readable, simple exponential smoothing was used. It was chosen over a simple moving average that weights the past data equally, whereas exponential smoothing exponentially decreases weight over time. A simple MATLAB script was used to get the smoothed value of the voltage U_i and was applied 5 times to achieve the maximum possible smoothing. The script takes the original voltage reading in the current time-step $U_{0,i}$, multiplies it by a smoothing constant α and adds a voltage reading from the previous time-step U_{i-1} multiplied by the difference of the smoothing constant from 1 (1). The value of a smoothing constant α was set at 0.9. Because the function only works from the second time-step, the smoothed voltage in the first time-step U_1 value was set to the original value in the first time-step $U_{0,1}$ (2).

$$U_i = \alpha \cdot U_{0,i} + (1-\alpha) \cdot U_{i-1} \quad (1)$$

$$U_1 = U_{0,1} \quad (2)$$

2.3.2 Calculating the temperature

The electromotive force (EMF) or a voltage (U) produced by the thermocouple must be converted to temperature. For this robust datasheet, it is best done by a polynomial equation (3) for which a MATLAB script was written. The coefficients (v_0; p_i; q_i) are slightly different for different temperature ranges. But because in this application the temperature never exceeds one temperature range, the coefficients are constant. The calculated temperature is the temperature difference from the cold junction of the thermocouple. Due to the zero-point thermostat, in this case, the value is the total temperature. The only variable in the equation is the voltage U.

$$T_i = \frac{(U_i - v_0)\cdot(p_1 + (U_i - v_0)\cdot(p_2 + (U_i - v_0)\cdot(p_3 + p_4\cdot(U_i - v_0))))}{1 + (U_i - v_0)\cdot(q_1 + (U_i - v_0)\cdot(q_2 + q_3\cdot(U_i - v_0)))} \quad (3)$$

3 Results

All the measurements were performed with the sample rate of 11.8 kS/s for 50 seconds. The pipe was completely cooled down by cold water at the beginning of every measurement to have comparable results and then the three-way valve started to switch the water source every 5 seconds.

The first measurement was performed with module NI 9222 without any amplification. The signal oscilated around constant value of 0.6 mV with an amplitude of 0.6 mV. The core signal from the thermocouple was so low that the module wasn't able to register it and showed only the white noise of the ADC.

As the module couldn't register the core signal, it needed to be amplified. For that reason the voltage amplifier was connected to the circuit as shown if Fig. 2 to achieve better results. It was powered by the included power supply that plugs into an electrical outlet. The gain was set to ×200 but the module could not read such a signal and has gotten out of the measurement range even though the signal was not supposed to exceed it. To ensure that the system worked properly, the amplifier was connected to a DC power supply in the form of two differentially connected laboratory power supplies. This approached solved the issue and the signal was properly registered but the noise was still prominent with the same amplitude of 0.6 mV but now there was noticeable tendency of the main signal.

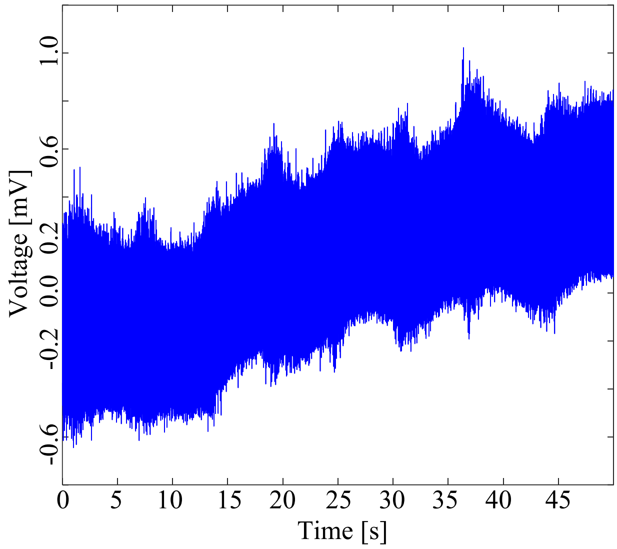

Fig. 3. Signal acquired by NI 9234 with the thermocouple directly touching the copper pipe

The next module NI 9234 was evaluated. Although the amplifier was used, the signal was still very noisy (Fig. 3). Because the registered noise was no longer white, the thermocouple might have been picking up noise coming from the 3-way valve power system by directly touching the copper pipe. To test this theory, a strip of clear adhesive tape was adhered to the surface of the pipe where the thermocouple was mounted so that it does not touch the pipe directly and does not pick up this noise.

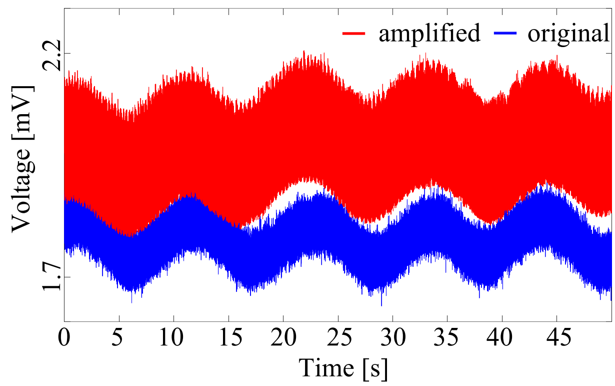

Fig. 4. Signal with amplifier noise and the original signal

The NI 9234 module was then used with and without the amplifier. The sampling rate remained the same. The amplifier was powered by the included power supply to see if there was any difference in behaviour. The amplified signal and the original signal from that module are shown in Figure 4. The noise associated with the amplified signal is higher than in the original data and does not appear to be white, meaning that the included power supply could be a source of noise.

As a confirmation that the differential connection of the second thermocouple mounted on the zero-point thermostat, acting as compensation for cold junction, is needed, a measurement with only a single thermocouple was done. The signal from the thermocouple is set a bit higher, which was to be expected, and the local peaks are more pronounced (Fig. 5.).

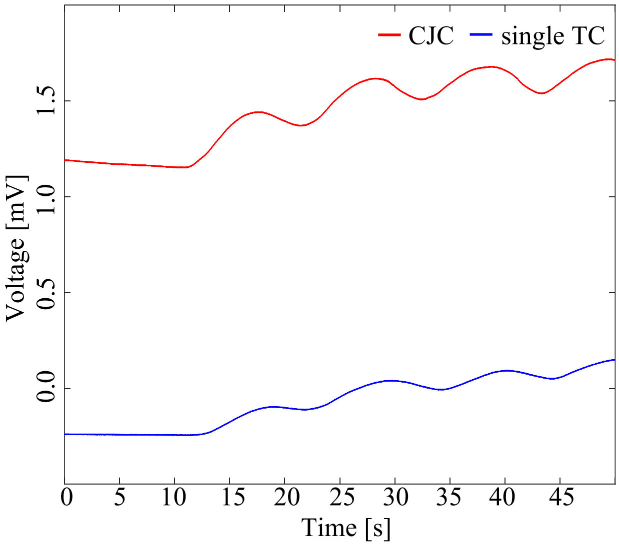

Fig. 5. Comparison of the signal from one thermocouple (blue) and two differentially connected thermostats where one is on the zero-point thermostat (red).

Finally, the signal acquired by module 9234 without an amplifier was processed by the exponential smoothing described above. It was compared to the signal acquired by the same module with an amplifier that was not smoothed. The surface temperature was then calculated from both sets of data using the polynomial equation (3). The smoothed signal is set slightly below the amplified signal and has a more noticeable noise (Fig. 6). The amplified signal appears to be cleaner, which is caused by the resolution. The local peaks are so close together that they form a line.

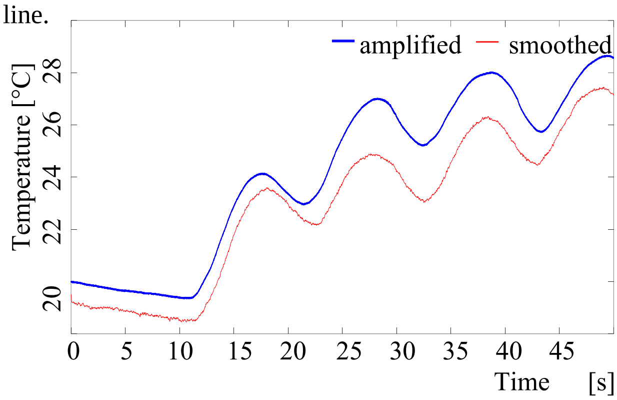

Fig. 6. Temperature deducted from amplified and smoothed data

4 Discussion and Conclusions

Coaxial thermocouples are widely used in situations where the temperature suddenly changes because they offer a response time close to 1 μs [1,2,3]. Appropriate hardware is needed to acquire the data fast enough to register a sudden temperature change.

In this study, the National Instruments modules NI 9222 and 9234 were used with and without signal amplification as data acquisition systems for type E coaxial thermocouples. The thermocouple measured the change in surface temperature of a copper pipe through which variable temperature water flowed.

The main challenge when measuring temperature at a high sample rate turned out to be noise. The measurement of high sample rate temperature in different applications is the subject of several studies, but few mention this issue or how they overcome it [3]. There is a different type of noise to consider when working with this setup. One is the so-called white noise that has a constant power spectral density. This noise in this application comes from the resolution of the data acquisition system. This is affected by the measurement range of the DAS and the bit rate of the analog-to-digital converter. As can be seen in Figure 3., although it has a high sampling rate, it is not very fitting for this kind of measurement because the voltage from the thermocouple is very low, the module has a large measuring range coupled with 16 bit ADC. For that reason, even an amplified signal is not strong enough to be readable by the module.

Another source of noise can be any type of AC electricity supply system. In this case, when the amplifier was powered by the included AC/DC adapter, it introduced a lot of noise, as can be seen in Figure 6. Although that could be filtered out by a low-pass or a band-pass filter, the sensitivity of the module could be negatively affected.

The last source of noise observed in this paper came from the 3-way mixing valve. Although it is powered by a 24 V DC system, it is connected to the grid, introducing another AC noise that the thermocouple was able to pick through the copper pipe. This issue was solved by adhering a strip of clear adhesive tape to the surface of the pipe.

To reduce the noise, the exponential smoothing method was proposed. Although it can smooth the data, it is quite demanding for computational power and the results do not appear to be very accurate, as can be seen in Figure 8. The best results were achieved with the amplifier powered by a laboratory DC power supply because it did not introduce any noise into the system. Another possible solution is to power it with the battery pack.

Lastly, the need for cold junction compensation was tested. For instance, where only the temperature difference is important, it might seem like there is no need to have cold junction compensation. As in Figure 7, the signal is offset, which makes sense, but the signal peaks are much less pronounced. This corresponds to previous research work [6]. The signal from thermocouple differentially connected with one in the zero-point thermostat is stronger and therefore easily readable by the DAS.

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Nomenclature

U	[mV]	Thermoelectric voltage
α	[-]	Smoothing constant
T	[°C]	Temperature
$v_0; p_i; q_i$	[-]	Polynomial constant

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