Development of a high frequency response temperature sensor for turbulent flow based on a cold wire

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La mesure de température est essentielle dans toute expérience en dynamique des fluides comportant des transferts thermiques. Dans un écoulement thermiquement turbulent, la fréquence des fluctuations atteint facilement un ordre de grandeur de 1 kHz*, nécéssitant une sonde capable de les capturer. Cet article va procéder au développement d'une sonde de température appelée "fil froid" capable de mesurer ces fluctuations. Ceci permettra une meilleure compréhension des comportements d'un écoulement thermiquement turbulent.*

Mots-clefs : Sonde de température, turbulence thermique, fil froid, fluctuation de température.

Measuring temperature is essential in any fluid dynamics experiments involving heat transfer. In a thermally turbulent flow, the frequency of the fluctuations easily reach the order of 1 kHz*, requiring a sensor capable of capturing it. This article will proceed in the development of a temperature sensor called "cold wire" capable of measuring these fluctuations. This will enable a better understanding of the thermal behaviour of a thermally turbulent flow.*

Keywords : Temperature sensor, thermal turbulence, cold wire, temperature fluctuation.

1. Introduction

These days, an increasing number of projects involving fluid dynamics rely mostly on numerical simulations rather than experiments, as it is much more flexible and easy to implement for specific cases. The most widely used method is a simulation based on RANS equations [1], due to its low cost, where only the average flow field is computed, while all fluctuations are modeled by using turbulence models. These turbulence models rely themselves on experimental datafor validation, it is therefore essential to be able to measure thermal quantities with great accuracy.
To be able to validate these models thermally, the type of experiment will determine the type of sensor required, with few characteristics such as range, reliability, response speed, etc. In experiments with thermally turbulent flow, the temperature fluctuations can easily reach frequencies up to 1 kHz. Currently, the fastest thermocouple available is limited to a frequency response of 75 Hz, due to its thermal inertia, hence the need for a sensor capable of capturing frequency content up to one order of magnitude higher.

Figure 1 : Illustration of the cold wire temperature sensor

This document will proceed with the development of a temperature sensor with these capabilities. Since it is based on a non-heated resistive wire, it shall be named ”cold wire”. As the illustration on figure 1 suggests, the exposed wire will be facing the flow to measure its temperature, and the electronic board will acquire the measured signal.

1. RANS : Reynolds averaged Navier Stokes equations

2. Theoretical background in steady state

A body placed in an environment will interact with its environment until it reaches a thermal equilibrium.

Hence if one places a wire in a fluid flow, both will reach a thermal equilibrium that can be deduced from the known properties of the wire. If the thermal inertia of the wire is negligible compared to the one of the fluid, and provided that no extra energy is added to the system, one can then assume that the wire is affected thermally by the fluid, but the fluid is not.
As a temperature sensor, the so called ”cold wire” is held in the environment that needs to be thermally characterized. To do so, one may take advantage of the fact that the wire's electrical resistance will depend on its temperature as expressed in equation (1).

$$R_w = R_{ref}\left(1+\beta\left(T_w - T_{ref}\right)\right), \tag{1}$$

where β is the temperature coefficient of resistance of the wire, and R_{ref} the electrical resistance of the wire at the temperature T_{ref}, all these quantities being constants. The relationship relating the temperature of the wire and its electrical resistance is therefore linear.
By measuring the resistance of the wire through an electrical circuit, the temperature can be deduced experimentally. The most accurate method consists in using a Wheatstone bridge powered with a constant current source as illustrated in figure 2. The hypothesis here is that the heat produced by Joule effect can be neglected. This power can be evaluated with equation (2). To be able to neglect this effect, the current needs to be minimised.

$$P_{joule} = R \cdot I^2 \tag{2}$$

Minimising the current will reduce the Joule effect but will also increase noise in the output signal. A trade off needs to be found between reducing Joule effect and reducing noise. The optimum current value will be found experimentally in section 4. The complete circuit is composed of an adjustable constant current source, a Wheatstone bridge, an instrumental amplifier used to measure the difference between the two branches and to amplify the signal, then a low-pass filter mandatory before converting the signal digitally using an ADC [2] as illustrated in figure 2.

2. ADC : Analog to digital converter

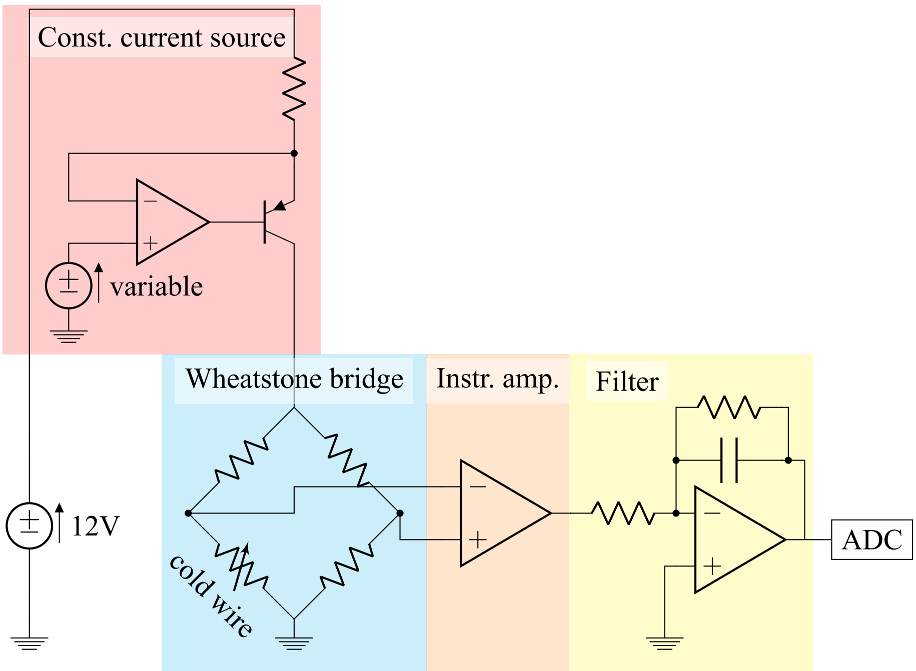

Figure 2 : Simplified electrical circuit

The output voltage recorded by the ADC is directly proportional to the change in electrical resistance from the equilibrium of the Wheatstone bridge. In the complete schematic, the gain is adjustable as well as the resistance opposite to the cold wire to set the equilibrium at room temperature.
The resulting relationship between the output voltage and the temperature is therefore linear.

3. Theoretical background in unsteady state

The interest now is to identify the response of the wire in its transient-state. The acting phenomena are : the convection between the fluid and the surface of the wire, and the conduction from the surface to the center of the wire. Any radiative phenomenon can be neglected. Conduction from the prongs to the wire will also be neglected for the analytical calculation and will be discussed afterwards.
The goal here is to evaluate the overall temperature of the wire rather than the temperature distribution within the material, which will be recorded via its total resistance. This allows the problem to be simplified using the lumped capacitance approximation by theoretically placing a control volume around the object as illustrated in figure 3. An energy balance will include all of the relevant energy transfers and the internal energy U [**Heat_transfer**].

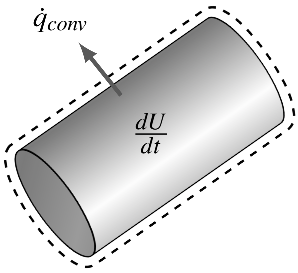

Figure 3 : Lumped Capacitance approximation

The energy balance within the control volume is defined as :

$$0 = \dot{q}_{conv} + dU/dt, \tag{3}$$

where $\dot{q}_{conv}$ is the rate of convective heat transfer between the surface and the total energy stored in the material U.
By substituting equations (4) and (5) into equation (3), the result is a first order system with its time constant τ_{lumped} expressed in equation (6).

$$\dot{q}_{conv} = \overline{h} \cdot A_s \left(T_w - T_{flow}\right), \tag{4}$$

$$\frac{dU}{dt} = M \cdot c_{p_w} \cdot \frac{dT_w}{dt}, \tag{5}$$

where $\overline{h}$ is the average heat transfer coefficient ($\overline{h} = f_{(Re,Pr)}$), A_s the surface area, M the mass of the wire, and c_{p_w} the specific heat capacity of the wire.

This time constant τ_{lumped} conveys both the dynamics of conduction and convection.

$$\tau_{lumped} = \underbrace{\left(\frac{1}{\overline{h} \cdot A_s}\right)}_{\text{Convection}} \cdot \underbrace{(M \cdot c_{p_w})}_{\text{Conduction}} \tag{6}$$

The aim is to get a temperature sensor with the highest frequency response, therefore the lowest time constant τ_{lumped}. The material used is a Platinum-coated Tungsten wire, setting c_{p_w}. The mass can be minimised by reducing the total volume. To ensure that the wire would not break when subjected to a flow, a reduced length of 0.5 mm is associated to the small 2.5μm wire diameter.
The last parameter to analyse is the heat transfer coefficient $\overline{h} = f_{(Re,Pr)}$, which will be affected by the flow velocity (as expressed by the Churchill and Bernstein equation). This response in the frequency domain can be represented using a bode diagram in figure 4.

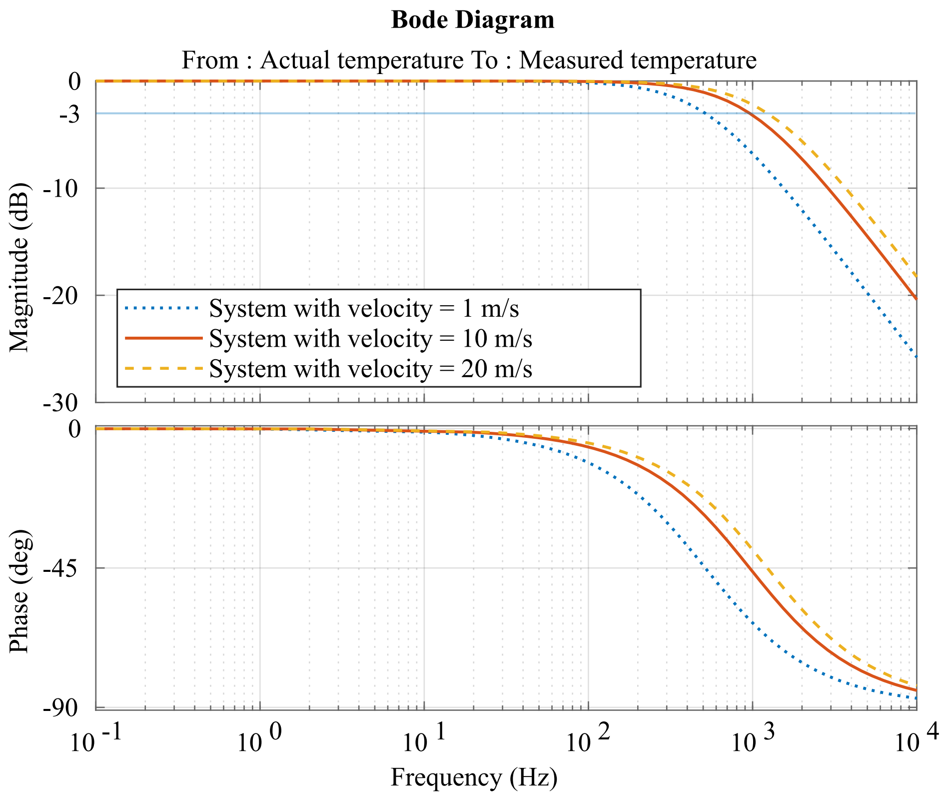

Figure 4 : Theoretical Bode diagram of the system

Representing the dynamic behaviour in the frequency domain brings much more information than a time-based analysis. Here one can observe that the mean value, hence the steady state value will not be affected by the flow velocity as the magnitude at low frequency is 0 dB (representing a unity gain). Beyond a certain frequency, time-dependant measurement looses part of its frequency content and is therefore erroneous. Consequently any sensor should not be used at frenquencies above its cut-off frequency which is defined as the frequency where the system has an gain of -3 dB. This threshold is marked on figure 4.

4. Static experimental characterisation

The wire is manufactured as specified in section 2. with the following dimensions :

— Diameter : 2.5μm.

— Length : 0.5 mm.

— Material : Platinum coated tungsten.

A detailed view of the probe can be found in figure 5.

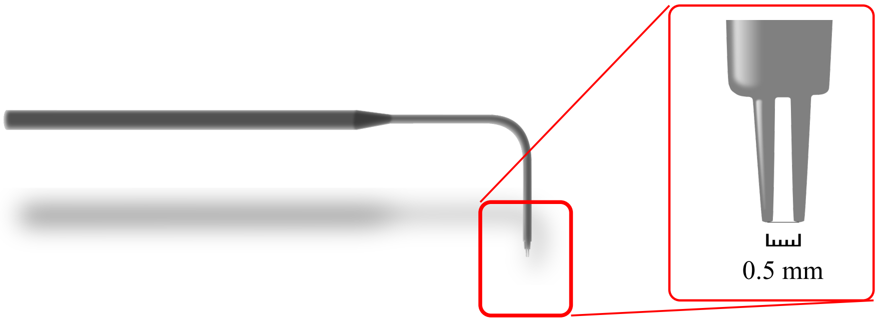

Figure 5 : Probe detailed view

Using the electrical circuit described in section 2., a static calibration will be performed and the optimum current balancing noise and joule effect needs to be found experimentally.
To do so, a calibration is done by measuring the output voltage and the flow temperature using a reference thermometer. This shall be done at multiple velocities to create a cloud of points. This process will be repeated with different values of current, and the parameter R^2 [3] in the linear regression will determine the optimum current. With the current decreasing, noise in the signal increases, thus increasing R^2. With the current increasing, joule effect is spreading the results away from the linear regression, increasing R^2. The optimum current can be found by minimising R^2.
This experimental characterisation suggests that the optimum current for velocities ranging from 1 m/s to 25 m/s is 1 mA, as shown in figure 6. As seen here, the relationship is confirmed to be linear, and joule effect can be neglected with this defined current (within the velocity range). while testing, the slope and offset can be adjusted on the electronic board. As suggested by the theory, this relationship can be considered as linear ($R^2 = 0.9998051$).
While a static calibration is required for each new measurement, it has been noticed that it remains valid for two days, thus suggesting that ageing of the wire remains nigligible in this time frame.

3. R^2 is a statistical measure that represents the proportion of the variance for a dependent variable that's explained by an independent variable or variables in a regression model[**R_squared**]

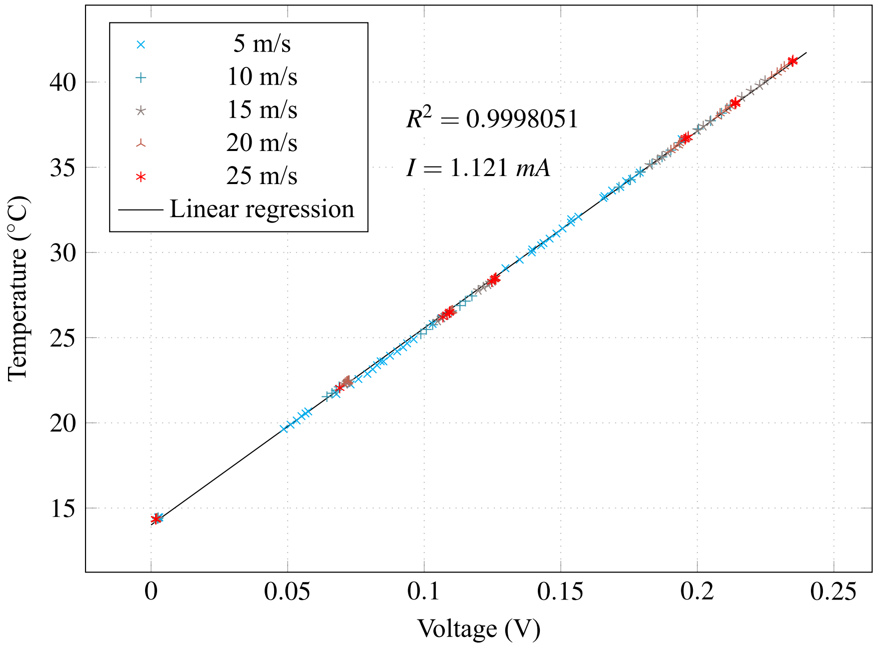

Figure 6 : Static calibration with the optimum current

The total measurement error is the combination of the systematic and random error. The systematic error using this method is the combination of the uncertainty of the reference temperature (here : $\Delta T_{ref} = 0.001°C$) and the uncertainty of the voltage brought back to a temperature measurement using the slope of the linear regression. The random error is computed using the standard deviation of the fitted curve and the desired accuracy.

In a measurement, the systematic error from the uncertainty of the voltage is cancelled through the calibration as long as the same measuring device is used during the calibration and the measurements. Therefore, the total error on the measurement is only dependant on the uncertainty of the reference temperature, and the random error affected by the quality of the measuring tools and the number of calibration and measuring points.

The systematic errors of the measurements cannot be further reduced at this point, but the random error can be reduced by two means :

— Increasing the number of calibration points, therefore reducing the standard deviation of the fitted curve, affecting the total error.

— Increasing the number of measured points, affecting directly the total error.

This method is the most precise, but requires a new calibration each time it is disconnected from the electronics powering it.

5. Dynamic experimental characterisation

To characterise a system in its transient state, one of the most common solutions is to impose a step change [4] at the input, and analyse the response at the output. An ideal step in the time domain results in the superposition of a variety of frequencies, which is used to determine a model representing the system.
Since it is not currently possible with the available means to create a temperature step in the airflow, another technique will be explored using a laser heating the wire.
The cold wire being placed in a flow of constant temperature, it will be heated with a laser to simulate a change in temperature flow. Since the speed of light is far greater than the response time measured here, it can be considered instantaneous. This set-up is illustrated in figure 7. The laser can be blocked periodically with a rotating perforated disk creating a square wave input signal.

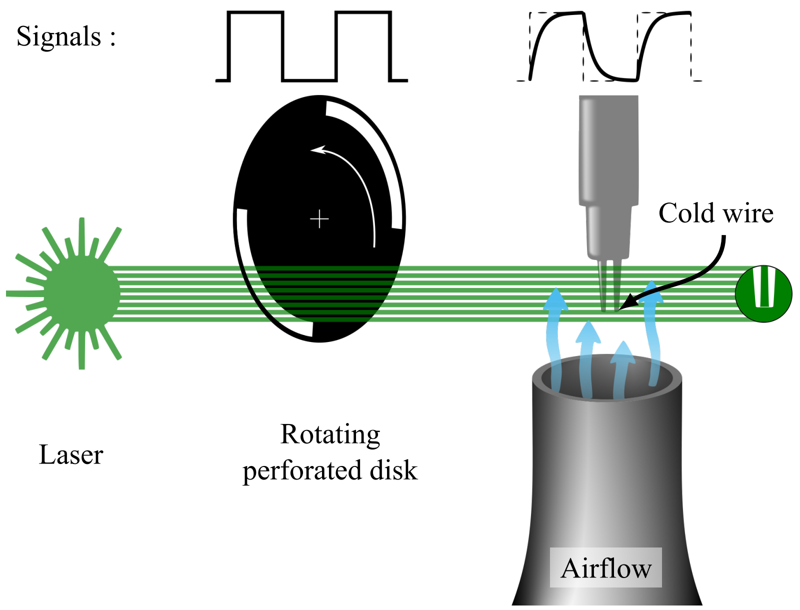

Figure 7 : Wire heated by a laser beam

By recording the input and output signals (converted to temperature using the static calibration), an experimental dynamic response can be evaluated through its transfer function. This dynamic characterisation shall be done with several flow velocities to compare its effect.
The model fitting the experimental results in the frequency domain is shown in figure 8 for different flow velocities.

4. Step change : instantaneous change in the quantity of interest

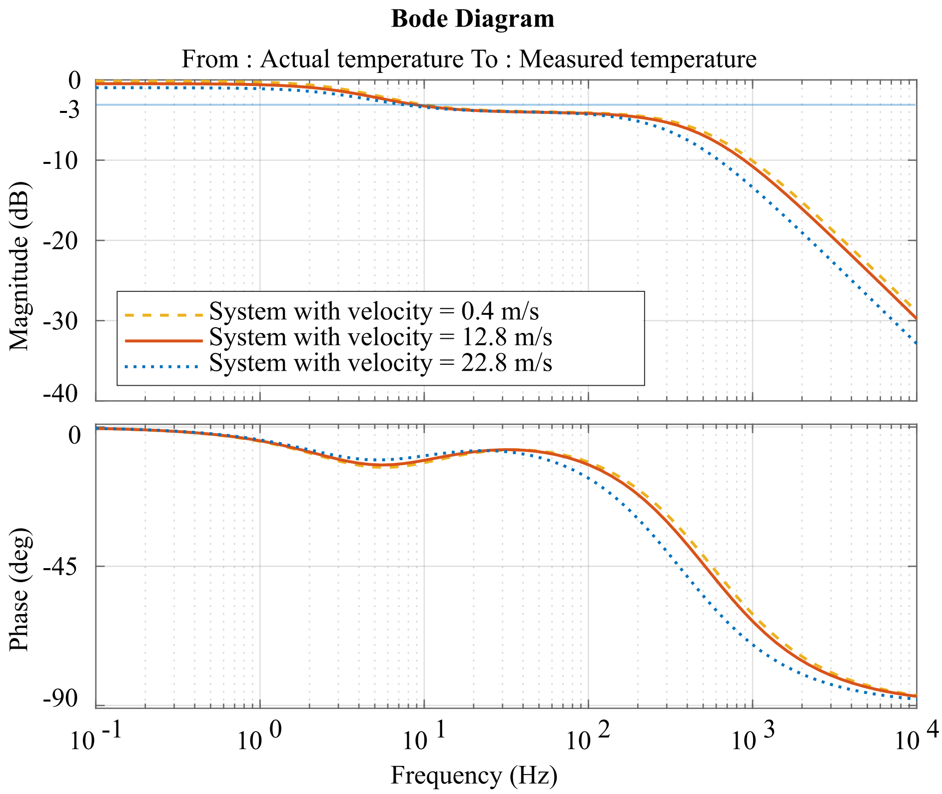

Figure 8 : Bode diagram evaluated with the laser set-up

This model is a transfer function including two poles and one zero provided by the equation (7). Each time constant τ_n is representative of a specific phenomenon.

$$H_s = \frac{1}{\tau_1 \cdot s + 1} \cdot \frac{\tau_3 \cdot s + 1}{\tau_2 \cdot s + 1}, \tag{7}$$

τ_1 is the time constant due to the convection on the surface of the wire and the conduction within the wire, as expressed theoretically in section 3..
τ_2 is the time constant due to the convection on the surface of the prongs and the conduction within the prongs.
τ_3 is not a physical time constant, but the result of the conduction between the prongs and the wire, both acting on the system.
In this Bode diagram, the first "drop" in magnitude (occurring at about 5 Hz) is related to the time constant τ_2 from equation (7), which is the convection and conduction of the prongs. It is then followed by a horizontal part caused by the "zero" in the system related to τ_3, caused by the conduction between the prongs and the wire, considered

instantaneous (compared to the other time constants). The last part (acting at around 500 Hz) is related to the time constant τ_1, which is the convection and conduction of the wire.

Comparison

In the theoretical framework, the main hypothesis in transient state was to neglect the effect of the prongs.

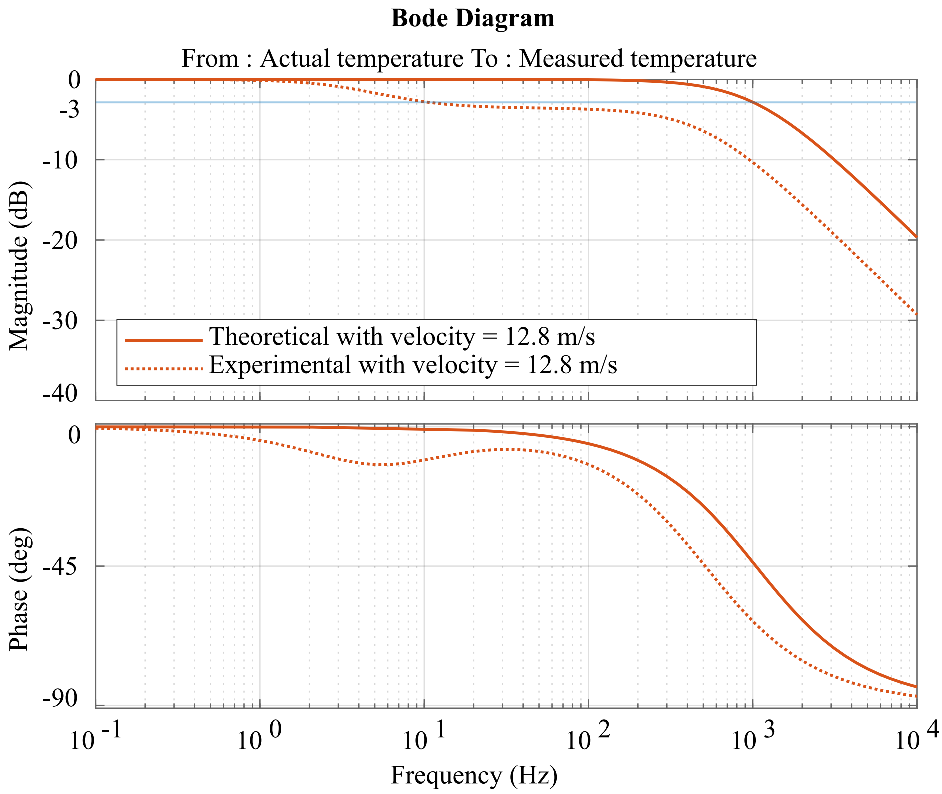

Figure 9 : Comparison

When comparing at a given velocity, the transient response of the cold wire with the theory to the experimental results as shown in figure 9 it is clear that the prongs have a significant effect on the response, especially at low frequencies (1 to 100 Hz). The hypothesis to neglect this effect is to be refuted.

The effect of convection and conduction of the cold wire expressed theoretically in section 3. can be compared to the experiment. This phenomenon is acting at frequencies lower than the theory suggests (500 Hz instead of 900 Hz for this velocity) but remains in the same order of magnitude. The difference can be explained mainly with the uncertainty of the wire diameter, affecting the theoretical response. At this scale, a small change in diameter results in an important difference in cut-off frequency of the resulting system. The uncertainty on the diameter is not provided by the manufacturer, and no tool capable of measuring the diameter at this scale was available to check it.

6. Compensation

The experimental $-3\,\mathrm{dB}$ threshold seen in figure 8 suggests that this sensor cannot be used to capture fluctuations at frequencies above 100 Hz. Since the dynamic response is known experimentally, the attenuated frequencies can be amplified and phase-shifted by the appropriate amount in post-processing to compensate the physical sensor dynamics, therefore improving its overall capability. This compensation is a transfer function which is opposite to the experimental, as seen in figure 10.

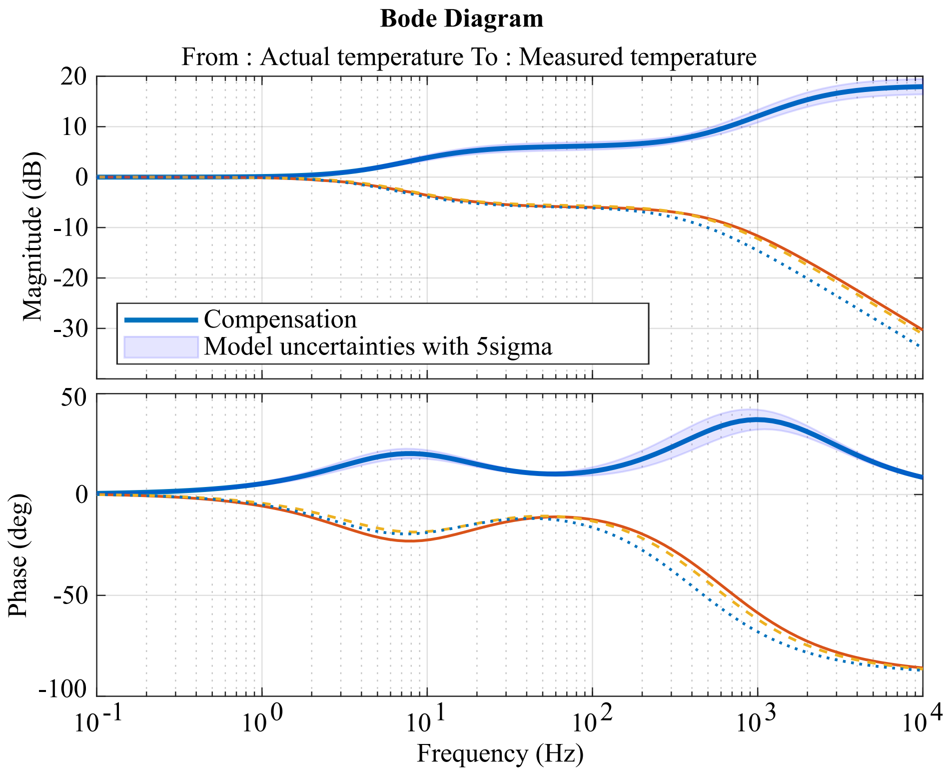

Figure 10 : Compensation

Using this technique to improve the capability of the sensor comes with limitations too : amplifying some on the recorded frequencies, also amplifies the noise. A reasonable amplification is to stay below 10 dB (which amplifies the signal and noise by a factor of 3).

$$H_s = \underbrace{\frac{\tau_1 \cdot s + 1}{1} \cdot \frac{\tau_2 \cdot s + 1}{\tau_3 \cdot s + 1}}_{\text{Inverse dynamic}} \cdot \underbrace{\frac{1}{\tau_4 \cdot s + 1}}_{\text{Pole added}}, \tag{8}$$

A transfer function cannot contain more zeros than poles, therefore one needs to be added to the equation with a time constant τ_4 at a frequency above all the others as expressed in equation (8). In this case it affects the shape of the compensation above 1 kHz. The result combining the physical response of the probe and the compensation is a first order system with its cut-off frequency provided by τ_4. The cold wire temperature sensor can thus be used up to 1 kHz with this compensation. In applications with velocities above those explored here (1 to 25 m/s), the capability can be extended above this threshold.

7. Validation with a turbulent flow

To validate the behaviour of the sensor, the best example is to expose it to a thermally turbulent flow. Opposing a laminar flow which does not contain much high frequency content, a turbulent flow provides a wide range of frequencies to capture.
A fully turbulent flow has a distinctive characteristic when observing its power spectrum in the frequency domain. All frequencies (except the null frequency which is the mean temperature) stay at a fixed level until a certain frequency from which one can observe the energy cascade at a fixed slope. [**NEEDS SOURCE FOR THE ENERGY CASCADE**] Analysing this slope as well as the frequency at which the energy cascade starts tells a lot of information about the fluid flow.

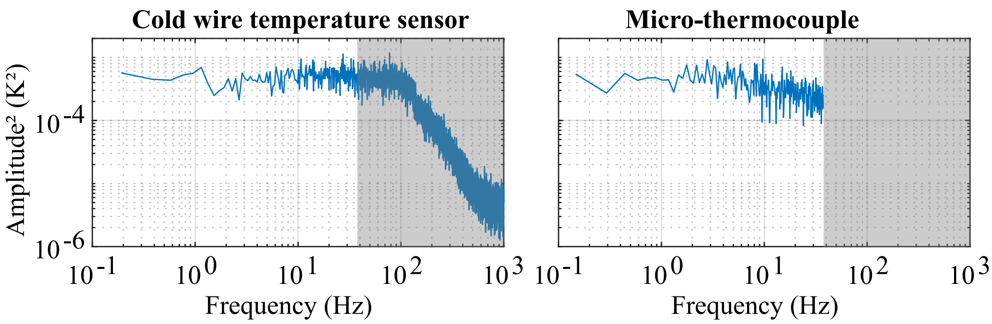

Figure 11 : Power spectrum of a turbulent flow

The figure 11 shows this energy cascade captured by the cold wire, it is computed using a windowed FFT [5] with 11 windows of 524 288 (2^{19}) points.
This validates experimentally that the signal recorded (and compensated) represents a physical thermal behaviour of the fluid, rather than some sort of noise.
It is then compared to a micro-thermocouple (12μm) which is the fastest thermocouple currently available, capable of capturing fluctuations up to 75 Hz. All of the energy cascade of the turbulent flow is missing here, whereas the cold wire is able to capture it. The advantage here is obvious, and can be used to improve the understanding of thermally turbulent flow.
As another illustration of this comparison, the signal recorded by the cold wire and micro-thermocouple can be compared in a time-based manner as shown in figure 12.

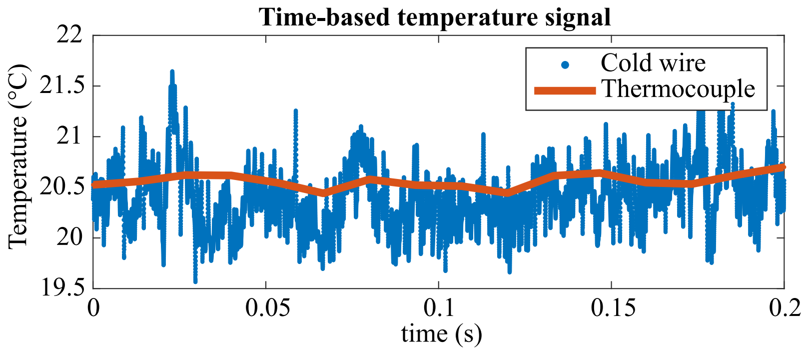

Figure 12 : Time-based signal analysis

5. FFT : Fast Fourier transform

8. Conclusion

The hereby presented sensor is a temperature sensor with great characteristics for validating RANS simulation models.
To conclude the development of the sensor, both static and dynamic response have been explored. For the static characterisation the experiment fit the theory at 99.98% (using the parameter r^2), which is satisfactory and confirms the proposed hypothesis. For the dynamic response, the hypothesis of neglecting the conduction of the prongs cannot be used as observed experimentally, but all the other hypothesis are valid. The explored time parameter did not match perfectly the theory, but remains in the same order of magnitude, the uncertainty on the diameter of the wire can explain this phenomenon. Finally the compensation is based on experimental results, making it as accurate as the measurements for the sensor used.
Due to the material used (platinum coated tungsten), it can be theoretically used up to 1700 °C (if the other components of the mechanical structure can withstand this temperature), even though the conducted tests were done up to 140 °C. With the adjustable range and offset of the electronic board, the sensibility can be adjusted to fit the use case.
The great advantage of this technique over some others such as a micro-thermocouple, is its faster response. The cold wire temperature sensor is capable of capturing fluctuations up to 100 Hz without compensation, and 1 kHz with compensation in post-processing.
The disadvantage of this sensor is its fragility due to the low diameter of the wire. This is absolutely required to provide a low inertia, hence a high frequency response. It is therefore suited for clean gaseous flow.