FABRICATION OF HOT-WIRE PROBES AND ELECTRONICS FOR CONSTANT TEMPERATURE ANEMOMETERS

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***Abstract*— The purpose of this paper is to discuss the construction of constant temperature hot wire anemometers. Different options are analyzed for the fabrication of sensors and electronics. A practical and simple method is developed to manufacture the probe and associated electronics. The fabricated sensor has a diameter of 2 µm and approximately 500 µm in length. The associated electronics are designed to keep the sensor working at a constant temperature and allow the indirect measurement of speed. The design is simple, inexpensive and highly flexible regarding its use and modifications. The dynamic tests performed and the comparison with a commercial model shows a satisfactory performance. The unit built also includes an option for testing with a square wave, which is generated internally, and a comparator mode to measure the resistance of the sensor.**

***Keywords*— Anemometer circuit, hot-film sensor, sensor fabrication.**

I. INTRODUCTION

Despite the development of optical techniques, for fluid flow measurements, such as Laser Doppler Anemometry and Particle Image Velocimetry, constant temperature hot-wire anemometry remains a basic tool for measuring velocity fluctuations in turbulent flows. The principle of this technique is the variation of heat transfer from a thin metal wire to a flow of liquid or gas with flow velocity. The most widely used strategy is to adopt a wire whose resistance varies with temperature. This resistance is kept constant by means of a feedback system and the power required to achieve this is measured. A general review of the subject was published by Fingerson (1994), Goldstein (1996) and Tavoularis (2005).

Hot-wire anemometers consist of two systems: the hot-wire probe and the feedback and measurement electronics. The wire is very fragile and is often broken. For practical use of this technique, the ability to build or at least repair the probes is a need.

The present work describes a low cost and simple construction technique for both the sensor and associated electronics using equipment generally available in laboratories. The probe was assembled using a Wollaston-type wire, which is a very fine platinum wire in a silver jacket, following the method of Westphal *et al.* (1988) and Ligrani *et al.* (1989). This makes the wire easier to manipulate and solder but requires the posterior removal of the silver by chemical etching.

Electronics were built following the design of Itsweire and Helland (1983) but including modifications to avoid the use of components not readily available, like variable inductors and delay lines.

Frequency response was measured as suggested by Freymuth (1977) and Fingerson (1994). Measurements of a turbulent flow field were performed simultaneously with the present electronics and a commercial unit (TSI1051). The two measurements were equivalent for frequencies up to approximately 50 kHz.

II. PROBE CONSTRUCTION

Hot-wire probes are built with a thin wire of 0.5 to 20 µm diameter supported by two relatively sharp prongs. There are several ways to adhere the wires to these prongs. The principal techniques make use of conductive glue, spot welding, or soft soldering. Spot welding is the fastest method for relatively thick platinum alloy or pure tungsten wires. A primitive way to do this is by discharging a capacitor via a copper tip pressed on the wire to be welded to the prong. A more sophisticated device for spot welding is presented by Walker and Moss (1998). It should be noted that spot welding is easier to perform on stainless steel prongs. When using a Wollaston wire the other two methods are typically applied. The use of glue avoids the residual stresses that arise in the welding or soldering processes and thus allows the construction of sensors with thinner wires, but the process is slow and cumbersome.

In the present case the sensors were built using Wollaston wire attached to the tips using soft solder. The wire that was used has a platinum core with a purity of 99.9% and 2 µm in diameter, according to data provided by the manufacturer -Goodfellow Cambridge Limited, Huntingdon, England. An alternative provider is Sigmund Cohn Corp., Mount Vernon, NY, USA. The wire has a silver jacket, with an overall diameter of 37 µm. The reason that motivated such choice was the availability of the wire in a small diameter, although the use of platinum wire diameters of 5 µm or larger is perhaps better suited for most applications. The first step in the procedure was to solder the wire on two sharp prongs of copper wire. Then a portion of the silver coating is removed, leaving a small section of platinum wire (approximately 500 µm long) exposed.

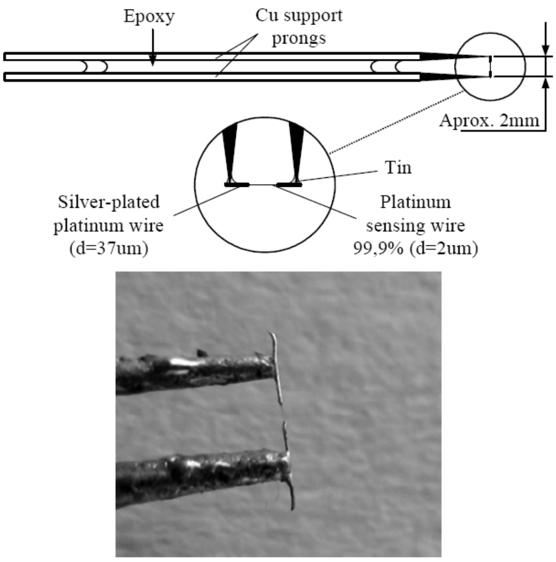

Fig. 1. Basic elements that make up the hot-wire sensor type.

The two prongs of copper on which the sensor is held are separated 2 mm (see Fig. 1). These prongs are attached together with epoxy adhesive to provide sufficient stiffness to avoid mechanical vibrations and wire breakage.

To manufacture the probes, the following tools were used: (a) stereoscopic microscope with zoom capability adjustable between at least 7.5 x and 50 x, (b) positioner that allows translation along the three axes and rotation about one axis (c) lamp to provide adequate light for the microscope, (d) small fan to remove fumes from soldering that would damage the microscope, (e) source of 5V DC used for the chemical attack to the wire, and (f) receptacles for the acid solution and washing water connected to pipettes yielding controlled jets. All these instruments were mounted firmly on a table to avoid vibrations during the manufacturing process.

A. Mounting the Probe

As a first step in the assembly of the probe, the prongs that hold the wire are built. The copper wires used for the prongs are 1.7 mm in diameter and 100 mm long. Usually the wires need to be straightened. This can be done by simultaneous stretching and twisting the wires, with the added benefit of increasing their hardness. The ends are then sharpened and attached parallel to each other with epoxy glue. Once the adhesive obtains its final hardness, the tips are ground to generate a small flat surface. This procedure facilitates soldering and improves the positioning of the wire perpendicular to the tips. It is advisable to cure the epoxy adhesive in an oven. While the curing temperature and time depend on the resin used, keeping the prongs at least one hour at 120 ºC should improve the resin mechanical properties.

To solder the Wollaston wire, the ends of the prongs are tinned and varnished with soldering paste or liquid flux. In this case, a standard lead-tin alloy for electronics soldering was used. A fixed length of Wollaston wire is held under the binocular microscope and the prongs are positioned such that they make contact with the wire. It is enough to make contact between the wire and the prong ends and heat the prongs with a soldering iron to re-melt the tin until it wets the wire. A computer fan is used to suck the smoke produced and thus protect the optics of the microscope.

In order to eliminate any trace of mechanical stresses that arise from the thermal expansion of the prongs, once the ends of the wire are cut with a sharp knife, the soldering iron is applied on both ends at once until the solder re-melts.

Finally the tips are cleaned with a solvent, i.e. Acetone, to completely remove the remains of the soldering process.

B. Etching the wire

The etching procedure was described by Ligrani (1984), Ligrani and Bradshaw (1987) and Ligrani *et al.* (1989). Figure 2 shows the system used in this process which consists of a glass reservoir containing a 5 % dilution of nitric acid in water connected through a valve and a hose to a glass pipette of 0.3 mm inner diameter. To speed up the etching process an electrical current is set between the wire in the probe and the reservoir through a platinum wire immersed in the nitric acid solution. Such wire is connected to the negative terminal of the voltage source through a resistance of 100 kΩ. The positive terminal is connected to the probe, closing the circuit through the acid solution. The working current should be set to 25 μA in the beginning and it drops to 15 μA at the end of the process. This working current may be obtained from a controlled power supply or a fixed power supply in series with a suitable potentiometer. It takes approximately 10 minutes to remove the silver jacket. The positioner is used to hold the probe under the jet of acid solution.

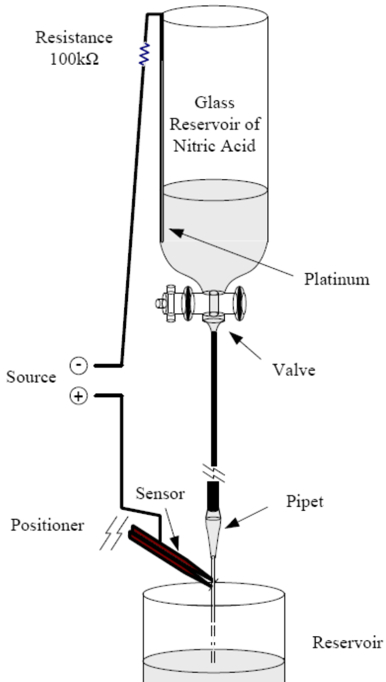

Fig. 2. Schematic of pickling without washing system.

C. Washing the sensor

The probes are washed after the etching to remove any residual acid (Ligrani, 1984; Ligrani and Bradshaw, 1987). If the sensors are not washed properly, there is a significant drift in resistance with time. Filtered and deionized water is used for this purpose. Also a water container is used and a pipette of diameter slightly larger than used for the etching process (needs not to be glass). The formation of drops has to be avoided as the surface tension of water is sufficient to break the 2 µm wire. The procedure requires at least 2 minutes but longer times are recommended to insure the complete removal of the etching acid.

Once the sensor is ready, the resistance value reached is close to the theoretical value calculated from the resistivity of the material (10.6 µΩ/cm) and the geometry. In the present case that value is approximately 16.8 .

II. ANEMOMETER ELECTRONICS

A typical schematic for a constant temperature anemometer is shown in Fig. 3. The sensor is connected as part of a bridge; there is a stage of amplification, a feedback line, and the dotted lines show two ways to compensate for the frequency response of the anemometer.

The resistance of the sensor varies with temperature. For a linear approximation, the resistance variation is described as

$$R = R_r\left[1 + \alpha\left(T_m - T_r\right)\right], \tag{1}$$

where R is the resistance of the sensor at temperature T_m, R_r is the resistance at a reference temperature T_r and α is the temperature coefficient.

The role of the bridge and the feedback system is to keep the resistance value of the sensor constant, and hence also its temperature. The tension on the bridge U (see Fig. 3) is proportional to the current that is flowing through the sensor to keep its temperature constant, and therefore increases with the heat transfer from the sensor. The latter is in turn a function of the speed of the flow passing by the sensor. The operation of the bridge may ultimately be reasoned as follows: an increase in the speed of passage of fluid by the sensor means that its value of temperature and therefore R decreases, causing an increase in the output of the amplifier, increasing the current on the bridge and leading to a recover of the sensor temperature, thus keeping constant the sensor resistance R.

Given the inertia of the sensor and the delay introduced by cables it is necessary to include compensation in the measurement bridge. The two most commonly used alternatives are shown in Fig. 3 and were analyzed by Freymuth (1977). The first corresponds to a capacitance in parallel with R_2, and the second to an inductance in series with R_3, both with similar performances.

The circuit built in the laboratory is shown in Fig. 4. It is based on a design presented by the Itsweire and Helland (1983) which uses an inductance for compensation. This kind of component is rare and difficult to obtain. In the present circuit a bank of capacitors was chosen instead. This allows only discrete variations in the compensation but sufficient to achieve the desired frequency response. It is important that the compensation capacitors and the resistances of the measurement bridge have low thermal drift.

In our circuit we use the OP37 as the feedback operational amplifier as in the original design by Itsweire and Helland (1983), but an alternative circuit using the OP27 is presented in the Purdue University website (Norris and Schneider, 1996). The OP37 provides a high open-loop gain up to high frequencies while keeping a low noise and low thermal drift.

Instead of the decade resistor used in most anemometers as variable resistance R_3, we have used a wire wound potentiometer. This is a very convenient solution but it does bring some drawbacks. The most important is that it introduces a considerable inductance in the bridge. The 100 Ω wire wound potentiometer we have used had an inductance that varied between .1 and 6 µH (varying almost linearly with the resistance value), while for a similar potentiometer of 1 kΩ it varied between .1 and 70 µH. From our experience, the addition of a capacitor of a suited value in parallel with the wire wound potentiometer is enough to achieve a stable behavior of the anemometer. In the circuit shown in Fig. 4 we have added a capacitor of 10 nF in parallel with the potentiometer and obtained a stable behavior for sensors with resistance values in the range of 3 to 35 Ω.

The selection of resistors for the bridge is done considering the relationship

$$R_3 = \left(R_2 / R_1\right).R_{sensor} = n.R_{sensor}, \tag{2}$$

where n is 1 or a multiple of 10. In this way, the reading on the indicator of the variable resistance R_3 corresponds to multiples of 10 of the sensor resistance in ohms.

When using high overheat ratios or relatively large sensors the power dissipated in the measurement bridge may become a problem, leading to thermal drift or even component failure. In this case a larger value for R_2 and R_3 is desirable. We have achieved good results with a potentiometer of 1 kΩ for R_3 and a resistor of 100 Ω for R_2. In this case, to achieve good stability the capacitor in parallel with the potentiometer was reduced to 1 nF.

The stability of the feedback system requires limiting the working bandwidth of the OP37. This is achieved with a low pass filter placed at the entrance of the OP37. The filter chosen permitted the stable operation of the anemometer while allowing a bandwidth of 64 kHz as will be discussed later.

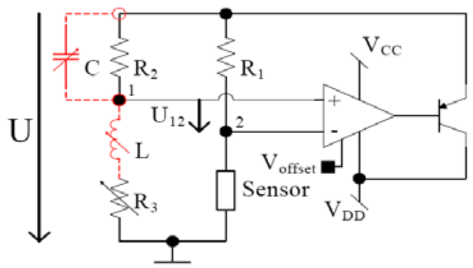

Fig. 3. Schematic of a typical constant temperature anemometer.

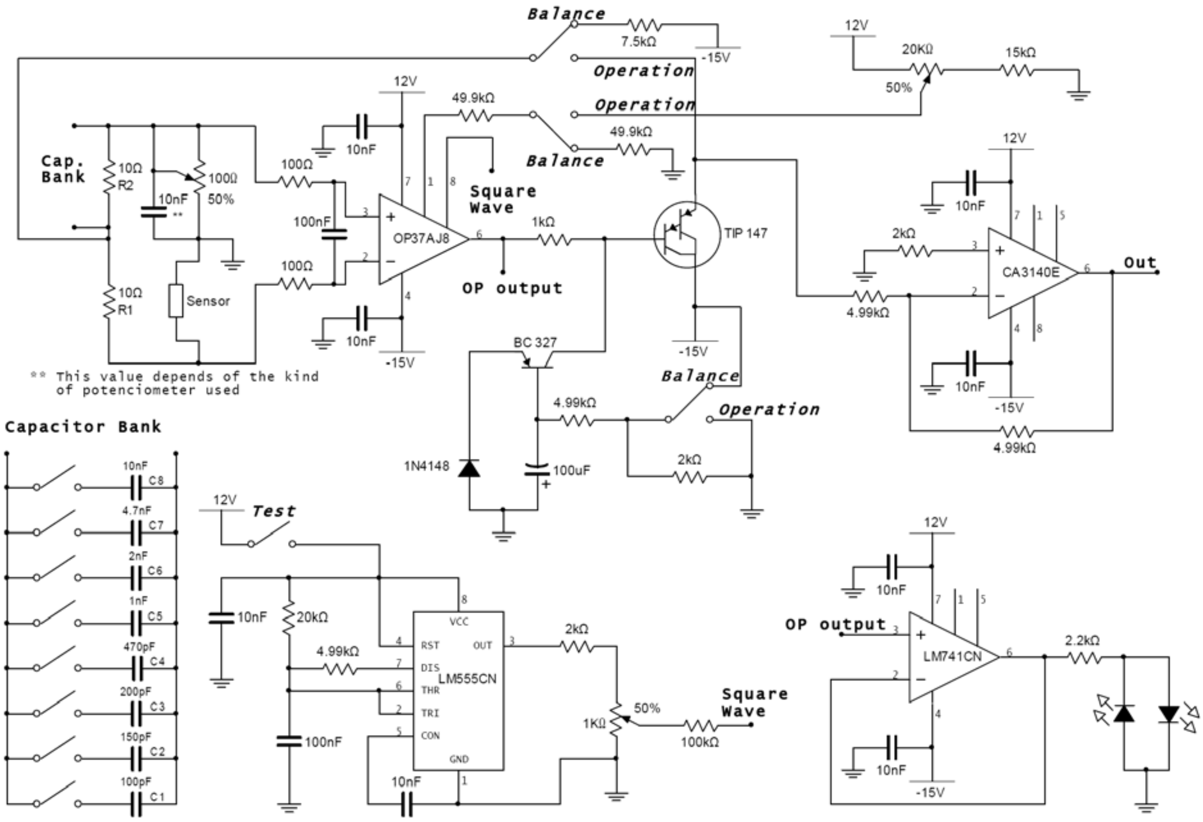

Fig. 4. Circuit of anemometer. The switches are displayed in balance mode.

An alternative circuit with lower performance but simpler is presented by Kreider (1973). An interesting alternative design is the Bruhn constant temperature anemometer circuit proposed by Norris and Schneider (1996).

A. Balance Mode

This mode should be selected initially, and every time a sensor is changed. It operates the measurement bridge as a Wheatstone bridge with a low current to determine the resistance of the sensor at the reference temperature T_r. This mode uses the OP37 as a comparator and the potentiometer is used to balance the bridge. Once the balance has been achieved the overheating can be varied by changing the resistance of the potentiometer (for general use it is advised not to exceed 50 %).

B. Operation Mode

Once the resistance of the sensor and the overheating are established, the anemometer can be set in the mode of operation. It is clear that by increasing the overheat ratio, the circuit responds with greater sensitivity, but natural convection effects in the sensor will affect measurements at low speeds.

The first tests were carried out using a tungsten filament lamp in place of the sensor. The filament of a lamp is very endurable, allowing for fine tuning of the electronics without risking expensive sensors.

C. Frequency Response

The most desirable feature of the feedback bridge is the extension of the range of frequency response of the sensor. In turbulent measurements it is important that the output amplitude of the instrument is constant over the frequency range of interest. An ideal test would result from a variation of measured flow speed at the desired frequency range, but in practice this is extremely difficult. For such reason an electronic test is usually applied.

D. Square wave test

The test typically used to adjust the hot wire anemometer response is the injection of a disturbance in the form of square wave. The electronics is then adjusted to yield the desired response. The circuit has a built in oscillator which provides a square wave perturbation when in the "test" mode. The square wave is such that the system is stabilized between leaps, and may result in any of the output waveforms shown in Fig. 5.

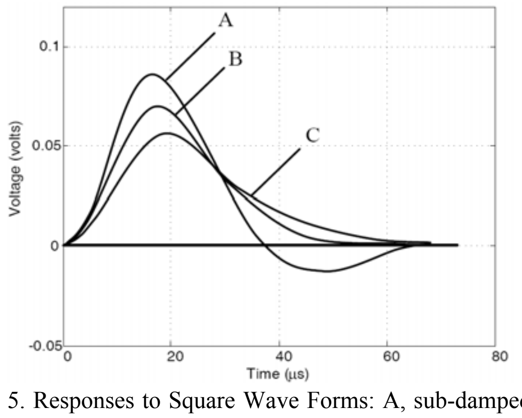

Fig. 5. Responses to Square Wave Forms: A, sub-damped, B, critical damping, C, over-damped.

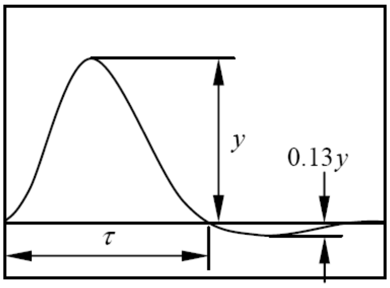

Fig. 6. Output response of a jump in the input current to an appropriate adjustment of the constant temperature anemometer with a sensor wire.

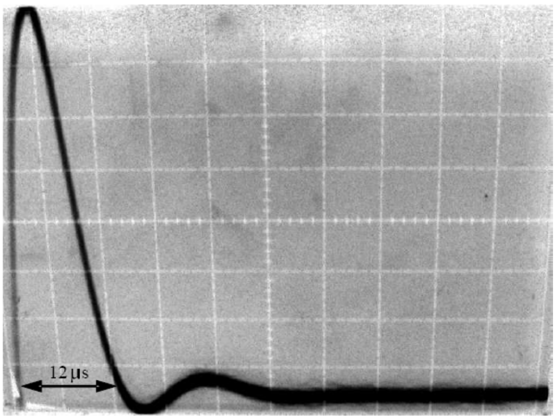

Fig. 7. Response of the anemometer in the "test".

The adjustment is carried out with the sensor exposed to a flow similar to the average speed in the implementation (but with low turbulence), since the response depends on the flow velocity. The frequency response is adjusted by controlling two parameters: the offset of the amplifier (through the 20 kΩ potentiometer), and the capacitance of a branch of the bridge (through the bank of capacitors).

Measurements shown below were made after adjusting the anemometer for a slightly sub-damped response to the square wave test. To estimate the frequency response from the square wave test, the time constant should be measured as described Freymuth (1977) and Fingerson (1994), from which an approximate value of the circuit cut-off frequency is obtained as:

$$f_{cutoff} = 1/1.3\tau, \tag{3}$$

where τ is defined as shown in Fig. 6.

The sensor was connected to the electronics via a 50 cable of 5 m in length. Figure 7 shows the response previously described measured with the oscilloscope.

This waveform was obtained with a sensor of R= 17Ω, with an overheat of 40%, in a flow of speed $v \approx$ 9.1m/s, and capacitors C_2, C_3, C_4, C_6, C_7 assets. The value of τ obtained is 12 µs, which yields $f_{cutoff} \approx$ 64 kHz.

E. Sine wave test

The cutoff frequency can also be determined from a test which consists of injecting a sinusoidal signal in the branch of the bridge for the sensor, connected to pin 2 of OP37, conducting a sweep in frequency and measuring the output. The input sinusoidal signal is low in amplitude and is coupled to the circuit through a resistance of 50 kΩ. The results obtained in this test, for the present circuit and for a commercial unit TSI 1051, with a bridge ratio 5:1, are shown in Fig. 8.

The cutoff frequency can be estimated as that frequency for which the curve drops below the line indicated as an attenuation of -3 dB, which corresponds to approximately 64 kHz. This agrees with the value obtained from the square wave test. Both measurements were carried out with the fabricated sensors. Differences can be noted in the behavior of the two electronics for the same operating conditions, especially at low frequencies. However, between 10 kHz and 100 kHz the curves are similar.

In Fig. 8 we can also appreciate the dynamic response of the sensor wire without frequency compensation, which operates as a low-pass filter. The value of the abscissa where the curve is practically horizontal is identified, and the point where the amplitude reaches 3 dB can be estimated from the graph. The frequency is approximately 400 Hz.

F. Power spectral density

To compare the performance of the anemometer with a commercial unit the following test was carried out. Measurements were made on a turbulent flow with two sensors, one connected to a TSI-1051 commercial anemometer unit and the other connected to the presented circuit. The flow measured was a completely developed turbulent flown in a circular tube with smooth walls having an inner diameter of 40mm and a flow mean velocity of 10m/s. The length of the tube was 30 hydraulic diameters to achieve a fully developed flow. The two sensors were separated about 200 µm from each other and placed on the tube axis 10mm downstream from the end of the tube. The overheat ratio of both units was set to 20%.

The resulting power spectrum is presented in Fig. 9 and shows a good agreement between the two power spectra over a bandwidth of 50 kHz. There are only minimal differences between the measurements of both sensors around 80 Hz and 300 Hz. Furthermore the differences shown in the electronic test in Fig. 8 are not reflected in this measurement.

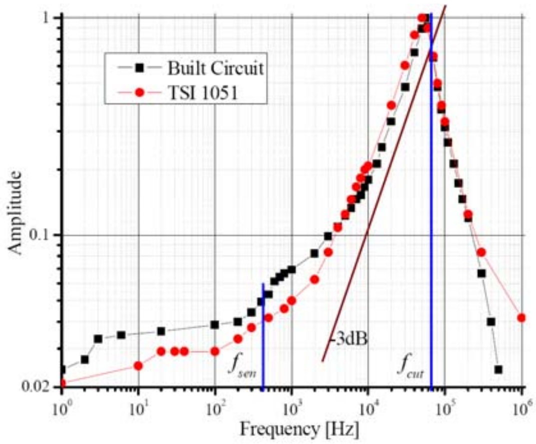

Fig. 8. Test with a sine wave.

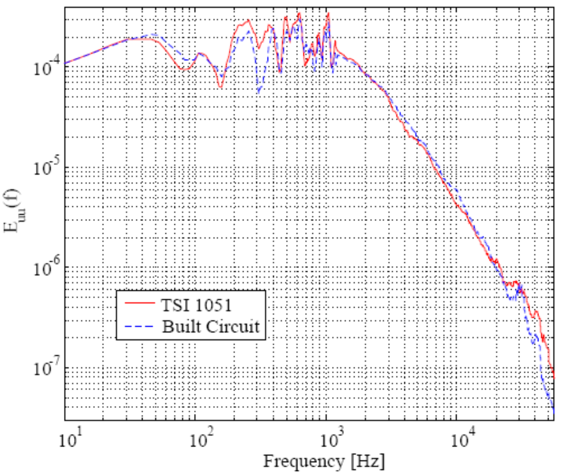

Fig. 9. Power spectrum of velocity for the proposed circuit and TSI 1051. Overheating 20 % and u = 10 m/s.

G. Implementation details

Figure 10 shows a picture of the finished prototype. The printed circuit board was designed so that, it could be mounted on a commercial electronic module (size 45 x 80 x 100 mm), with the possibility to be mounted on a standard 35 mm rail with a shared power bus. This allows the grouping of several measuring modules with minimum wiring. The printed circuit board is freely available under request.

III. OTHER ASPECTS

During the preliminary tests, the hot wire sensor constructed with this methodology could withstand air flows of 10 m/s for several hours. These tests were always conducted with air filtered using a 0.5 μm filter as dust or other particles would break the wire. On the other hand, even though we have not performed long term stability tests, preliminary measurements conducted during a period of four days in still air showed a drift smaller than 0.5% per day.

IV. CONCLUSIONS

The constant temperature anemometer with a hotwire sensor presented in this paper proves to be an instrument of simple fabrication, easy to use, inexpensive and the components are easily available. The constant temperature anemometer allows a satisfactory compensation of frequency response for different sensors, although the time constant achieved (τ = 12 μs) is somewhat larger than the one of the TSI 1051 (τ close to 5 μs).

It is worth noting that the ability to manufacture these instruments provides the fluid dynamicist with an invaluable tool. It makes possible the assembly of sensors taylored to specific uses or complex geometries and the adaptation of electronics to use of sensors with different resistance values.

The good performance of the circuit was thoroughly verified, and most of the recommendations and observations of other researchers in the field were verified.

It is a valuable asset both for laboratory and educational institutions to have this kind of instrumentation whose performance is almost as good as expensive commercial models and covers most typical applications of hot wire anemometry.

V. ACKNOWLEDGEMENTS

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Fig. 10. Final Prototype.

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