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An airflow vortex-shedding flowmeter with PVDF piezoelectric film sensors: development and characterization

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Abstract*— The vortex-shedding flow meter shows good accuracy, a high range of measurement and small intrusively in flow measurements. The systems presently in commerce have very good throughputs but a high costs which discourage their employment in many industrial applications. In particular, high costs depend on the presence of a pressure's sensor. In fact, the mechanic construction results very simple. The flow measurement is obtained by inserting a special shedder along a pipeline's diameter. When a flow invests the shedder, the vortex (the von Karman vortices) produce alternating forces or local pressures on the shedder. The vortex frequencies, for a wide range of Nr (Reynolds number), linearly depend on the flow speed. The Strouhal number that depends on the shedder shapes connects the vortex frequencies with the speed. In this work a new vortex-shedding flowmeter for airflow fluid has been built and characterized. The instrument uses pressure sensors realized by piezoelectric film PVDF to measure the vortex frequency and therefore the flow velocity. The PVDF films are piezoelectric materials with a good pressure sensitivity and very high frequency response. Moreover, they are not expensive and it is easy to set them up. For this reason it is possible to use the vortex shedding for a lot of different applications. Unfortunately the temperature influence and the surface deformation, that the shedder can have, mitigates the signal-to-noise ratio in the measurement. The instrument realized has been installed in a wind tunnel and has been calibrated in large flow velocity range. Hot wire anemometers and Pitot tubes have been used as reference sensors for the calibration. We have studied the interfering and modifying input in the chain of measurement and the effects of the pipe vibrations. A specific low-cost electronic circuit for the identification and analysis of the signal, which is generated by the PVDF pressure sensors, has also been developed. In this way, the flow velocity on the liquid crystals display can be directly read. The low measurement uncertainty and the low cost of the system encourage further developments of the present work, in order to refine the construction techniques.

Index Terms— **airflow vortex-shedding flowmeter, flowmeter, piezoelectric film sensors, PVDF.**

I. INTRODUCTION

The Vortex flowmeter uses the phenomenon called "Vortex Shedding", that occurs when a fluid (steam, gas or liquid) flows against a non streamlined obstruction, termed a bluff body. The peripheral layers of the fluid are unable to follow the defined contours of the bluff body and separate from its surfaces to form vortices that are swept downstream (Karman vortex Street). The vortices are shed alternatively from both sides of the bluff body at a frequency which is proportional to the mean flow velocity in the pipe.

Strouhal started his scientific observations in 1878. He found that a wire was set in motion in an airflow. The frequency of the oscillation is proportional to the flow velocity. The same whistling tone of the wind is dependent on the velocity of the flow. Strouhal did experimental observations on the phenomenon and found that for a large range of the Reynolds number the relation between the frequency of separation of the vortexes and the velocity of the flow that invests the body is linear in accordance with the relation:

$$S_t = \frac{f \cdot d}{V_O} \qquad (1)$$

where f = vortex frequency, d = diameter of resistance body, V_o = velocity of the fluid.
Since the average fluid velocity is equivalent to the volumetric flow rate, Q, divided by the cross-sectional area, A, we can rewrite Equation (1) as:

$$f = \frac{Q \cdot S_t}{d \cdot A} \qquad (2)$$

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Since S_t, d and A are constant, we can group them together as a constant, K, and thus obtain a simple, direct relationship between volumetric flow and vortex frequency: $Q = k \cdot f$.

Vortex flowmeters have been used for industrial flow measurement since 1970, but only in recent years bluff bodies were developed [3] with a good signal-to-noise ratio [5] and sensors drastically improved. The reason of their rapid diffusion is due to the good characteristics of sensitivity and linearity in a large range of flow rate. Moreover, it is possible to measure flow rates of liquid, gases, steam and cryogenic fluids at temperatures from -200°C to + 400°C which pressures up to 300 bar; range ability is about three to six times greater than with equivalent orifice methods; accuracy is not influenced by temperature, pressure, density and viscosity variations; zero calibration and periodical checks are unnecessary; there are no moving parts; leakage resistance for toxic or explosive fluids is greater than that of equivalent orifice meter because there are significantly fewer gasketed points; output signal is linear with flow rate; pressure loss is low; installation and maintenance costs are low.

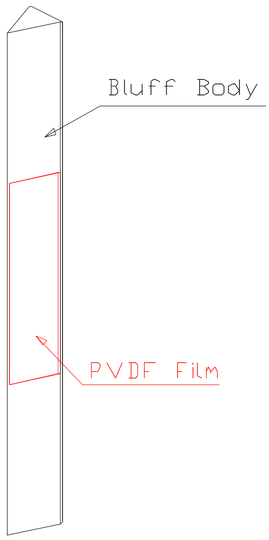

Fig. 1: Application piezoelectric film in the bluff body.

The linearity of the ratio between V_o and f depends on the shape and dimensions of the bluff body [7] – [2]. In recent past, in order to improve the throughputs of these instruments, two ways of studies have been carried out: the first has involved seeking a conformation of the bluff body that allows to obtain a good linearity, regular vortexes, with reduced leakages of load.

The second trend of research concerns the development of solutions of frequency vortex measurements that are reliable, precise and low-cost. In this work, this second aspect has been particularly developed and a new flow meter to detachment of vortexes has been built and characterized [6]. This uses the piezoelectric PVDF films as pressure sensors [9] – [10] – [11] for the measurement of the frequency of separation of the Von Karman vortexes. In this way, a low-cost sensor has been obtained, with good throughputs. It can be used in all those industrial applications where the high costs of the instruments were not until today justifiable.

II. REALIZATION AND SET UP OF THE SYSTEM

The bluff body used is prismatic, with trapezoidal base, obtained for mechanics processing with routing of turnings from an aluminum bar. Recent studies show that sections of the bluff body of this shape are preferable compared to more complex geometries because it introduces small pressure loss and avoids the formation of secondary vortices. PVDF film has been used as pressure sensors.

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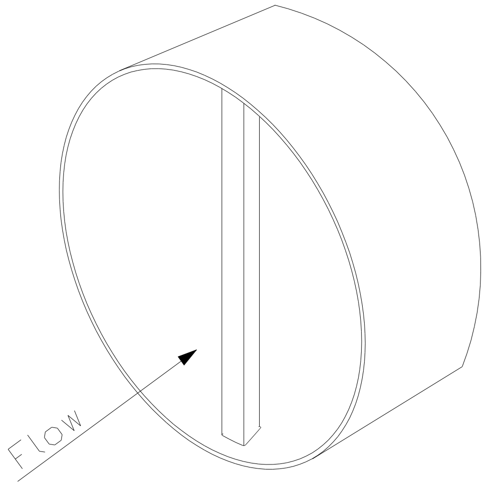

Fig. 2: Installation of the vortex flowmeter in the wind tunnel.

It consist of a tough plastic film available in a wide variety of thickness and in large areas. Its advantages as a transducer include a wide frequency range (near 0 to 109 Hz), vast dynamic range (10-8 to 106 psi), high elastic compliance, high voltage output (10 times higher than piezo ceramic for the same force input), high mechanical strength and impact resistance (109 ÷ 1010 Pascal modulus), high stability, resistance to moisture, to most chemicals and oxidants, and to intense UV radiation. Its water absorption factor is less than 0.01%, little raw material is needed and fabrication costs are low. Furthermore, the film can be cut, formed and glued with commercial adhesives.

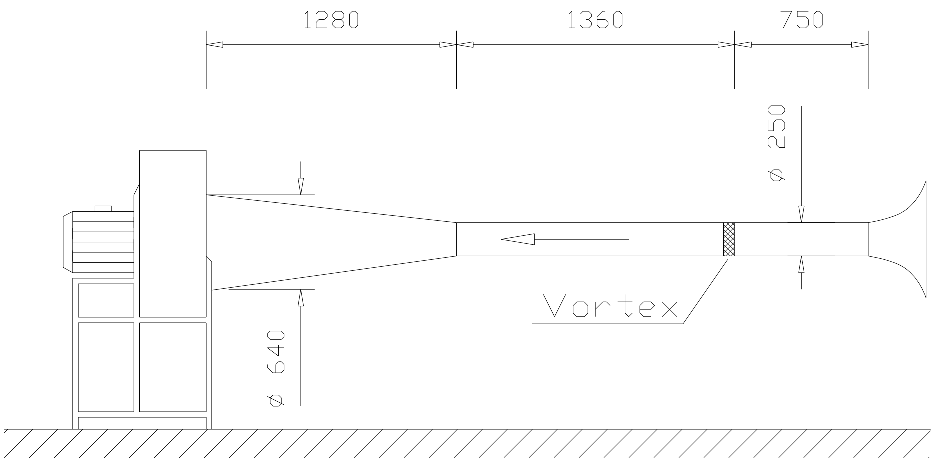

Fig. 3: Geometric dimensions of wind tunnel.

However piezo film has certain limitations which make it inappropriate for certain applications: maximum operating temperature is 100 °C, and in addition to this, exposed electrodes are sensitive to electromagnetic radiation.

Two piezoelectric films, electrically independent, have been glued on two sides of the bluff body, as shown in Fig. 1. The surface of the films is completely invested by the vortices in order to avoid the effects of the “passive film” [1]. The measurer thus obtained has been set up in a wind tunnel, for its calibration, so that the largest base of the bluff body was exposed to the flow (Fig. 2). Fig. 3 shows the main dimensions of the wind tunnel employed for the experimental analysis. In particular, the section of test is cylindrical, with a diameter of 250 mm and maximum rate of the flow (air) as 95 m/s. The vortex has been placed in the section of test in the rectilinear segment between the choke conic of aspiration of the fan and the convergent intake of the tunnel. A filter passes band and a converter frequency voltage have been placed to the exit of the signal from the piezoelectric PVDF films. In this way a signal in Volt which is directly proportional to the frequency of detachment of the von Karman vortices and then to the flow rate is directly available.

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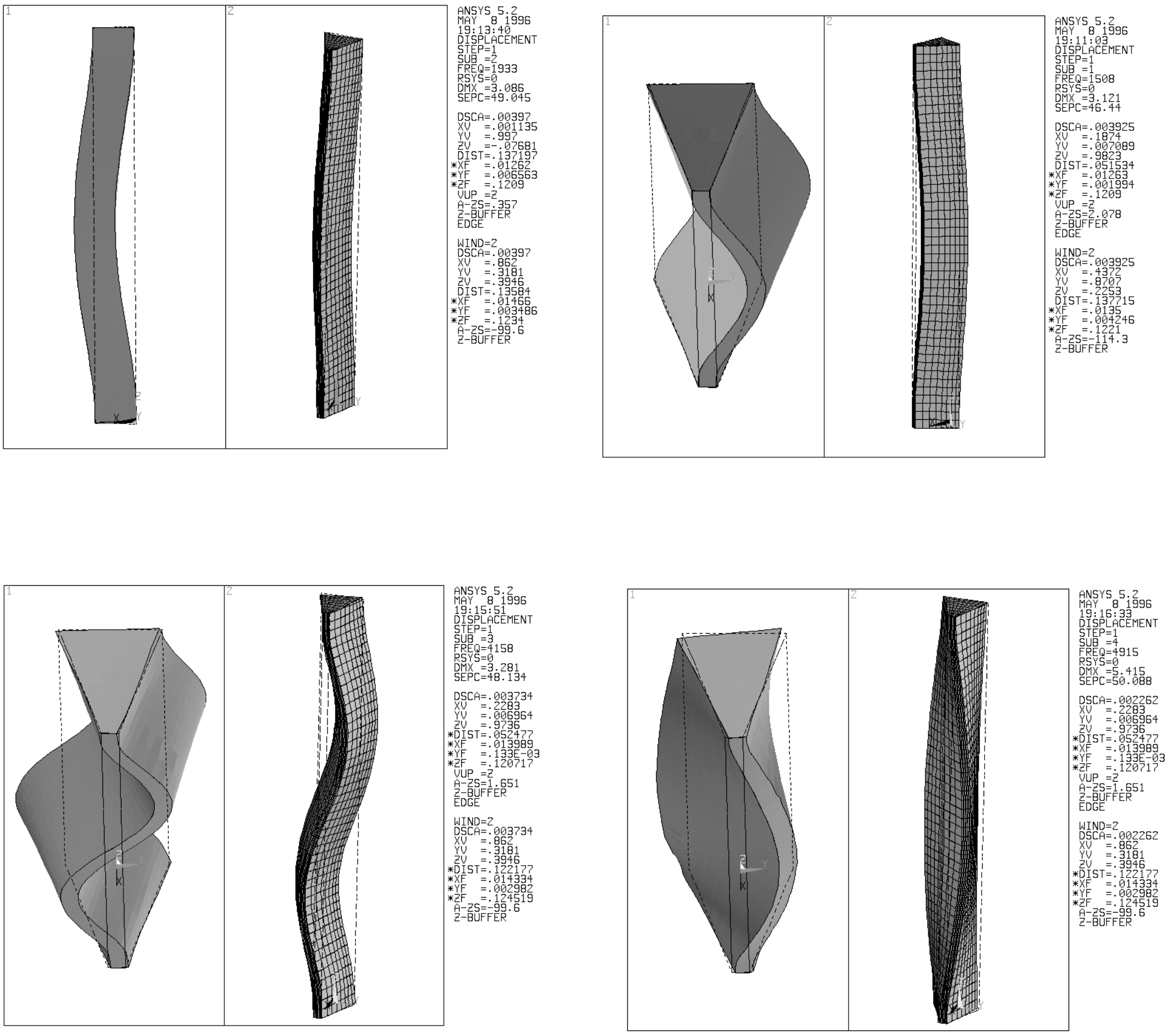

Fig. 4: Modal analysis of the bluff body

III. CHARACTERIZATION AND CALIBRATION OF THE SYSTEM

An important limit in the employment of vortex shedding flowmeter is the non-desired inputs due to the vibrations of the bluff body [8]. Often, in fact, the sensors result sensible not only to the fluctuations of pressure due to the von Karman vortices, but also to the vibrations transmitted to the body by the conduct in which it is installed. The pipelines in fact are interested by vibrations because of the presence of machines in motion. A modal analysis of the bluff body, set up in the wind tunnel, has been performed in order to determine its vibration modes with the relative frequencies. Fig. 4 shows the first own frequencies of the bluff body, with the relative vibration modes. The first four own frequencies are situated at 1508, 1933, 4158 and 4915 Hz, in a range that, as can be easily seen, is outside the range of frequencies interested by von Karman vortices (150 □ 600 Hz). The calibration of the vortex flow meter has been performed by employing Pitot tubes and Hot wire anemometers as reference sensors for the measurement of the flow rate in the wind tunnel. The flow profile in the section of test of the tunnel is completely turbolent, then the mean velocity of the flow could be considered even to the local velocity measured by Pitot tubes and Hot wire anemometers. The flow speed has been changed by a gate valve placed below the centrifugal fan.

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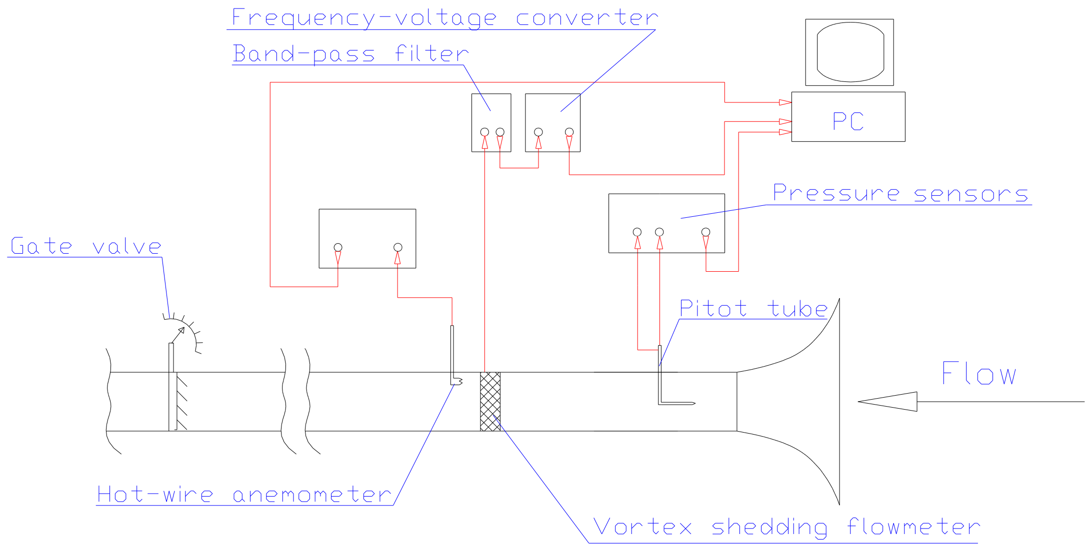

Fig. 5: Block diagram of the measurement system.

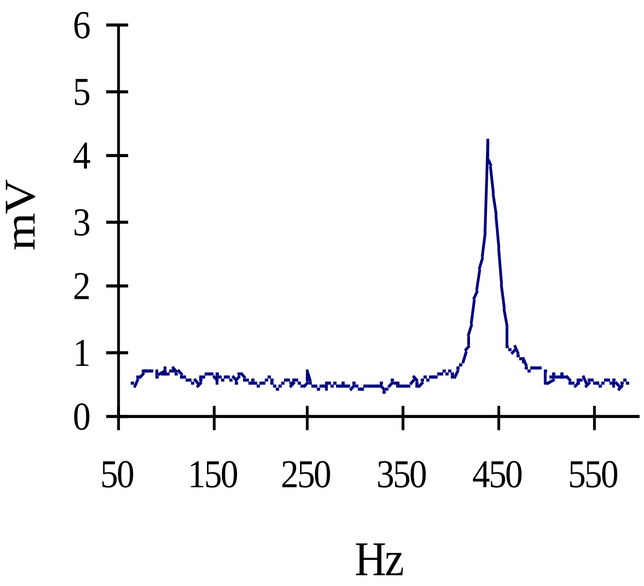

Fig. 6: Signal from the PVDF films in the frequency domain.

In Fig. 5 a block diagram of the measurement system is shown. Fig. 6 shown an example of the output signal from the PVDF films in the frequency domain. A peak at the frequency of 437.5 Hz can be seen. This frequency coincides with the frequency of separation of the vortices for a definite flow rate. The signal of Fig. 6 has been sent as input to Voltage frequency converter, from which a voltage signal goes out which is directly proportional to the value of the frequency. The flow rate in the wind tunnel has been changed with continuity and the correspondent frequency spectrum of the piezo film signals is shown in Fig. 7 in correspondence to the flow rate, measured in m/s, by hot-wire anemometer.

In Fig. 8 the points of calibration are shown or, in other word, the values of the output voltage from converter in correspondence to the flow rate. The average calibration curve was calculated using the least squares criterion. The standard deviations value of the points of calibration has resulted (for a range of speed between 10 and 95 m/s) equal to 0.51 m/s, white the confidence level of 99.7%. The uncertainty relative to the full scale was lower than 3%.

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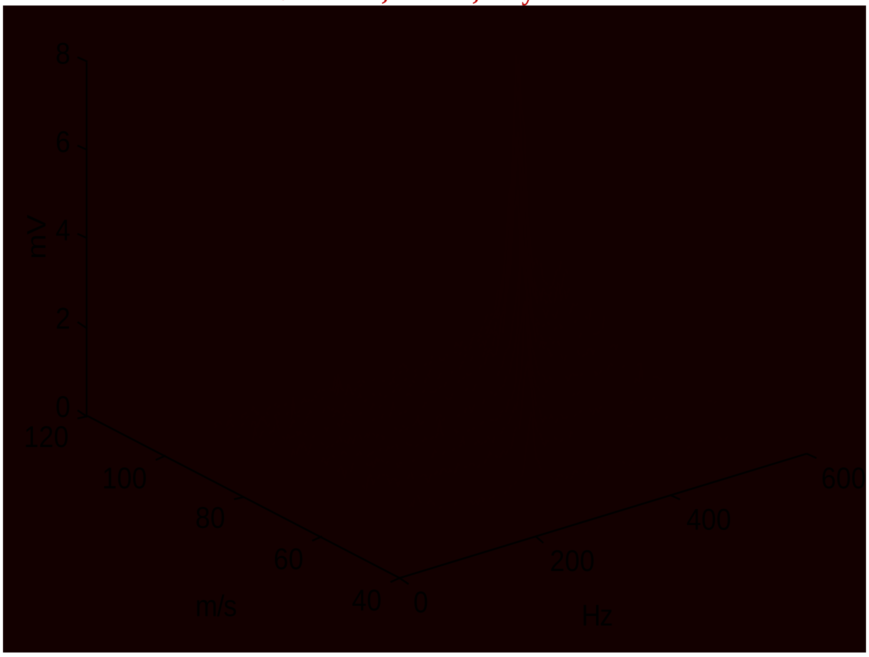

Fig. 7: Spectrum of the piezofilm signals in correspondence to the flow rate.

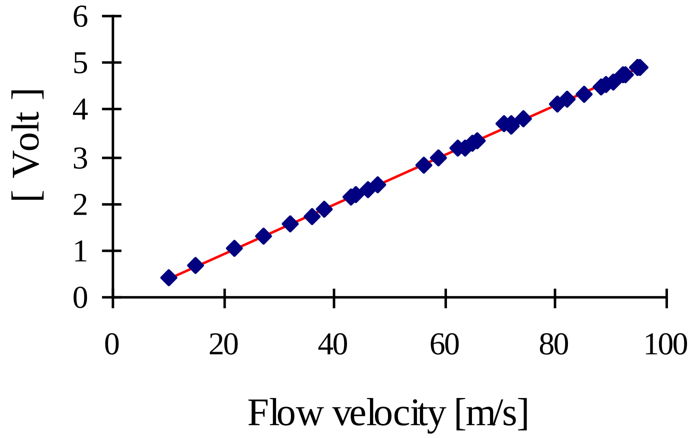

Fig. 8: Calibration of the vortex-shedding flowmeter.

IV. CONCLUSIONS

A vortex-shedding flowmeter using piezoelectric films for mapping the pressure fluctuations of the separation of the vortexes has been built and calibrated in air. The choice of these sensors offers many economic advantages for the realization of the instrument. These advantages are due to their simplicity of installation and to their cost-effectiveness. The calibration has been performed by comparison with hot wire anemometers and Pitot tubes. The dimensions of the bluff body have been chosen so that the values of the frequencies of separation of the vortices do not coincide with the own frequencies of the bluff body, in order to reduce as much as possible the non-desired input due to the mechanical vibrations of the structure. The uncertainty of the measuring has been valued inferior to 3% of the maximum value, for a range of flow rate between 20 and 93 m/s. For future developments of the present work, characterization of the instrument in different conditions of operation of the plant is anticipated, in particular with fluids with superior temperatures at 60 °C.

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