Piezoresistant Probe for Measurement of Velocity in One-Dimensional Incompressible Flow

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Working on the problem of calibration of hot wire probes within (3), *we came to the need to have a probe for measuring the instantaneous velocity in a one-dimensional air jet. Soon after the idea concerned with the first domestic piezoresistant probe by means of which the instantaneous differential pressure can be measured was developed on the Faculty of Mechanical Engineering. The probe was realized in the collaboration with IHTM, the Center for microelectronic technology and monocrystals.*

First tests with the probe showed that it could be successfully used for measuring the instantaneous velocity in one-dimensional incompressible flows. In that sense, some more similar probes were produced after the pioneering one.

In this paper the basic elements of the technological procedure for the production of the pressure sensor are given. In addition to a detailed description of the sensor chip we show here some other elements of the probe JR-p also. Before any use the probe must be calibrated. The probe JR-p is calibrated statically in a quasi-steady air jet. The results of such a calibration are presented here.

Keywords: *Piezoresistant probe, measurement, differential pressure, velocity.*

1. INTRODUCTION

In techniques and in research we are very often faced with the problem of measuring the instantaneous values of the velocity vector and the pressure in the flow field. Probes, which represent the main part of the equipment, are divided into two large groups. The first group is constituted by the anemometers, i.e. by the sensors for velocity measurement. Among them hot wires anemometers occupy an important place. Pressure sensors make the second group, to which the contemporary piezoresistant pressure sensors belong too.

It is well known that classical Pitot-Prandtl probe measures the mean dynamic pressure $\Delta p_d = \rho V^2 / 2$ in an one-dimensional flow field, and thus it measures the mean velocity *V*.

The probe JR-p, described in this paper, represents an uninertial Pitot-Prandtl probe. Namely, this probe is capable of measuring instantaneous differential pressure and instantaneous velocity in one-dimensional turbulent flow fields.

In Pitot-Prandtl probe-case total pressure is detected at the front hole, while the pressure is detected at the lateral hole. Their difference is measured by a differential manometer. In JR-p probe the total pressure from the front hole acts on a side of the membrane of a piezoresistant sensor, while the pressure from the lateral hole acts on the other side of the membrane. The pressure difference, acting on the piezoresistant sensor, builds a voltage signal, which is led in the form of sample array into the acquisition system. A single value of the differential pressure in the finite measuring volume of the probe head corresponds to single sample voltage signal.

A functional relation between the voltage and the differential pressure is determined by the probe calibration. It is also possible to establish a relation between the differential pressure and the dynamic pressure by the calibration, so that JR-p probe can be applied for direct measurement of the velocity in the one-dimensional flow field. Detailed description of the calibration procedure and the results obtained by the calibration are given in this paper.

The JR-p probe was produced in IHTM, Center for microelectronic technologies and monocrystals. A piezoresistant chip, built by silicium monocrystals with diffused piezoresistors in the form of a Wheatstone bridge, makes the heart of the probe.

Resistors are formed by the diffusion of wrinkles in the direction of the individual crystal axes. Resistance depends on the orientation of the crystals. In addition, the action of the pressure changes the resistance of resistors. The connection between these crystal-resistors in the Wheatstone bridge enables one to register deviations of their resistance, and thus the changes of

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the pressure difference on the membrane. The Wheatstone bridge applied to this probe is voltage supplied from low-noise / low ripple DC/DC power supply unit.

By the proper choice of the parameters governing the diffusion of wrinkles, a passive compensation of the temperature was undertaken, i.e. a sensor was developed, which is practically insensitive in relation to temperature changes. In addition to all semi-conductor properties of the silicium, silicium sensors are characterized by an extraordinary steadiness and accuracy, particularly when one has in mind linearity, repeatability and negligible hysteresis.

Preliminary investigations of the probe were done in labs of the Faculty of Mechanical Engineering in Belgrade by the use of ultra fast acquisition system ADS 2000. It is concluded that the probe possesses a fast response, high linearity, small hysteresis and that it is practically insensitive to temperature variations in a very wide temperature range.

2. DEVELOPMENT OF THE PIEZORESISTANT PROBE JR-P

2.1. Technology of the production of silicium membrane pressure sensor [1]

For the production of high quality integrated, silicium membrane pressure sensors it is necessary to take over three basic technological units. These are formation of miniature membranes by the method of chemical anisotropic etching, planar procedure for the production of the piezoresistant bridge, and electrostatic joining of glass and silicium in vacuum.

Sensor chip was made out of a monocrystal silicium platelet (n-type, orientation <100>), polished from both sides. On one side of the platelet, diaphragm is made by anisotropic etching, whose thickness depends on the range of the pressure measurements.

By the procedure of two-sided photolithography, circular holes are made in the oxide, which serve for the selective etching of the membrane from one side. On the other side holes for markers are formed, which are used in further process for the production of piezoresistors.

Platelet prepared in such a way is subject to etching in the corresponding solution. The solution is chosen so that it etches about 100 times faster in <100> direction, than in <111> direction, and also that it etches protecting layer, obtained by usual procedures of planar technology, much slowlier.

By the diffusion of wrinkles, or by other standard procedures of planar technology (thermal oxidation, spattering of contact materials, etc.), it is now possible to form four resistors on the rim of the diaphragm in the direction of <100> resistors axis, on the front side of membranes. Resistors are connected within a Wheatstone bridge, whereby a voltage of 5 to 10 V is brought to a diagonal of the bridge.

Under the action of the pressure diaphragm is bent, so that the change in the piezoresistance is detected in the other diagonal of the bridge, as a change of the voltage signal ΔV_{out}. This change is proportional to the relative change of piezoresistance $(\Delta R / R)$, i.e $\Delta V_{out} = (\Delta R / R)\, V_{in}$. Here R is the value of the resistance of the semi-conductive resistor that is not mechanically loaded, while ΔR is the increment of this resistance, and V_{in} is the voltage at the brid

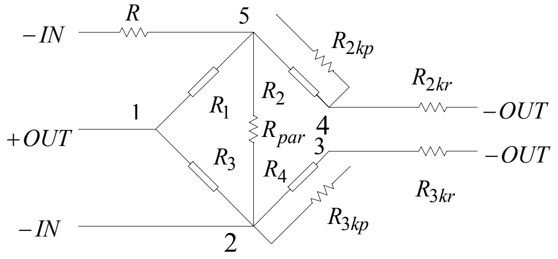

Figure 1. Wheatstone bridge sensors chip with resistance for compensacion.

The neighboring resistors in this Wheatstone bridge change their resistance under the action of pressure in the opposite direction, so that the maximum voltage output is achieved in this way.

Silicium monocrystal does not possess the property of plastic deformation, so that the bend of the sensor diaphragm practically has no hysteresis. Accuracy of the pressure measurements by a silicium chip, regarding linearity, repeatability and hysteresis, is thus 0.02% of the measurement range.

In order to keep such a high accuracy until the end of the sensor production, one must take care about the variety of elements that constitute the technology of the procedure.

First, chip is joined to the base made of Pyrex glass by the method of anodic or electrostatic bonding. This glass has the coefficient of thermal dilatation very close to the one of silicium, so that there is no stress in the membrane without the change in the outer pressure. At that a referential chamber of the volume $0.4\ \text{mm}^3$ is formed. For chips that are provided for measuring absolute pressures, very high vacuums of the order 10^{-5} bar should be produced in this chamber.

Sandwich between the silicium chip and the glass formed in this way is glued for the base, which is most frequently a kind of transistor support, and which enables further leading of contacts from the chip (Fig. 2). Contacts are made by bonding of a golden wire from the chip to the isolated electrical exits of the base.

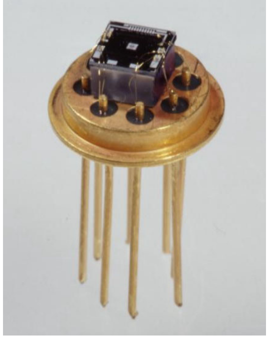

Figure 2. Sensor chip of the piezoresistant probe.

2.2. Final formation of the probe JR-p

Pioneering probe (Fig. 3) has a head of diameter 10 mm and the length of about 50 mm. There is a hole of diameter 3 mm in front, and a hole of diameter 2 mm on the distance of 20 mm. Inside the head, between the holes, a small chamber is situated. The chamber is separated into two parts by the sensor chip.

Figure 3. Head of the probe JR-p

Sensor chip in the probe JR-p, which measures some pressure difference, possesses a hole on the back, referential side of the diaphragm. In this way diaphragm is exposed to the pressure difference between the front and the lateral hole of the probe.

During the mounting of the sensor in the head of the probe, care was taken to lessen the volume in front of the sensor as much as possible, in order to speed the response of the probe.

Sensor chip has dimensions 3×3 mm. Sensor diaphragm has the approximate form of a square and eigenfrequency determined by dimensions and the thickness of the diaphragm. For pressure ranges for which the probe was designed eigenfrequences of the diaphragm are from 35 kHz to higher values. In order to keep such a speedy response of the probe at the sensor too, the volume of the chamber in front of the diaphragm of the chip was reduced to be as small as possible.

By using this probe for measurements some unavoidable errors occur due to its finite dimensions. In addition greatest error in measurements with piezoresistant sensors arises due to zero thermal change, and due to sensitivity. However, by the proper choice of the diffusion of wrinkles thermal change of sensitivity can be considerably reduced. Since these changes appear mostly because of the imperfect balance in the Wheatstone bridge, thermal errors can be removed by a simple passive compensation by using outer resistors. In the design of this probe thermal compensation was done by means of miniature resistors on the backside of the chip base, taking care not to disturb airflow from the referential side of the sensor.

The rest of the pipe of the diameter 10 mm, behind the lateral hole, was practically filled with protected five – wired cable, which provides the connection between the sensor and the amplifier. Namely, on one side of the cable is the sensor chip, and on the other side is a five-pole connector, which serves for connecting the probe to the amplifying circuit with PGA202KP Burr-Brown amplifier, which is connected to an electrical source of 5V (Fig. 4). The amplified analog voltage signal of the probe, taken from the transmitter, is conveyed to an A/D converter of the acquisition system by isolated cables with BNC connectors at the ends.

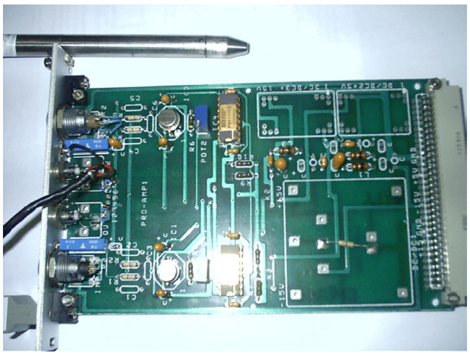

Figure 4. Transmitter of probe JR-p

3. ACQUISITION SYSTEM USED DURING INVESTIGATION AND CALIBRATION OF THE PROBE [2]

Acquisition system must meet two important requirements – it must be fast enough, and must be practically unerring. Both of these two requirements are fully satisfied be the unsurpassable ultra fast measuring and control system AD2000 (Jankov 2000).

This domestic system was conceived in 1985, and a small research team has developed few similar systems, with some weaker performances, afterwards. It is to be mentioned that the first conception of the system was at that time the first system in the world of that kind.

The conception of this complex domestic measuring and control system with high performances is based on VME-bus. The system is modular, which offers a possibility of upgrading its performances by use of more VME-CPU modules, which may possess one or more processors. Within the system there are two VME-ADC modules. Each of them contains two fast A/D converters (Burr-Brown ADC 803) with Sample/Hold high-resolution amplifiers (Burr-Brown SHC 803). S/H and ADC are adjusted to the conversion speed 2x350 kHz, with the resolution of 12 bits. In addition, the system contains also four fast, programmable multyplexer amplifiers (VME – MUKS - PGA). In this way, simultaneous measurement (simultaneous A/D conversion) in assortments of four channels is enabled. By means of one multyplexer and a particular set of high-quality BNC connectors entrance is enabled for 8 analog signals.

Special applicative software was developed for use in the system ADS2000, which enables a very effective use of the hardware with wide possibilities. Out of much available software we directly use in this paper the program Indi.for. only. This program, together with its graphic presentation, is able to determine the characteristic parameters, to perform the statistic analysis per one ensemble (series of consecutive circles), and to store measured and processed parameters. A universal graphic module presents in 2D and 3D techniques the measured results and the results of calculations in real time, in 30 windows, with simultaneous file production with direct entry into the processor text. This model can be used in all applicable programs of the system ADS2000.

4. CALIBRATION OF THE PIEZOPROBE JR-p [3]

The probe JR-p has two small chambers on both sides of the sensor, i.e. it contains a small amount of gas, which provides a small inertia of the probe. It can be said that the probe is able to register the instantaneous pressure difference. More detailed investigation of the probe response in the frequency domain is underway, so that the initial results will not be presented here.

In order to measure the instantaneous pressure difference in one-dimensional flow field with the probe JR-p, it is absolutely necessary to reveal the dependence of the differential pressure Δp_{dif}, detected on the probe holes, on the increment ΔE_{ps} of the time-averaged voltage exit signal. An estimate of the dependence $\Delta p_{dif}(\Delta E_{ps})$ is obtained by a static calibration of the probe.

4.1. Static calibration

Releasing the air from the compressor bottle different total pressures are maintained in the bottle. Silicon pipes transmit these pressures to the front hole of the probe, and to the Betz manometer, while the side hole is exposed to the atmosphere.

For every change of the total pressure its values were read with the Betz manometer. Differential pressure Δp_{dif} registered by piezo probe is the difference between the total and the atmospheric pressure. This pressure difference induces voltage E_{ps} of the piezo probe, which is registered and averaged by the acquisition system AD2000. Signal was recorded by the sampling frequency of 500 Hz during a period of 10 s. Voltage increment ΔE_{ps} is the difference between the average voltage E_{ps}, induced by the corresponding pressure, and the average voltage E_{ps0} for Δp_{dif}. In Fig. 5 the calibration points in the diagram $\Delta E_{ps} - \Delta p_{dif}$ are shown.

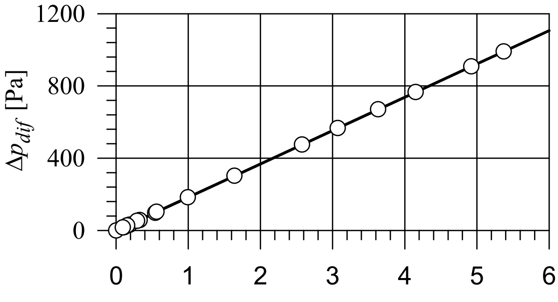

Figure 5. Relation between the differential pressure and the voltage increment of JR-p probe

Distribution of calibration points in this diagram clearly point out to the linear relation between the voltage increment ΔE_{ps} and the differential pressure Δp_{dif}. Assigning greater statistical weight to points with greater Δp_{dif}, because they have smaller measured error, the following linear equation is obtained:

$$\Delta p_{dif} = 184,69\,\Delta E_{ps}$$

4.2. Calibration in a steady jet

First of all, the probe JR-p is provided for measuring the velocity in a one-dimensional flow field. Before it is used it is necessary to determine the relation between the dynamic pressure Δp_{din} and the voltage increment ΔE_{ps}.

An estimate of the dependence $\Delta p_{din}(\Delta E_{ps})$ is obtained by the probe calibration in a steady jet in a wind tunnel. This calibration was carried out in the open wind tunnel in the Laboratory for hydraulic machines, at the Faculty of Mechanical Engineering. This tunnel satisfies all necessary criteria for calibration of anemometers.

At the exit cross section of the tunnel a nozzle, made of wood, and consisting of two parts is placed. The first part is shaped according to the rotational surface made by the rotation of the curve, which definition was proposed by Witoshinsky [3]. The second part is a diffuser extension that enables the uniformity of the velocity profile in the jet. The length of the nozzle is L=320 mm, and diameters of the inlet and the exit cross section are: D_{in}=250mm and D_{out}=150mm, respectively.

Behind this nozzle an axisymetric jet is achieved, with the uniform velocity profile at the exit cross section. We differ between the beginning part of the jet, with the jet core and the boundary layer, and the basic part, with the boundary layer only, and with the substantially different flow picture.

Area of the beginning part of the jet, in which the calibration takes place, is about 200 times greater than the area of the front part of the probe. Thus, the probe disturbs the flow field only slightly, and this guarantees the successful calibration of the probe JR-p in such a jet.

In addition to this condition a satisfactory uniformity of the flow field in the calibrating cross section is also necessary. A check was done in the calibration section, 70 mm from the exit cross section of the nozzle, as well as in two cross sections around the calibration one. Measurements conducted at 20 locations in the horizontal direction, and at 20 locations in the vertical direction along the section diameter ensured that the condition of uniformity was fulfilled with an accuracy of 1% (Lecic 2003).

During the course of calibration an etalon Pitot probe and the piezo probe JR-p are placed in the calibrating cross section, close to each other, on a distance equal to the radius of the nozzle (Fig. 6).

Average total pressure detected by Pitot probe was measured by Betz micro manometer. Average dynamic pressure Δp_{din} equals the difference between the total and the surrounding pressure. Instantaneous differential pressure, detected by the probe JR-p, induces the voltage sampled on the frequency 2 kHz, during 60 s. Voltage signals coming from of the probe are registered and averaged by the acquisition system ADS2000. In this way a single calibration point $(\Delta E_{ps}, \Delta p_{din})$ is obtained.

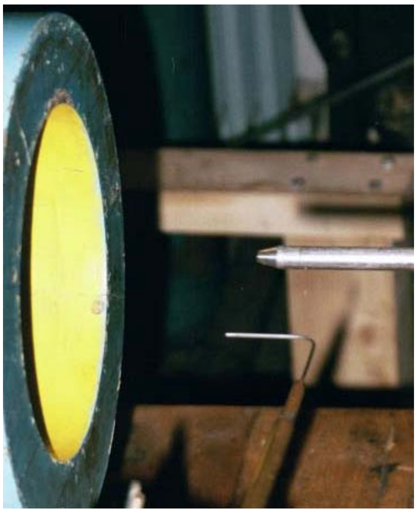

Figure 6. Calibration of probe JR-p in a steady jet.

By varying the calibration velocities in a wide range, a set of calibration points $(\Delta E_{ps}, \Delta p_{din})$ for the JR-p probe is obtained, and shown in Fig. 7.

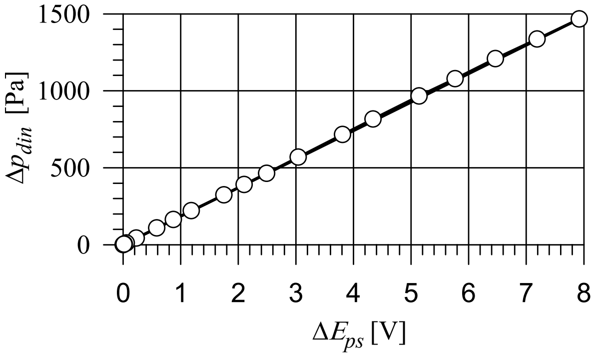

Figure 7. Dependence dynamic pressure - voltage increment of the JR-p probe placed in a steady yet

Calibration points on the diagram $\Delta E_{ps} - \Delta p_{din}$, shown in Fig. 7, give a linear dependence between the voltage increment of the JR-p probe and the dynamic pressure of the probe located in the jet:

$$\Delta p_{din} = 186{,}4\,\Delta E_{ps}$$

Functional relations given with this equation show an almost absolute correlation between the differential pressure of the JR-p probe and the dynamic pressure. Value of the calibration coefficient k_p , which is almost equal 1, is one more indicator of that. This coefficient is defined as a ratio of the differential pressure detected by the piezo probe, and the dynamic pressure measured by Pitot probe:

$$k_p = \Delta p_{dif} / \rho V^2 / 2 = 184{,}69 / 186{,}4 \approx 1$$

This points out that the lateral hole does measure the stream pressure, which means that this pioneering probe can be safely used for measuring the velocity in one-dimensional flow fields also. Of course, measurements in one-dimensional flows are possible even if the calibration coefficients are different from one. For the atmospheric pressure $p_a = 998$ mbar and the jet temperature $t = 21^\circ$ C , the following relation between the air velocity and the voltage increment of the piezo probe is obtained:

$$V = 17{,}76\sqrt{\Delta E_{ps}}$$

In this way we get the dependence of the velocity in the jet on the voltage increment of the piezo probe, shown in Fig. 8.

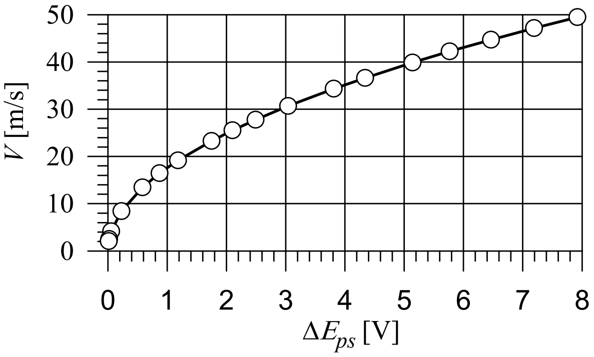

Figure 8. Relation velocity in the jet - voltage increment of the JR-p probe

4. CONCLUSIONS

The aim in this paper was not the investigation of the physics of a silicium piezoresistant pressure sensor, which is discussed in the related literature. Our aim was to make the researchers involved in flow measurements known with an original result, which can be very useful.

Namely, the probe JR-p is existent. It primarily evolved from the need to be able to measure instantaneous jet velocity in the above-mentioned wind tunnel (Lecic 2003). The concept of the probe was developed on the Faculty of Mechanical Engineering. Research and development in the field of semi-conductors within the IHTM, lasting several years, resulted in an excellent sensor chip. Mutual effort was awarded by the first domestic probe of this kind.

After the pioneering probe, described here, several similar probes were built. All of them were successfully used in flow measurements in one-dimensional, incompressible flows.

Further research will be directed toward the investigation of the response of this probe in the frequency domain, as well as toward the realization of the sensors of smaller dimensions and of the probes of different forms and purposes.

Acknowledgment

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ПИЕЗООТПОРНА СОНДА ЗА МЕРЕЊЕ БРЗИНЕ У ЈЕДНОДИМЕНЗИЈСКОМ НЕСТИШЉИВОМ СТРУЈАЊУ

Милан Р. Лечић, Раде Јанков, Слободан Ј. Поповић, Милан Матић

Радећи на проблему калибрације сонди са загрејаним влакнима у оквиру рада [3], јавила се потреба за сондом којом се може мерити тренутна брзина у једнодимензијском ваздушном млазу. Убрзо потом на Машинском факултету у Београду је разрађена идеја о првој домаћој пиезорезистивној сонди којом се мери тренутни диференцијални притисак. Сонда је реализована у сарадњи са ИХТМ, Центром за микроелектронске технологије и монокристале.

Пробна испитивања су показала да се сонда може успешно користити за мерење тренутне брзине једнодимензијског нестишљивог струјања. У том смислу је после првенац сонде направљено још неколико сличних сонди.

У раду су дати основни елементи технолошког поступка за добијање сензора притиска. Поред детаљног описа сензорског чипа овде су приказани и други елементи сонде JR-p. Пре сваког мерења сондом она мора да се баждари. Сонда JR-p се баждари статички и у квазистационарном ваздушном млазу. Овде су приказани резултати једног таквог баждарења.