THE BENCHMARKING OF FORCE SENSORS FOR THE WEIGHING OF SMALL MASSES IN COST-SENSITIVE APPLICATIONS

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Key words: weighing instruments, force sensors, strain gauges, characterization, sensitivity

Abstract: An overview of the requirements for weighing instruments is presented and some of the sources of the measurement errors are discussed. Four types of force sensors, intended for use in small kitchen appliances, with an integrated scale were constructed and evaluated. The sensing elements for two types were thick-film resistors, and for the other two types they were diffused resistors on silicon dies. In the case of the first two types the substrates with the thick-film resistors were bonded on to metallic spring elements. The other two types of sensors are based on the so-called force-to-pressure transformation principle and are known as hydraulic (or hydrostatic) force sensors. The sensitivities of the sensors with silicon sensing elements were between 10 to 20 times higher than the sensitivities of sensors with thick-film resistors. The offset voltages of the unloaded force sensors were significantly higher for the hydraulic force sensors with silicon sensing elements. Also, the temperature coefficients of the resistivities of thick-film resistors (around or below 100×10^{-6} /K) were much lower than the values for the resistors on silicon dies.

Primerjalna analiza senzorjev za tehtanje majhnih mas za uporabo v nizko-cenovnih napravah

Kjučne besede: tehtnice, senzorji sile, merilniki mehanskih deformacij, karakterizacija, občutljivost

Izvleček: V začetku članka predstavljamo osnovne zahteve za tehtnice. Opisali smo nekatere vzroke napak pri tehtanju. Konstruirali, izdelali in testirali smo štiri tipe senzorjev sile, primernih za vgradnjo v male gospodinjske aparate z vgrajeno tehtnico. Dva tipa senzorjev uporabljata senzorske elemente na osnovi debeloplastnih uporov, medtem ko pri drugih dveh izkoriščamo pretvorbo sile v tlak (hidravlični senzorji sile) in pri tem uporabljamo kot senzorske elemente difundirane upore na silicijevih tabletkah. Temperaturni koeficienti upornosti debeloplastnih uporov (okrog ali pod 100×10^{-6} /K) so za več kot velikostni razred manjši kot temperaturni koeficienti upornosti difundiranih uporov na silicijevih tabletkah. Pri senzorjih sile z debeloplastnimi upori so keramični substrati prilepljeni na kovinsko vzmetno telo. Hidravlični senzorji sile so napolnjeni s tekočino (silikonsko olje), ki je medij pri pretvorbi sile v tlak. Občutljivost senzorjev s silicijevimi senzorskimi elementi so deset do dvajset krat večje, kot občutljivosti senzorjev z debeloplastnimi upori. Ničelne napetosti neobremenjenih senzorjev sile so precej višje za hidravlične senzorje sile.

1. Introduction

A weighing instrument is a device that determines the mass of a body by using the action of gravity on this same body. The instrument may also be used to determine other quantities, magnitudes, parameters or characteristics related to the determined mass. The accuracy classes for weighing instruments, their symbols and typical fields of use are given in Table 1 /1/.

Table 1: Symbols for accuracy classes and typical fields of use /1/.

Mark	Name	Typical use
(I)	special accuracy	laboratory
(II)	high accuracy	trading with jewelry
(III)	medium accuracy	general trading
(IIII)	ordinary accuracy	general use

However, unless precautions are taken to correct for local gravity, air buoyancy and a number of other factors, the declared accuracy of the scale cannot usually be realized. In fact, considerations that are often overlooked can result in a significant error, especially with scales that have a higher accuracy. Some of those concerns are described in /2/.

Latitude is the most significant variable in determining the acceleration due to gravity. This acceleration (g) varies from 9.780 m/s^2 at the equator to 9.832 m/s^2 at the poles and can cause an error of up to 0.53 % in the final result of the weighing. Altitude also has a great influence, since the gravitational attraction to the earth at a particular location varies as the square of the distance from the centre of mass of the earth. These variations can cause an error of up to 0.26 % over the surface of the earth. Variations in the acceleration due to gravity, because of position and height, result in a change in the weight of an object by about 0.8 % over the surface of the earth. Objects being measured displace a volume of air, which has a density of approximately 1.2 kg/m^3, and whose density can vary due to weather. The resulting "upward" force is a function of the object's size. For large, low-density objects a failure to correct for buoyancy may result in an error of 0.5 %, or even more. Other concerns (i.e., tidal effects, gravitational anomalies, electrostatic and magnetic attractions to nearby objects, air currents) can be neglected, except in the case of very precise measurements.

Kitchen scales are intend for personal use and are, therefore, not metrologically inspected at the place of use. Usually, these can be classified in the ordinary accuracy class (ⅢⅢ) according to Table 1. This is why all these scales are manufactured and adjusted to a standard defined acceleration due to gravity, which is 9.80665 m/s^2. However, since there are for personal use the producer can "freely" choose the parameters and declare the precision.

The tendency in small kitchen appliances, especially for kitchen robots and food processors, is to integrate the function of the scale into the appliance. Usually, four force sensors (load cells) are used and integrated into the bottom of appliance. In this case, low-cost sensors are preferred. In such a case the integrated force sensors are loaded with the mass of the appliance (dead load) as well as with the mass being weighed. This dead load can be equal or even greater than the load that will be measured. In such a case, force sensors for a higher measuring range must be used and the actual measuring range is only a part of the declared measuring range of the sensor.

The aim of this paper is to benchmark different types of force sensors that can be used in certain types of small household appliances for weighing applications. Four types of force sensors were studied and evaluated.

The first two types of evaluated force sensors are based on thick-film technology, where the sensing piezoresistive resistors are screen printed and fired on an alumina substrate. The change in resistance of the resistors under an applied stress is partly due to the deformation, i.e., changes in the dimensions of the resistor, and partly due to an alteration in the specific resistivity as a result of microstructural changes /3, 4/. The gauge factor (GF) of a resistor is defined as the ratio of the relative change in the resistance ($\Delta R/R$) and the strain (ε), defined as ($\Delta l/l$), and is described by equation (1).

$$GF = (\Delta R/R)/(\Delta l/l) = (\Delta R/R)/\varepsilon \qquad (1)$$

Geometrical factors alone result in gauge factors of 2-2.5. Higher gauge factor values are due to microstructural changes, which alter the specific conductivity. The GF values of thick-film resistors are mostly between 3 and 15, and are higher than those of metal strain gauges (GF ~2) and lower than those realized with semiconducting elements (GF 50–200) /3, 4/. In the first type of force sensor, four thick-film sensing resistors are screen printed and fired on an alumina substrate, which is bonded to an aluminium double bending beam spring element (more details in Section 2.1). With a special design of this element, areas with concentrated strain can be achieved. Sensing resistors, which are connected in a Wheatstone bridge, are placed at the areas where the highest strain occurs. A simple planar construction of the spring element is used for the second type of force sensor. The alumina substrates with two screen-printed and fired thick-film resistors are bonded to the spring element, which is punched out from a steel plate. Since only two sense resistors are used, two additional fixed resistors of the same value are needed to realize half of the Wheatstone bridge circuit.

The third and fourth types of evaluated sensors based on the so-called force-to-pressure transformation principle are known as hydraulic (or hydrostatic) force sensors. Such kinds of force sensors are also generally known as hydraulic load cells. Hydraulic force sensors are force-balance devices, measuring force as a change in the pressure of an internal filling fluid. A force acting on a loading head is transferred to a piston, which in turn compresses a filling fluid confined within an elastomeric diaphragm chamber. As the force increases, the pressure of the hydraulic fluid rises. A pressure sensor – in these two cases with a small-sized piezoresistive absolute-pressure sensor chip – measures the fluid pressure. With such a kind of transformation the voltage output signal of the pressure sensor is proportional to the force that acts on the loading member of the sensor. Hydraulic force sensors are generally used to measure relatively large forces (i.e., from 500 N upwards) in harsh and industrial environments. The output is linear and relatively unaffected by the amount of filling fluid. With careful design and manufacturing, the accuracy can be within 0.25 % full scale /5/, but in general their accuracy is 0.5 % to 1 % of full scale.

The housing of the third type of force sensor is made from plastic and closed with rubber on one side. The interior is completely filled with fluid – a silicon oil is used. At the upper side of the force sensor the absolute silicon pressure sensor chip is bonded onto the ceramic substrate and through the contact pins connected to the measuring system. This type of sensor is described in Section 4 in more detail.

The forth type of force sensor is made from a copper-based metallic housing. A hydroformed metallic bellows is used as the loading member and this is soldered together with the base housing of the sensor. An absolute silicon pressure sensor is bonded to a hermetically closed TO-5 transistor header, which is soldered onto the body of the sensor. The details of this hydraulic force sensor are described in Section 5.

The most important characteristics of force sensors are non-linearity, hysteresis error, sensitivity and repeatability. Non-linearity is the deviation from a straight line of the increasing force sensor signal output curve. For this benchmarking, the linear approximation between the first and last measured points was taken. The hysteresis error is defined as the difference between the force-sensor readings for the same applied load: one reading obtained by increasing the load from the minimum load and the other by decreasing the load from the maximum load. The sensitivity is the ratio of the change in the response (output) of a force sensor to a corresponding change in the stimulus (load applied). Repeatability is the ability of a force sensor to provide successive results that are in agreement when the same load is applied several times and applied in the same manner on the force sensor under constant test conditions.

In this paper, measurements of these characteristics of the evaluated sensors are compared and discussed.

2. Force sensor with double bending beam with tHick-film strain gauge

2.1 Design and construction

The double bending beam (also called a binocular form beam) is often used as a spring element in force sensors. The key parts of the spring element are the two "weak" points, with the aim to concentrate the strain induced by the applied force on the sensing resistors /6/. The double bending spring element is presented in Fig. 1 and the two "weak" points are shown in Fig. 2.

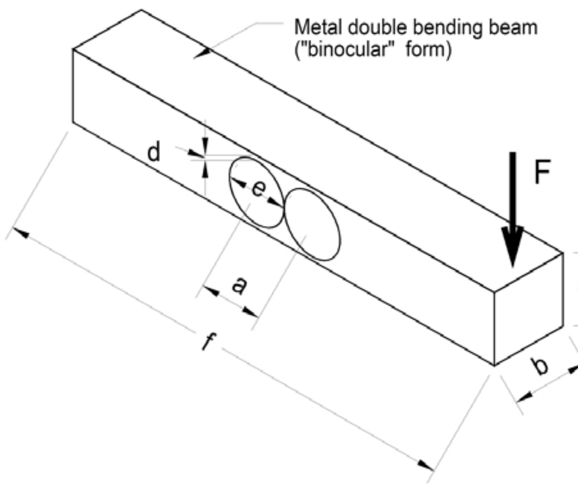

Fig. 1: The double bending spring element.

The strain in the most sensitive part of the beam is described by equation (2)

$$\varepsilon = \frac{1.5\, Fa}{Ebd^{2}} \tag{2}$$

where the strain (m/m) is a function of the applied force, *F* (N), the Young's modulus, *E* (Pa), and the dimensions *a* (m), *b* (m) and *d* (m), as denoted in Fig. 1. The working principle of the double bending beam is schematically shown in Fig. 2. The strain is concentrated in two points: the positive (tensile) strain is concentrated in the first weak point, and the negative (compressive) strain is concentrated in the second weak point, marked in Fig. 2 by *R+dR* (the increase of resistance) and *R-dR* (the decrease of resistance), respectively.

In our case the force sensor converts a mechanical quantity (force) into strain, and then translates it into an electrical signal (voltage) using the resistance change of the thick-film sensing resistors printed and fired on the alumina substrate.

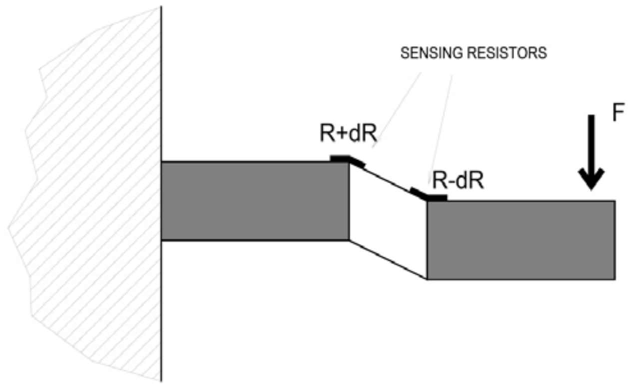

Fig. 2: Working principle of the double bending beam.

The thick-film strain gauge, i.e., the ceramic substrate with the thick-film sensing resistors, is shown in Fig. 3. The working principle of the thick-film strain gauge is piezoresistivity – the property of resistor materials to change their resistivity under strain. Four thick-film sensing resistors are located on the double bending beam, so that two are under tensile strain, and two are under compressive strain. Sensing resistors are placed on the positions of the maximum tensile and compressive stains on the double bending beam. These four sensing resistors are electrically connected in a Wheatstone-bridge configuration and are excited with a stabilized bridge voltage (Fig. 4). The output of such a strain gauge is the voltage vs. strain induced by the applied force.

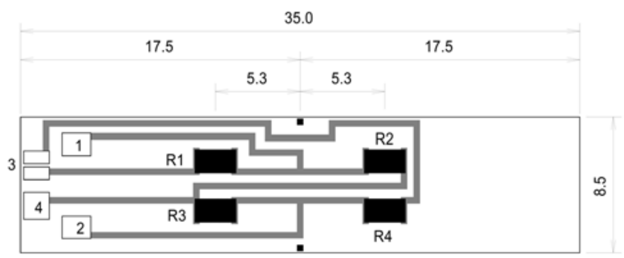

Fig. 3: Alumina substrate with thick-film resistors connected in a Wheatstone bridge.

The aluminium double bending beam, shown in Fig. 1 (and described by equation (2)), was designed with the following dimensions: a = 10.6 mm, b = 13 mm, c = 12 mm, d = 1.2 mm, e = 10 mm, and f = 80 mm. The material for the double bending beam is aluminium, which has a Young's modulus of 73 GPa, and a thermal expansion coefficient of 23×10^{-6}/K. The thick-film strain gauge shown in Fig. 3 consists of four thick-film resistors printed and fired on the alumina substrate. Sensing resistors have a resistance of 1300 ohm and have a value for the gauge factor of around 8. The thick-film strain gauge is bonded with glue onto the aluminium double bending beam. An example of the realized force sensors with the thick-film strain gauge is shown in Fig. 5.

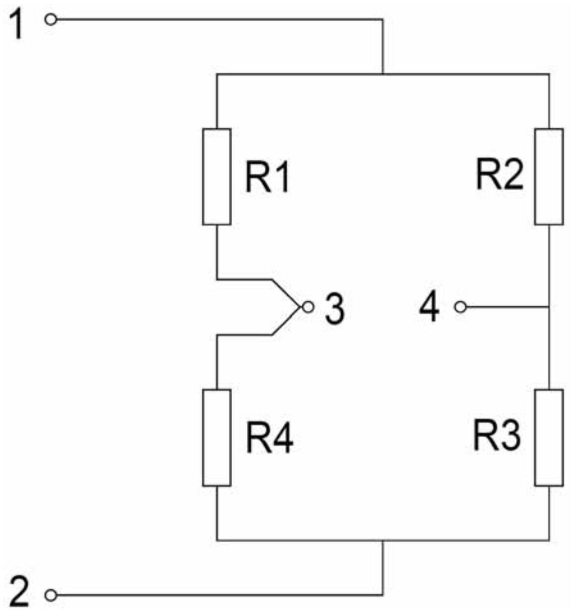

Fig. 4: Four sensing resistors connected in a Wheatstone bridge.

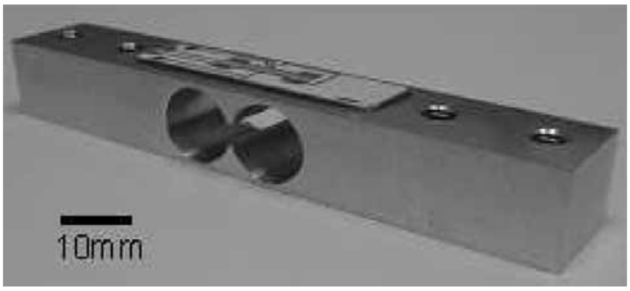

Fig. 5: The thick-film strain gauge on the alumina substrate is bonded on a double bending aluminium spring element.

2.2 Results

The fabricated samples (see Fig. 5) were mechanically fixed on one side and loaded with different forces (loads) on the other side. The thick-film strain gauges were excited with a stabilized bridge voltage of 5 V and the output voltage was measured. All the test samples were tested at different applied forces (weighing loads). The range of the applied forces was from 0 N to 34 N (0–3.4 kg). The output voltage versus loading force for a typical test sample is presented in Fig. 6.

The calculated force sensitivity from the measured data is about 45 µV/V/N. Some other characteristics of this type of force sensor with a thick-film strain gauge are presented in Section 6, Table 2. The non-linearity is 0.2 %, the hysteresis error is less than 0.2 %, and the offset voltage of the unloaded sensor is up to ±4 mV.

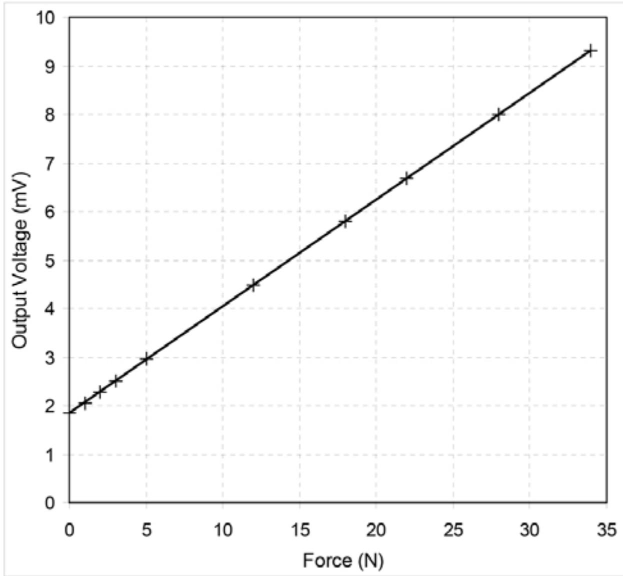

Fig. 6: Output characteristics of the force sensor with a thick-film strain gauge.

3. Thick-film double bending planar force sensor

3.1 Design and construction

A thick-film double bending planar force sensor was evaluated. The spring element, with outer dimensions of 32 mm x 29.9 mm, and with an 8-mm-wide and 18.6-mm-long flexure bar, is punched out from a 1.2-mm-thick sheet of 1.4016 ferritic steel. The Young's modulus, the Poisson's ratio and the thermal expansion coefficient of this steel are 200 GPa, 0.3 and 12×10^{-6}/K, respectively. The alumina substrate with screen-printed and fired sensing resistors is glued onto the flexure bar. The spring element with the glued alumina substrate on the double bended flexure bar is presented in Fig. 7.

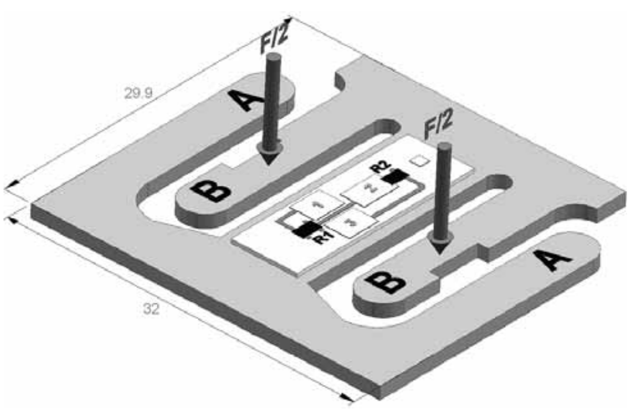

Fig. 7: Main dimensions of the double bending spring element where the outer arms are marked with A and the inner arms are marked with B.

The spring element consists of three key parts. Two outer arms, marked with A, are meant to be on a fixed support.

Both inner arms, marked by B, are loaded, through a special connecting mechanical structure, with the applied force.

The force is applied equally on both inner arms. The thick-film strain gauge is realized with two thick-film resistors printed and fired on alumina. The force sensor converts the mechanical quantity (force) into a strain and translates it into an electrical signal (voltage) using the resistance change in two sensing resistors.

Both resistors are trimmed to a resistance value of 10,000 ohm and are electrically connected to half the Wheatstone-bridge (two additional resistors are needed on the measurement side). The sensing resistor R1 lies on the positive (tensile) strain, while the sensing resistor R2 lies on the negative (compressive) strain. The alumina substrate with two thick-film sensing resistors and the main dimensions are schematically shown in Fig. 8.

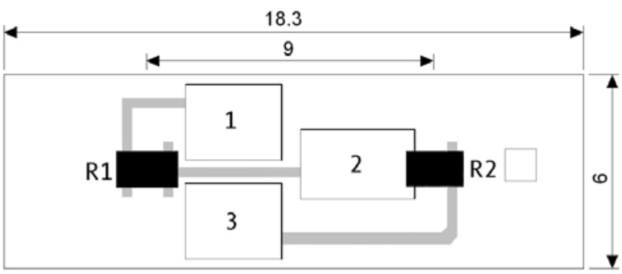

Fig. 8: Alumina substrate with two thick-film resistors. The contact pads are marked with 1, 2 and 3.

When a force is applied on the spring element of the force sensor a typical double bending of the flexure bar occurs. The deformation of the spring element under applied force was simulated using the finite-element method /7/. In Fig. 9 the deformation and the normal component of strain, which is along the axis of the flexure bar, are shown – for better clarity the deformation is over scaled. Lighter areas represent the areas under tensile strain and the darker areas represent the areas under compressive strain.

The strain reaches its peak value at both ends of the flexure bar. The peak values of the positive and negative strains are almost identical. At the areas of the maximum peaks there is also a lot of transverse strain. It is well known that the sensing resistors are also sensitive to transverse strain /8/.

To minimize the measuring error the influence of the transverse strain must be minimized. To achieve this, the sensing resistors are placed away from the areas of maximum strain and some sensitivity is sacrificed for a better accuracy. In the case of an uneven load to both inner arms a twisting of the flexure bar occurs. To minimize this effect, both sensing resistors are placed on a symmetric axis along the flexure bar.

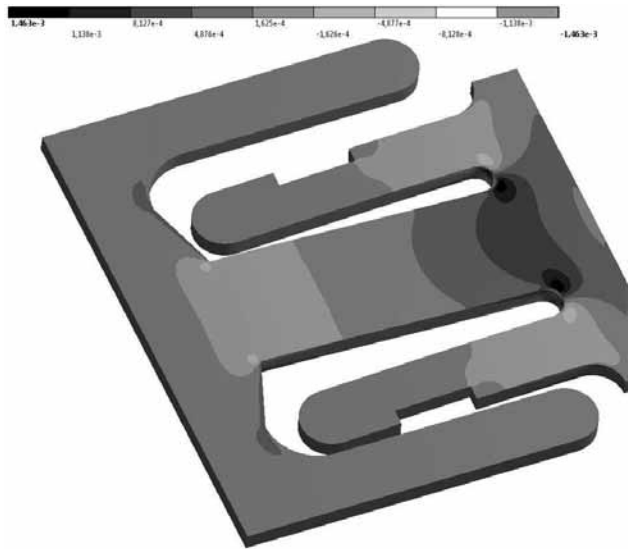

Fig. 9: Planar force sensors under an applied force. The normal component of strain (along the axis of the flexure bar) and the over-scaled mechanical deformation.

3.2 Results

The samples were supported under both outer arms and loaded with different forces (loads) through the mechanical structure on both inner arms, which are located on the other side of the flexure bar. The range of the weighting loads was from 20 N to 32 N, with 20 N of preload (dead load). The thick-film strain gauges were excited with a stabilized bridge voltage of 3.3 V and the output voltage was measured. An additional two resistors of 10 kΩ were used to complete the Wheatstone bridge and to achieve more accurate measurements. The output voltage versus the loading force for a typical test sample is presented in Fig. 10.

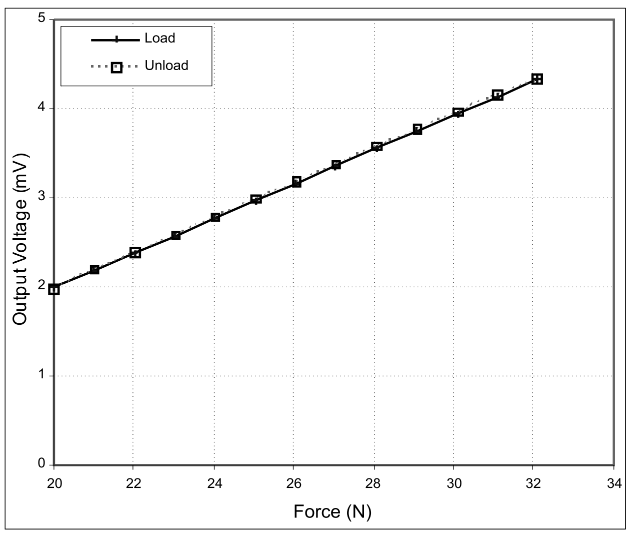

Fig. 10: Output characteristics - voltage vs. force - of the planar force sensor with a thick-film strain gauge.

The calculated force sensitivity from the measured data is about 58 µV/V/N. Some other characteristics of this type of force sensors with a thick-film strain gauge are presented in Section 6, Table 2. The non-linearity is 0.3 %, the hysteresis error is less than 0.4 %, and the offset voltage of the no-load sensor is up to ±4 mV.

4. Hydraulic force sensor with plastic housing and rubber meMbrane

4.1 Design and construction

The housing of this hydraulic force sensor is made from glass-reinforced Nylon (PA66-GF30). EPDM (ethylene-propylene-diene Monomer) rubber was vulcanized directly onto the plastic housing on a specially designed and custom-made moulding tool.

In Fig. 11 the main dimension of the realized force sensor in cross-section is shown.

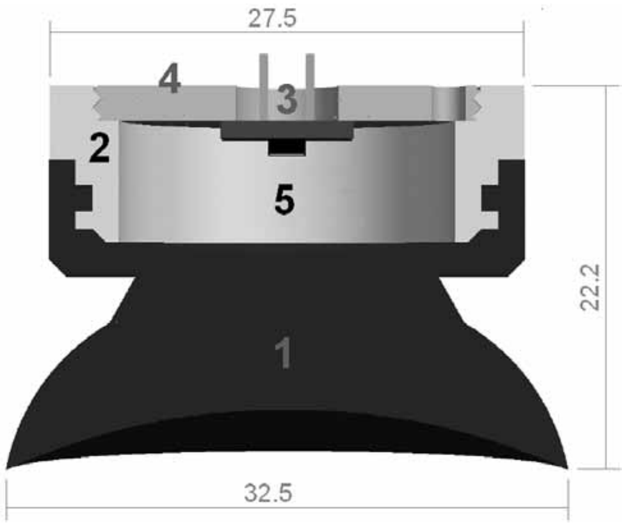

Fig. 11: Hydraulic force sensor with main dimensions. The rubber part (denoted by 1) is vulcanized directly to the plastic body (denoted by 2).

As already mentioned, the plastic housing (denoted by 2) was made from reinforced nylon. The surfaces that are in contact with the rubber were treated with a special primer 24 hours before the vulcanization to ensure a reliable junction between the plastic housing and the rubber part (denoted by 1). The rubber part functions as a membrane for the hydraulic force sensor and also as suction feet on the other side. After the vulcanization of the rubber to the plastic housing, the cover lid (denoted by 4) with a sensing element (denoted by 3) is placed onto the plastic body. The sensing element is an absolute silicon pressure chip bonded onto the alumina substrate.

Through four contact pins a sensing element is connected to a measurement system. The interior (denoted by 5) is filled with fluid - a Wacker AK100 silicon fluid is used. After the filling process both the filling holes were sealed. In Fig. 12 a fabricated sample of the hydraulic force sensor with a plastic housing and a rubber membrane is presented.

Fig. 12: Hydraulic force sensor with plastic housing and integrated vacuum suction feet.

4.2 Results

The fabricated samples (shown in Fig. 12) were loaded with different forces (loads). The silicon pressure chip was excited with a stabilized bridge voltage of 3.3 V and the output voltage was measured. The range of the measured forces was from 20 N to 32 N, with 20 N of preload (dead load). The output voltage versus loading force for a typical test sample is presented in Fig. 13.

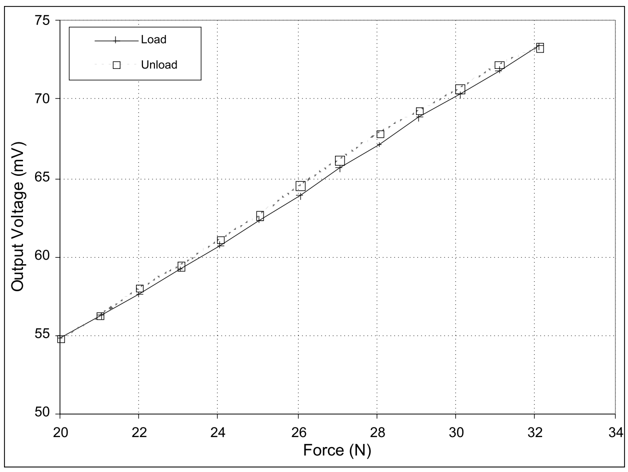

Fig. 13: A force-to-pressure transformation, sensor made from plastic and rubber.

The calculated force sensitivity from the measured data is about 470 µV/V/N. Some other characteristics of this type of force sensor with a silicon pressure sensor are presented in Section 6, Table 2. The non-linearity is 1.5 %, the hysteresis error is around 3.5 % and the offset voltage of the no-load sensor is up to 25 mV.

5. Hydraulic force sensor with METALLIC body

5.1 Design and construction

This type of force sensor is made from metallic parts. A cross-section of such a construction is shown in Fig. 14. With such a construction, better measurement parameters of the hydraulic force sensor were expected (based on the hydraulic force sensor described in Section 4). A copper cap (denoted by 1) with a 1-mm-thick wall and an 8.2-mm hole at the bottom is used as the housing for this type of hydraulic force sensor. A hydroformed metal bellows (denoted by 2), which is made from phosphor bronze, is soldered at the other side of the copper cap. The metal bellows with three convolutions of 19.1 mm for the outside diameter and a 0.1-mm-thick wall is designed for a nominal pressure of 200 kPa. Since one convolution is soldered to the housing only two of them are actually active.

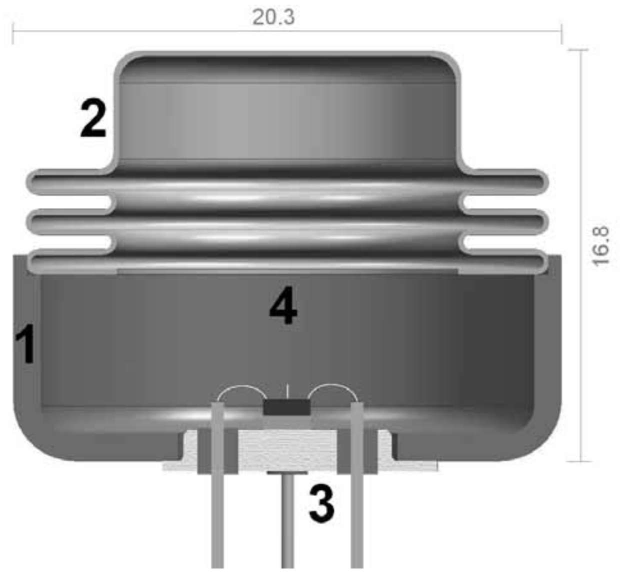

Fig. 14: Hydraulic force sensor with metallic body and metal bellows in cross-section.

An absolute silicon pressure chip is placed on the TO-5 transistor header (denoted by 3) and electrically connected with bonded wires to four connecting pins. The connecting pins are insulated with glass and hermetically sealed. Through these four contact pins a sensing element is connected to a measurement system. The interior (denoted by 4) is filled with fluid - a Wacker AK100 silicon fluid, like in the case of the hydraulic force sensor with the plastic housing (see Section 4.1). The realized hydraulic force sensor with a metallic body is presented in Fig. 15.

5.2 Results

The fabricated samples (shown in Fig. 15) were loaded with different forces (loads). The silicon pressure chip was excited with a stabilized bridge voltage of 3.3 V and the output voltage was measured. The range of the measured forces was from 20 N to 32 N, with 20 N of preload (dead load). The output voltage versus loading force for a typical test sample is presented in Fig. 16.

Fig. 15: Hydraulic force sensor realized with metallic body and metal bellows.

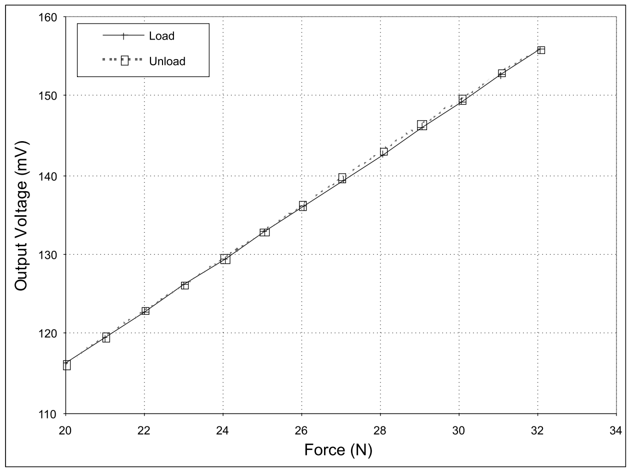

Fig. 16: A force-to-pressure transformation made from the hydroformed bellows.

The calculated force sensitivity from the measured data is about 1000 μV/V/N. Some other characteristics of this type of force sensors with a silicon pressure sensor are presented in Section 6, Table 2. The non-linearity is 0.3 %, the hysteresis error is less than 0.8 %, and the offset voltage of the no-load sensor is up to 60 mV.

6. Benchmarking and conclusions

The force sensors for weighing small masses in cost-sensitive applications can be realized with different types of sensing elements. Four types of sensing element were investigated:

Table 2: Some characteristics of force sensors realized with different types of sensing elements

Characteristics	Type 1	Type 2	Type 3	Type 4
Resistance (Ohm)	1300	10 000	3500	3500
TCR (10^{-6}/K)	± 100	± 100	~ 2800	~2800
Non-linearity error (%)	0.2	0.3	1.5	0.3
Hysteresis error (%)	0.2	0.4	3.5	0.8
Sensitivity (µV/V/N)	45	58	470	1000
Offset (mV)	± 4	± 4	± 25	±60

Type 1: Force sensor realized with a double bending beam with a thick-film strain gauge

Type 2: Force sensor realized with a double bending planar spring element with a thick-film strain gauge

Type 3: Hydraulic force sensor with a plastic housing and rubber feet as a load-member part.

Type 4: Hydraulic force sensor with a metallic housing and a metal bellows.

Some characteristics of the realized force sensors with different types of sensing elements are presented in Table 2. The resistances and temperature coefficient of resistivity (TCR) are given. The measured and calculated values for the non-linearity errors, the hysteresis errors, the sensitivities and the offset voltages (unloaded samples) are presented.

The TCRs of thick-film resistors (types 1 and 2) are around 100×10^{-6}/K and are much lower than the TCRs on silicon pressure sensor chips, which were used as the sensing elements for the types 3 and 4 hydraulic force sensors. The non-linearity errors were similar for the types 1, 2 and 4 force sensors, while for the type 3 force sensor the values were five times higher. The hysteresis errors were around 3.5 % for the type 3 – hydraulic sensors with plastic housing, while for the other types the values were below 1 %. The sensitivities of the sensors with silicon sensing elements were between 10 to 20 times higher than the sensitivities of the sensors with thick-film resistors. On the other hand, the offset voltages of the unloaded force sensors were significantly higher for the hydraulic force sensors with the silicon sensing elements.

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