Development of a Novel Mechanical Transducer for Force Monitoring Using Micro-Electromechanical Sensor (MEMS)

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Abstract

MEMS piezoresistive sensors are more favourable and attractive option for strain detection due to a number of key advantages such as high sensitivity, low noise, better scaling characteristics, low cost and their ability to have the detection electronics circuit further away from the sensor or on the same sensing board. This paper represents the results obtained at characterization of novel transducers to be employed into force monitoring systems. Each transducer comprises a coherently designed mechanical transducer and a position MEMS sensor with very high accuracy.

The exploited position MEMS microsensor and the mechanical transducer are presented in this paper. The particular MEMS sensor provides a voltage output signal having sensitivity in the range of 240µV/µm at 1V DC voltage supply. The range of operation of the mechanical transducer is optimized to fit the 300µm travel range of position microsensor. Respectively, the flexures' stiffness corresponds to achieve the max displacement at 1000N load force. A finite element model is constructed to simulate the system structure using the commercial FE package. A prototype of the force transducer is described and manner of used silicon MEMS sensor attachment is demonstrated. An experimental set-up and experimentally measured load curve are presented in the paper. Diagrams force/voltage for two prototypes at different supply voltage 1V and 2V are revealed.

Keywords: Mechanical Transducer, Force Monitoring, MEMS Sensor, Experimental Data

1. Introduction

A load cell is a transducer that converts load acting on it into an analog electrical signal. Typically, this conversion is achieved by strain gauges which are bonded into the load cell beam and wired into a Wheatstone bridge configuration. Strain gauge load cells dominate the weighing industry [1].

High-performance strain sensing systems, consisting of sensors and interface electronics, are highly desirable for advanced industrial applications, such as point-stress and torque sensing, and strain mapping. Conventional strain sensors made from metal foils suffer from limited sensitivity, large temperature dependence and high power consumption. Further, the metal-foil strain gauges offer flexibility and the potential for use in this format, but they suffer low gauge factor (GF) and limited scalability to large areas due to lack of strategies for multiplexed addressing [2].Therefore, they are inadequate for high performance and low power consumption applications [3] and hence other strain sensing methods, based on the Micro Electro Mechanical Systems (MEMS) technology, have been proposed [4, 5].

New advances in the field of Micro Electro Mechanical Systems (MEMS) have broadened considerably the applications of these devices. MEMS technology has also enabled the miniaturization of the devices, and a typical MEMS sensor is at least one order of magnitude smaller compared to a conventional metal-foil strain sensor that is used to measure the same quantity. Consequently, MEMS devices can be batch-fabricated, which offers a high potential for cost reduction. Moreover, proper design can solve problems related to power consumption, while providing improved performance characteristics, such as accuracy, sensitivity and resolution. Finite Element Analysis (FEA) provides a reliable tool to carry out the required parametric studies in order to optimize the sensor performance [6].

Several physical sensing principles have been explored in MEMS strain sensors including the modulation of optical, capacitive, piezoelectric, and piezoresistive properties or frequency shift [7, 8].

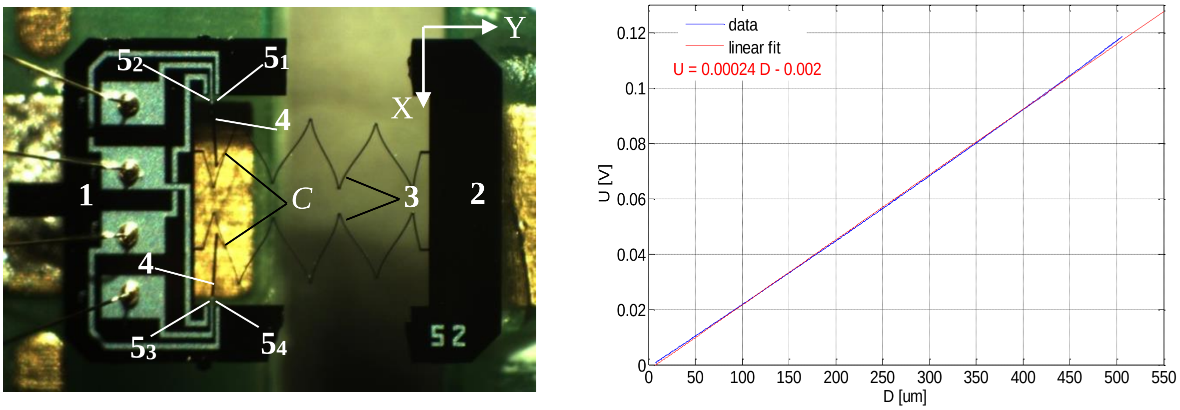
More particularly, MEMS piezoresistive strain sensors are more favourable and attractive due to a number of key advantages such as high sensitivity [1], low noise, better scaling characteristics, low cost and their ability to have the detection electronics circuit further away from the sensor or on the same sensing board. Moreover, they have high potential for monolithic integration with low-power CMOS electronics. Furthermore, piezoresistive strain sensors need less complicated conditioning circuits [9].

MEMS load sensors capable of both steady-state and dynamic measurements are generally designed as compliant structures. The device geometry and operating voltages can be optimized for maximum force resolution and range, subject to a number of manufacturing and electromechanical constraints [10].

In present paper a force measuring system including a mechanical transducer and a silicon MEMS position sensor with sidewall piezoresistors [11] has been studied. Thus, the performance of the entire force monitoring systems, such as high class electronic scales, can be strongly improved by replacing the currently employed force transducers.

2. MEMS position sensor for detection of 500µm range displacement

The particular approach is based on exploitation of contact MEMS device for displacement detection in the range of 500µm [12]. The envisaged position microsensor comprises of a single anchored (1) and a single moveable (2) part. Both parts are connected with a monolithic flexure (3), shown in the Fig. 1 (a). The monolithic flexure (3) comprises two pairs of differential springs and two detecting cantilevers (4), which are also attached at the point *C* of spring’s connection.



(a) **(b)**

Figure 1: (a): Optical micrograph of a position microsensor with a single anchored (1) and a single actuated (2) part and a flexure (3) comprising two cantilevers (4) oriented in X direction; four sidewall piezoresistors (5_1–5_4), sensitive in Y direction are built-in at the fixed ends of cantilevers; (b): Plot of the sensor signal showing 240µV/µm.V sensitivity @ 500µm travel range

The cantilevers are oriented in X direction and the move of part (2) in Y direction is transduced to a bending of cantilevers’ (4) by differential springs. In the sidewalls of the fixed end of the both cantilevers (4) four piezoresistors are embedded (5_1 - 5_4). In more details, each cantilever possesses a pair of two piezoresistors, 5_1 - 5_2 and 5_3 - 5_4 respectively, which are electrically connected in two voltage dividers. Both voltage dividers are further so connected in a full bridge configuration, to amplify each other, when actuated part (2) moves in Y (horizontal) direction. This particular sensor has demonstrated a displacement sensitivity of 240µV/µm at 1V DC voltage supply of the bridge as plotted in Fig. 1(b), and the travel range is limited to approx. 650 µm.

Since differential springs displayed in Fig. 1(a), are mechanically instable in compression mode, this particular flexure (3) can be used in tensile mode, only. Additionally, the devices with sidewall embedded piezoresistors exhibit very low noise and extremely low (i.e., non-detected, at all) temperature dependence [13]. By means of a modification of the flexure layout the sensitivity and the travel range can be tuned to meet optimization criteria [14].

As far, the detecting cantilevers (4) with sidewall piezoresistors ensure sensor signal having above 1,000,000 of intervals in the full scale range, there is a room to achieve a ppm (part per million) resolution of the force transducers, if optimized mechanical transducers are developed.

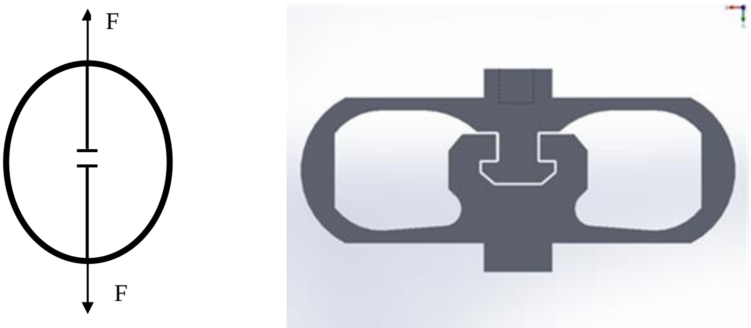
Since the silicon flexures are extremely fragile, auxiliary mechanical parts having package features for fixing and protecting the both MEMS parts and providing a relative displacement in the range of from 50µm to 1.5mm, have been developed. They could be made of different materials and the mechanical properties could be tuned to measure in desired force range. Based on experimentally measured results, a method of force monitoring with ppm-accuracy, independently on ambient conditions, has been proposed [14]. Thus, the performance of the entire force monitoring systems, such as high class electronic scales, can be strongly improved by replacing the currently employed force transducers.

Since the moveable part of the MEMS sensor possesses six Degrees of Freedom (DoF), up to six independent values can be simultaneously measured, if appropriate flexures are provided.

3. Development of a mechanical transducer for force monitoring using MEMS sensor

The goal of present study is to develop a new high performing mechanical transducer applicable in force monitoring systems. To monitor the forces within specified limits it is necessary to develop a flexible transducer mechanism, which transforms the force-load to a displacement of the MEMS sensor, and the stiffness of the transducer determines the range of the measured forces. In order to develop the targeted high performing force monitoring systems, the design approach exploiting flexure mechanisms [15] has been proposed. Respectively, a flexible transducer mechanism, which transforms the applied load to an elastic strain to be detected by the position microsensor, has been created.

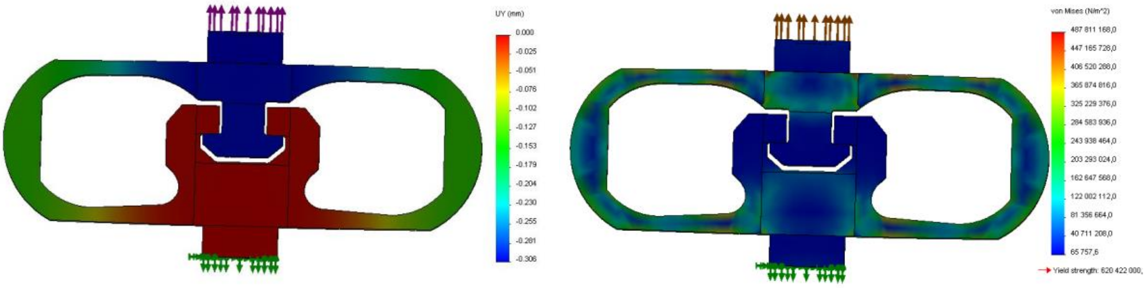
The mechanical transducer is an "O-ring" type, as illustrated in Fig.2 (a). Tensile load is applied to one side of the "O-ring" and support reaction is applied in the opposite side. The MEMS position sensor is placed and fixed in the middle of the ring along the axis of the applied force, thus it monitors the displacements directly. The constructed 3D CAD model of the mechanical transducer is shown in Fig. 2(b). Admissible deformations of MEMS sensor are determined - 0.6 mm, and the upper limit of the measured force is specified – 1000N.



(a) (b)

Figure 2: Mechanical transducer mechanism: (a) kinematic scheme; (b) CAD model

To meet the specified range of monitored forces, it is necessary to provide the relevant stiffness of mechanical transducer. Commercial CAD system exploiting finite element modelling (FEM) has been used for caring out a simulation of a static load. Computer simulations were conducted, assuming that the load has been attached at the upper end of the transmission mechanism and the lower end has been rigidly immobilized. Load with a static force of 1000N was simulated, using a model with varying thickness of the transducer plate. After a series of experiments, plate with thickness of 11 mm has been selected to achieve a suitable stiffness. Steel alloy with Young’s modulus of E = 210 GPa and Yield strength of σ = 0.620 GPa has been chosen as a raw material. The screen plot with calculated results for effective displacements is shown in Fig. 3 (a). At so selected stiffness of the transducer, a load of 1000 N generates a displacement of 0.300 mm, which is to be measured by the MEMS position sensor. The screen plot with effective stress is shown in Fig. 3 (b). The highest normal stress does not exceed the yield strength of the material.



(a) (b)

Figure 3: Simulations of mechanical transducer mechanism: (a) screen plot with effective displacements, (a) screen plot with effective stress

A prototype of the mechanical transducer has been manufactured with the help of wire electro-discharge machining. Photos of both sides of the force transducer prototype are shown in Fig 4. Both parts of the piezoresistive MEMS position sensor are firmly bonded to chip-carriers which are further fixed by screws to both loaded sides of the "O-ring", as shown in Fig.4. (a). The maximum travel range of the transducer is constrained to 0.300 mm, by cutting into the housing a gap with same clearance - the gap *G* in Fig. 4 (b), thus, limiting the monitored force-load to 1000N. This constrain prevents mechanical overload and damage to the MEMS position sensor, as well as keeps the tensile and bending stresses in the transducer bellow yielding stress with a safety factor of 1.2.

(a) **(b)**

Figure 4: Photo of a prototype of the mechanical transducer– (a) front side with mounted MEMS position sensor, (b) rear side

4. Experimental set-up and experimental data

The mechanical transducer prototype is tested for load measurements by a precise loading test machine TIRAtest 2300. The system exploits a load cell with a measuring range of 10kN, a digital multi-meter PeakTech 3415 connected to a computer and the prototype of force transducer, connected on both sides with loading machine traverses. The MEMS sensor is supplied with a stabilized DC voltage supply – one test has been carried out at 1V and other test - at 2V. The output voltage of the sensor is recorded using a digital multi-metre Protek D470 connected to the computer. Fig. 5 shows the experimental set-up used for load monitoring.

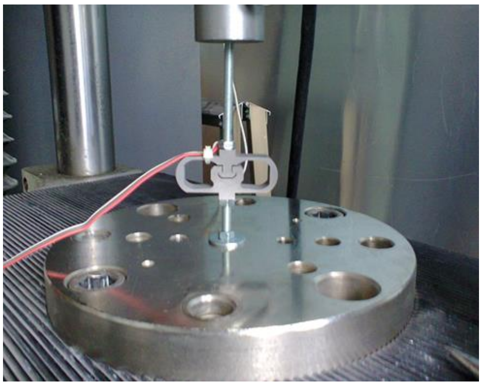


Figure5: Optical photo of the experimental set-up for load measurements used in present study

The testing machine loads the prototype at a constant speed by measuring both: the loading force and the output voltage of the position sensor. To obtain the force/voltage ratio, both registered signals are time synchronized.
Measurements are made of two identical prototypes marked as P1 and P2, at power supply of 1V and 2V and loading/unloading from 0 to 1000 N and vice versa. There are three experiments made to each prototype under loading and unloading at a speed of mobile traverse of 0.480 mm/min. The obtained force/voltage diagrams of these experiments under different sensor supply voltage are shown in Fig.6. The resulting diagrams are linear, which can be expressed by $\boldsymbol{F = aU + b}$, where $\boldsymbol{F}$ is loading force and $\boldsymbol{U}$ is output voltage.
The slope $\boldsymbol{a}$ of each diagram depends on the supply voltage. Both transducers have identical slopes at the same supply, but each transducer has a different offset $\boldsymbol{b}$**.** This offset is defined by the sensor used as a result of the

sensor preload. The average values of coefficients $\boldsymbol{a}$ and offset voltage $\boldsymbol{U_o=-b/a}$, at a given supply for each prototype areas follows $\boldsymbol{U}$=1V: $\boldsymbol{a_1}$= 21767 N/V, $\boldsymbol{U_{01}}$=0,0660 V, $\boldsymbol{a_2}$=22047N/V, $\boldsymbol{U_{02}}$=0,0315 V; $\boldsymbol{U}$=2V: $\boldsymbol{a_1}$=11027N/V **,** $\boldsymbol{U}_{01}$= 0,1318 V, $\boldsymbol{a_2}$=11226N/V , $\boldsymbol{U_{02}}$=0,0624 V.

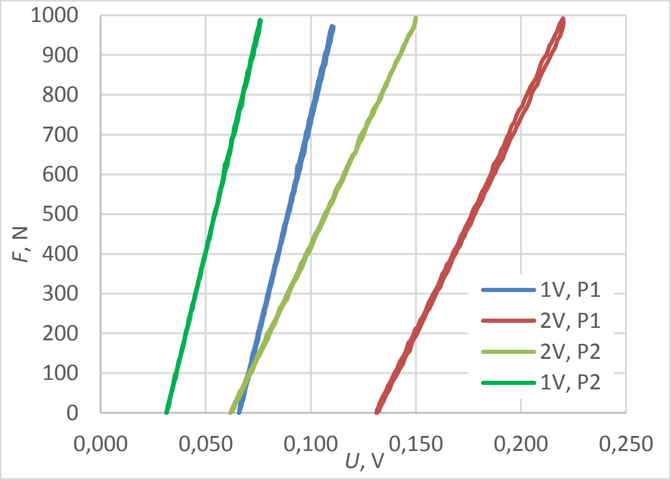


Figure6: Diagrams force/voltage for two prototypes P1 and P2 at supply voltage of 1V and 2V

The charts show that the unloading curve does not tally with loading chart but the hysteresis get is fairly small. Hysteresis observed can be due to imperfections of the measuring system, i.e. miss-synchronization between the two measurements channels when switching load/unload measurements, etc.

Conclusions

This paper represents the results obtained at characterization of novel transducers to be employed into force monitoring systems. Each transducer comprises a coherently designed mechanical transducer and a MEMS position sensor with very high accuracy.

The MEMS position microsensor and the design of the mechanical transducer are presented in the paper. The range of operation of the mechanical transducer is optimized to fit the 300µm travel range of the position microsensor. Respectively, the flexures' stiffness corresponds to achieve the max displacement at 1000N load force. A finite element model is constructed to simulate the system structure using the commercial FE package. The force transducer range of operation is limited by the width of the gap *G*, which also, avoids damages of the mechanical transducer and MEMS position sensor. A prototype of the force transducer is described and manner of usage of the silicon MEMS position sensor attachment is demonstrated. An experimental set-up for measuring the load curves are reported in the paper. Diagrams of force vs. sensor output voltage of two prototypes at different supply voltage 1V and 2V are demonstrated and discussed.

As a result of the experiment it has been concluded that the force/voltage ratio is constant. Piezoresistive MEMS position sensors can be successfully used for strain detection at force loading of the mechanical transducer. Respectively, other than force values like: 3D strain, acceleration, torque, temperature and other environmental parameters, as well as their combinations can be accurately monitored, when suitable transducers are designed.

Acknowledgments

We gratefully acknowledge the financial supports of this work by grant 6IF-02-13/15.12.2012 of the Bulgarian National Innovation Fund and by FP7 Integrated Project VERE - No. FP7-257695 of the European Commission.

References

[1] Kumar, Sh., K P Venkatesh, S. S. Baskar, S. P. Madhavi. System integration design in MEMS–A case study of micromachined load cell. – Sadhana, Vol. 34, 2009, No. 4, pp. 663–675.

[2] Won, S. M., Hoon-Sik Kim, N. Lu, Dae-Gon Kim, Cesar Del Solar, T. Duenas, A. Ameen, J. A. Rogers. Piezoresistive Strain Sensors and Multiplexed Arrays Using Assemblies of Single-Crystalline Silicon

Nanoribbons on Plastic Substrates. - IEEE Transactions on electron devices, Vol. 58, 2011, No. 11, pp. 4074- 4078.

[3] Nagy, M.; C. Apanius; J. A. Siekkinen. A user friendly, high-sensitivity strain gauge. - Sensors, Vol. 18, 2001, pp. 20-27.

[4] Hrovat, M., D. Belavic, Z. Samardzija, J. Holc. An investigation of thick-film resistor, fired at different temperatures, for strain sensors. - International Spring Seminar on Electronics Technology, 2001, pp. 32-36.

[5] A. Mohammed, W. Moussa, E. Lou. Mechanical Strain Measurements Using Semiconductor Piezo-resistive Material.The 4th IEEE International Conference on MEMS, Nano and Smart Systems, and The 6th IEEE International Workshop on System-on-Chip for Real-Time Applications 2006, pp.5-6.

[6] Mohammed, A., W. A. Moussa, E. Lou. High-Performance Piezoresistive MEMS Strain Sensor with Low Thermal Sensitivity. - Sensors, Vol. 11, 2011, pp. 1819-1846; DOI: 10.3390/s110201819].

[7] Cao, L., T. Kim, S. Mantell, D. Polla. Simulation and fabrication of piezoresistive membrane type MEMS strain sensors. - Sensors and Actuators A: Physical, Vol. 80, 2000, pp. 273-279.

[8] Han, B., J. Ou. Embedded piezoresistive cement-based stress/strain sensor. - Sensors and Actuators A: Physical, Vol. 138, 2007, pp. 294-298.

[9] Fraden, J. Handbook of modern sensor: physics, designs, and applications. 2nd ed. AIP Press-Springer: New York, 1996.

[10] Torrents, A, K. Azgin, S. W. Godfrey, E. S. Topalli, T. Akin, L. Valdevit. MEMS resonant load cells for micro-mechanical test frames: feasibility study and optimal design. - J. Micromech. Microeng., Vol. 20, 2010, No. 12, pp. 1-17. DOI: 10.1088/0960-1317/20/12/125004.

[11] Stavrov, V., Tomerov, E., Stavreva, G., Hardalov, C., Shulev, A., “Lateral Displacement MEMS Sensor,” Proc. Eurosensors XXIV, Linz, Austria. pp 649-652. (2010).

[12] Stavrov, V., Todorov, V., Shulev, A., Hardalov. C., “MEMS Sensors for mm-Range Displacement Measurements with Sub-nm-Resolution”, Proc. of SPIE Conf. Microtechn. 2013, Grenoble, France v. 8763 87632G-1-6A (2013)

[13] Todorov, V., Stavreva, G., Stavrov, V., “Contact mode MEMS position sensors with piezoresistive detection” Proc. XXVIII EUROSENSORS 2014, Brescia, Italia (2014)

[14] Stavrov V., Shulev A., Chakarov D., Stavreva G., „Force monitoring transducers with more than 100,000 scale intervals“, Proc. of SPIE Conf. Microtechn. 2015, Barcelona, Spain v. 9517 95171Q-1-6

[15] Pham, H., Chen, I., “Stiffness modeling of flexure parallel mechanism”, Precision. Engineering 29, pp. 467–478. (2005)