NONLINEAR PHYSICS AND MECHANICS

MSC 2010: 93B18, 93B52

MEMS Sensor of Force

R. Hart'anský, J. Hricko, M. Mierka, J. Halgoš, M. Dzuriš

The paper is focused on the design of a compact compliant mechanical body (CCMB) that will be used as a transducer of the one-axis force to the distance of two plates. The conversion principle of the distance (which carries information about the acting force) to the frequency of the electrical signal is carefully described in the article too.

Keywords: compact compliant mechanical body, mechanical force sensor, transfer response

1. Introduction

Force measuring is needed in the industry, as well as in science or research and therefore there are many applications for force measuring sensors [5]. The magnitude of the force can be measured by a variety of specific types of sensors, which are commonly called “load cells”. Nowadays there is a need for compact and ultraprecision sensors, which will also operate in wide magnitudes of the measured unit. Unfortunately, for most of the sensor types, there is a limitation, which is restricting at least one criterion. Stepwise refinement of these sensors in last years has been accomplished by advanced and more detailed numerical analysis. Thanks to faster

Received May 31, 2019
Accepted October 01, 2019

This work was supported by the Slovak Research and Development Agency under contract No.: APVV-14-0076 — “MEMS structures based on load cell” and by the national scientific grant agency VEGA under project No.: 2/0155/19 — “Processing sensory data via Artificial Intelligence methods”.

René Hart'anský
`rene.hartansky@stuba.sk`

Martin Mierka
`xmierka@stuba.sk`

Ján Halgoš
`jan.halgos@stuba.sk`

Michal Dzuriš
`xdzurism@stuba.sk`

Institute of Electrical Engineering, Faculty of Electrical Engineering and Information Technology,
Slovak University of Technology, Bratislava, Slovakia

Jaroslav Hricko
`hricko@savbb.sk`
Institute of Informatics, Slovak Academy of Sciences
Banska Bystrica, Slovakia

Fig. 1. Variable types of load cells.

and more detailed simulations, new materials and better understanding of flexible joint geometry, type of force sensors, which are called “elastic deformation structure” are on the increase. This type could potentially be compact, ultraprecision and also be able to work in broad magnitudes of measured forces. The process of measuring with these “elastic deformation structure” is that the measured force is transferred into the structural stress, which is indicated by the deformation of the body. This deformation is subsequently transferred via one of the available methods into a signal that contains information about applied force on the body of the load cell. The most popular methods for transferring such a information are by changing resistive, capacitive, inductive, optical, piezoelectric or piezoresistive properties. A specific category of elastic deformation structures is the type of sensor known as “compact compliant mechanical body” (CCMB) [3]. CCMB structures are characterized by a variety of shape and material construction (Fig. 1). The advantage of many possible shapes is why CCMBs are used in many different applications mainly as weight sensor, scales, fluid level sensor in small tanks, overload sensors in elevator, or as mechanical stress and deterioration sensors in machines [9].

2. Mechanical design

Compact compliant mechanical body (CCMB) should be designed with respect to measurement physical principle [2] and [4]. In the case of the proposed wireless electromagnetic principle, one of the important design requirements is to develop the mechanism’s geometry so that two parallel surfaces can be utilized for a capacitor of the parallel resonance circuit. With this condition, there is requirement to minimal deformation of such plates and they should be consistent in parallel movement within 2 mm. Other functional requirements and boundary conditions are similar for the design of any sensor’s elastic body. A two-stage design procedure was adopted, where the basic sensor’s dimensions were calculated by analytical approaches. Then the dimensions and structure optimization procedure were carried out by FEM analysis in Comsol Multiphysics as a consequence of different results from analytical and numerical calculations (3–10% for one flexure element [8]).

For the first group of physical samples, Teflon (PTFE) with Young’s modulus $E_{PTFE} = 0.7$ GPa, Yield Strength $\sigma_{yPTFE} = 30$ MPa and Poisson ratio $\mu_{PTFE} = 0.42$ was chosen as a material of the deformable part of the sensor body. Such samples had been manufactured by the water cutting technology. Considering the demanding manufacturing process, the second group of physical samples had been manufactured by the 3D printing technology; and Polylactic acid (PLA) with Young’s modulus $E_{PLA} = 2.852$ GPa, Yield Strength $\sigma_{yPLA} = 38$ MPa and Poisson ratio $\mu_{PLA} = 0.36$ had been used as a material of CCMB. In the design of the

3D printed sensor's elastic bodies the change of Young modulus as a consequence of the print settings was neglected (for a detailed explanation see [11]). As mentioned above, the external force/load $\mathbf{F} = [F_x, F_y, F_z, M_x, M_y, M_z]^T$ can be evaluated as a dependence of the CCMB deflection $\mathbf{u} = [u_x, u_y, u_z, \theta_x, \theta_y, \theta_z]^T$ and compliance/stiffness $\mathbf{C} = \mathbf{K}^{-1}$, which express material mechanical properties, the shape of flexure and dimensions.

$$\mathbf{u} = \mathbf{C}\mathbf{F} \rightarrow \mathbf{F} = \mathbf{K}\mathbf{u} \quad (2.1)$$

For calculation of the compliance and stiffness matrices of the whole structure (see Fig. 2), the transformation matrix $\mathbf{T}_{1P}$ between the local coordinate system and reference frames is defined:

$$\mathbf{T}_{1P} = \begin{bmatrix} \mathbf{R}_{1P} & -\mathbf{R}_{1P}\mathbf{P}_{1P} \\ 0 & \mathbf{R}_{1P} \end{bmatrix} \quad (2.2)$$

where $\mathbf{R}_{1P}$ is the rotation matrix between the coordinate systems and $\mathbf{P}_{1P}$ is the position matrix of point P expressed in reference coordinates O_1 (see Fig. 2). Because of the symmetrical configuration of the proposed CCMB the stiffness to a specific point can be calculated as

$$\mathbf{K}_1 = \sum_n {}^i\mathbf{T}_1^* \mathbf{K}_i ({}^i\mathbf{T}_1^*)^T. \quad (2.3)$$

Using Eqs. (2.2) and (2.3), it is possible to express the whole compliance/stiffness of CCMB to the place of the acting load:

$$\mathbf{K}_P = 2 (\mathbf{T}_{1P} \mathbf{T}_{01} \mathbf{C}_0 \mathbf{T}_{01}^{-1} \mathbf{T}_{1P}^{-1})^{-1} \quad (2.4)$$

where $\mathbf{K}_P$ is the stiffness matrix (6×6 or simplified 3×3 for only in-plane deflections) to the point P , $\mathbf{T}_{ij}$ are transformation matrices and $\mathbf{C}_0$ is the compliance matrix of the flexure (curved beam). The curved beam compliance/stiffness matrix is expressed by using Castigliano's theorem, where the partial derivatives of the strain energy depending on elements of the deflection vector $\mathbf{u}$ are calculated. As the main input function for calculation of strain energy one uses the simplified piecewise function (two straight lines and half the ellipse) describing the radius of the curved beam $R(\phi)$:

$$R(\phi) = \begin{cases} \frac{L_1 - 0.5t_F}{\cos \phi}, & -\arctan \frac{L_4 + L_5}{L_1} \leq \phi < 0, \\ \frac{(L_1 - 0.5t_F)(L_7 - 0.7t_F)}{\sqrt{(L_1 - 0.5t_F)^2 \sin^2 \phi + (L_7 - 0.7t_F)^2 \cos^2 \phi}}, & 0 \leq \phi < \pi, \\ \frac{-L_1 + 0.5t_F}{\cos \phi}, & \pi \leq \phi \leq \pi + \arctan \frac{L_4 + L_5}{L_1}, \end{cases} \quad (2.5)$$

Fig. 2. The shape and main dimensions of the CCMB from PTFE (left); The curved beam elements from PTFE and PLA deformable sensor part (right).

Fig. 3. a) Dimensions of the designed elastic body. b) Dependences of the acting force and displacement plates of the elastic body (Polylactic acid, Teflon).

where for the PLA CCMB the boundary part of the function $(+0.5L_8)$ is changed as a result of the optimization in FEM analysis. The dimensions of the proposed elastic bodies are clear from [1] (for PTFE variant) and from Fig. 2a (for the PLA). The optimized sensor's elastic body (from PLA material) is shown in Fig. 2a, and Fig. 2b shows its transfer function as a dependence between an acting load and the distance of the sensor's plates. From the analytical calculations the corresponding element of the compliance matrix is $k_{\text{PTFE}} = 7.948 \cdot 10^{-4}$ m/N and $k_{\text{PLA}} = 3.867 \cdot 10^{-4}$ m/N. The FEM analysis yields the following results: $k_{\text{PTFE}} = 8.333 \cdot 10^{-4}$ m/N and $k_{\text{PLA}} = 3.45 \cdot 10^{-4}$ m/N.

3. Electrical design

In the next step, it is necessary to convert the distance of CCMB plates to the easily measurable electrical quantities. Such are, for instance, time and frequency. Both quantities are the most accurately measurable SI units. In the CCMB, the electrical part — parallel resonance circuit (PRC) should be integrated. The capacitor of the PRC will be constituted by the CCMB's plates. As a result of combining PRC and CCMB, the Micro-Electro-Mechanical System is created (MEMS). The PRC's resonance frequency is sent wirelessly by our developed method, based on the change of the high-frequency emitter scattering parameters [7]. The article will compare theoretical values and measured values of resonance frequencies depending on the acting force.

By changing the distance between two plates of CCMB a change in the capacity of PRC takes place, which can be detected by the changed resonant frequency of the PRC. The capacity

Fig. 4. Microelectromechanical system, 4 — CCMB, 3 — capacitor, 2 — inductor.

of PRC can be calculated by the formula

$$C = \frac{\epsilon_0 \epsilon_r S}{d_0 - kF} \quad (3.1)$$

where ϵ_0 is the permittivity of vacuum (8.86 pF/m), ϵ_r is the permittivity of medium in the gap between two plates, in our case air (≈ 1), S is the plate area of CCMB ($0.048 \text{ m} \times 0.006 \text{ m}$), d_0 is the distance between two plates of CCMB in the resting position without applied force (0.002 m), k is the conversion factor depending on material attributes, which CCMB is made of (m/N) and F is the magnitude of the applied force (N). Then we can calculate the resonant frequency of PRC as

$$f = \frac{1}{2\pi\sqrt{CL}} \quad (3.2)$$

where L is the coil inductance (2.5 turns $\approx 1.2 \mu\text{H}$). Figure 5 shows the transfer characteristic of MEMS, illustrating the dependence of resonance frequency of PRC on the applied force on MEMS body. As we can see from the diagram, conversion response is not linear and therefore we have to take this aspect into account during data processing.

Fig. 5. Dependence resonance frequency of the acting force on MEMS.

4. Measurement

By the measuring setup pictured in Fig. 6 and the described method [3], the transfer characteristic has been measured on both PTFE and PLA MEMS variation. The procedure of measurement is that the MEMS is placed into an electromagnetic field (EMF) radiator, which is also a protective shell of the MEMS device. In EMF radiator box (TEM Cell) a high-frequency field is created and the data processing hardware detects the coefficient S_{11} of the created and reflected EM wave. The parameter S_{11} will rapidly change if the frequency of the generated EMF and resonated frequency of PRC will match. Calibration of the MEMS device is done by calibration weights, see Fig. 6. Different loads will change S_{11} parameter differently and therefore we can set a calibration curve. The microprocessor unit based on DSP — TM4C129X will process the frequency dependent characteristic and analyze the resonance of PRC with precision of 1–10 Hz. Figure 7 shows MEMS transfer characteristics both from PTFE and PLA. MEMS made of PLA has a range of action load force from 0 N to 5.8 N with measured

Fig. 6. Probe of force.

Fig. 7. Dependences of the acting force and the resonant frequency of MEMS (blue — Poly-lactic acid, orange — Teflon).

Fig. 8. a) Dependences of the acting force and the resonant frequency of MEMS made of Teflon (blue — measurement, orange — theoretical). b) Dependences of the acting force and the resonant frequency of MEMS made of Poly-lactic acid (blue — measurement, orange — theoretical).

frequencies between 156 MHz and 118 MHz. MEMS made of PTFE has a range of the action load force between 0 N and 2.4 N with measured frequencies between 150 MHz and 112 MHz. Both PLA and PTFE MEMS has nonlinear transfer characteristic between the action force load and the resonant frequency. We can also check the theoretical analysis from Chapter 3. As can be seen, we were right in assuming a negative curve trend with more force applied. Figure 8 shows a section comparison of PLA and PTFE transfer characteristic. The curves are very similar, but shifted around 50 MHz with respect to each other. Because the measurement of the one-axis force is based on the high-frequency effect, there are variables such as permeability of environment, permittivity of environment, shape of MEMS inductor coil, diffraction effect of MEMS conductor, etc.. Because of these variables, the additive shift is larger than expected.

5. Data processing

Data processing of the measured readout can be done by a simple linear function if we simplify the force/frequency conversion by linearizing the curve. Because such a conversion (force/frequency) is not linear and would require much more computing power, we have to be aware of an error that we committed by simplifying. We can approximate the measured data

from the transfer characteristic of teflon MEMS by the method of least squares and we will get the formula

$$f_a = 153.157 - 15.2721f \quad [\text{MHz}; \text{N}] \quad (5.1)$$

We can calculate the relative error of measurement by the formula

$$\delta f = \frac{f_a - f}{f} 100 \quad (5.2)$$

Based on the formulae (5.1) and (5.2), Figs. 8a and 8b were made to show the linearization of the transfer characteristic (Fig. 9a) and its relative error (Fig. 9b). As we can read from the diagram, the relative error caused by linearization is between -2.5% and $+4.8\%$. In the case where we are satisfied with such an error, we can use less powerful and cheaper hardware for data processing with rounding error caused by linearization of data. On the other hand, we will lose the advantage of fine measurement we accomplished with MEMS sensor.

Fig. 9. a) Transfer response and its linearization. b) Relative error of data linearization.

6. Conclusion

This paper has presented the design and application of the Micro-Electro-Mechanical System (MEMS), which can be used for extraordinary precise one-axis force measurements. It also shows a method of electro-mechanical conversion of force into frequency and consecutive data processing of measured data. Nowadays, the described methods are being investigated as part of the research project APVV. The goal of this APVV project is to implement this technology into industrial production. At the same time, work is now underway to make the technology and manufacture of MEMS in micrometer dimensions [6] and [10].

References

- [1] Hricko, J., Design and Shape Optimization of Novel Load Cell, in *Proc. of the 25th Conf. on Robotics in Alpe-Adria-Danube Region (RAAD 2016): Advances in Robot Design and Intelligent Control*, A. Rodić, Th. Borangiu (Eds.), Advances in Intelligent Systems and Computing, vol. 540, Cham: Springer, 2017, pp. 80–87.
- [2] Andok, R., Hart'anský, R., Hricko, J., and Halgoš, J., Concept of a MEMS Load Cell Sensor of Mechanical Quantities Based on the EM Field Principle, in *AIP Conf. Proc.*, 2018, vol. 1996, no. 1, 020002, 5 pp.

- [3] Hricko, J., Sensors and Compliant Robotic Mechanisms for Harsh Working Environments, in *Proc. of the 22th International Workshop in Aple-Danube Region (RAAD, Portorož, Slovenia, Sept 11–13 2013)*.
- [4] Hart'anský, R. and Mierka, M., A New Method of Measuring Physical Quantities, in *Measurement 2019: Proc. of the 12th Internat. Conf. on Measurement*, Bratislava: Slovak Acad. of Sci., 2019, pp. 139–142.
- [5] Budinská, I. and Havlik, Š., Task Allocation within a Heterogeneous Multi-Robot System, in *Cybernetics and Informatics: Proc. of the 28th Internat. Conf. (Levoca, Slovakia, Feb 2016)*, New York: IEEE, 2016.
- [6] Andok, R., Bencúrova, A., Kostic, I., Ritomsky, A., Skrinariova, J., and Vutova, K., Study of Negative Electron Beam Nanoresist HSQ on GaAs Substrate, in *ASDAM 2016: Proc. of the 11th Internat. Conf. on Advanced Semiconductor Devices and Microsystems (Smolenice, Slovakia, Nov 2016)*, New York: IEEE, 2016, pp. 133–136.
- [7] Marsalka, L., Electromagnetic Field Properties Influence by the Changes of Dielectric Material Constant, *Przegląd elektrotechniczny*, 2016, R92, no. 2, pp. 60–63.
- [8] Linß, S., Schorr, P., and Zentner, L., General Design Equations for the Rotational Stiffness, Maximal Angular Deflection and Rotational Precision of Various Notch Flexure Hinges, *Mech. Sci.*, 2017, vol. 8, pp. 29–49.
- [9] Muller, I., de Brito, R., Pereira, C., and Brusamarello, V., Load Cells in Force Sensing Analysis: Theory and a Novel Application, *IEEE Trans. Instrum. Meas.*, 2010, vol. 13, no. 1, pp. 15–19.
- [10] Kostic, I., Vutova, K., Bencúrova, A., Ritomsky, A., and Andok, R., Limitations of variable shaped electron beam lithography for advanced research and semiconductor applications, in *Proc. of the 40th Internat. Spring Seminar on Electronics Technology (Sofia, Bulgaria, May 2017)*, New York: IEEE Comput. Soc., 2017, 6 pp.
- [11] Dizon, J. R., Espera, A. H. Jr., Chen, Q., and Advincula, R. C., Mechanical Characterization of 3D-Printed Polymers, *Addit. Manuf.*, 2018, vol. 20 pp. 44–67.