Flexural Body for a Wireless Force/Displacement Sensor

J. Hricko and S. Havlik

Abstract This paper deals with the design of the flexural body for a two axis force/displacement sensor based on electro-magnetic sensing principle. The compact elastic structure consists of two independent parallelograms that provide decoupled flexural motions of sensing elements in two rectangular directions. The procedure proceeds by experimental verification of this new sensing principle for building sensors that exhibit specific functional features.

Keywords Force/displacement sensor · Elastic structure · Flexural analysis · Stiffness

1 Introduction

For sensing the components of external force/torque several sensing principles and many different constructions of sensors have been developed for past years (Stefanescu 2011; Wu and Cai 2013). Such multi-component force and torque (F/T) sensors are frequently used to provide the adaptation ability for robots performing contact tasks.

In design procedure of any sensor there are two main decisive steps: choosing the sensing principle and design of an appropriate mechanical structure. It is obvious that both problems are closely related. As to the sensing principle it depends on transducers and further processing output signals. On the other hand; the design of mechanical structure directly corresponds to correct function and

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quality of sensor, as whole. For this reason it is very important to pay attention to design the of sensor mechanisms.

There are several works dealing with problem of multi-component sensor design (Uchiyama et al. 1988). The most general approach is based on building the linear mathematical model represented by the sensitivity/compliance matrix that relate the force components and measured elastic deflections—strains, as sensor readings. As the optimality criterion the ratio of maximal and minimal sensing sensitivity of the particular components is defined. By using the singular value decomposition the condition number as the measure of structural isotropy is defined (Uchiyama et al. 1987).

This paper presents the design procedure and building the force/displacement sensor using the new sensing principle working on measurement of the electro-magnetic field around the flexural sensor body (Maršalka and Harťanský 2013). The first task is the design of the sensor elastic structure that exhibits displacements of two pairs of capacitor plates in two orthogonal directions.

In order to verify functional assumptions the first experimental tests were performed. Main parts of proposed test bed are in Fig. 1:

- experimental force/displacement sensor
- micro-positioning screw
- calibration force sensor
- E-M cover
- evaluation electronics

As can be seen in Fig. 1, the measured parameter of E-M field—the peak frequency depends on deflection of the elastic body, or, acting force. This dependence represents output reading from the sensor.

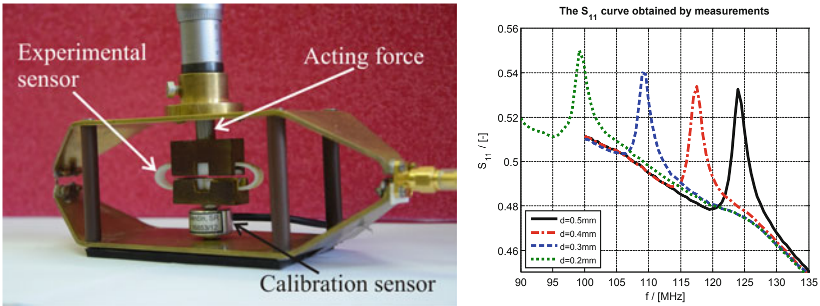

Fig. 1 Arrangement of experimental measurement (*left*); the S11 curve obtained by measurements (Maršalka and Harťanský 2013)

2 Design of Sensor Mechanisms

The two stage design procedure was accepted. The first stage includes building the functional—bigger scale model for verification of the assumed flexural performance and sensing characteristics. The second step includes design that corresponds to real dimensions and using appropriate manufacturing technology too.

2.1 Functional Requirements

Designing the sensor the input requirements related to expected performance should be considered. There are:

- The output—flexural displacements in particular directions should correspond to parameters of LC circuit. For the case of building the first stage model the capacitor plates should move strongly in parallel, within 2 mm.
- Accuracy. For many sensory control applications the sensor activity in quasi-static and dynamic processes is assumed. The sensor should have a prescribed accuracy in a supposed frequency range of force/displacement changes. When consider the dynamical range of sensor use a satisfactory high limit of natural frequency of mechanical oscillation is required. At the stage of the conceptual design the requirement for the sensor dynamics can be formulated in the following way:

Let ω be the supposed maximal frequency of the measured force/displacement oscillations. To have the proposed sensing accuracy within the whole frequency range 0–ω, the minimal frequency of free sensor oscillations should be (Havlik 1995).

$$\omega_0 \geq \frac{\omega}{\sqrt{\xi}} \tag{1}$$

where ξ is the error due to sensor dynamics.

- Compactness of the whole elastic mechanisms. In an ideal case the best quality of sensing will be reached when each component is measured with the same sensitivity. This practically means that the stiffness in all flexural directions should be equal.
- Decoupled motions of capacitor plates for sensing in x and y directions. This requirement results in minimal cross-sensitivity what means that particular force–displacement components can be directly evaluated.

In principle, for manufacturing complex forms there are two technologies: precise machining or 3D printing. In building models for first—experiments both technologies were used. Standard 3D printers support only specific types of materials like PLA or ABS; but both these materials exhibit small flexibility. As a suitable material can be processed by 3D printers seems the polyamide (PA2200). First samples were manufactured by precise machining the Teflon (PTFE). But when using this technology the restriction on the minimal thickness of flexural hinges/links should be considered.

2.2 *Proposed Compliant Structures*

Principal requirement related to the proposed sensing principle is that capacitor plates must be in mutual parallel positions. Then, the deformable structure should satisfy decoupled parallel motion of two pairs plates both in x, and y directions. Some examples of such flexural structures are discussed in (Hricko 2014; Beroz et al. 2011; Tian et al. 2009). In principle, the design of such compliant mechanisms proceeds from similarity with classic mechanisms.

The first design_1 of deformable part ideologically follows the design presented in (Peirs et al. 2004). The output characteristics in Fig. 2 are non-linear due to high number of flexure hinges. On the other side, such design provides displacements of plates bigger then the input deflections.

The designs in Fig. 3, use parallelograms as flexural element/prismatic joint. These compliant structures are designed for two axis sensor measuring forces in x and z axes.

Main disadvantage of both designs (design_2 and design_3) are mutually bounded motions of two parallelograms; i.e., if the only load in x axis is acting, the plate for z axis moves too. This fact naturally results in cross sensitivity between sensor readings. For more details see Maršalka and Harťanský (2013).

Our final design in Fig. 4 (left) consists of two independent parallelograms that deflect independently in two directions. Calculated force–displacement characteristics are shown in Fig. 4 (right). Both characteristics are practically linear and mutually decoupled.

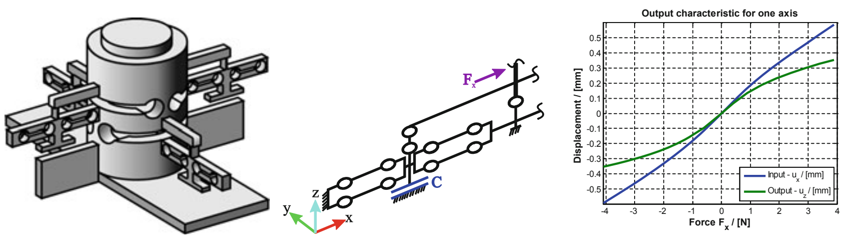

Fig. 2 Compliant structure (design_1), output characteristic for one axis

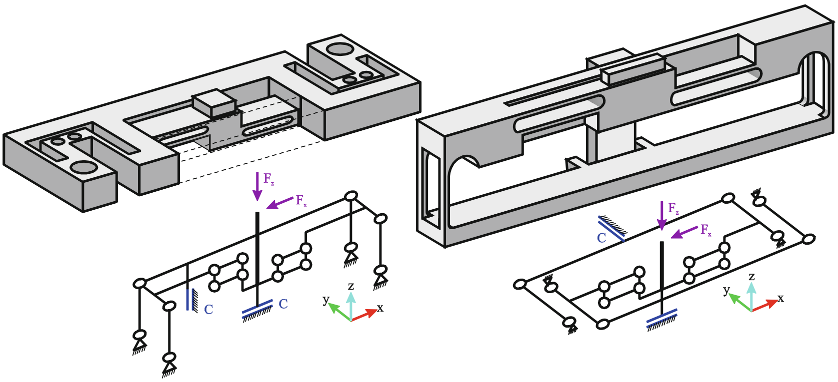

Fig. 3 Proposed compliant structures of deformable part of force/displacement sensor design_2 (*left*) and design_3 (*right*)

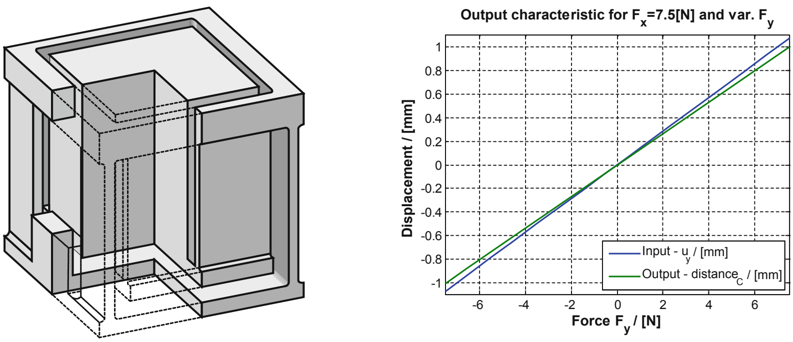

Fig. 4 Proposed compliant structure of sensor (design_4); Force–displacement characteristics of the proposed structure

2.3 Stiffness Analysis

In order to satisfy design criteria the careful compliance analysis of this flexure was made. The procedure how deflections of the structure in given points and directions were calculated is outlined below.

To build the full stiffness model of the flexure the approach the deflections in terms of bending, torsion, and tensile/compression of each part of the mechanism are calculated. Such model can be derived effectively by the matrix method under the assumption of Hooke's law for the material (Sciavicco and Siciliano 1996; Xu and Li 2006; Li and Xu 2009).

When an external load $F = [F_x, F_y, F_z, M_x, M_y, M_z]^T$ is applied on a certain (contact) point it causes a small deflection $u = [u_x, u_y, u_z, \theta_x, \theta_y, \theta_z]^T$ of this point. The dependence between applied load and deflection is expressed in matrix form

$$\mathbf{u} = \mathbf{CF} \rightarrow \mathbf{F} = \mathbf{Ku} \tag{2}$$

where K and C are the stiffness and compliance matrices respectively.

For calculation of the compliance and stiffness matrices of the whole structure it is defined transformation matrix T_{01} between the local coordinate system and reference frames

$$\mathbf{T}_{01} = \begin{bmatrix} \mathbf{R}_{01} & -\mathbf{R}_{01}\mathbf{P}_{01} \\ 0 & \mathbf{R}_{01} \end{bmatrix} \tag{3}$$

where R_{01} is rotation matrix between coordinate systems and P_{01} is position matrix of point O_1 expressed in reference coordinates O_0 (see Fig. 5)

$$\mathbf{P}_{01} = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix} \tag{4}$$

Then, according to configuration of those flexure elements the compliance, or, stiffness matrixes of the whole structure are calculated using relations where (5) for serial or (6) parallel connection.

$$C_1 = \sum_n {}^iT_1^* C_i \left({}^iT_1^*\right)^T \tag{5}$$

$$K_1 = \sum_n {}^iT_1^* K_i \left({}^iT_1^*\right)^T \tag{6}$$

The relative motion of the capacitor plate in x direction is given by relevant components of compliance matrix related to point O_6. Similarly, the motion of

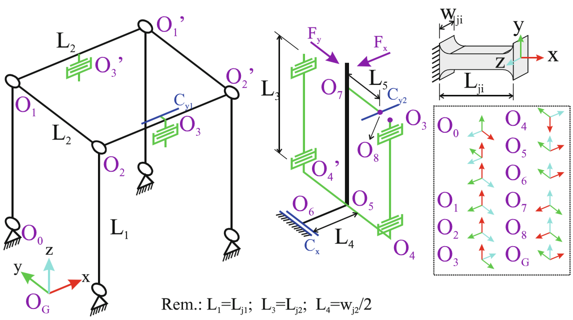

Fig. 5 Geometry of the final design, orientation of local coordinate system in observed points

capacitor plates for sensing y direction is calculated as displacement of point O_8 with respect to O_3.

Transformation matrices between particular local frames to that the compliance matrices were calculated are as follows:

$$\begin{gathered}
\mathbf{T}_{01} = \begin{bmatrix} \mathbf{R}_z\left(\frac{\pi}{2}\right)\mathbf{R}_x\left(\frac{\pi}{2}\right) & 0 \\ 0 & \mathbf{R}_z\left(\frac{\pi}{2}\right)\mathbf{R}_x\left(\frac{\pi}{2}\right) \end{bmatrix}; \quad \mathbf{T}_{12} = \begin{bmatrix} \mathbf{I} & -\mathbf{P}_z(L_2) \\ 0 & \mathbf{I} \end{bmatrix} \\
\mathbf{T}_{23} = \begin{bmatrix} \mathbf{R}_x\left(\frac{\pi}{2}\right) & -\mathbf{R}_x\left(\frac{\pi}{2}\right)\mathbf{P}_y\left(\frac{L_2}{2}\right) \\ 0 & \mathbf{R}_x\left(\frac{\pi}{2}\right) \end{bmatrix}; \quad \mathbf{T}_{34} = \begin{bmatrix} \mathbf{R}_z(\pi) & 0 \\ 0 & \mathbf{R}_z(\pi) \end{bmatrix} \\
\mathbf{T}_{45} = \begin{bmatrix} \mathbf{R}_y\left(\frac{\pi}{2}\right) & -\mathbf{R}_y\left(\frac{\pi}{2}\right)\mathbf{P}_y\left(\frac{L_2}{2}\right) \\ 0 & \mathbf{R}_y\left(\frac{\pi}{2}\right) \end{bmatrix}; \quad \mathbf{T}_{56} = \begin{bmatrix} \mathbf{I} & -\mathbf{P}_x(-L_4) \\ 0 & \mathbf{I} \end{bmatrix} \\
\mathbf{T}_{57} = \begin{bmatrix} \mathbf{R}_z(\pi) & -\mathbf{R}_z(\pi)\mathbf{P}_z(L_3) \\ 0 & \mathbf{R}_y(\pi) \end{bmatrix}; \quad \mathbf{T}_{78} = \begin{bmatrix} \mathbf{I} & -\mathbf{P}_y(L_5) \\ 0 & \mathbf{I} \end{bmatrix}; \quad \mathbf{T}_{j2} \\
= \begin{bmatrix} \mathbf{I} & -\mathbf{P}_y(-L_2) \\ 0 & \mathbf{I} \end{bmatrix}
\end{gathered} \tag{7}$$

Rem.: Orientation of local frame in point O_0 is equal with orientation of coordinate system to which is calculated compliance matrix of flexure hinge.

By substitution of Eq. (7) into Eqs. (5) and (6) it is possible to calculate compliance/stiffness matrix of whole structure as

$$\begin{aligned}
\mathbf{C}_7 = \mathbf{T}_{57}\mathbf{T}_{45}\Bigg(&\mathbf{T}_{34}\left(2\mathbf{T}_{23}\left(\left(\mathbf{T}_{01}\mathbf{C}_{j1}\mathbf{T}_{01}^T\right)^{-1} + \left(\mathbf{T}_{12}\mathbf{T}_{01}\mathbf{C}_{j1}\mathbf{T}_{01}^T\mathbf{T}_{12}^T\right)^{-1}\right)\right)^{-1}\mathbf{T}_{34}^T \\
&+ \left(\mathbf{C}_{j2}^{-1} + \mathbf{T}_{j2}\mathbf{C}_{j2}^{-1}\mathbf{T}_{j2}^T\right)^{-1}\Bigg)\mathbf{T}_{45}^T\mathbf{T}_{57}^T
\end{aligned} \tag{8}$$

3 Conclusions

Paper presents an innovative solution of the two component force and displacement sensor working on the electro-magnetic sensing principle. The development of sensors working on this principle is actually in initial phase. There are shown first results from measurements have been made on experimental one-component force/displacement sensor. Such sensor consists of two principal functional parts: elastic–mechanics and transducers. Main attention in this paper is devoted to design of flexural mechanics for building the two-component sensor.

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References

Beroz J, Awtar S, Bedewy M, Sameh T, Hart AJ (2011) Compliant microgripper with parallel straight-line jaw trajectory for nanostructure manipulation In: Proceedings of 26th American society of precision engineering annual meeting, Denver, CO

Havlik S (1995) Modeling, analysis and optimal design of multicomponent force/displacement sensors, Proceedings of ECPD conference, Athens, 1995

Hricko J (2014) Straight-line mechanisms as one building element of small precise robotic devices. In: Hajduk M, Koukolova L (eds) Applied mechanics and materials, vol 613, pp 96–101. ISSN 1660-9336

Li Y, Xu Q (2009) Design and analysis of a totally decoupled flexure-based XY parallel micromanipulator. In: IEEE transactions on robotics, vol 25, No 3, June 2009

Maršalka L, Harťanský R (2013) Proposal of novel sensor applicable to contactless displacement measurement. In: Measurement 2013: Proceedings of the 9th international conference on measurement. Smolenice, Slovakia, May 27–30, 2013. Bratislava: Slovak Academy of Sciences, pp 287–290. ISBN 978-80-969672-5-4

Peirs J, Clijnen J, Reynaerts D, Brussel H-V, Herijgersm P, Corteville B, Boonea S (2004) A micro optical force sensor for force feedback during minimally invasive robotic surgery. Sens Actuators A 115(2004):447–455

Sciavicco L, Siciliano B (1996) Modeling and control of robot manipulators, Electrical Engineering Series. McGraw-Hill International Editions. ISBN 0-07-114726-8

Stefanescu DM (2011) Handbook of force transducers: principles and components. Springer Science & Business Media 16(3):2011

Tian Y, Shirinzadeh B, Zhang D, Alici G (2009) Development and dynamic modelling of a flexure-based Scott-Russell mechanism for nano-manipulation. Mech Syst Sig Process 23 (2009):957–978

Uchiyama M, Nakamura T, Hakomori K (1987) Evaluation of robot force sensor structure using singular value decomposition. J Robot Soc Jpn 5(1):4–10

Uchiyama M, Bayo E, Palme-Villalon E (1988) A mathematical approach to the optimal structural design of a robot force sensor. Paper ASME, reprint from Crossing bridges: advances in flexible automation and robotics, vol I, pp. 539–546. (Book No. 10271A)

Wu B, Cai P (2013) Decoupling analysis of a sliding structure six-axis force/torque sensor. Measur Sci Rev 13(4):2013

Xu Q, Li Y (2006) Stiffness modeling for an orthogonal 3-PUU compliant parallel micromanipulator. In: Proceedings of the 2006 IEEE international conference on mechatronics and automation, Luoyang, China, 25–28 June 2006