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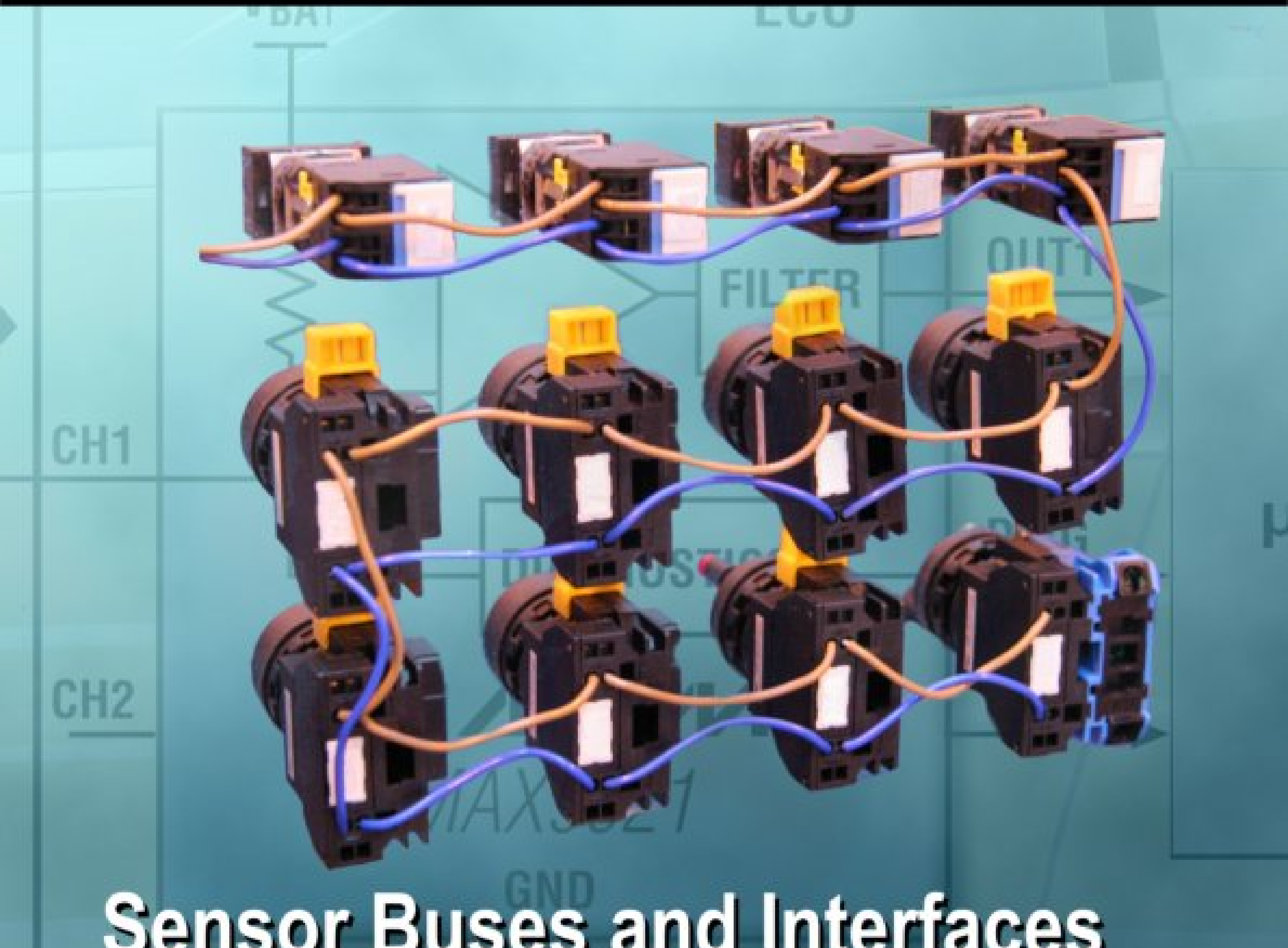

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Simulation-Driven Development and Optimization of a High-Performance Six-Dimensional Wrist Force/Torque Sensor

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Abstract: This paper describes the Simulation-Driven Development and Optimization (SDDO) of a six-dimensional force/torque sensor with high performance. By the implementation of the SDDO, the developed sensor possesses high performance such as high sensitivity, linearity, stiffness and repeatability simultaneously, which is hard for tranditional force/torque sensor. Integrated approach provided by software ANSYS was used to streamline and speed up the process chain and thereby to deliver results significantly faster than traditional approaches. The result of calibration experiment possesses some impressive characters, therefore the developed fore/torque sensor can be usefully used in industry and the methods of design can also be used to develop industrial product. *Copyright © 2010 IFSA.*

Keywords: Simulation-driven development of production, Optimization, Six-dimensional force/torque

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1. Introduction

Since the Oak Ridge and Argonne National Laboratories began their development of master-slave manipulators during the late 1940s, both serial and parallel robot manipulators have been introduced by manufacturing industries for performing certain production tasks, such as material handling, spot welding, spray painting, and assembling [1]. At the meantime, control algorithm based on force has been recognized and studied as an essential control scheme for using robots in advanced application [2, 3]. Recently, various types of force/torque sensor are developed and used for controlling motions of robots and industrial machines [4-7]. Several six-axis force sensors are commercially available at present such as force sensors of ATI and JR3. A major drawback in developing force sensors is the design of the elastic component, which has been done heuristically, dependent on the experience of designers [8].

As an appropriate design of an elastic component is always the consequence of a trade-off between various objectives such as sensitivity, stiffness, repeatability, linearity, therefore the exploration of the design cannot be performed by using only direct optimization algorithms which lead to a single design point. It is necessary to gather enough information about the design so as to be able to quantify the influence of design variables on the performance of the sensor in an exhaustive manner. By doing so, the right decisions about the dimensions of the elastic element can be made based on accurate information –even in the event of an unexpected change in the design constraints [9].

In addition, Classical closed-form analysis techniques are primarily applicable to parts that are made up of simple geometry [10]. However, the elastic component of the six-dimensional force/torque sensor have more complicated geometric shapes as it has corresponding active sensing portions to three forces and three torques, making accurate calculation of strains and deflection difficult or even impossible with classic techniques.

Almost all existing developments of six-dimensional force/torque sensors are designed via simplified and approximate theory calculating [11, 12] or one-step Finite Element Analysis [13]. In this study, a six-dimensional force/torque wrist sensor is designed via simulation-driven design and optimization exploration. The Simulation-driven development of the force/torque sensor makes sure the sensor possesses high performance such as high sensitivity, repeatability and linearity as it solves the trade-off among various objectives. The static and dynamic characters of the sensor are obtained and the influence of the dimensions on the behaviors of the elastic element such as normal strain, stress, deformation and response frequency are quantified.

2. Overview of Measuring Principle

The most common methods of detecting the forces and moments is the technique of measuring strain with strain gauges, whose electrical resistance varies in proportion to the amount of strain in the device. When the strain gauges mounted onto the elastic element of sensor, they will undergo the changes of resistances as the elastic element deforms. Gage factor, a fundamental parameter of the sensitivity to strain, is defined as:

$$G_f = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}, \tag{1}$$

where R is the nominal resistance value of the strain gauge, L is the original length, and ε is the strain that the stain gauge experiences.

In practice, strain measurements requires signal processing such as amplification as the quantities of strains that take place in elastic element are less than 1000 micro-strains (10e-6), which means the changes in resistance are less than 0.2R%. A bridge circuit always used to measure such small changes in resistances. Full-bridge circuits, whose four arms are all active strain gages, increase the sensitivity of the circuit further. And its measurement sensitivity is:

$$\frac{V_0}{V_E} = -G_f \cdot \varepsilon \quad , \tag{2}$$

where V_0 and Vdenote the output of the circuit and the voltage excitation source, respectively.

When forcesF_x, F_y, F_z along X-, Y-, Z-axis and moments M_x, M_y, M_z around X-, Y-, Z-axis are applied to the sensor, the outputs of strain gauges attached at various locations will be S(S_1, S_2, S_3, …). Relationship could be expressed as below using detection matrix T:

$$S = TF \tag{3}$$

Therefore, the applied forces and moments could be determine and calculated by using the inverse matrix of T:

$$F = T^{-1}S \tag{4}$$

Finally, since the force/torque sensors measure forces $F_s = [f_{xs}\ f_{ys}\ f_{zs}]^T$ and moments $M_s = [m_{xs}\ m_{ys}\ m_{zs}]^T$ with respect to the sensor coordinate *Os-XYZ* fixed at the sensor, the forces and moments applied to the end-effector can be transformed and represented

$$F_c = R_s^c F_s \tag{5}$$

$$M_c = R_s^c M_s + r \times \left(R_s^c F_s \right) \quad , \tag{6}$$

which requires knowledge of the position r_{cs}^{c} of the origin of Frame s with respect to Frame *c* as well as of the orientation R_s^c of Frame s with respect to Frame *c*.

3. The Structure Design of the Sensor

Fig. 1 shows the structure of the elastic element of the six-dimensional force/torque sensor. It composes of a central platform serve as a connection with the environment, an annular rim and four radial spoke portions extend outwardly form the platform to mutually orthogonal radial directions and connecting the rim portions. The thin beams of the rim portions, so called elastic beams, are designed to exhibit substantial flexibility in the extending direction of the corresponding spoke portions. Active sensing portion in this type are the four cross beams with a rectangular parallelepiped shape. In case of measurement, the annular rim is fixed as a base frame and the platform is applied with forces and moments. Heat treatment was carried out by the generally used technological process.

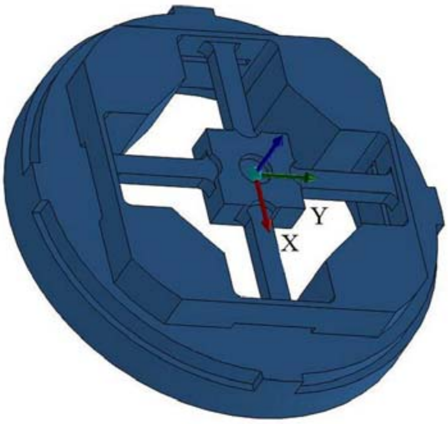


Fig. 1. CAD model of the elastic element of the six-dimensional force/torque sensor.

4. Simulation-Driven Development and Optimization of the Elastic Element

The Simulation Driven production development (SDPD), which allows accelerating the process of structure development from the conceptual design to the last product, has been studied for decades. Integrated with optimization, the SDPD makes the procedure more efficient and economical. Approach Design Exploration provided by ANSYS is a powerful tool for design and understanding the analysis response of products by using a deterministic method based on Design of Experiments and various optimization methods [9]. The project schematic of the simulation-driven development and optimization of the novel elastic element of the six-dimensional force/torque sensor is shown in Fig. 2.

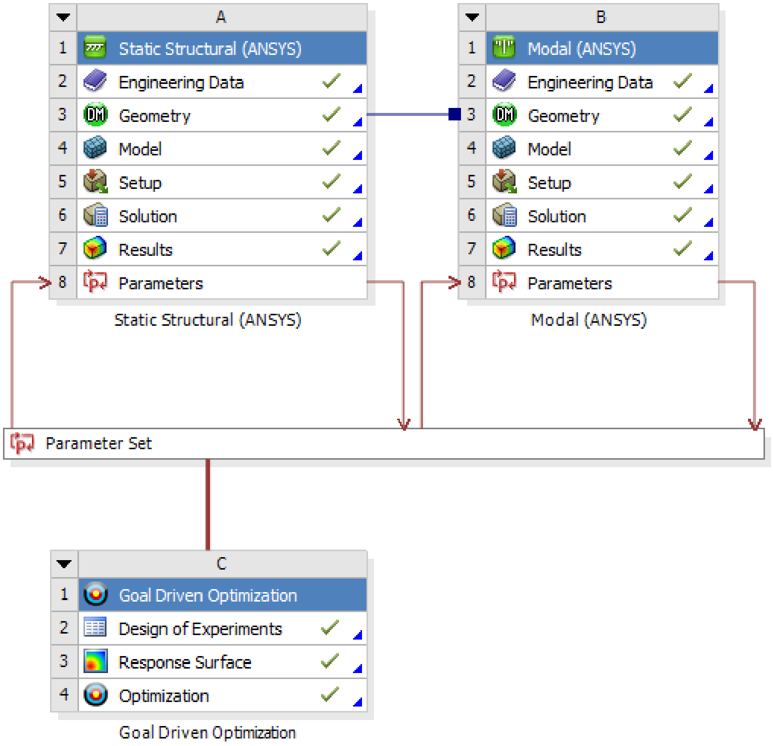


Fig. 2. Project schematic of the simulation-driven development and optimization.

We pose the mechanism design as a multi-objective optimization based on Design of Experiments (DOE) approach provided by the software ANSYS, which can capture the behavioral changes due to parameter variations, optimize a set of goals for quantities such as strain, stress, deflection and response frequency and get the most optimal values of the parameters. The geometric dimensions of the force-sensing element are set as design variables, and the maximum equivalent stress, the minimum elastic strain minimum, maximum total deformation and the first response frequency are used to evaluate the performance of the elastic element such as sensitivity, stiffness repeatability and linearity.

In this study, the dimensions of the cross beams and the elastic beams of the rim portions are set as the input parameters, as shown in Table 1.

Table 1. The design parameters and their bounds (all dimensions in mm).

	Width of the cross beams	**Height of the cross beams**	**Length of the cross beams**	**Width of the elastic beams**	**Height of the elastic beams**	**Length of the elastic beams**
Input parameter	P2-Plane4.V3	P1-Plane4.H1	P6-Exturde2.FD1	P3-Extrude3.FD1	P5-Plane5.V3	P4-Plane5.H1
Predefined ranges	4<P2<6	3<P1<5	22<P6<28	1<P3<2	8<P5<12	22<P4<28

And the output parameters and their bounds are set as:

$$\sigma_{eq\max} < \sigma_p \tag{7}$$

$$\varepsilon_{e\min} < -600(micro-strain) \tag{8}$$

$$d_{\max} < 0.05(mm) \tag{9}$$

$$f_1 > 1200(Hz)\,, \tag{10}$$

where σ_{eqmax} and σ_p denote the maximum equivalent stress and proportional limit stress of the material, and ε_{emin}, d_{max} and f_1 represent the minimum elastic strain, the maximum deformation and the first response frequency occurred on the elastic element of the six-dimensional force/torque sensor. The first and second objectives can make sure the elastic element of the force sensor works within the elastic limit and have enough elastic strain to sense the applied forces and moments. And the third objective is to make sure the sensor has a good linearity and stiffness. The fourth objective can enable the sensor possess an appropriate dynamic character. The possible sample points chosen by the software are shown in the Fig. 3, which also shows whether the output goals can be achieved and if this entails sacrificing the goal attainment of other output parameters.

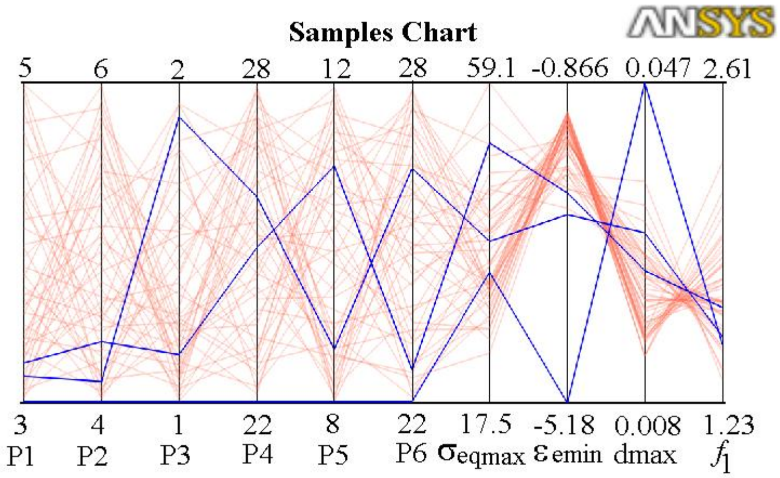
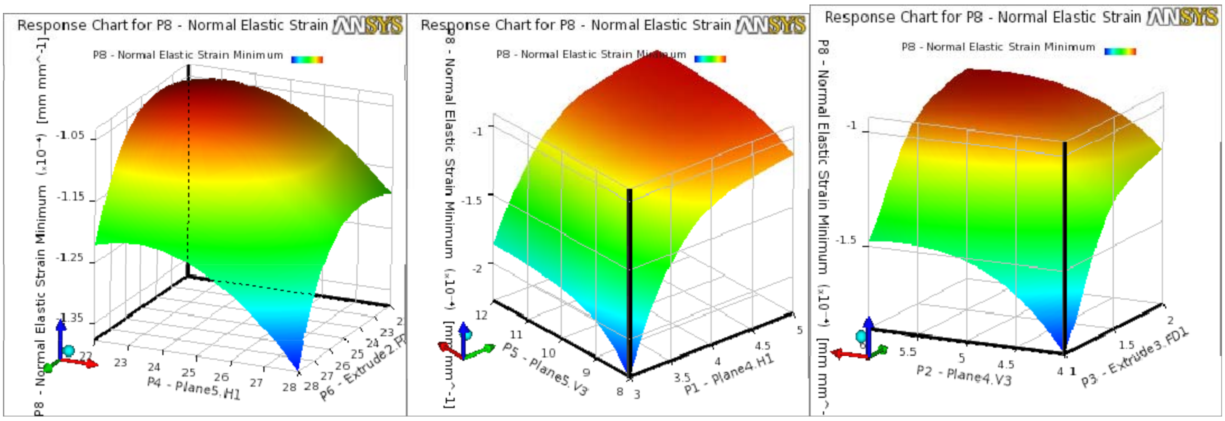


Fig. 3. Samples chart with objectives.

Influences of design variables on the minimal normal elastic strain occurred on the elastic element are shown in Fig. 4.



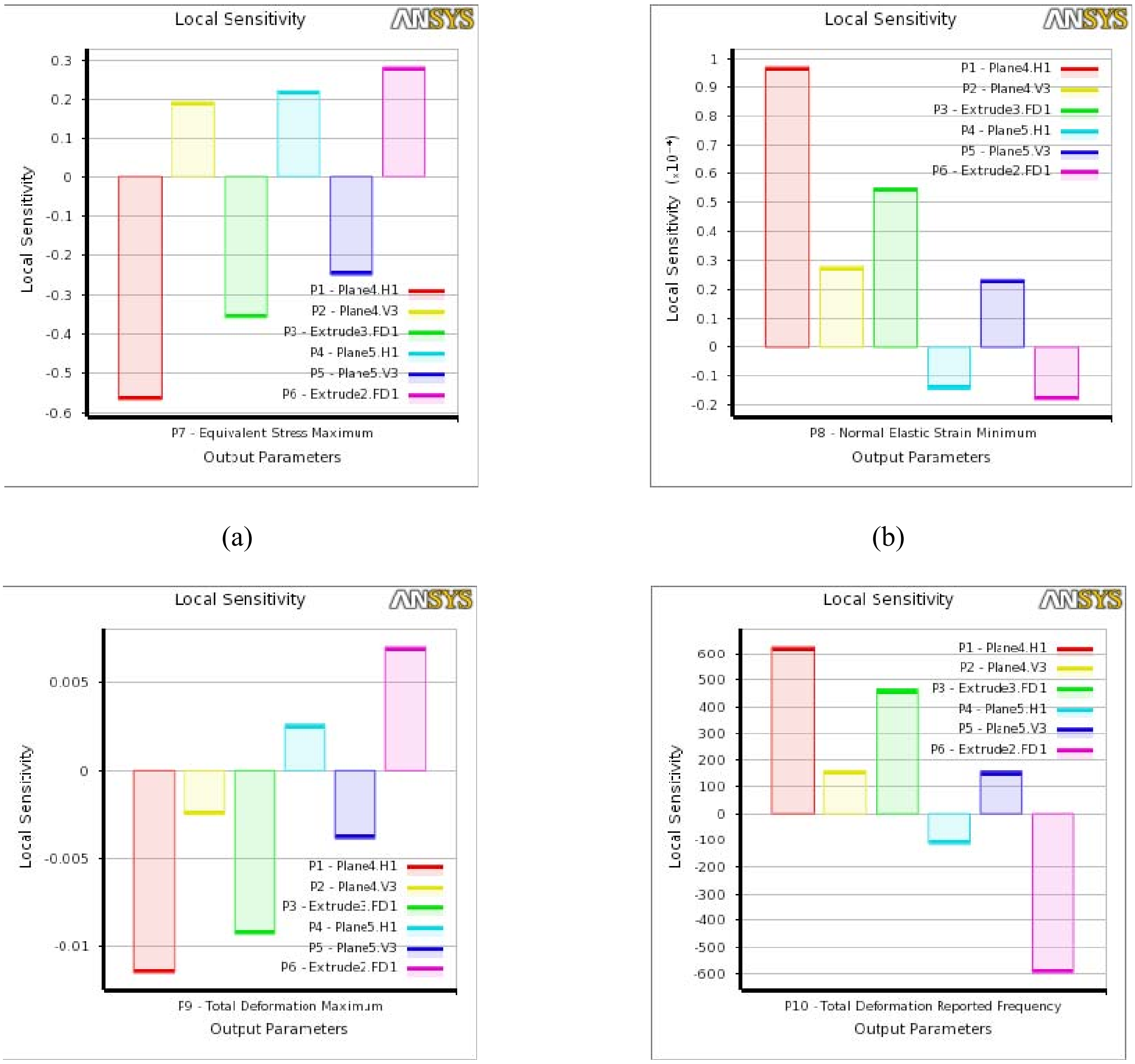
(a) (b) (c)

Fig. 4. The influence of the design variables on the Minimal Normal Elastic Strain: (a) MNES verse P4 and P6; (b) MNES verse P1 and P5; (c) MNES verse P3 and P2.

At last, the software captures three best candidates from the sample set based on the stated objectives, which are shown as blue lines in Fig. 3. However, these results represent only a section of the available design points. Finally, we adapt group 2 to fabricate the sensor. Fig. 5 shows the sensitivities of the input parameters, it is clear that the input parameter P1 is the most sensitive parameter for the three output parameters.

6. Fabrication of the Six-dimensional Force/torque Sensor

The strain gauges should be bonded onto the elastic element with appropriate place and orientation, which is always chosen according to the places having maximum elastic strains, to get the maximum sensitivity and repeatability. All gauges used in the present study are Y series linear strain gage (LY11) made in HNM GmbH. The measuring grid foil of the gauges is made of constantan and the nominal resistance is 120 Ohm.



(a) (b)

(c) (d)

Fig. 5. sensitivities of parameters: (a) Maximum equivalent stress verse input parameters; (b) Minimum normal elastic strain verse input parameters; (c) Maximum total deformation verse input parameters; (d) First response frequency verse input parameters.

On the surfaces of the cross-beams, each of the four surfaces of the beam section carries one or two strain gauges arranged longitudinally thereon and each beam includes six stain gauges in total, as show in Fig. 6. These strain gauges are connected in separate six bridge circuits as shown in Fig. 7. The torque about Z-axis appears as strain in front and rear surfaces of each beam, and then R1, R2, R3, R4 are chosen to detect the M_z. The component of torque M_x about X-axis (M_y about Y-axis) causes beams alone X-axis (Y-axis) to bend and appear strain on the top and bottom surfaces, so R5, R6, R7, R8 (R9, R10, R11, R12) are used to detect M_x (M_y). The force alone X-axis F_x (Y-axis F_y) causes beams alone Y-axis (X-axis) to bend, then R13, R14, R15, R16 (R17, R18, R19, R20) are used to detect the F_x. The component of F_z alone Z-axis is measured by means of the strain gauges R21, R22, R23, R24 on both side surfaces alone Y-axis.

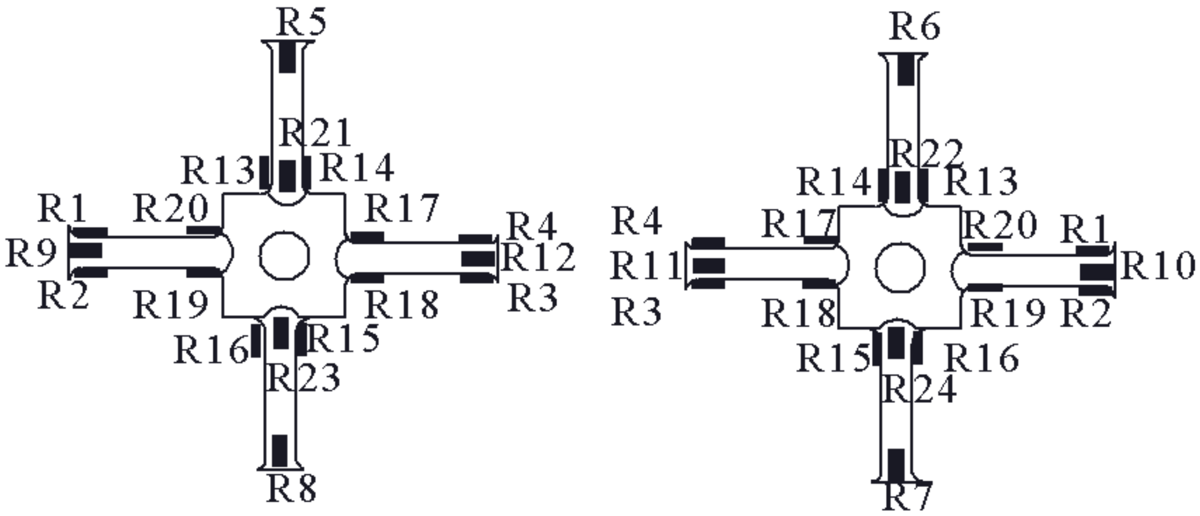


Fig. 6. Strain gauges arrangement on the sensor based on cross beams.

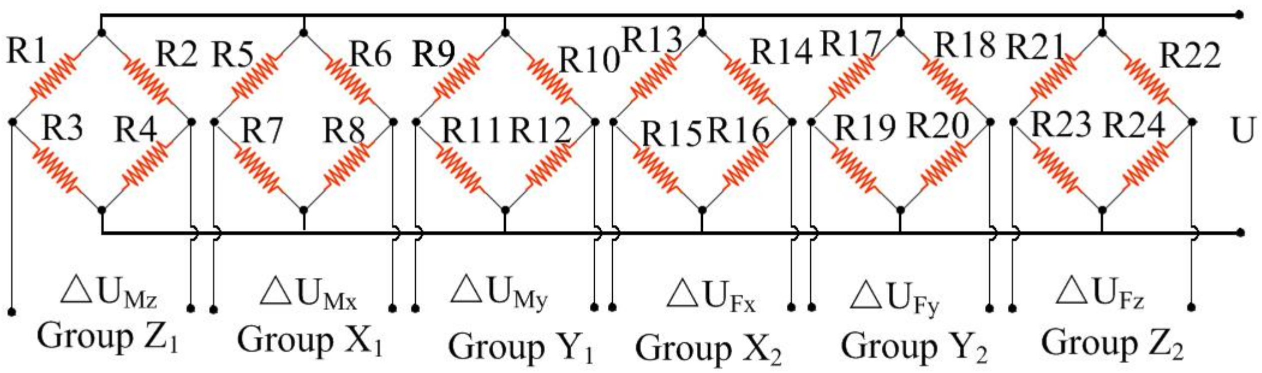
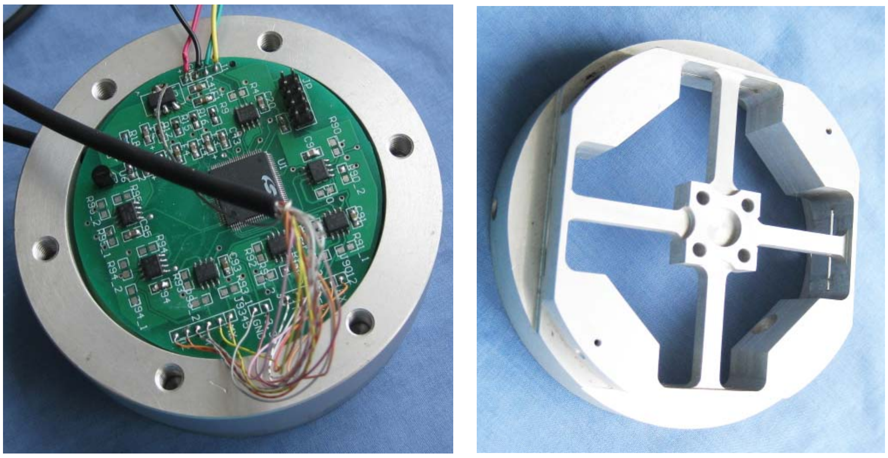


Fig. 7. Connection mode of strain gauges.



(a) (b)

Fig. 8. The fabricated six-dimensional force/torque sensor: (a) the integrated printed circuit board; (b) the elastic element.

7. Dynamic Analysis

When subjected to the applied loads or displacements, the sensor actually behaves dynamically. So we made a modal analysis via ANSYS to confirm that the sensor has a good dynamic performance such as vibration characteristics (natural frequencies and mode shapes), which are important parameters in the design of a structure for dynamic loading conditions [13].

We apply a fixed support to the ends of the elastic beams through which the sensor is connected with manipulators, and specify the number of frequencies of interest for the first six natural frequencies. Finally, we get the first six natural frequencies (shown in Table 2), and first six mode shapes pictures (Fig. 9) which are helpful in understanding how the sensor vibrates. The first, second and third mode shapes are approximately moving along the three axes respectively, and the else are approximately moving about the three axes. Work bandwidth of the sensor is almost 0–1247 Hz, which is often determined to the two thirds of the first natural frequency according to experience.

8. Conclusions

By the calibration method mentioned in Ref. [13], we obtain the test results, the output curves of each component of the sensor, as shown in Fig. 10. The calibration results indicated the nonlinearity errors of Fx, Fy, Mx and My measurement are about 0.2 % F. S., and those of the else components are about 0.4 %. By the calculating method proposed in Ref. [11], the uncertainty of the developed sensor is less than 2.4 %.

The major contributions of this work involve the solving of the trade-off between sensitivity, stiffness, repeatability, linearity and robust via Simulation-Driven Development and Optimization. The proposed methodology can be applied to the modeling of other types of multi-dimensional force/torque sensors as well. Additionally, the presented approach provides a guideline for development of other kinds of sensors and transducers that always exists some trade-off.

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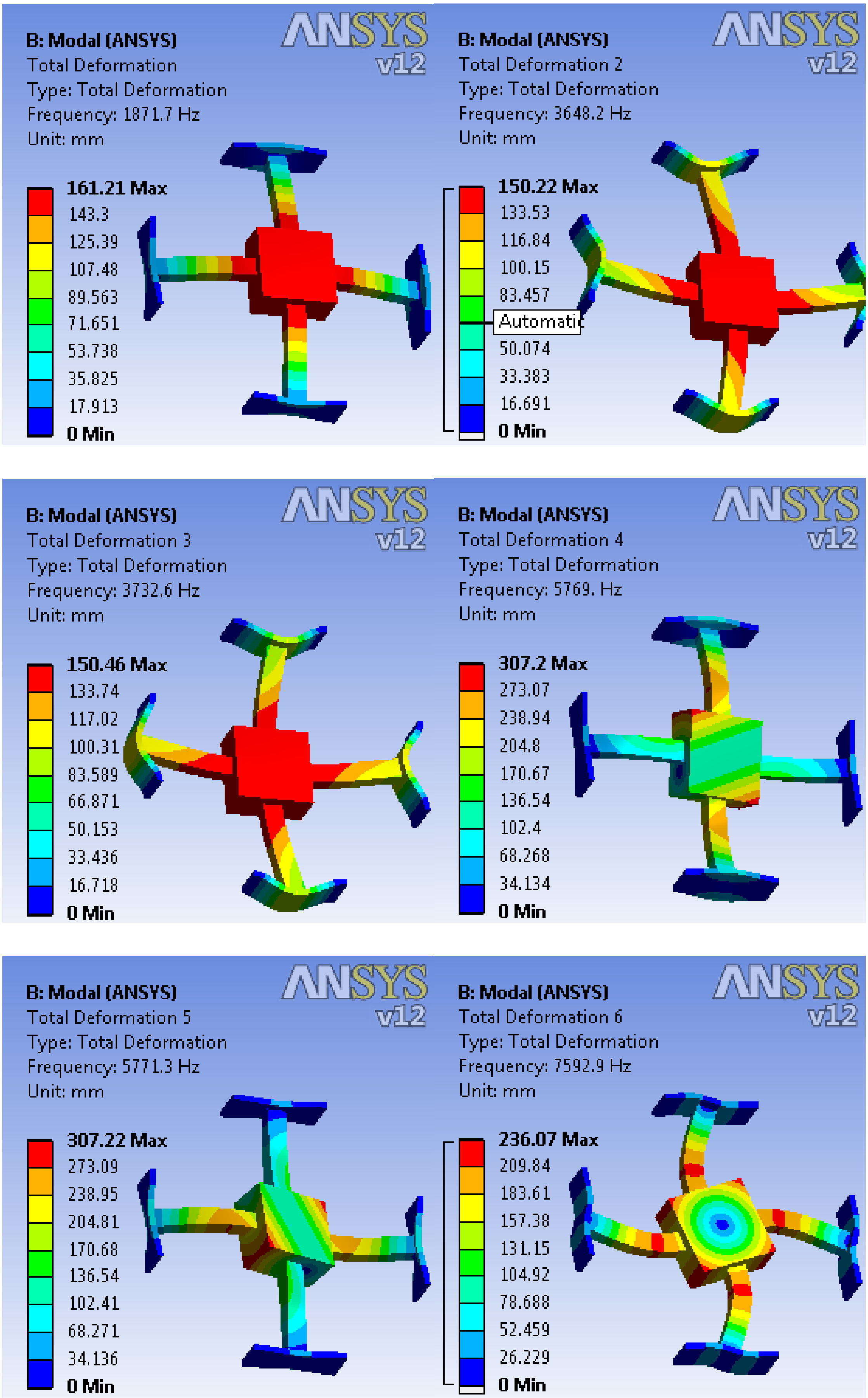
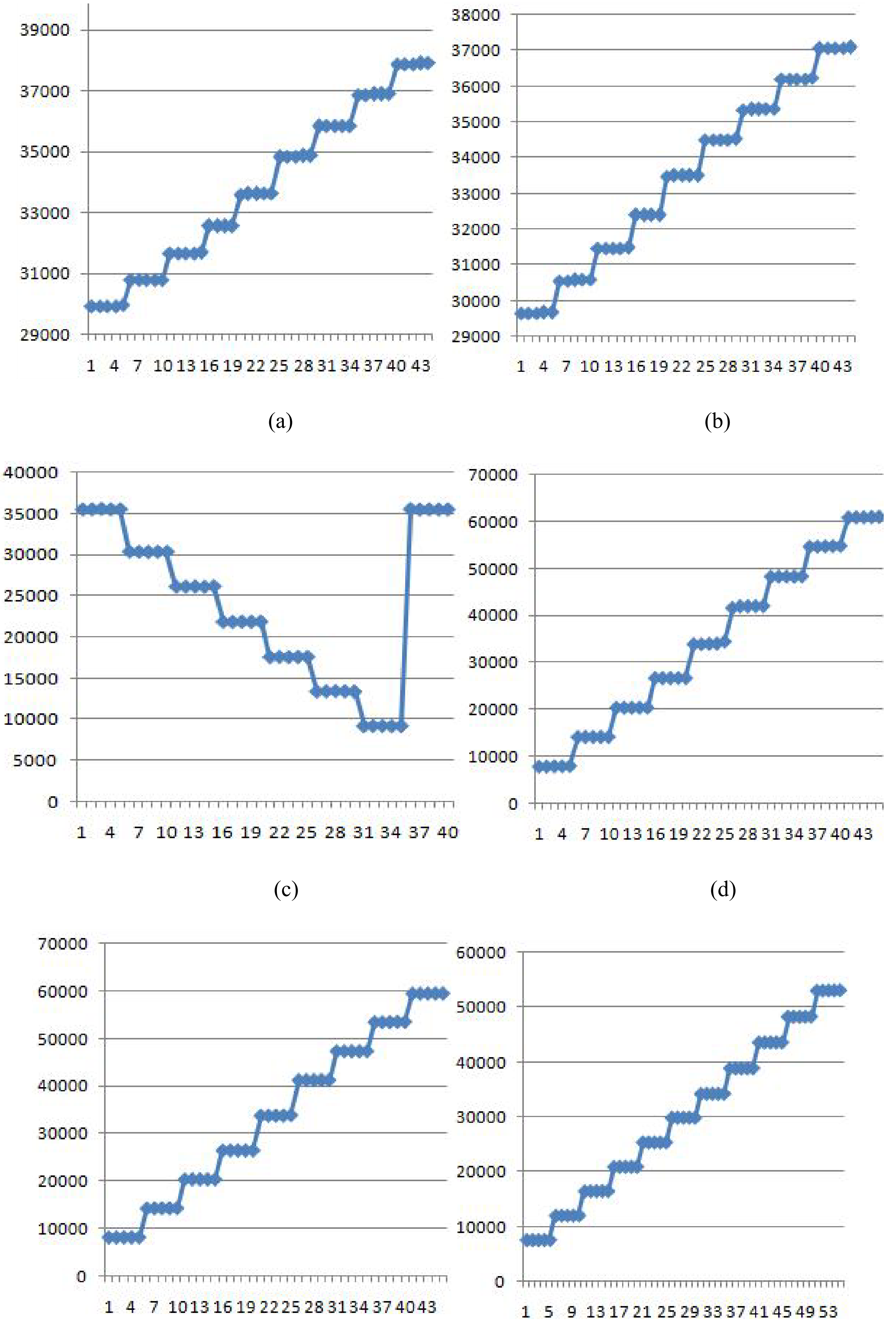


Fig. 9. The first six Mode shapes of the sensor.



(a) (b)

(c) (d)

(e) (f)

Fig. 10. The calibration test results: (a) A/D output of component F_x; (b) A/D output of component F_y; (c) A/D output of component F_z; (d) A/D output of component M_x; (e) A/D output of component M_y; (f) A/D output of component M_z.

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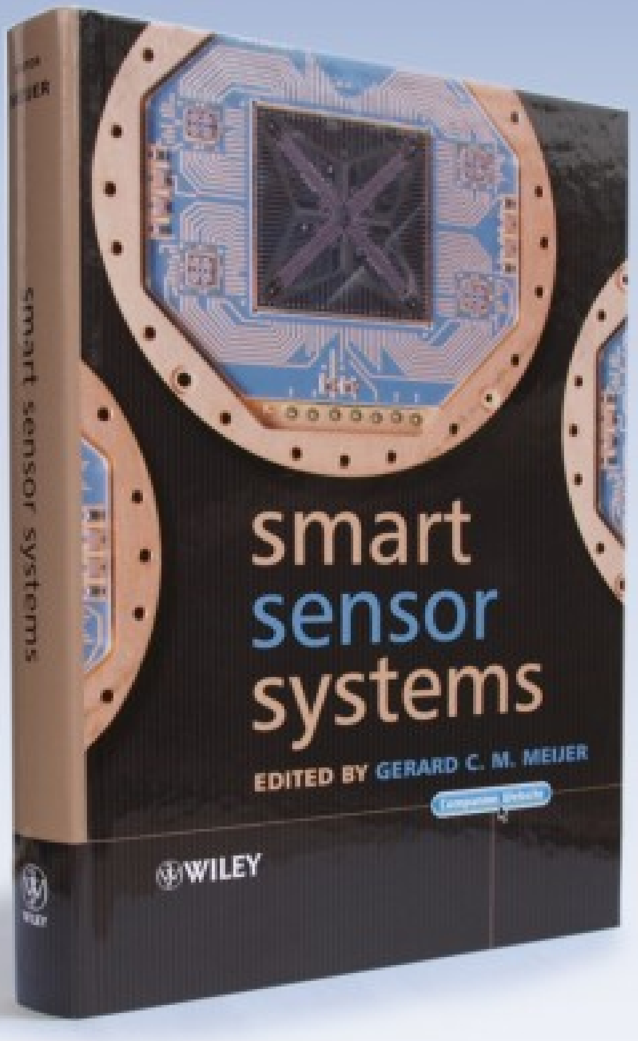

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