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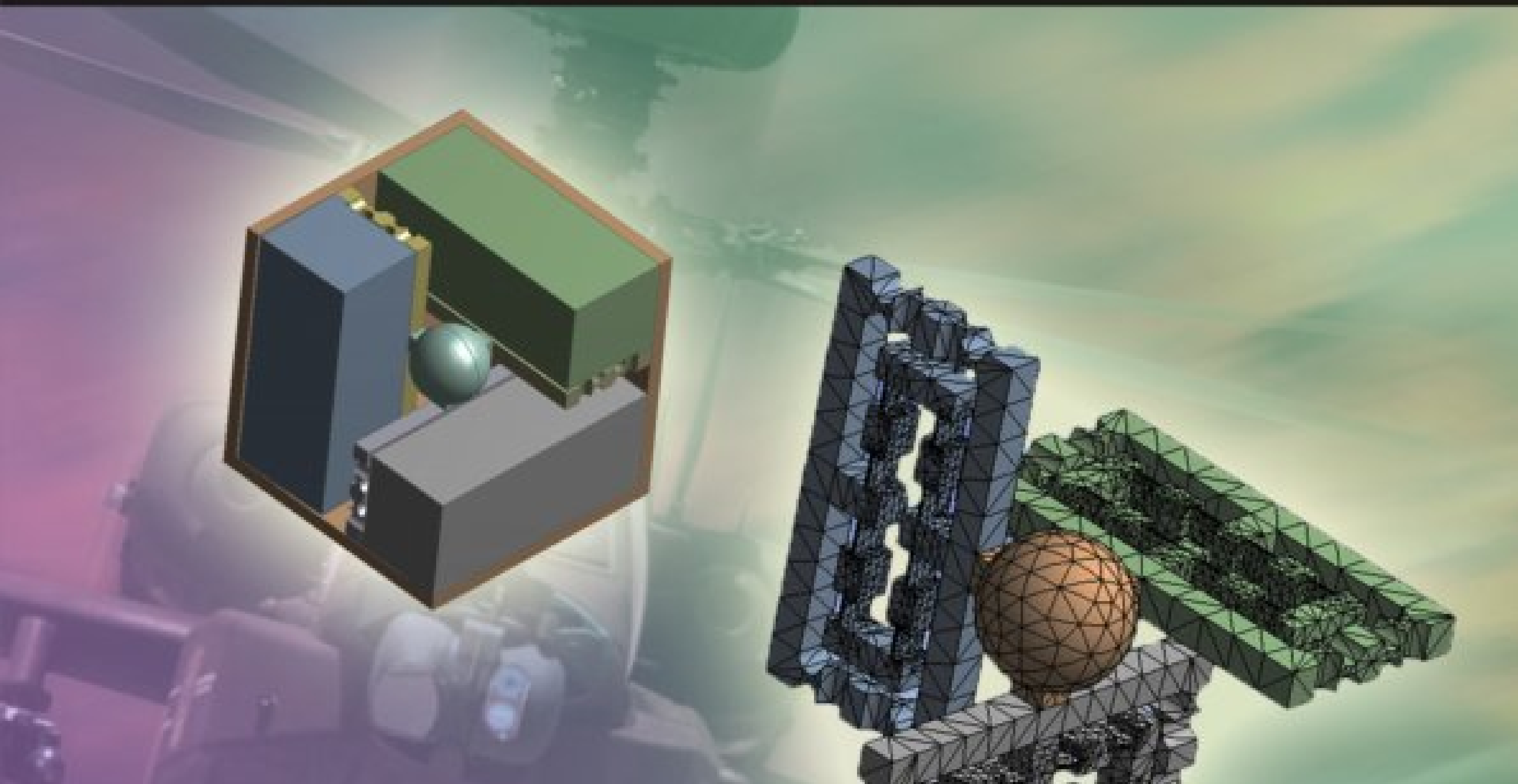

## Sensors and Transducers Applications

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# Fully Decoupled Compliant Parallel Mechanism: a New Solution for the Design of Multidimensional Accelerometer

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**Abstract:** In this paper, a novel multidimensional accelerometer is proposed based on fully decoupled compliant parallel mechanism. Three separated chains, which are served as the elastic body, are perpendicular to each other for sensing the kinetic information in different directions without decoupling process. As the crucial part of the whole sensor structure, the revolute and prismatic joints in three pairwise orthogonal branches of the parallel mechanism are manufactured with the alloy aluminium as flexure hinge-based compliant joints. The structure development is first introduced, followed by the comprehensive finite-element analysis including the strain of the sensitive legs, modal analysis for total deformation under different frequency, and the performance of harmonic response. Then, the shape optimization is conducted to reduce the unnecessary parts. Compliance optimization with particle swarm algorithm is implemented to redesign the dimension of the sensitive legs. The research supplies a new viewpoint for the mechanical design of physical sensor, especially acceleration sensor. *Copyright © 2010 IFSA.*

**Keywords:** Compliant parallel mechanism, Multidimensional accelerometer, Flexure hinge, Particle swarm optimization

## 1. Introduction

As a milestone for the rapid development of modern mechanism theory and applications, parallel mechanism has become a paramount close-loop configuration that supplies great potential for the design of force/torque sensors [1-8], machine tools [9-15], micro-motion devices [16-20], and others [21-22], due to its excellent mechanical properties in terms of high stiffness, high dexterity, high precision and easy for control.

Previous work was concentrated on the six degree-of-freedom force/torque sensor with the traditional Gough-Stewart platform [1-8]. However, the configuration design of Gough-Stewart platform and its variation for force/torque sensors failed to produce a decoupled one. Besides, the measuring accuracy is affected by the point of applied force. As shown in Fig. 1, suppose that there are three identical forces applied on the different position of the moving stage of the Gough-Stewart platform based force/torque sensor, and it is expected that the outputs will also be identical. Actually, the outputs are different since the six parallel chains obtain disparate strains and deformations under the diverse input matrix that is applied at the six sensing components which are located in the sensitive parts of these parallel chains.

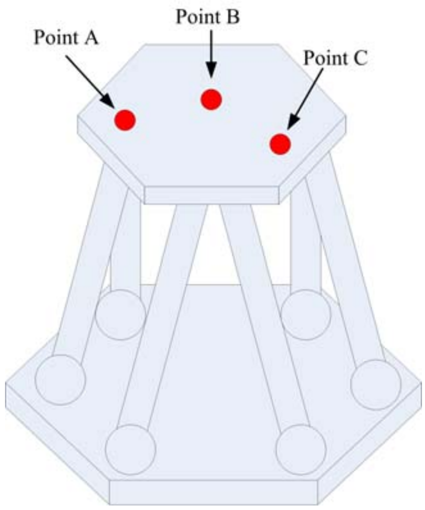



**Fig. 1.** Three positions for the applied forces on the moving stage.

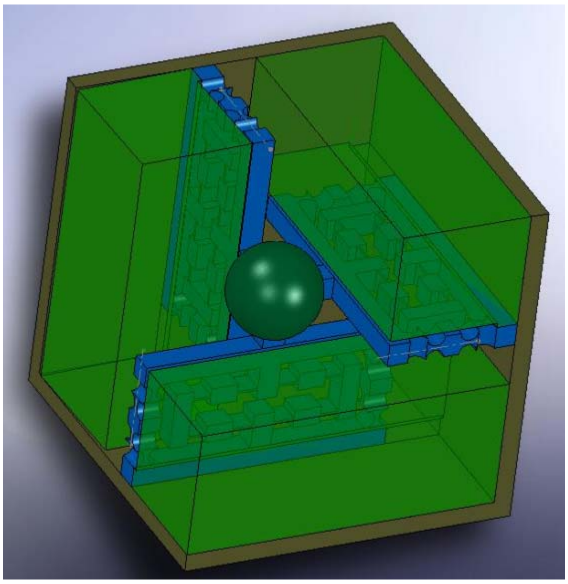
Because the flexure hinge-based compliant mechanisms can be applied for ultra-high precision applications thanks to their outstanding characteristics [23-26], the revolute joints and prismatic joints in this special sensor are considered to utilize compliant joints to constitute the instrumented elastic legs. This work focuses on the conceptual design and performance analysis of a novel multidimensional accelerometer based on fully decoupled compliant parallel mechanism. The sensor is featured with high compactness, high linearity, high sensitivity, and without decoupling. In what follows, the structural description of the proposed multidimensional accelerometer based on fully decoupled compliant parallel mechanism is introduced in Section 2. In Section 3, comprehensive finite-element analysis including the strain of the sensitive legs and modal analysis for total deformation under different frequency is investigated. The performance of harmonic response is conducted in Section 4. Section 5 presents the process of the shape optimization to reduce the unnecessary parts. Besides, particle swarm algorithm is performed for redefining the dimension of the sensitive legs to obtain the optimal compliance. Section 6 gives the conclusion.

## 2. Structure Development

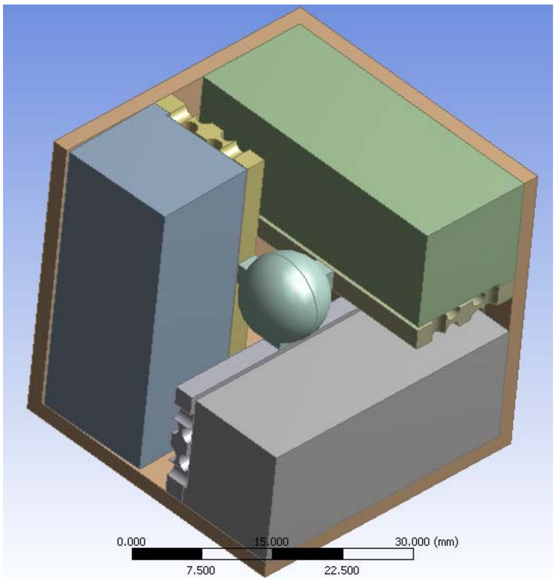
As shown in Fig. 2, the mechanism contains three separated components: a parallel mechanism with three elastic legs, a spherical mass to supply the strain source, a half-shelled basement and the three solid parts to protect the sensor.

In the domain of parallel mechanism, the three elastic legs are viewed as the parallel chains which are manufactured by passive joints and the active joints. The function of the active joints is to actuate the moving platform with the installed motors, which the function of the passive joints is to guarantee the required mobility of the end-effector. In the field of sensor, the elastic legs are served as the sensitive parts which the sensing components can be fixed on it. A spherical mass, namely the moving platform of parallel mechanism, is employed as the strain source. The three solid parts not only make the whole mechanism more compact, but also play an important role to protect the elastic legs.

The conventional decoupling procure is not necessary for this special sensor. Suppose that a random acceleration is applied at this sensor, the related component can be automatically dispensed to three elastic legs.



(a)




(b)

**Fig. 2.** The proposed multidimensional accelerometer based on fully decoupled compliant parallel mechanism: (a) semi-transparent model; (b) solid model.

## 3. Finite-Element Analysis

### 3.1. Mesh Generation and Initial Condition

The performance of a compliant mechanism is affected by the property of the selected material. The various factors contain cost, quality, and physical characteristics. Through a critical evaluation of vital design criteria for materials, the most applicable candidates can be chosen as the mechanical body of the proposed acceleration sensor. There were several materials that would be been most suitable - spring steel, hardsteel, brass 70/30, bronze 90/10, Phos. Bronze, Be. Copper - however, in the interests of cost and easy of manufacture, aluminium alloy is chosen and its elastic modulus, yield strength, Poisson's ratio and density are 72 GPa, 414 MPa, 0.33 and $2.78\times10^3$ kg/m$^3$. ANSYS 12.0 Workbench is utilized to implement a comprehensive FEM analysis.

Fig. 3 shows the meshing representation of the three elastic legs and the spherical mass. Since the thinnest parts of the eight flexible cantilever beams are most sensitive, the refinement processing is implemented. The refined cantilever beams will enhance the analysis accuracy of FEM. Table 1 illustrates the mechanical property as the initial condition.

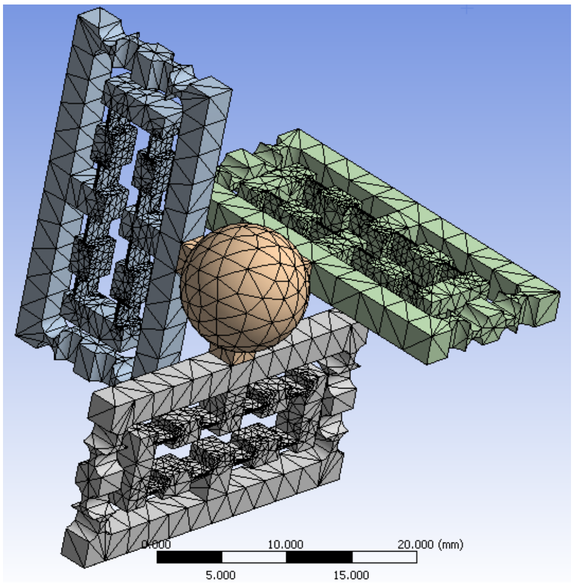



**Fig. 3.** The meshing representation.

**Table 1.** The mechanical property as the initial condition for FEA.

| | | | | |
|---|---|---|---|---|
| **Bounding Box** | | | | |
| Length X | 24.228 mm | 17.051 mm | 30.228 mm | 10.54 mm |
| Length Y | 26.316 mm | 19.605 mm | 28.952 mm | 10.45 mm |
| Length Z | 16.983 mm | 31.812 mm | 13.622 mm | 11.15 mm |
| **Properties** | | | | |
| Volume | 568.22 mm³ | | | 544.33 mm³ |
| Mass | 1.574e-003 kg | | | 1.5078e-003 kg |
| Centroid X | 20.072 mm | 26.748 mm | 8.4463 mm | 17.613 mm |
| Centroid Y | 20.107 mm | 15.869 mm | 14.775 mm | 24.049 mm |
| Centroid Z | -29.191 mm | -12.32 mm | -15.642 mm | -16.939 mm |
| Moment of Inertia Ip1 | 0.14809 kg·mm² | 0.14808 kg·mm² | 3.8104e-002 kg·mm² | 1.5282e-002 kg·mm² |
| Moment of Inertia Ip2 | 3.8105e-002 kg·mm² | 0.11158 kg·mm² | | 1.5335e-002 kg·mm² |
| Moment of Inertia Ip3 | 0.11158 kg·mm² | 3.8104e-002 kg·mm² | 0.14808 kg·mm² | 1.5317e-002 kg·mm² |
| **Statistics** | | | | |
| Nodes | 2989 | 3161 | 2749 | 968 |
| Elements | 1255 | 1309 | 1159 | 494 |

### 3.2. Strain Results

In FEA, the strain results reflect the performance of sensitivity and linearity of the accelerometer. Since the random acceleration which is applied on the sensor can be decomposed along each coordinate axes, the different inputs of acceleration in single-direction (x-axis) is conducted to calculate the related strain results.

As shown in Fig. 4, four different accelerations, 1*G*, 4 *G*, 7 *G*, and 10 *G*, are applied on x-axis. Both the maximal and the minimal strain happen at the thinnest parts of the eight flexible cantilever beams. It is proved that we can paste the sensing components (e.g. the strain gauge) on the end of thinnest parts. Due to the bending force, the other two legs have a little strain which can be neglected.

Fig. 5 displays the fitting curves of the maximal and the minimal strain under different inputs of acceleration. It is observed that the proposed sensor have excellent linearity.

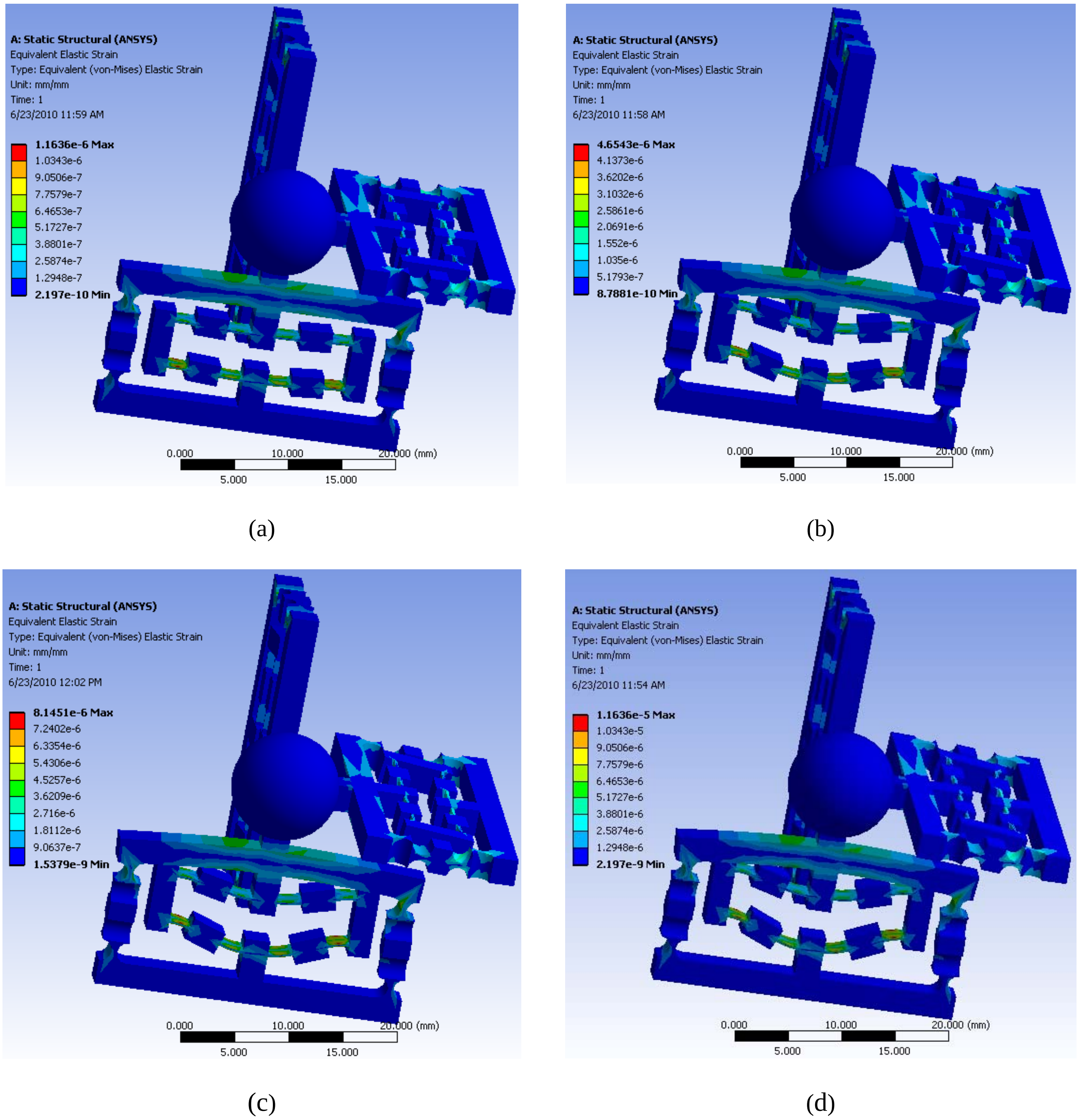
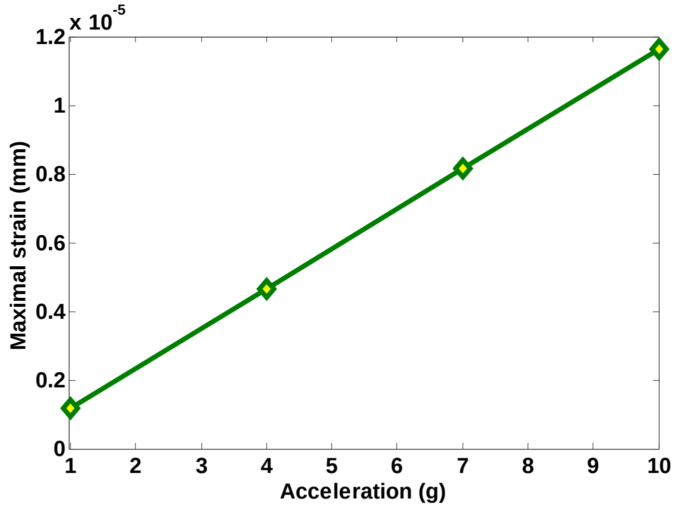



**Fig. 4.** The strain results under different inputs of acceleration in single-direction; (1) when $a = 1$ *G*, the maximal strain is $1.1636\times10^{-6}$ *mm*, and the minimal value is $2.197\times10^{-10}$ *mm*, (2) when $a = 4$ *G*, the maximal strain is $4.6543\times10^{-6}$ *mm*, and the minimal value is $8.7881\times10^{-10}$ *mm*, (3) when $a = 7$ *G*, the maximal strain is $8.1451\times10^{-6}$ *mm*, and the minimal value is $1.5379\times10^{-9}$ *mm*, (4) when $a = 10$ *G*, the maximal strain is $1.1636\times10^{-5}$ *mm*, and the maximal negative strain is $2.197\times10^{-9}$ *mm*.

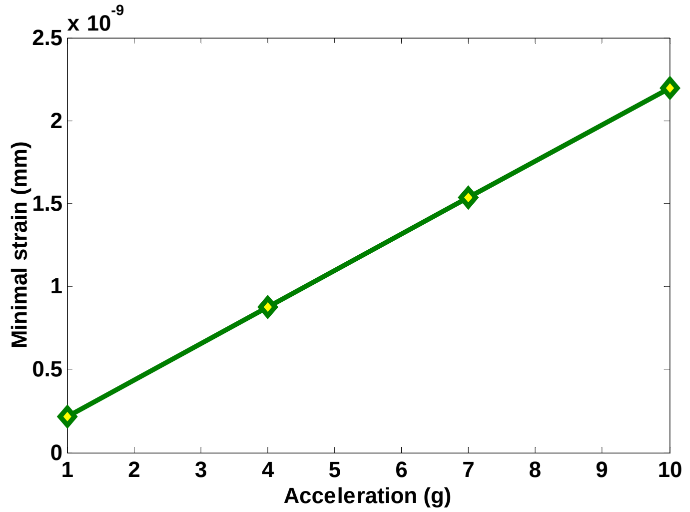
### 3.3. Modal Analysis

The value of the resonant frequency is utilized for the modal analysis. The simplest case of a mechanical resonant system is a discrete system consisting of a mass *m* attached to a spring with a force constant *k*, where is given as [28],

$$\text{Resonant frequency} = \frac{1}{\pi}\sqrt{\frac{k}{m}} \tag{1}$$




(a)




(b)

**Fig. 5.** The fitting curve of the maximal strain under different inputs of acceleration (a); the fitting curve of the minimal strain under different inputs of acceleration (b).

However, the proposed sensor is more complex than a single spring, which implies that it possesses more than one resonance frequency. Through calculation, it can be found that there are at least four resonance frequencies as shown in Table 2. The total deformation under different frequency inputs are displayed in Fig. 6.

**Table 2.** Mode and resonance frequency.

| Mode | Frequency [Hz] |
|---|---|
| 1. | 1745.9 |
| 2. | 1758.1 |
| 3. | 1762.7 |
| 4. | 1814. |

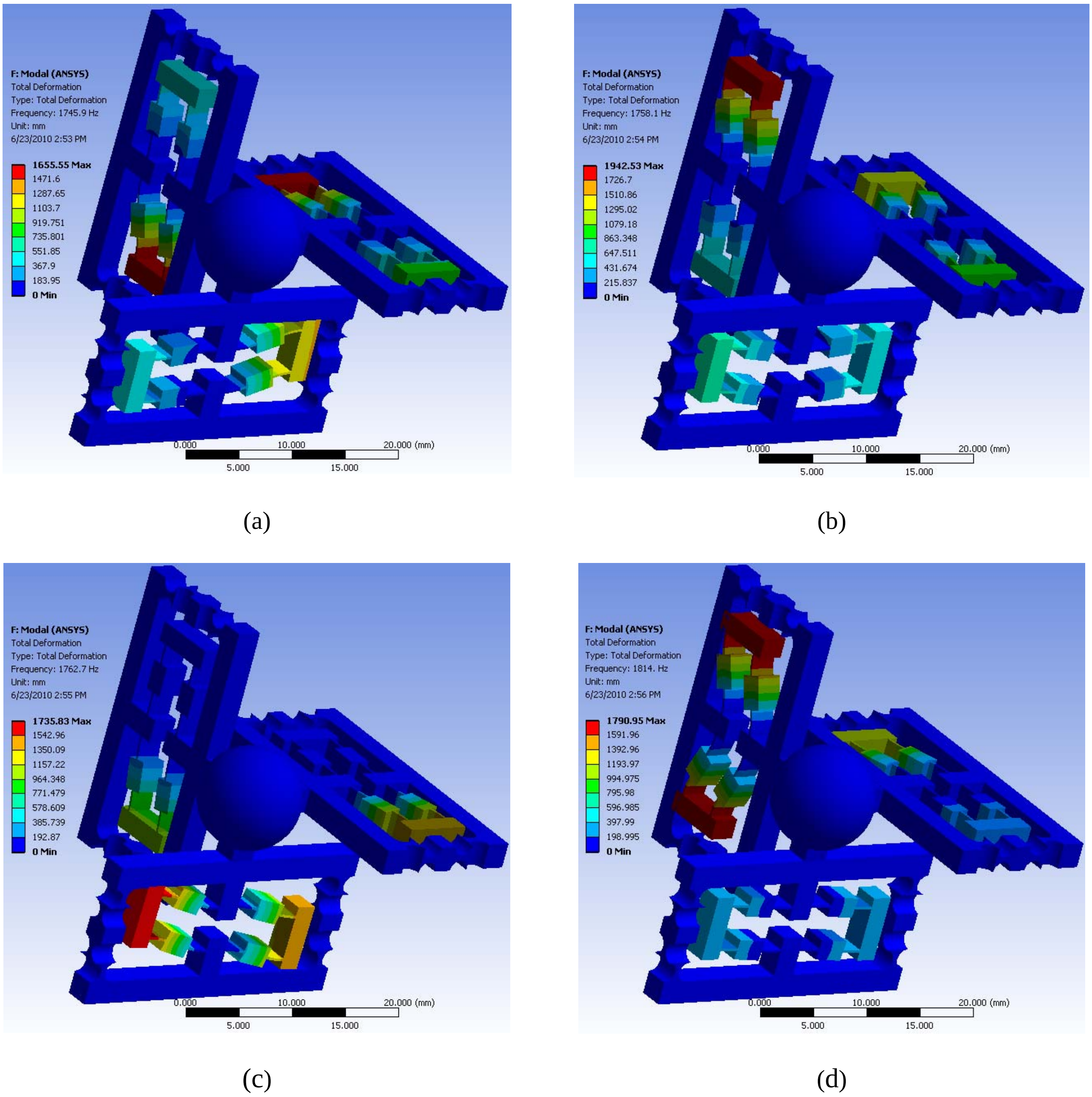



**Fig. 6.** Modal analysis for total deformation under different frequency input; (1) 1st modal with the resonance frequency 1745.9, (2) 2nd modal with the resonance frequency 1758.1, (3) 3rd modal with the resonance frequency 1762.7, (4) 4th modal with the resonance frequency 1814.

## 4. Harmonic Response

Harmonic response analysis is to determine the steady-state response and forced vibrations of a linear structure to loads that vary sinusoidally with time [29]. Some assumption is given for the harmonic response analysis:

1) Damping is neglected for a modal analysis.
2) Any applied loads are ignored.
3) Static structural analysis is conducted first.

Table 3 shows the alternating stress under different cycles. Fig. 7 reflects the frequency response of stress, strain, deformation, and acceleration. The phase response of stress, strain and displacement is given in Fig. 8. The corresponding phase angle is shown in Fig. 9.

**Table 3.** Alternating stress under different cycles.

| Alternating Stress, MPa | Cycles | R-Ratio |
|---|---|---|
| 275.8 | 1700 | -1 |
| 241.3 | 5000 | -1 |
| 206.8 | 34000 | -1 |
| 172.4 | 1.4e+005 | -1 |
| 137.9 | 8.e+005 | -1 |
| 117.2 | 2.4e+006 | -1 |
| 89.63 | 5.5e+007 | -1 |
| 82.74 | 1.e+008 | -1 |
| 170.6 | 50000 | -0.5 |
| 139.6 | 3.5e+005 | -0.5 |
| 108.6 | 3.7e+006 | -0.5 |
| 87.91 | 1.4e+007 | -0.5 |
| 77.57 | 5.e+007 | -0.5 |
| 72.39 | 1.e+008 | -0.5 |
| 144.8 | 50000 | 0 |
| 120.7 | 1.9e+005 | 0 |
| 103.4 | 1.3e+006 | 0 |
| 93.08 | 4.4e+006 | 0 |
| 86.18 | 1.2e+007 | 0 |
| 72.39 | 1.e+008 | 0 |
| 74.12 | 3.e+005 | 0.5 |
| 70.67 | 1.5e+006 | 0.5 |
| 66.36 | 1.2e+007 | 0.5 |
| 62.05 | 1.e+008 | 0.5 |

## 5. Shape and Compliance Optimization

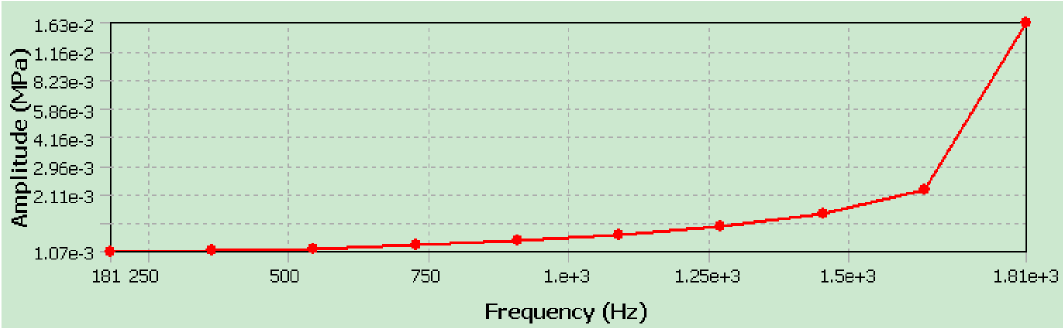
### 5.1. Shape Optimization

The purpose of shape optimization is to reduce the unnecessary parts of the whole mechanical mechanism without changing the system characteristics. Fig. 10 shows that almost 10% of the existed system is not necessary. The marked parts to be reduced are given in Fig. 10 a, and the results after optimization is supplied in Fig. 10 b.

### 5.2. Compliance Optimization with Particle Swarm Algorithm

To improve the sensing ability of the proposed sensor, the compliance optimization based on artificial intelligent method will be implemented in this scenario. Generally speaking, the basic evolutionary algorithms can be divided into four subsets: 1) genetic algorithms, 2) evolutionary programming, 3) evolution strategies, 4) genetic programming.

Inspired by social behavior such as bird flocking, particle swarm optimization (PSO) is swarm intelligence based stochastic optimization technique. Different with the traditional genetic algorithm, PSO has no evolution operators including crossover and mutation.

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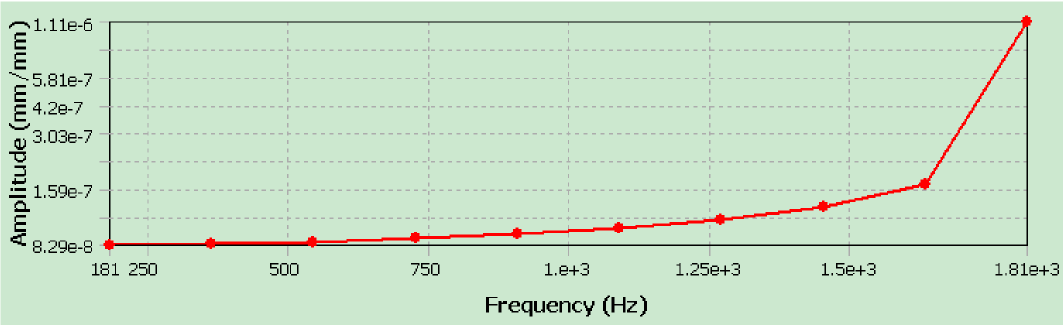


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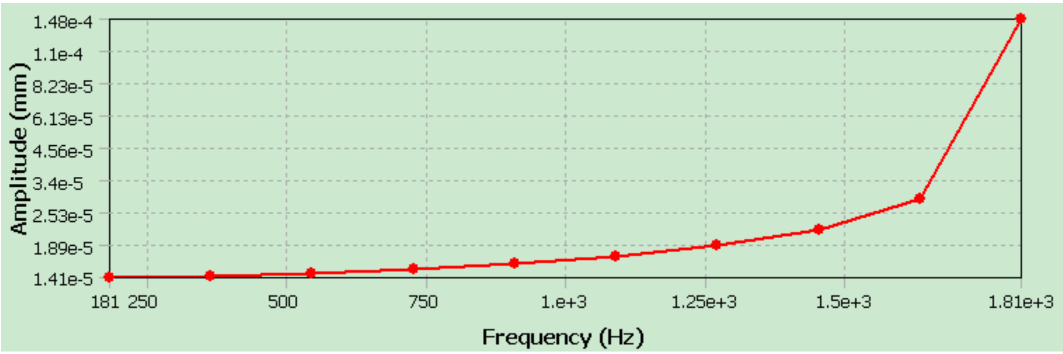
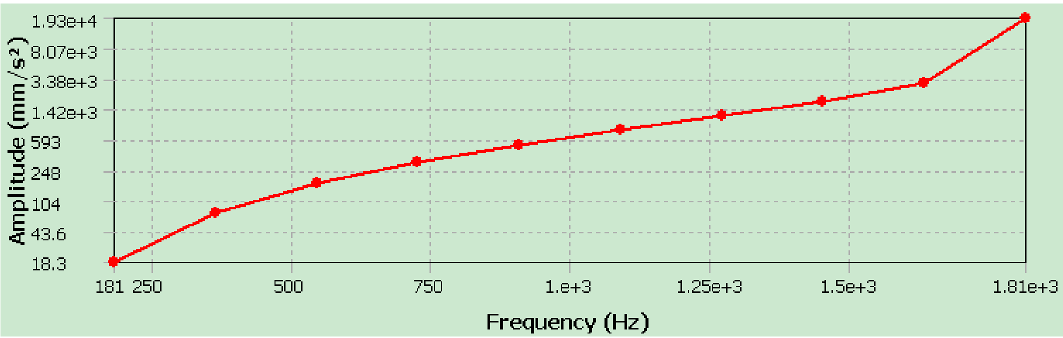
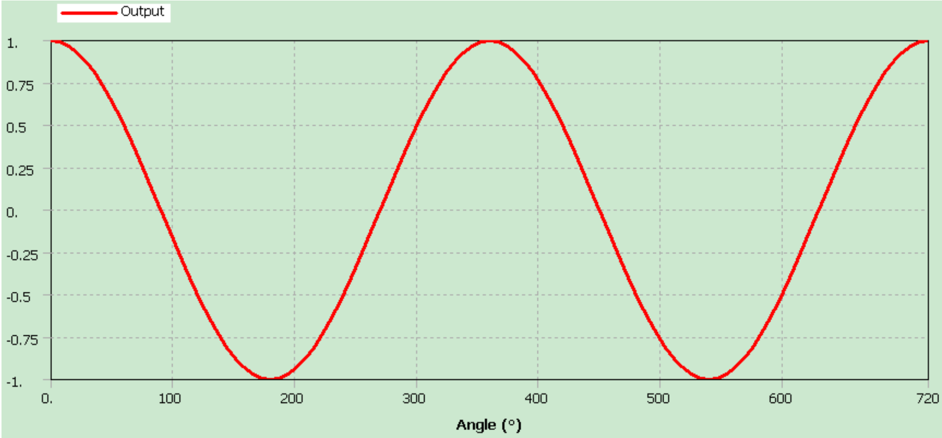



(c)

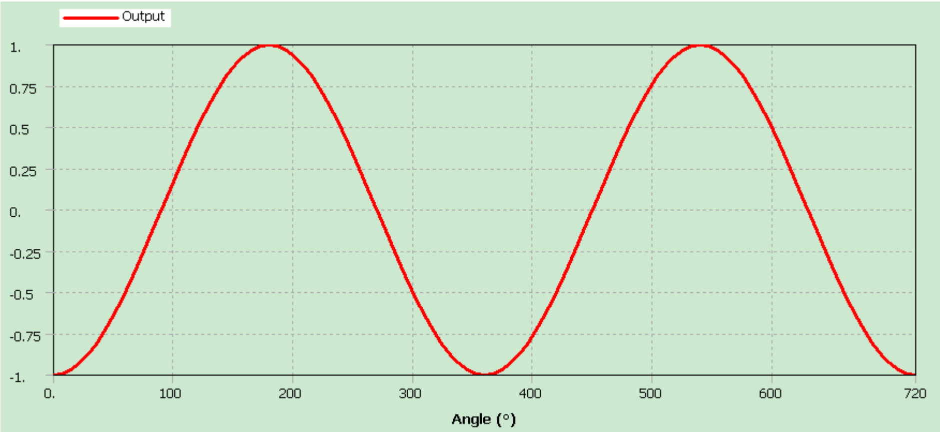



(d)

**Fig. 7.** Frequency response: (a) stress; (b) strain; (c) deformation; (d) acceleration.




(a)

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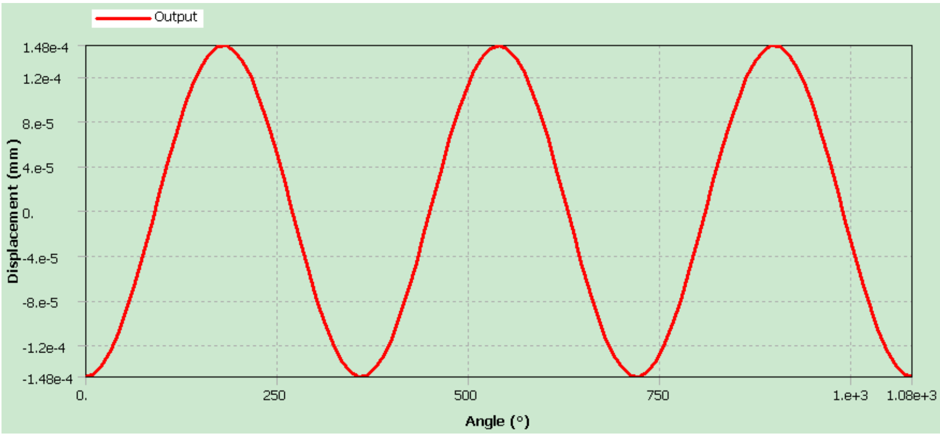



(c)

**Fig. 8.** Phase response: (a) stress; (b) strain; (c) displacement.

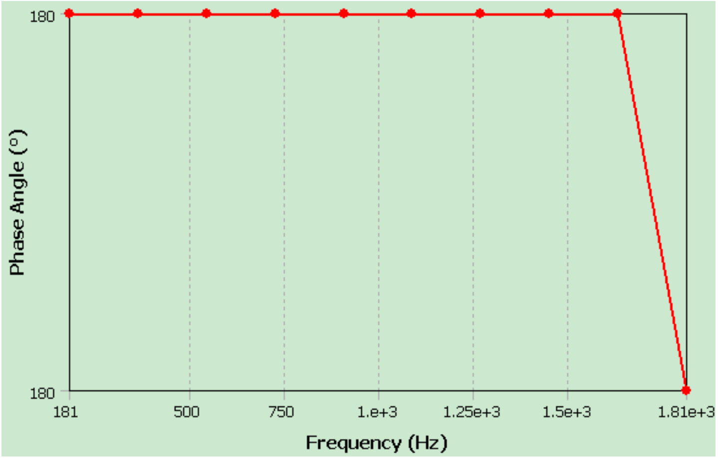
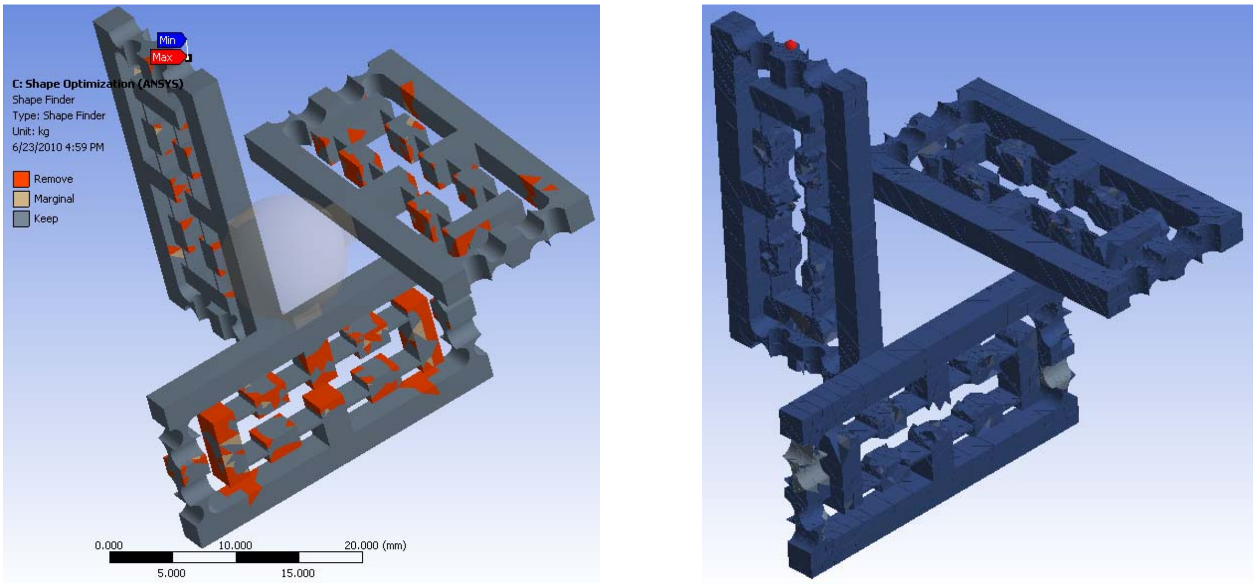



**Fig. 9.** Phase angle.




(a)

(b)

**Fig. 10.** Results of shape optimization; (a) the marked parts to be reduced, (2) the optimized mechanism.

The general PSO algorithm is constituted with the following velocity and position [30]:

$$v_i(n+1) = v_i(n) + \gamma_{1i}(bestP_i - x_i(n)) + \gamma_{2i}(bestG - x_i(n)) \tag{2}$$

$$x_i(n+1) = x_i(n) + v_i(n+1)\,, \tag{3}$$

where, $i$ denotes the particle index, $n$ is the discrete time index, $v_i$ is the velocity of $i^{th}$ particle, $x_i$ denotes the position of $i$th particle, $bestP_i$ means the best local position found by $i$th particle, and $bestP$ is the global best position found by swarm.

In this scenario, Trelea's model is utilized to perform the optimization process. The maximal velocity divisor is 2, the particles number is 24. Fig. 11 shows the optimal compliance with PSO. Before optimization, the compliance of the elastic leg is 0.03943 *mm/N*. After optimization, the compliance is improved by a factor of 1.1412.

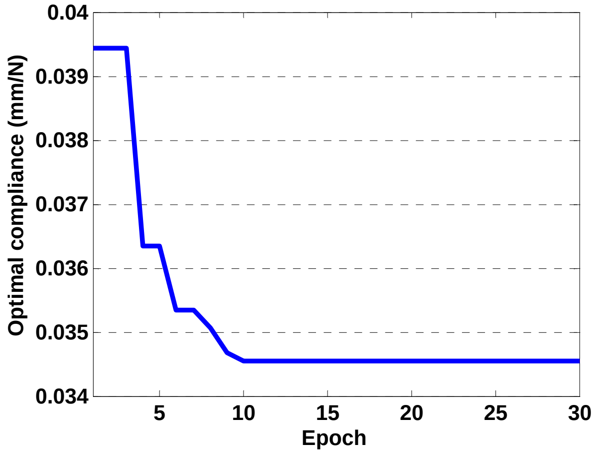



**Fig. 11.** The optimal compliance with PSO.

## 6. Conclusion

The conventional Gough-Stewart platform and its variations failed to produce a decoupled physical sensor. This study has endeavored in designing a novel three dimensional accelerometer based on fully decoupled compliant parallel mechanism. Design methodology of the decoupled accelerometer is generic. So it is available for the fabrication of other type of sensors, such as force/torque sensor. Besides, this facilitates the assembly procedures and the cost reduces due to the number of parts are significantly reduced. Through the finite-element analysis, it can be found the proposed accelerometer has high sensitivity, high compliance, high linearity and good dynamic characteristics. This special configuration supplies a novel approach for the mechanical design and analysis of the physical sensor. If it is integrated with MEMS machining technology, the application potential will be enlarged.

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# Guide for Contributors

## Aims and Scope

*Sensors & Transducers Journal (ISSN 1726-5479)* provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

## Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

## Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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