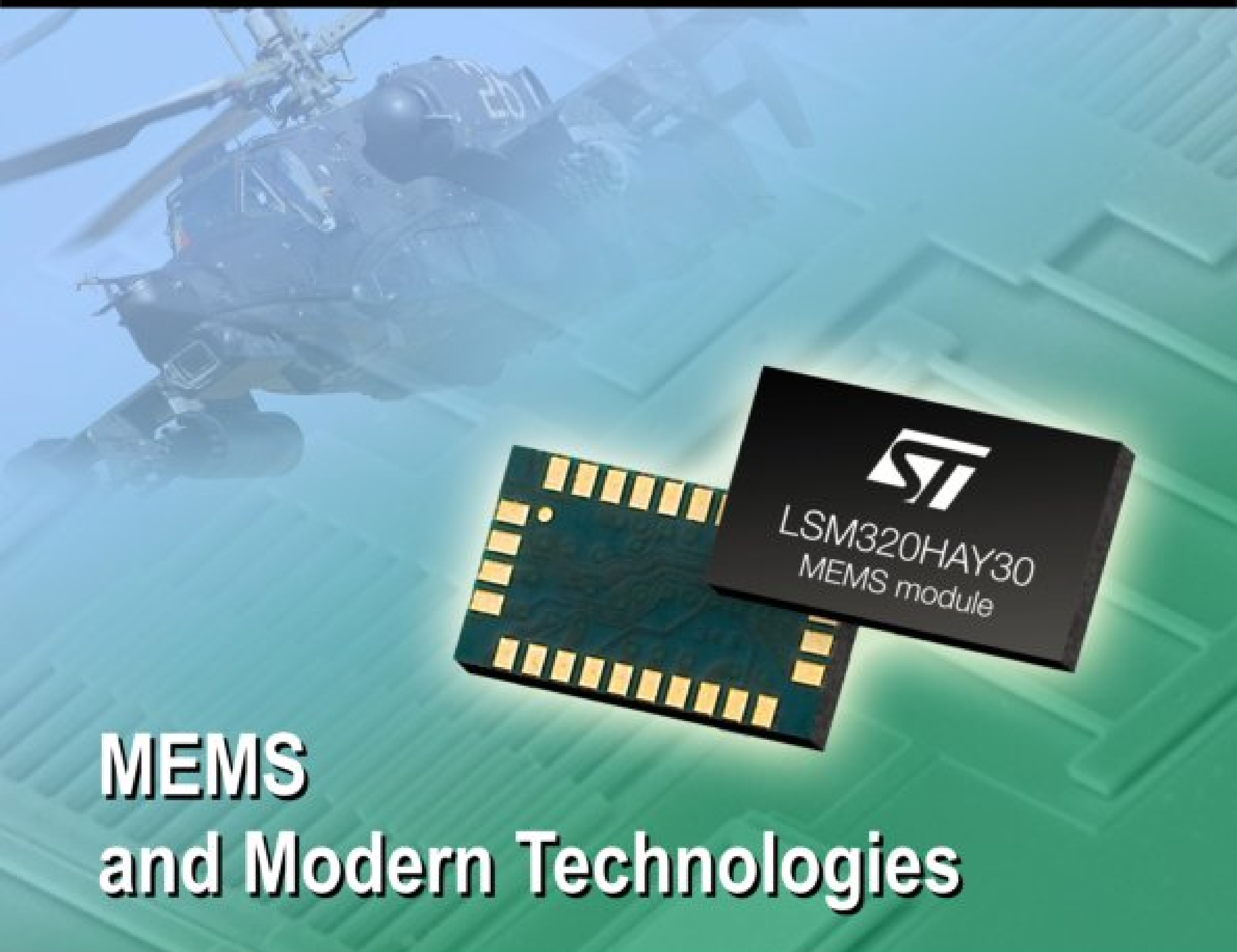
ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 139
4/12



MEMS and Modern Technologies

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 139, Issue 4, April 2012 **www.sensorsportal.com** **ISSN 1726-5479**

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Sensors & Transducers Journal

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Volume 139
Issue 4
April 2012

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 139, Issue 4, April 2012, pp. 45-51

Sensors & Transducers

ISSN 1726-5479

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Investigation of the Effect of Residual and Axial Stress, on Pull-in Instability of a Fully Clamped Micro-beam under Electrostatic Actuation, Considering Fringing Field Effect

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Received: 2 December 2011 /Accepted: 23 April 2012 /Published: 30 April 2012

Abstract: In this paper the effect of residual stress due to fabrication process and axial stress due to self stretching, on Pull-in instability of a Clamped-Clamped micro-beam, exposed to electrostatic actuation is investigated. The nonlinear electromechanical integro-differential equation governing the problem is solved using a Finite element code. The problem is solved for various values of residual stresses, and initial gaps. The achieved results are finally compared to that of reported ones.

Keywords: Micro beam, Pull in instability, Fringing field effect, clamped-clamped, Residual stress, axial stress.

1. Introduction

Today the ever-increasing demand for utilizing micro-electromechanical devices in various fields of industry makes researchers to study MEMS problems more preciously. So that investigating the effect of even inconspicuous parameters governing the MEMS designing process, is quite essential. Pull-in phenomenon is the most common failure which occurs in micro-electromechanical devices [1].

Whenever potential difference is applied between two conducting structures, they deform due to the attractive electrostatic force created due to the potential difference, the equilibrium is achieved whenever the elastic force equals the electrostatic one .The electrostatic force is inversely proportional to the square of the distance between two structures however, the elastic one is approximately proportional to the deflection , the more the potential difference increases the more does the deflection increase. This behavior is continued up to a critical voltage called Pull-in voltage, in which the rate of increase in electrostatic force exceeds that of elastic one which leads in Pull-in instability. Although the Pull-in phenomenon is mostly considered undesirable, it is sometimes used as a method of determining the Young's modulus, residual stress [2] and material properties [3] of MEMS switches or any other micro-electromechanical structures. Nathanson et al. [4] were the first to observe the pull-in phenomenon when studying an electrically actuated resonant gate transistor. Taylor found the same instability during his study of the electrostatic deflection of soap films [5]. Up to now various numerical methods for solving the differential equation governing the pull-in instability has been presented. Some of these methods are using of lumped energy model [6], step by step linearization method [7-11], reduced order method [12], meshless local kriging method [13] and so on. Osterberg [14] presented closed-form models for Pull-in instability in MEMS devices. Chowdhunry et al [15] developed a simple computationally efficient closed-form model to determine the Pull-in voltage of a cantilever beam actuated by electrostatic force. Their investigation was based on a linearized uniform approximate model of the nonlinear electrostatic pressure and the load deflection model of a cantilever beam under uniform pressure. In the present study the effect of residual stress due to fabrication process or temperature variations, axial stress due to self stretching and Fringing field effect on static Pull-in instability of a fully clamped micro-beam is studied.

2. Mathematical Modeling

As it is shown in Fig. 1 the studied model is a clamped-clamped micro-beam of length, thickness, and width. The initial gap between the micro-beam and the substrate is, and the applied voltage is denoted by V.

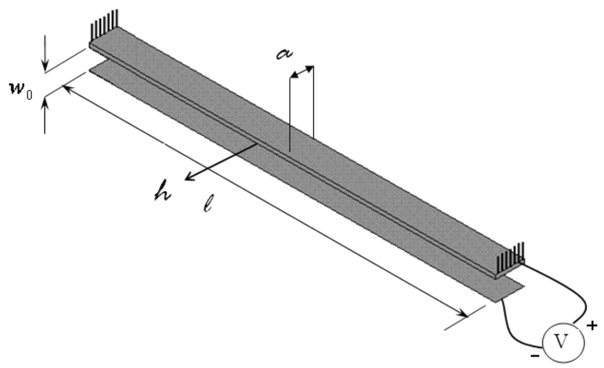

Fig. 1. Schematically drawn microbeam exposed to electrical potential difference.

The differential equation governing the problem is:

$$\tilde{E}I\frac{\partial^4 w}{\partial x^4}-[T_r+\frac{\tilde{E}ah}{2l}\int_0^l(\frac{\partial w}{\partial x})^2dx]\frac{\partial^2 w}{\partial x^2}=\frac{\varepsilon a(V_0 g(t))^2}{2(w_0-w)^2}(1+F_r) \tag{1}$$

where:

$\widetilde{E}$ is the effective Young's modulus, $\widetilde{E}$ is dependent on the beam width a and beam thickness. A beam is h considered wide when $a > 5h$. Wide beams exhibit plane-strain conditions, and therefore, $\widetilde{E}$ becomes the plate modulus, where E is the young's modulus $E/(1-\nu^2)$ and ν is the Poisson's ratio. A beam is considered narrow when $a < 5h$. In this case, $\widetilde{E}$ simply becomes the young's modulus, E. I is the moment of inertia of the cross section. $T_r = \sigma_0 (1-\upsilon) ha$ and σ_0 is the biaxial effective residual stress. ε_0 is the permittivity constant of the dielectric material between the micro-beam and the substrate. Since a uniform electric field cannot abruptly drop to zero at an edge, so in actual situation, there is always a Fringing field effect which must be considered to increase the accuracy of the solution. In Eq. (1), F_r is Fringing field correction denoted as:

$$F_r = 0.65 \frac{\omega_0 - \omega}{a} \tag{2}$$

The boundary conditions for the clamped-clamped micro-beam are as defined below:

$$\begin{aligned} w(l,t) = 0 \quad &, \quad \frac{\partial w}{\partial x}\Big|_{x=l} = 0 \\ w(0,t) = 0 \quad &, \quad \frac{\partial w}{\partial x}\Big|_{x=0} = 0 \end{aligned} \tag{3}$$

3. Numerical Solution

It is considered that the approximate solution in each element, denoted by w_a^e, is in the form:

$$w_a^e(x) = \sum_{i=1}^{i=4} \varphi_i H_i(x) \tag{4}$$

where φ_i are the nodal values of w_a^e and its derivatives and $H_i(x)$ are Hermit interpolation functions as defined below in term of ς:

$$\begin{aligned} H_1(\varsigma) = \frac{1}{4}(1-\varsigma)^2(2+\varsigma) \ , H_3(\varsigma) = \frac{1}{4}(1+\varsigma)^2(2-\varsigma) \\ H_2(\varsigma) = \frac{1}{4}(1-\varsigma)^2(\varsigma+1) \ , H_4(\varsigma) = \frac{1}{4}(1+\varsigma)^2(\varsigma-1) \end{aligned} \tag{5}$$

where ς is the normalized local coordinate system related to global coordinate system as:

$$\varsigma = \frac{x - x_e}{x_{e+1} - x_e} \times 2 - 1 \tag{6}$$

In Eq. (6) x_e, x_{e+1} refer to the global coordinate of the first and the second node of the element respectively. Constituting the residual function $R(x)$, one will have:

$$R(x) = EI \frac{\partial^4 w_a^e}{\partial x^4} - (T_r + \frac{EA}{2l} \int_{x_e}^{x_{e+1}} (\frac{\partial w_a^e}{\partial x})^2 dx) \frac{\partial^2 w_a^e}{\partial x^2} - \frac{\varepsilon_0 a V^2(t)}{2(w_0 - w_a^e)^2}(1 + F_r) \tag{7}$$

The integral $\int_{x_e}^{x_{e+1}} R(x)v(x)dx$ in which $v(x)$ is the weighting function must be vanished over the domain $[x_e, x_{e+1}]$. Using integration by part the integral will lead to:

$$\left.(EI\frac{\partial^3 w_a^e}{\partial x^3}v - EI\frac{\partial^2 w_a^e}{\partial x^2}\frac{\partial v}{\partial x} - T_r\frac{\partial w_a^e}{\partial x}v - (\frac{EA}{2l}\int_{x_e}^{x_{e+1}}(\frac{\partial \hat{w}_a^e}{\partial x})^2 dx)\frac{\partial w_a^e}{\partial x}v)\right|_{x_e}^{x_{e+1}} + \int_{x_e}^{x_{e+1}}(EI\frac{\partial^2 w_a^e}{\partial x^2}\frac{\partial^2 v}{\partial x^2} + T_r\frac{\partial w_a^e}{\partial x}\frac{\partial v}{\partial x})dx + \frac{EA}{2l}\int_{x_e}^{x_{e+1}}(\frac{\partial \hat{w}_a^e}{\partial x})^2 dx\int_{x_e}^{x_{e+1}}\frac{\partial w_a^e}{\partial x}\frac{\partial v}{\partial x}dx + \int_{x_e}^{x_{e+1}}\frac{\varepsilon_0 a V^2(t)}{2(w_0-\hat{w}_a^e)^2}dx\left[\int_{x_e}^{x_{e+1}} v dx + \int_{x_e}^{x_{e+1}} 0.65\frac{w_0-\hat{w}_a^e}{a}dx\int_{x_e}^{x_{e+1}} v dx\right] = 0 \tag{8}$$

To overcome the nonlinearity of the equation, the nonlinear terms are considered to be known and are shown with hat; ultimately, in order to achieve an acceptable accuracy an iterative procedure is used. Substituting w_a^e from (4) in (8) and using Galerkin method, Eq. (8) will reduce to:

$$[K^e]\{\varphi^e\} = [f^e] + [Q^e] \tag{9}$$

In Eq. (9) the term $[Q^e]$ refers to the natural boundary condition terms. The problem is solved for the beam length ($l = 250\mu m$), beam width ($a = 50\mu m$), beam thickness $(3\mu m)$, initial gap (0.5, 1, 2 μm). Air dielectric ε_0 is $8.854*10^{-12}$ (F/m) and the effective Young modulus is supposed to be $169.1\,GPa$.

4. Results and Discussion

In order to determine the suitable number of elements to get acceptable converged results, first of all the dependency of the results on element numbers is studied. Table 1 represents the dependency of the convergence of the results on element numbers.

Table 1. Pull in voltages obtained with various element numbers
(**AS** stands for axial stress and **RS** stands for residual stress).

Number of elements	**4**	**6**	**10**	**14**	**16**	**40**	**Ref. [5]**	**Ref. [1]**
With AS, RS=0 MPa	42.1	40.5	39.8	39.6	39.6	39.5	39.5	39.1
With AS, RS =-25 MPa	35.5	33.9	33.2	33.1	33.1	33.1	33.7	33.0

As mentioned the procedure of overcoming the nonlinearity is based on iteration. The results show that as the applied voltage increases number of iterations also increases this behavior is continued up to Pull-in instability in which no convergence is achieved. The results of analysis are represented in Table 2. These results are in a good agreement with those of [1, 2].

In above table IG/l is a non dimensional number which is the ratio of the initial gap to the microbeam length. ASE is a parameter which shows the increase percentage of the pull-in voltage in compare with the corresponding case in which axial stress is ignored.

Fig. 2 illustrates the remained space between the center of the microbeam and the substrate-defined as center gap- versus applied voltage.

Table 2. Pull-in voltages achieved in different cases.

Initial gap (μm)	Without A.S and without R.S	Without A.S and R.S=-25 MPa	Without A.S and R.S=100 MPa	With A.S and without R.S	With A.S and R.S=-25 MPa	With A.S and R.S=100 MPa
0.5	14.28 (V)	11.9 (V)	21.08 (V)	14.29 (V)	11.95 (V)	22.0 (V)
IG/l	0.002	0.002	0.002	0.002	0.002	0.002
ASE	------	------	------	0.07%	0.4%	0.4
1.0	39.3 (V)	32.8 (V)	57.6 (V)	39.6 (V)	33.2 (V)	58.3 (V)
ASE	------	------	------	0.08%	0.9%	1.2%
IG/l	0.004	0.004	0.004	0.004	0.004	0.004
2.0	110.6 (V)	92.6 (V)	162.6 (V)	113.3 (V)	95.2 (V)	167.6 (V)
ASE	------	------	------	0.6%	2.8%	3.0%
IG/l	0.008	0.008	0.008	0.008	0.008	0.008

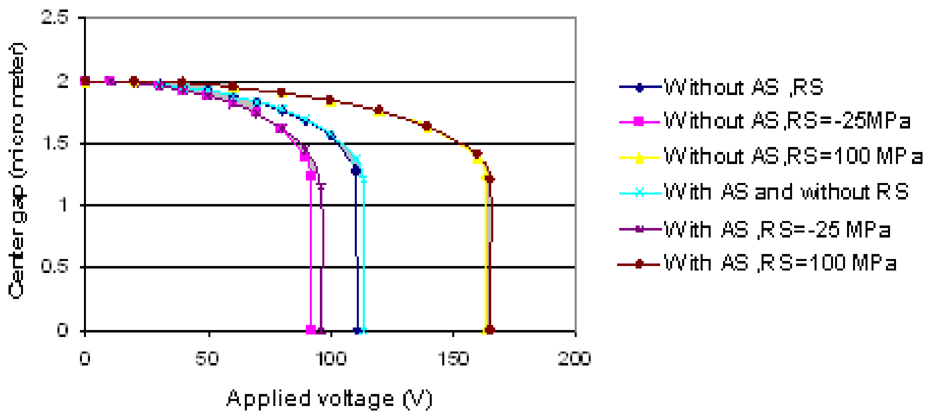

Fig. 2. Center gap versus applied voltage for initial gap=2 μm.

Fig. 3. Illustrates the beam deflection for various applied voltages for initial gap=1 μm .with axial stress and without residual stress effects.

Fig. 4 illustrates the deflection of the microbeam for a definite applied voltage, with various residual stresses, once considering and once neglecting the effect of self stretching (axial stress).

5. Conclusion

The nonlinear electromechanical integral differential equation is successfully solved using a FE code. To overcome the nonlinearity an iteration procedure was used to achieve an acceptable accuracy. One of the significant parameters in solution process is the convergence. It is seen that by applying voltages very lower than the pull-in voltage the convergence is achieved even with lower element numbers. However the convergence around the pull-in voltage is strongly depended on the element numbers and it is achieved with small divisions. According to the results, residual stress plays an important role in Pull-in instability of micro-beams and neglecting it, may lead in undesired results. Furthermore in small air gaps the effect of axial stress is negligible. The results show that the effect of axial stress in pull-in voltage increases as the non-dimensional parameter $(IG$ increases. Also it is clear that for a definite value of (IG , the axial stress effect (ASE) depends on the residual stress and it increases by the increase of residual stress.

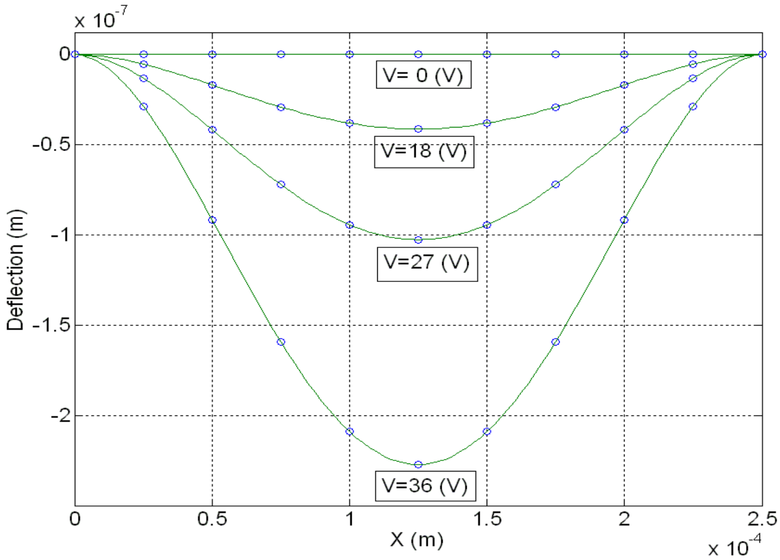

Fig. 3. Beam deflection due to various applied voltages.

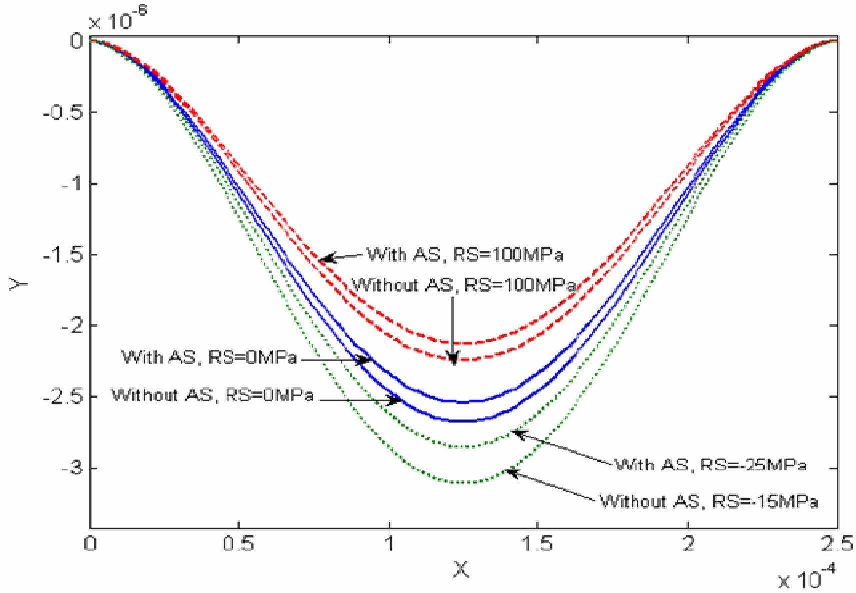

Fig. 4. The deflection of the microbeam for a definite applied voltage, with various residual stresses, once considering and once neglecting the effect of self stretching.

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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 of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor 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. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

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