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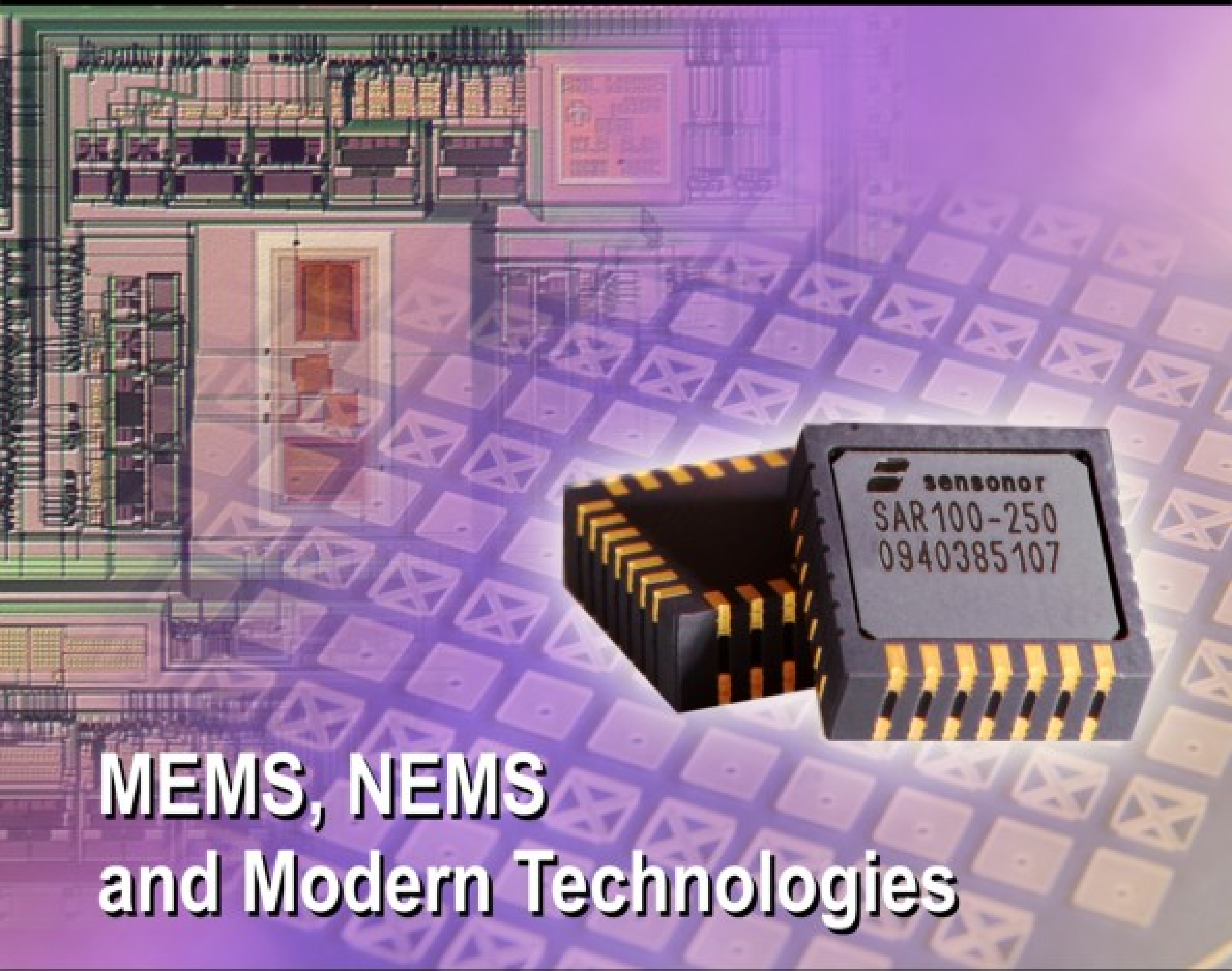

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Pull-In Phenomenon Investigation in Nonlinear Electromechanical Coupled System by Distributed Model Frequency Analysis Method

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Abstract: In the present paper, a new approach for investigating pull-in phenomenon in nonlinear, electromechanical, multi-domain problems based on Eigen frequency analysis of perturbed motion about nominal equilibrium point has been developed. In order to study the stability of the system at the equilibrium position due to the applied voltage, the nonlinear equations of small flexural vibration about this position have been derived and linearized via Taylor expansion theory. The first Eigen frequency of the linearized perturbed motion has been calculated. It has been shown that the instability occurs when the Eigen frequency diverges to zero, while the pull-in phenomenon is divergence instability. To calculate the equilibrium position at given applied voltage a Step-by-Step linearization method has been used. The obtained results have been compared to other theoretical results, and good agreement is observed. *Copyright © 2010 IFSA.*

Keywords: MEMS, Pull-In Phenomenon, Perturbation, Eigen frequency, Stability, Nonlinear

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1 Introduction

Today's advantages of electrostatic micro-electro-mechanical systems (MEMS) switches, with their favorable scaling property, low power consumption, low cost, relative ease of fabrication, and others, have led to the replacement of traditional electronic switching components (such as pin diodes). More widely applied electrostatic MEMS switch applications may be formed in micro-electro-mechanical systems. The electrostatic MEMS switch is one of the most important devices in such systems.

The most important issue in electrostatic MEMS switches is the well-known pull-in phenomenon as an instability phenomenon [1].

Instability phenomenon can be divided broadly speaking into two categories, statical and dynamical. All buckling problems that are statical in nature, i.e. they take place at zero frequency, fall into the first category. Intuitively what happens is that, due to the increase in the loading, the stiffness of the structure decreases enabling buckling to occur. Dynamical instability, in contrast, is an instability phenomenon, which takes place at a critical load as well as a critical frequency different from zero. Statical buckling as well as dynamical buckling can in turn be subdivided into different types. Divergence and flutter instabilities are two major types of statical and dynamical instabilities, respectively that occur only in non-conservative systems [6Fat]. Divergence occurs at zero frequency whereas flutter occurs when two Eigen frequencies coalesce [2].

The pull-in instability indeed takes place at zero frequency falls into the first category, and is a kind of static or buckling instability. The electrostatic force is a displacement dependent force therefore in the coupled electrostatic and elastic domain the equivalent stiffness of the system is the difference of the mechanical and electrical stiffness where due to the increase in the applied voltage in a MEMS switch the equivalent stiffness of the system decreases enabling static instability or buckling to occur. In the other words the Pull-in phenomenon is a discontinuity related to the interplay of the elastic and electrostatic forces. The electrostatic force is related to the applied voltage, thus the specific applied voltage that leads to pull-in phenomenon is often called the "pull-in voltage". In MEMS switches, the pull-in voltage causes it to switch. Because of the micro-scale MEMS switches, some phenomena and factors, such as residual stress in thin films, fringing field effect, axial stress and so on, can influence the pull-in voltage. The other factors relevant to a determination of the pull-in voltage in dude measuring the Young's modulus and the residual stress [1] and material properties [3] of MEMS switch materials, and other micro-electro-mechanical structures such as cantilever micro-beams, fixed-fixed micro-beams, and clamped micro-diaphragms. The proposed applications make the pull-in voltage a relevant aspect of numerical prediction capabilities for design methods when the determination of the pull-in voltage and position requires the solution of a coupled electrostatic-elastic system. Determination of the pull-in voltage has been already investigated. Some of numerical methods used in dude the lumped energy model [4], Galerkin’s method whose basis functions were obtained by selecting a few linear undamped mode shapes, discretization techniques for both of microstructure and electromagnetic field for 2D and 3D models such as BEM, FEM [5], and the differential quadrature method (DQM) [5], reduced order model [7], meshless local Kriging method [8] and so on. Although the number of techniques already available is quite high, and they cope the need for advanced CAE tools for MEMS, the availability of a number of methods, proposed in literature can make it difficult for engineers to select the most suitable approach, especially when considering on the level of approximation required to determine the pull-in voltage. One of the best approaches to evaluate the pull-in voltage in MEMS switches is an examination of their stability when voltage is applied voltage. The pull-in voltage phenomenon occurs when the stability of a MEMS switch vanishes. Because of the frequency shifting occurring with increasing voltage [9], one of the best methods to study the stability of microbeams is the examination of the Eigen frequencies of the small flexural vibrations about the equilibrium position. The first results using this approach were produced by Shashkov [10]. Later, this approach was developed by the others including Ziegler, Makushin, Morris, Rezazadeh [11, 12] et al. for use in the similar problems. Brusa et al. [13] developed an approach to calculate the frequency of the lumpe d electrostatic microbeam respect to its equilibrium position under a specific applied voltage.

In this work, we have attempted to predict the pull-in voltage in a distributed electrostatic MEMS switch model by analyzing the first Eigen frequency of the small flexural vibrations about the equilibrium position. Whit voltage applied we consider the effects of residual stress, fringing field and axial stress. The results obtained for a fixed-fixed (dual cantilever) MEMS switch have been compared with results from the lumped model method [11], a 2D simulation and MEMCAD data [1] and good agreement have been observed.

2. Electromechanical Behavior of Microbeams

2.1. Model Description and Assumptions

As shown in Fig. 1, we consider a fixed-fixed MEMS switch with thickness t, width b, length L, material density ρ and an isotropic Young's modulus E. Suppose that x is the coordinate along the length of the beam with its origin at the left end, and $u(x)$ is the deflection of the beam (defined to be positive downward).

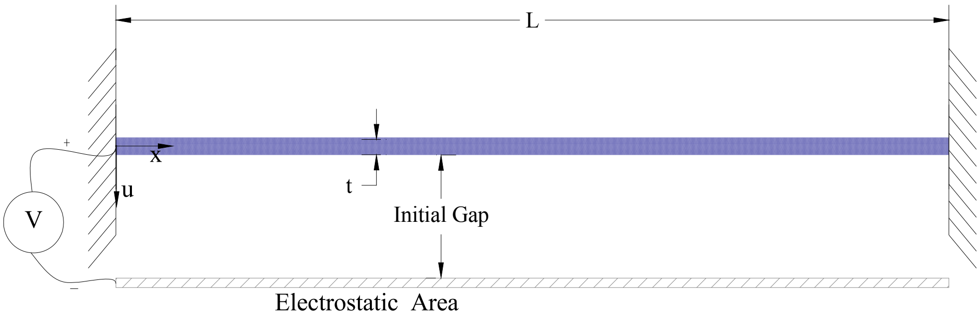

Fig. 1. Schematic of the Fixed-Fixed MEMS switch.

Electromechanically actuated microbeams are usually modeled as continuous and prismatic straight beams, made of homogeneous elastic material [14], with principal axes of elasticity equal in all directions. The above assumption allows for uncoupling flexural, torsional and axial behaviors. Since the flexural behavior is here mainly considered, transverse displacement and rotation are suitable to write equilibrium equations.

2.2. Mathematical Model for Electrostatic MEMS Switches

Based on the static behavior of the electrostatic MEMS switches subject to a non-uniform transverse electrostatic force, the governing equation can be expressed as [15]:

$$\frac{d^2}{dx^2}\left(EI(x)\frac{d^2u}{dx^2}\right) = p\big(u(x),V\big) = \frac{\varepsilon_0 b V^2}{2\big(g_0 - u(x)\big)^2} \tag{1}$$

(permittivity) of air; V is the voltage applied to the parallel plates and g_0 is the initial gap between parallel plates (beam as a movable plate and fixed ground plate). For a wide beam, for which $b \geq 5t$, the effective modulus $\tilde{E}$ can be approximated by the plate modulus $\frac{E}{(1-\upsilon^2)}$. If $b \leq 5t$ $\tilde{E}$ simply Young's modulus E [15].

2.2.1. Residual Stress Effect

Considering the fabrication sequence of the MEMS switches, the residual stress is very important and inevitable. Residual stress, a result of the mismatch of both thermal expansion coefficient and crystal lattice period between substrate and thin film, is unavoidable in surface micromachining techniques. In variably, these residual stresses are not distributed uniformly throughout material. Rather, they depend on position and are present in the form of stress gradients. Accurate and reliable data for the distributed residual stress is crucial to the proper design of the MEMS devices [16, 17]. The effective residual stress can be calculated as follows [18]

$$\hat{\sigma} = \sigma_0(1-\nu) \tag{2}$$

where σ_0 is the biaxial residual stress, $\hat{\sigma}$ is the effective residual stress and ν is the Poisson's ratio. As a consequence the effective residual force can be expressed as:

$$T_r = \hat{\sigma} bt \tag{3}$$

2.2.2. Fringing Field Effect

A tangential electric field cannot drop abruptly to zero at a boundary. A ‘‘fringing field’’ will always exist at such boundaries. If the fringing field is taken into account, then the transverse force per unit length can be rewritten as [1]:

$$p(u,V) = \frac{\varepsilon_0 b V^2}{2\left(g_0 - u(x)\right)^2}\left(1 + F_r\right) \tag{4}$$

The first order fringing-field correction can be expressed as [1]:

$$F_r = 0.65\frac{g_0 - u(x)}{b} \tag{5}$$

2.2.3. Axial Stress Effect

When a fixed-fixed beam is in tension, the actual beam length *L'* is longer than the original length *L*. Although there is no displacement in the *x* direction at the beam ends, the tensile stress due to bending generates an axial force [15]:

$$T_a = \sigma_a bt \cong \tilde{E} bt \frac{\Delta L}{L}, \tag{6}$$

where:

$$\Delta L \cong \frac{1}{2}\int_0^L \left(\frac{du}{dx}\right)^2 dx$$

2.2.4. Model of Electrostatic Microbeam with Consideration of all Effects

Now by considering all of the above effects and assuming the cross-sectional area is constant among the length of the Microbeam, the governing nonlinear equation of the electrostatic MEMS can be rearrange as follow:

$$\widetilde{E}I\frac{d^4u}{d^4x}-[T_r+\frac{\widetilde{E}bt}{2L}\int_0^L(\frac{du}{dx})^2dx]\frac{d^2u}{dx^2}=p(u(x),V), \tag{7}$$

where:

$$p(u(x),V)=\frac{\varepsilon_0 bV^2}{2(g_0-u(x))^2}\left(1+0.65\frac{g_0-u(x)}{b}\right), \tag{8}$$

3. Coupled Electrostatic Actuated Microbeam Analysis

To determine the pull-in voltage, the behavior of the first Eigen frequency of the microbeam with respect to its equilibrium position is studied. By increasing the applied voltage, the equivalent electrical stiffness is increased and so the total stiffness of the system is decreased, then the first Eigen frequency go to zero causes to the lose beam static stability. For a specific applied voltage, the divergence phenomenon occurs, and that specific applied voltage becomes the pull-in voltage. To obtain the first Eigen frequency of the microbeam, a lumped or distributed model can be used.

3.1. Lumped Model Frequency Analysis Method (LMFAM) [13]

For a preliminary analysis of the system shown in Fig. 2 a low-order model is considered by assimilating the microbeam into a system with lumped elements. As it is mentioned in [13], the frequency of the fixed-fixed MEMS switch with equivalent lumped elements respect to the equilibrium position can be written as:

$$\omega_i=\sqrt{\frac{k_m-k_e}{m}}, \tag{9}$$

where k_m mechanical stiffness and k_e electrical stiffness can be express as:

$$k_m=\frac{192EI}{L^3}\ ,\ k_e=\frac{\varepsilon_0 bV_i^2}{(g_0-u_i)^3}\ ,m=\rho AL/2$$

where the displacement u_i is found from the solution of a cubic equation written by imposing the static equilibrium between mechanical and electrostatic actions due to the applied voltage V_i . That means u_i can be calculated from [13]:

$$k_m u_i=\frac{\varepsilon_0 bV_i^2}{2(g_0-u_i)^2} \tag{10}$$

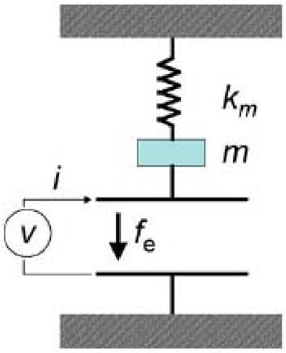

Fig. 2. Lumped electromechanical model.

So by examination the ω_i for different applied voltages, the stability can be studied. The pull-in voltage can be found when ω_i goes to zero and the static instability or buckling occurs. As it is mentioned in [13] it can be appreciated that the lumped model assumption is the easiest one. The following method modified this method and it can be also used to account the residual and fringing field and axial force effects.

3.2. Distributed Model Frequency Analysis Method (DMFAM)

The lumped model operates with lumped elements, and assumes uniform electrostatic force through a capacitor with rigid plates connected to an equivalent spring. A more realistic model takes into account distributed parameters for both the structural and the electric domains. So the distributed model frequency analysis method (DMFAM) is used to calculate the Eigen frequencies of perturbed motion of a microbeam about a given equilibrium position so as to evaluate the stability.

Assume that $u_i\,(x)$ is the equilibrium position of the fixed-fixed MEMS microbeam due to the applied voltage V_i . Thus, by examining of the first Eigen frequency with respect to its equilibrium position, the pull-in voltage can be obtained when first Eigen frequency goes to zero or a static instability occurs.

Suppose that in the equilibrium position, the microbeam can oscillate about the equilibrium position, so the transverse displacement can be noted as:

$$u(x,t) = u_i\,(x) + \varepsilon(x,t)\,, \tag{11}$$

where $\varepsilon(x,t)$ is the perturbation about nominal equilibrium position $u_i(x)$. The nonlinear dynamic behavior of the microbeam with respect to the equilibrium position can be formulated as governed by the Woinowsky-Krieger equation [19]:

$$\tilde{E}I\frac{\partial^4 u}{\partial x^4} - [T_r + \frac{\tilde{E}bt}{2L}\int_0^L (\frac{\partial u}{\partial x})^2 dx]\frac{\partial^2 u}{\partial x^2} + m\frac{\partial^2 u}{\partial t^2} = p\big(u,t,V_i\,\big) \tag{12}$$

Whereas:

$$p\left(u,t,V_i\right)=\frac{\varepsilon_0 bV_i^2}{2\left(g_0-u(x,t)\right)^2}\left(1+0.65\frac{g_0-u(x,t)}{b}\right),\ m=\rho bt$$

By substituting the Eq. (11) into Eq. (12), the following equations can be obtained:

$$\widetilde{EI}\frac{\partial^4(u_i+\varepsilon)}{\partial x^4}-[T_r+\frac{\widetilde{E}bt}{2L}\int_0^L(\frac{\partial(u_i+\varepsilon)}{\partial x})^2dx]\frac{\partial^2(u_i+\varepsilon)}{\partial x^2}+m\frac{\partial^2(u_i+\varepsilon)}{\partial t^2}=p\left(u_i,\varepsilon,t,V_i\right), \tag{13}$$

where:

$$p\left(u_i,\varepsilon,t,V_i\right)=\frac{\varepsilon_0 bV_i^2}{2\left(g_0-(u_i+\varepsilon)\right)^2}\left(1+0.65\frac{g_0-(u_i+\varepsilon)}{b}\right)$$

Meanwhile, u_i the static equilibrium position due to the applied voltage V_i isn't a function of time. Using of the first order approximation $p(u_i,\varepsilon,V_i,t)$ via Taylor's series expansion the following linear differential equation for perturbed motion about equilibrium position can be obtained:

$$p\left(u_i,\varepsilon,V_i,t\right)=\frac{\varepsilon_0 bV_i^2}{2\left(g_0-u_i\right)^2}\left(1+0.65\frac{g_0-u_i}{b}\right)+\frac{\varepsilon_0 bV_i^2}{2\left(g_0-u_i\right)^3}\left(2+0.65\frac{g_0-u_i}{b}\right)\varepsilon \tag{14}$$

Therefore, by using the above assumptions and substituting the Eq. (14) into the Eq. (13) expanding and simplifying it, the small flexural vibration equation about the equilibrium position can be rewritten as:

$$\widetilde{EI}\frac{\partial^4\varepsilon}{\partial x^4}-[T_r+\frac{\widetilde{E}bt}{2L}\int_0^L(\frac{\partial u_i}{\partial x})^2dx]\frac{\partial^2\varepsilon}{\partial x^2}+m\frac{\partial^2\varepsilon}{\partial t^2}-\frac{\varepsilon_0 bV_i^2}{2\left(g_0-u_i\right)^3}\left(2+0.65\frac{g_0-u_i}{b}\right)\varepsilon=0 \tag{15}$$

By introducing the following non-dimensional parameters the Eq. (15) can be written as:

$$\frac{\partial^4\bar{\varepsilon}}{\partial\bar{x}^4}-\frac{L^2}{\widetilde{EI}}[T_r+\frac{\widetilde{E}bt}{2L}\int_0^L(\frac{\partial u_i}{\partial x})^2dx]\frac{\partial^2\bar{\varepsilon}}{\partial\bar{x}^2}-\left(\frac{mL^4}{\widetilde{EI}}\right)\frac{\partial^2\bar{\varepsilon}}{\partial\bar{t}^2}-\frac{L^3\varepsilon_0 bV_i^2}{2\widetilde{EI}\left(g_0-u_i\right)^3}\left(2+0.65\frac{g_0-u_i}{b}\right)\bar{\varepsilon}=0, \tag{16}$$

where:

$$x=L\bar{x}\ ,\ \varepsilon=L\bar{\varepsilon}\ ,\ t=\sqrt{\frac{mL^4}{EI}}\bar{t}$$

The general solution of the linearized Eq. (16) can be written as follow:

$$\bar{\varepsilon}(x,t)=\bar{\varepsilon}(x)\exp(i\bar{\omega}\bar{t}) \tag{17}$$

Hence:

$$\frac{d^4\bar{\varepsilon}}{d\bar{x}^4}-\frac{L^2}{\widetilde{EI}}[T_r+\frac{\widetilde{E}bt}{2L}\int_0^L(\frac{\partial u_i}{\partial x})^2dx]\frac{d^2\bar{\varepsilon}}{d\bar{x}^2}-\left[\varpi^2+\frac{L^3\varepsilon_0 bV_i^2}{2\widetilde{EI}(g_0-u_i)^3}\left(2+0.65\frac{g_0-u_i}{b}\right)\right]\bar{\varepsilon}=0 \qquad (18)$$

The non-dimensional boundary conditions for a fixed-fixed end type MEMS switch are:

$$\text{At } \bar{x}=0\Rightarrow\begin{cases}\bar{\varepsilon}=0\\ \dfrac{d\bar{\varepsilon}}{d\bar{x}}=0\end{cases}\quad\text{and at } \bar{x}=1\Rightarrow\begin{cases}\bar{\varepsilon}=0\\ \dfrac{d\bar{\varepsilon}}{d\bar{x}}=0\end{cases} \qquad (19)$$

The linear ordinary differential Eq. (18) can be solved using any discretizing methods [20].

4. Numerical Simulation and Discussions

4.1. Determination of the Equilibrium Position

To calculate the Eigen-frequencies of Eq. (18), one first needs to calculate the equilibrium position u_i due to the applied voltage V_i by using Eq. (7). Because of nonlinearity of the equation, its solution is complicated and time consuming. In order to solve it, one often tries to linearize it. But linearizing of Eq. (7) with respect to initial position of the microbeam $(u=0)$, because of considerable value of u with respect to initial gap, especially when the applied voltage is increasing, may causes to appear some considerable errors. Therefore, to minimize the value of errors, step by step increasing the applied voltage is proposed. Meanwhile, if the u_j is the equilibrium position of the microbeam due to the applied voltage V_j so [15]:

$$u_{j+1}=u_j+\delta u=u_j+\psi_j(x)\quad\left(u_i(x)=\sum_{j=0}^{k}\psi_j(x)\right) \qquad (20)$$

when:

$$V_{j+1}=V_j+\delta V\quad\left(\delta V=\frac{V_i}{k}\right), \qquad (21)$$

where k is the number of steps for applying a given voltage V_i to receive acceptable results for the beam deflection. By substituting Eq. (20) and Eq. (21) to Eq. (7) and applying the truncation to first order of Taylor's expansion series for the electrostatic force, the linearized equation for ψ can be expressed as:

$$\widetilde{EI}\frac{d^4\psi_j}{dx^4}-[T_r+\frac{\widetilde{E}bt}{2L}\int_0^L(\frac{du_j}{dx})^2dx]\frac{d^2\psi_j}{dx^2}-\frac{\varepsilon_0 b(V_j+\delta V)^2}{2(g_0-u_j)^3}\left(2+0.65\frac{g_0-u_j}{b}\right)\psi_j=\tilde{p}(u_j,V_j,\delta V), \qquad (22)$$

where:

$$\tilde{p}(u_j, V_j, \delta V) = \frac{\varepsilon_0 b}{2\left(g_0 - u_j(x)\right)^2}\left(1 + 0.65\frac{g_0 - u_j(x)}{b}\right)\left(2V_j\,\delta V + (\delta V)^2\right)$$

The nonlinear electrostatic Eq. (7) is converted to the linear electrostatic Eq. (22), therefore applying a finite difference method (FDM) and imposing the boundary conditions, Eq. (22) may be discretized into n nodes and then by solving the obtained linear system of equations, the ψ_j can be calculated at each step of applied voltage.

4.2. Investigation of the Pull-in Voltage

As an illustration, a silicon microbeam is considered with the geometric and material properties listed in Table 1.

Table 1. Geometrical and material properties of the electrostatic fixed-fixed MEMS switch.

Length	250 & 350 μm
Width	50 μm
Height	3 μm
Young's modulus	169 (GPa)
Poisson's ratio	0.06
Mass density	2331 (Kg/m^3)
(Initial gap) g_0	1 μm
(Dielectric of air) ε_0	8.8541878×10^{-12} (F/m)

First, consider the case of a microbeam with neglecting residual stress, axial stress and fringing field effects. Assuming that for the first step, displacement is equal to zero due to a zero voltage, then by using of *DMFAM*; the obtained non-dimensional Eigen frequencies are 22.3733 and 61.6728 for the first and second natural modes, respectively. These values compare well with the values that provided by D. Young and R. P. Felgar [21] for the first and second natural frequencies of a fixed-fixed beam, respectively.

By considering the lumped and distributed models, the LMFAM can only predict a poor approximation for pull-in voltage with neglecting existing effects. Thus, by assuming there are no effects, the obtained pull-in voltages of two methods are compared and it is presented in Table 2 and Figs. (3, 4).

Table 2. The comparison between calculated pull-in voltages for the fixed-fixed electrostatic Microbeam without considering any effect.

	Lumped Model Frequency Analysis Method (LMFAM) [13]	**Distributed Model Frequency Analysis Method (DMFAM)**	Δ_1
$L = 350\ (\mu m)$	12.8	20.2	36.63 %
$L = 250\ (\mu m)$	25	39.5	36.71 %

Where

$$\Delta_1(\%) = \frac{ABS(DMFAM - LMFAM)}{DMFAM} * 100$$

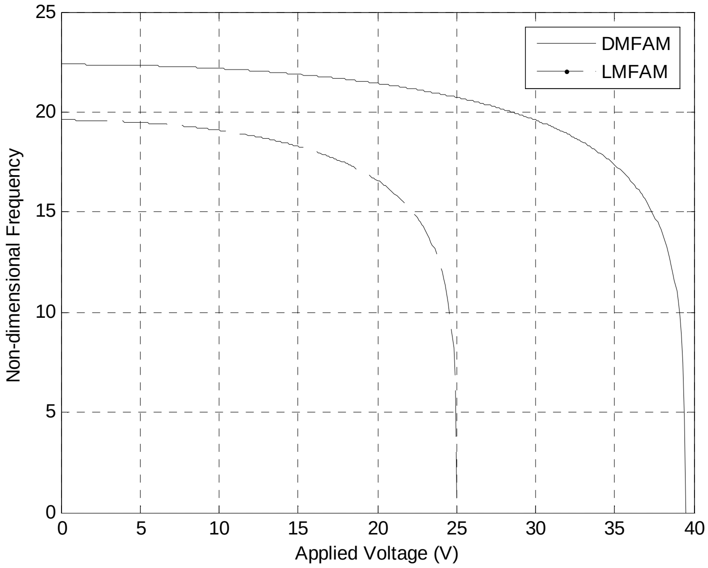

Fig. 3. Non-dimensional first Eigen frequency versus applied voltage using of Distributed Model Frequency Analysis Method (DMFAM) and Lumped Model Frequency Analysis Method (LMFAM) for $L = 250(\mu m)$.

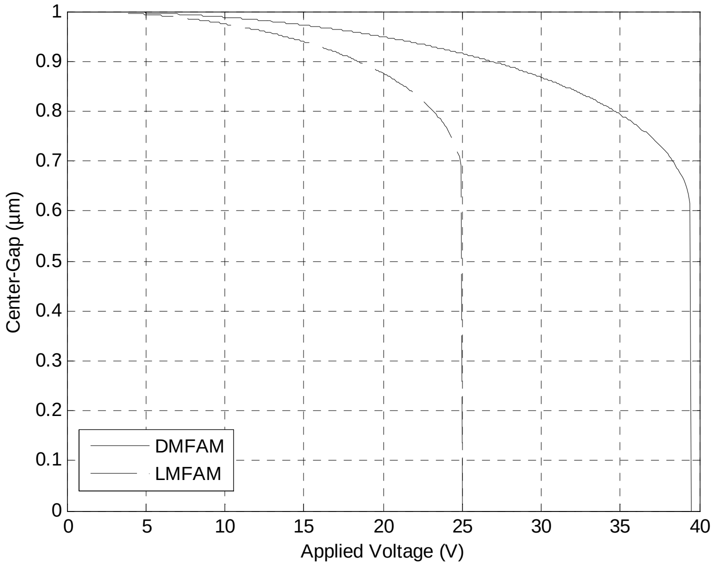

Fig. 4. Displacement of center-gap versus applied voltage using of DMFAM and LMFAM for $L = 250(\mu m)$.

4.2.1. Effect of Residual Stress

Depending on the fabrication sequences of the fixed-fixed MEMS switches, the residual stresses can be tensile or compression. Tensile residual stress stiffens microbeams but conversely compressive residual stress softens them. Theses stresses can make forces in the section of the beam as residual forces. These residual forces can influence on the characteristics of the switches, such as pull-in voltage. Polysilicon is typically deposited by Low Pressure Chemical Vapor Deposition (LPCVD) method using thermal decomposition of silane (SiH_4). With all deposition processes, the microstructure of polysilicon films is dependent on the deposition temperature. In fact, the deposition temperature for the individual layers alternates, which produces alternating tensile or residual compressive stresses [22].

Tensile stresses may be produced by using of Plasma Enhanced Chemical Vapor Deposition (PECVD) method, too [23]. Now by using of the DMFAM, for different residual stresses the pull-in voltage is obtained. Table 3 shows the values of the calculated pull-in voltage using of two different tensile and compressive residual stresses.

Table 3. The values of the calculated pull-in voltages for the fixed-fixed electrostatic Microbeam for different residual stresses.

	Residual stress (MPa)	**(DMFAM) Distributed Model Frequency Analysis Method**
$L = 350\ (\mu m)$	0	20.2
	100	35.8
	-25	13.4
$L = 250\ (\mu m)$	0	39.5
	100	57.4
	-25	33.4

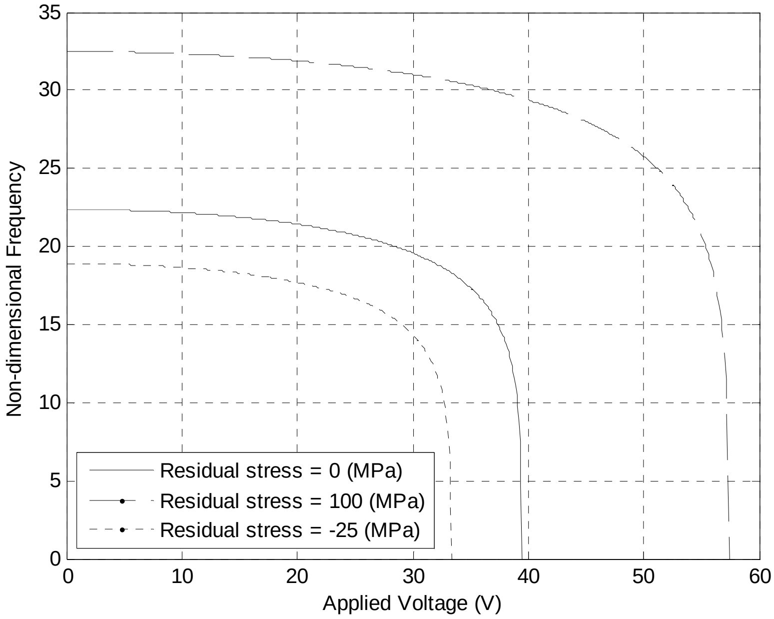

Fig. 5. Non-dimensional Eigen frequency versus applied voltage at different residual stresses for $L = 250(\mu m)$.

4.2.2. Effect of Fringing Field

The fringing field effect has influence on the behaviour of MEMS switches, and even causes the failure of devices [24]. Compared with the LMFAM, the DMFAM can include the influences of the fringing field. The desired result to compare the fringing field effect that is calculated is shown in Table 4 and Fig. 6.

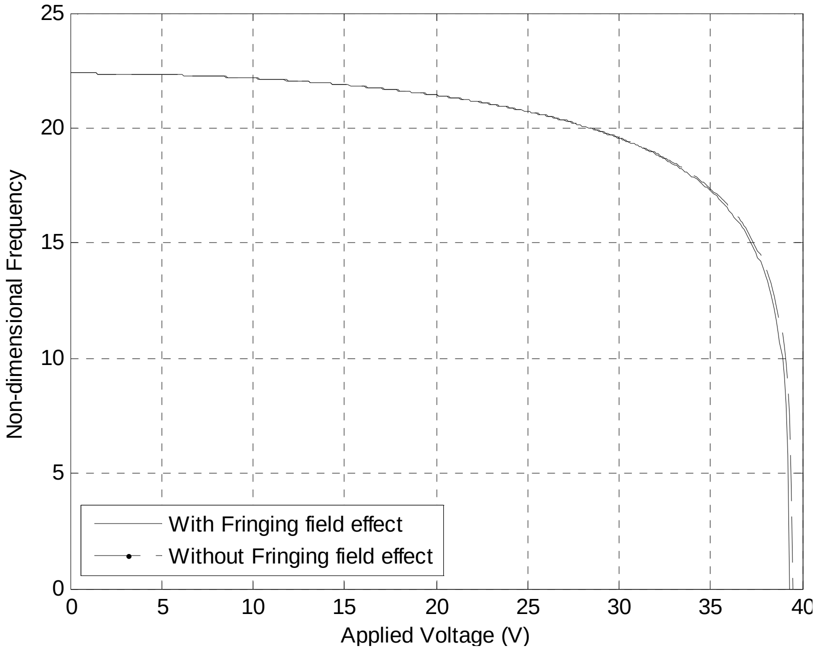

Fig. 6. Non-dimensional Frequency versus Applied voltage by considering fringing field effect for $L = 250(\mu m)$.

Table 4. The values of the calculated pull-in voltages for the fixed-fixed electrostatic Microbeam respect to the fringing field effect.

	DMFAM		Δ_2
	Without considering the Fringing field effect	**With considering the Fringing field effect**	
$L = 350\ (\mu m)$	20.2	20.2	0%
$L = 250\ (\mu m)$	39.5	39.3	0.51%

$$\Delta_2(\%) = \frac{ABS\big(DMFAM(with\ \ frining\ \ filed\ \ effect) - DMFAM(without\ \ frining\ \ filed\ \ effect)\big)}{DMFAM(without\ \ frining\ \ filed\ \ effect)} * 100$$

4.2.3. Effect of Axial Stress

The bending of a fixed-fixed beam involves generally a stretching. When the maximum deflection is less than the thickness, a small deflection can be considered valid, and the stretching can be neglected. But for MEMS switches, when the gap is almost equal the beam thickness, the maximum deflection in the middle point is large.

The effect of axial stress is calculated for three values of initial gap using of the DMFAM. The obtained results are shown in Table 5 and 6 and Fig 7.

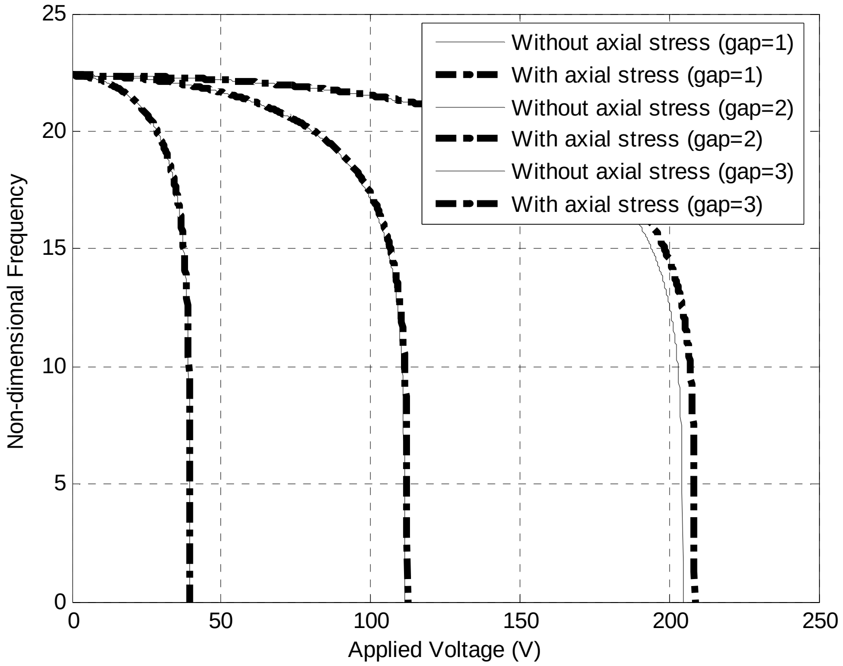

Fig. 7. Non-dimensional Frequency versus Applied voltage at different initial gap for $L = 250(\mu m)$.

Table 5. The values of the calculated pull-in voltages for the fixed-fixed electrostatic Microbeam respect to different values of initial gap.

	Without considering the axial stress			**With considering the axial stress**		
Initial gap (μm)	1	2	3	1	2	3
$L = 350\ (\mu m)$	20.2	56.9	104.4	20.3	57.4	106.5
$L = 250\ (\mu m)$	39.5	111.4	204.6	39.6	112.4	208.6

Table 6. The differences between calculated pull-in voltages for the fixed-fixed electrostatic Microbeam respect to different values of initial gap.

	Δ_3	Δ_4	Δ_5
$L = 350\ (\mu m)$	0.49 %	0.87 %	2.01 %
$L = 250\ (\mu m)$	0.25 %	0.89 %	1.95 %

$$\Delta_3(\%)\Big|_{(g_0=1)} = \frac{ABS\big(DMFAM(with\ axial\ stress\ effect) - DMFAM(without\ axial\ stress\ effect)\big)}{DMFAM(without\ axial\ stress\ effect)} * 100$$

$$\Delta_4(\%)\Big|_{(g_0=2)} = \frac{ABS\big(DMFAM(with\ axial\ stress\ effect) - DMFAM(without\ axial\ stress\ effect)\big)}{DMFAM(without\ axial\ stress\ effect)} * 100$$

$$\Delta_5(\%)\Big|_{(g_0=3)}=\frac{ABS\big(DMFAM(with\ axial\ stress\ effect)-DMFAM(without\ axial\ stress\ effect)\big)}{DMFAM(without\ axial\ stress\ effect)}*100$$

4.2.4. Comparison the Results of DMFAM with 2D Simulation and MEMCAD Data with Considering all Effects

By using of the DMFAM and considering all of the effects, the results are compared with the results predicted by employing the energy model (2D simulation) [1] and MEMCAD (3D simulation) [1], to demonstrate the feasibility. The results are shown in the Table 7 and Figure 8.

Table 7. The values of the calculated pull-in voltages for the fixed-fixed electrostatic Microbeam respect to all effects.

	Residual stress (MPa)	**DMFAM**	**2D Simulation [1]**	**MEMCAD [1]**	Δ_6	Δ_7
$L=350\ (\mu m)$	0	20.2	20.2	20.3	0 %	0.49 %
	100	35.7	35.4	35.8	0.84 %	0.27 %
	-25	13.4	13.8	13.7	2.90 %	2.19 %
$L=250\ (\mu m)$	0	39.4	39.5	40.1	0.25 %	1.74 %
	100	57.2	56.9	57.6	0.53 %	0.69 %
	-25	33.3	33.7	33.6	1.19 %	0.89 %

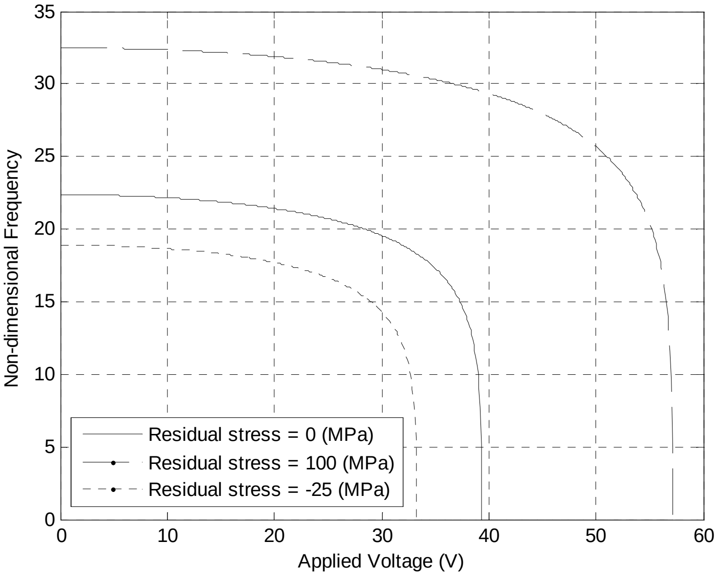

Fig. 8. Non-dimensional Frequency versus Applied voltage at different residual stresses and considering all of the effects for $L=250(\mu m)$.

$$\Delta_6(\%)=\frac{ABS\big(DMFAM-2D\ Simulation\big)}{2D\ Simulation}*100$$

$$\Delta_7(\%) = \frac{ABS(DMFAM - MEMCAD)}{MEMCAD} * 100$$

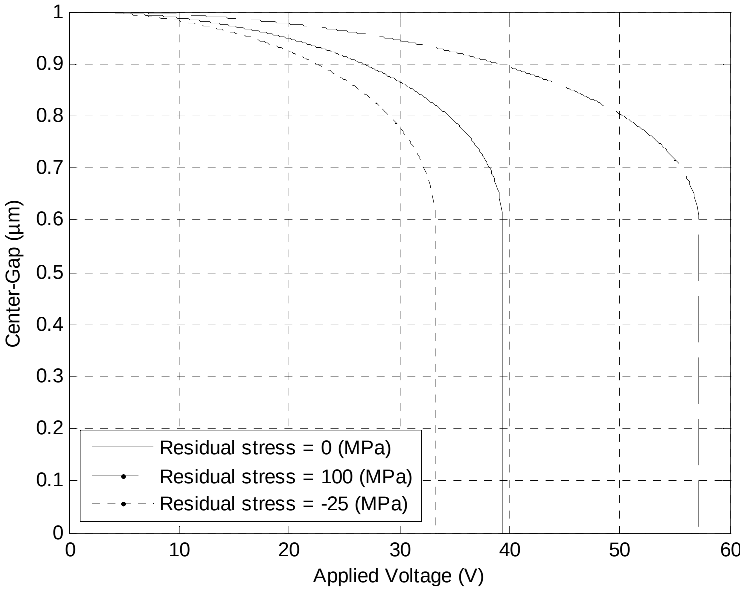

Fig. 9. Displacement of center-gap versus applied voltage at different residual stresses with considering all of the effects for $L = 250(\mu m)$.

5. Conclusions

A numerical algorithm based on the distributed model frequency analysis method (DMFAM) was developed for electrostatic MEMS switches to evaluate the stability of them. In the mentioned approach, the evaluation of the stability due to the equilibrium position at the specific applied voltage had been done using of the frequency analysis. That results were used to determine the pull-in voltages when all of effects such as: residual stress, fringing field and axial stress, were accounted.

Because of high accurate determination of the stability of electro MEMS due to the applied voltage, the pull-in voltage can be calculated with best accuracy.

It should be mentioned here that although there are many methods to evaluate the pull-in voltage of the MEMS structures, because of the novel idea behind the DMFAM, the results can be the most accurate results, and with comparison the previous methods, the efficient and accurate results were obtained.

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Guide for Contributors

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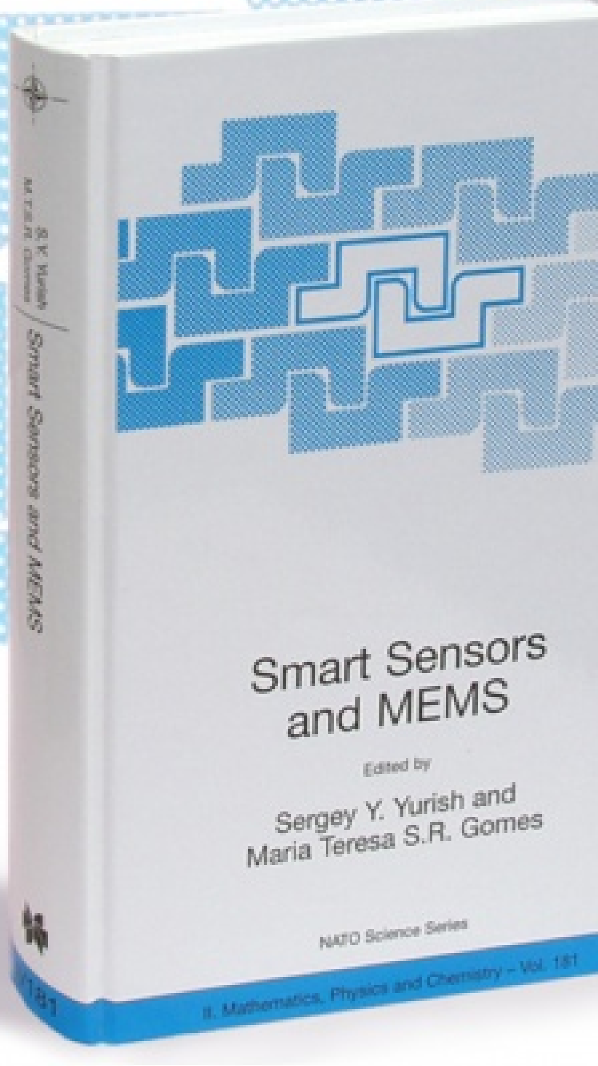
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