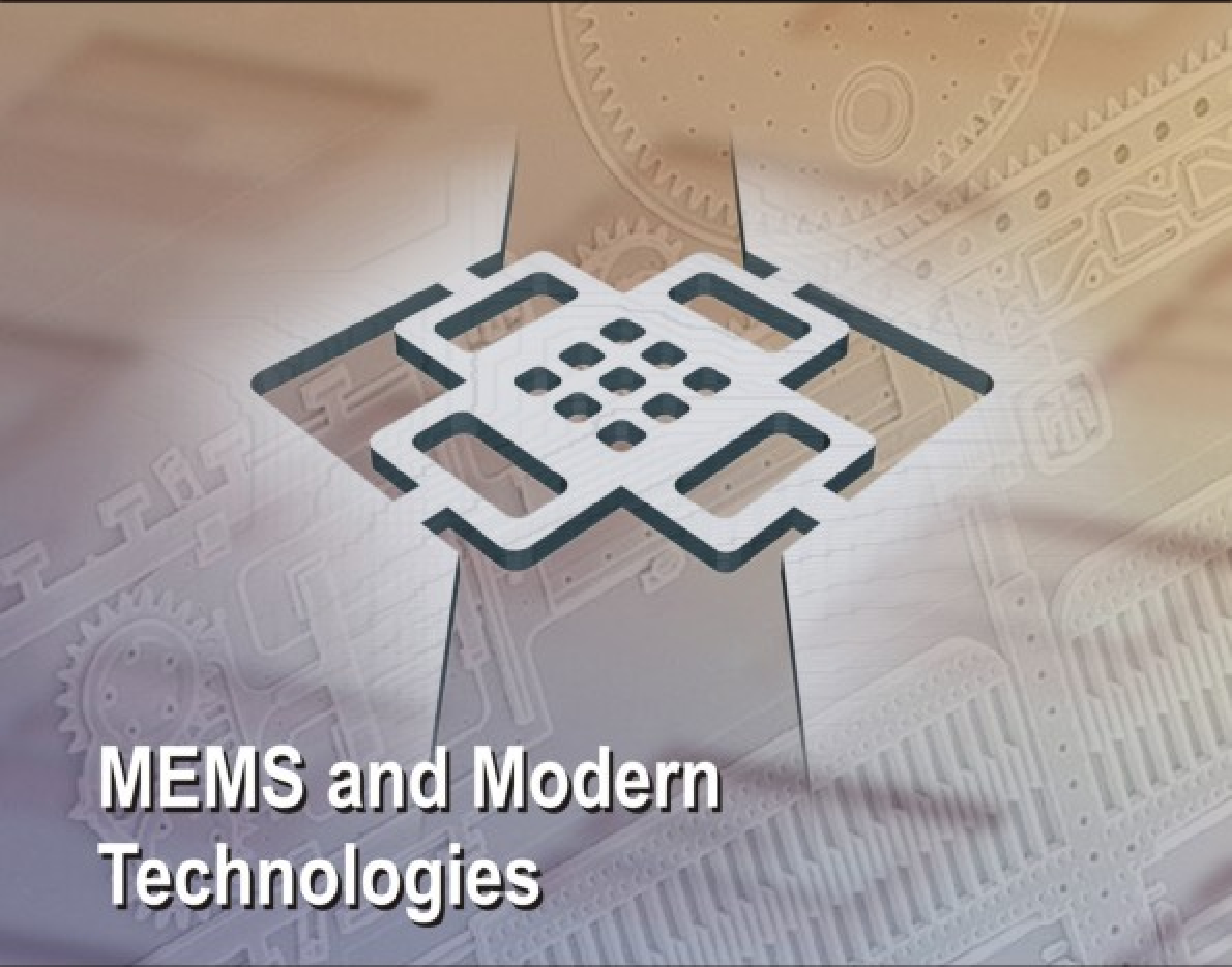
ISSN 1726-5749

SENSORS & TRANSDUCERS

vol. 78
4/07



MEMS and Modern Technologies

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 78
Issue 4
April 2007

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: professor Sergey Y. Yurish, phone: +34 696067716, fax: +34 93 4011989,
e-mail: editor@sensorsportal.com

Editors for Western Europe
Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vitorio, Universitá di Brescia, Italy

Editors for North America
Datskos, Panos G., Oak Ridge National Laboratory, USA
Fabien, J. Josse, Marquette University, USA
Katz, Evgeny, Clarkson University, USA

Editor South America
Costa-Felix, Rodrigo, Inmetro, Brazil

Editor for Eastern Europe
Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editor for Asia
Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, Karthigeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Bahreyni, Behraad, University of Manitoba, Canada
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, Priyadarshini College of Engineering and Architecture, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Binnie, T. David, Napier University, UK
Bischoff, Gerlinde, Inst. Analytical Chemistry, Germany
Bodas, Dhananjay, IMTEK, Germany
Borges Carval, Nuno, Universidade de Aveiro, Portugal
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, CNRS – UPMC, France
Brudzewski, Kazimierz, Warsaw University of Technology, Poland
Cai, Chenxin, Nanjing Normal University, China
Cai, Qingyun, Hunan University, China
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Cecelja, Franjo, Brunel University, London, UK
Cerda Belmonte, Judith, Imperial College London, UK
Chakrabarty, Chandan Kumar, Universiti Tenaga Nasional, Malaysia
Chakravorty, Dipankar, Association for the Cultivation of Science, India
Changhai, Ru, Harbin Engineering University, China
Chaudhari, Gajanan, Shri Shivaji Science College, India
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiriac, Horia, National Institute of Research and Development, Romania
Chowdhuri, Arijit, University of Delhi, India
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Corres, Jesus, Universidad Publica de Navarra, Spain
Cortes, Camilo A., Universidad de La Salle, Colombia
Courtois, Christian, Universite de Valenciennes, France
Cusano, Andrea, University of Sannio, Italy
D'Amico, Arnaldo, Università di Tor Vergata, Italy
De Stefano, Luca, Institute for Microelectronics and Microsystem, Italy
Deshmukh, Kiran, Shri Shivaji Mahavidyalaya, Barshi, India
Kang, Moonho, Sunmoon University, Korea South
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding Jian, Ning, Jiangsu University, China
Djordjevich, Alexandar, City University of Hong Kong, Hong Kong
Donato, Nicola, University of Messina, Italy
Donato, Patricio, Universidad de Mar del Plata, Argentina
Dong, Feng, Tianjin University, China
Drljaca, Predrag, Instersema Sensoric SA, Switzerland
Dubey, Venketesh, Bournemouth University, UK
Enderle, Stefan, University of Ulm and KTB mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
Fu, Weiling, South-Western Hospital, Chongqing, China
Gaura, Elena, Coventry University, UK
Geng, Yanfeng, China University of Petroleum, China
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National University of Singapore, Singapore
Gonzalez de la Ros, Juan Jose, University of Cadiz, Spain
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Hashsham, Syed, Michigan State University, USA
Hernandez, Alvaro, University of Alcala, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
Jaime Calvo-Galleg, Jaime, Universidad de Salamanca, Spain
James, Daniel, Griffith University, Australia
Janting, Jakob, DELTA Danish Electronics, Denmark
Jiang, Liudi, University of Southampton, UK
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia

Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
Kausel, Wilfried, University of Music, Vienna, Austria
Kavasoglu, Nese, Mugla University, Turkey
Ke, Cathy, Tyndall National Institute, Ireland
Khan, Asif, Aligarh Muslim University, Aligarh, India
Kim, Min Young, Koh Young Technology, Inc., Korea South
Ko, Sang Choon, Electronics and Telecommunications Research Institute, Korea South
Kockar, Hakan, Balikesir University, Turkey
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kratz, Henrik, Uppsala University, Sweden
Kumar, Arun, University of South Florida, USA
Kumar, Subodh, National Physical Laboratory, India
Kung, Chih-Hsien, Chang-Jung Christian University, Taiwan
Lacnjevac, Caslav, University of Belgrade, Serbia
Laurent, Francis, IMEC , Belgium
Lay-Ekuakille, Aime, University of Lecce, Italy
Lee, Jang Myung, Pusan National University, Korea South
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Liang, Yuanchang, University of Washington, USA
Liawruangrath, Saisunee, Chiang Mai University, Thailand
Liew, Kim Meow, City University of Hong Kong, Hong Kong
Lin, Hermann, National Kaohsiung University, Taiwan
Lin, Paul, Cleveland State University, USA
Linderholm, Pontus, EPFL - Microsystems Laboratory, Switzerland
Liu, Aihua, Michigan State University, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, Universidade NOVA de Lisboa, Portugal
Lorenzo, Maria Encarnacio, Universidad Autonoma de Madrid, Spain
Ma, Zhanfang, Northeast Normal University, China
Majstorovic, Vidosav, University of Belgrade, Serbia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Matay, Ladislav, Slovak Academy of Sciences, Slovakia
Mathur, Prafull, National Physical Laboratory, India
Maurya, D.K., Institute of Materials Research and Engineering, Singapore
Mekid, Samir, University of Manchester, UK
Mendes, Paulo, University of Minho, Portugal
Mennell, Julie, Northumbria University, UK
Mi, Bin, Boston Scientific Corporation, USA
Minas, Graca, University of Minho, Portugal
Moghavvemi, Mahmoud, University of Malaya, Malaysia
Mohammadi, Mohammad-Reza, University of Cambridge, UK
Molina Flores, Esteban, Benemirita Universidad Autonoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, DIMET, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mukhopadhyay, Subhas, Massey University, New Zealand
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucin, University of Guelma, Algeria
Pamidighanta, Sayanu, Bharat Electronics Limited (BEL), India
Pan, Jisheng, Institute of Materials Research & Engineering, Singapore
Park, Joon-Shik, Korea Electronics Technology Institute, Korea South
Pereira, Jose Miguel, Instituto Politecnico de Setebal, Portugal
Petsev, Dimiter, University of New Mexico, USA
Pogacnik, Lea, University of Ljubljana, Slovenia
Post, Michael, National Research Council, Canada
Prance, Robert, University of Sussex, UK
Prasad, Ambika, Gulbarga University, India
Prateepasen, Asa, Kingmoungut's University of Technology, Thailand
Pullini, Daniele, Centro Ricerche FIAT, Italy
Pumera, Martin, National Institute for Materials Science, Japan
Radhakrishnan, S. National Chemical Laboratory, Pune, India
Rajanna, K., Indian Institute of Science, India
Ramadan, Qasem, Institute of Microelectronics, Singapore
Rao, Basuthkar, Tata Inst. of Fundamental Research, India
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Rezazadeh, Ghader, Urmia University, Iran
Robert, Michel, University Henri Poincare, France
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK
Royo, Santiago, Universitat Politecnica de Catalunya, Spain
Sadana, Ajit, University of Mississippi, USA
Sandacci, Serghei, Sensor Technology Ltd., UK
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmaliy, Yuriy, Kharkiv National University of Radio Electronics, Ukraine
Silva Girao, Pedro, Technical University of Lisbon Portugal
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technology, India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Sumriddetchka, Sarun, National Electronics and Computer Technology Center, Thailand
Sun, Chengliang, Polytechnic University, Hong-Kong
Sun, Dongming, Jilin University, China
Sun, Junhua, Beijing University of Aeronautics and Astronautics, China
Sun, Zhiqiang, Central South University, China
Suri, C. Raman, Institute of Microbial Technology, India
Sysoev, Victor, Saratov State Technical University, Russia
Szewczyk, Roman, Industrial Research Institute for Automation and Measurement, Poland
Tan, Ooi Kiang, Nanyang Technological University, Singapore,
Tang, Dianping, Southwest University, China
Tang, Jaw-Luen, National Chung Cheng University, Taiwan
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tsiantos, Vassilios, Technological Educational Institute of Kaval, Greece
Tsigara, Anna, National Hellenic Research Foundation, Greece
Twomey, Karen, University College Cork, Ireland
Valente, Antonio, University, Vila Real, - U.T.A.D., Portugal
Vaseashta, Ashok, Marshall University, USA
Vazques, Carmen, Carlos III University in Madrid, Spain
Vieira, Manuela, Instituto Superior de Engenharia de Lisboa, Portugal
Vigna, Benedetto, STMicroelectronics, Italy
Vrba, Radimir, Brno University of Technology, Czech Republic
Wandelt, Barbara, Technical University of Lodz, Poland
Wang, Jiangping, Xi'an Shiyou University, China
Wang, Kedong, Beihang University, China
Wang, Liang, Advanced Micro Devices, USA
Wang, Mi, University of Leeds, UK
Wang, Shinn-Fwu, Ching Yun University, Taiwan
Wang, Wei-Chih, University of Washington, USA
Wang, Wensheng, University of Pennsylvania, USA
Watson, Steven, Center for NanoSpace Technologies Inc., USA
Weiping, Yan, Dalian University of Technology, China
Wells, Stephen, Southern Company Services, USA
Wolkenberg, Andrzej, Institute of Electron Technology, Poland
Woods, R. Clive, Louisiana State University, USA
Wu, DerHo, National Pingtung University of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Ymeti, Aurel, University of Twente, Netherland
Yu, Haihu, Wuhan University of Technology, China
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zeni, Luigi, Second University of Naples, Italy
Zhong, Haoxiang, Henan Normal University, China
Zhang, Minglong, Shanghai University, China
Zhang, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhou, Zhi-Gang, Tsinghua University, China
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

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 CD-ROM. Copyright © 2007 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 78
Issue 4
April 2007

www.sensorsportal.com

ISSN 1726-5479

Editorial

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal’s webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

Sensors & Transducers Journal, Vol.78, Issue 4, April 2007, pp.1083-1092

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Modeling Open-Loop MEMS Tunneling Accelerometer Based on Circular Plate

Hossein Jodat Kordlar[1], Ghader Rezazadeh[2]
[1, 2] Mech. Eng. Dept. Urmia University, Urmia, Iran,
[2]Tel.: +98-914-145-1407, [2]fax: +98-441-277-7022,
[2]E-mail: g.rezazadeh@mail.urmia.ac.ir

Received: 6 February 2007 /Accepted: 20 April 2007 /Published: 23 April 2007

Abstract: In this paper open-loop MEMS tunneling accelerometer was modeled based on a clamped micro circular plate with a tip tunneling at its centre. Mechanical behavior of the micro plate was studied deriving governing equation based on classic Kirchhoff thin plate theory and it was discretized using Galerkin method. Dynamic response of the proposed accelerometer due to step and harmonic external excitation was studied and the magnitude of the applied acceleration was identified by measuring of the changing of tunneling current. Obtained results show that the proposed tunneling accelerometer very sensitive and it can be measure acceleration with very high resolution but very small gap of tip tunneling limit the range of measurable acceleration. *Copyright © 2007 IFSA.*

Keywords: MEMS, Tunneling, Accelerometer, Micro Plate, Dynamic response

---

1. Introduction

MEMS accelerometers are the kind of most important mechanical transducers. An accelerometer produces an electrical out-put signal that is proportional to applied acceleration. One reason of its significance is that our world is a moving world; every thing is in one kind of motion or the other. Another reason of its significance is that by integrating the output signal of acceleration, an accelerometer can also provide a measure of velocity. And we can further get the measure of position by integrating the velocity signal once again.

Micromachined accelerometers made by means of Microelectromechanical Systems (MEMS) technique have many advantages. First they are much cheap yet accurate because of the batch process. Second, they are small and light weight. We can measure the acceleration of a subject at precise position by its small size. We can also locate many cheap accelerometers with the same performance into arrays to get the two or even three dimensional vibration modes of a subject. We can also make a three axial accelerometer directly by processes. It will not affect the motion subject itself much after a micromachined accelerometer is mounted on the measuring position because of its lightweight. Third, micromachined accelerometer works under low power consumption.

The demand for these sensors has increased recently quite considerably. They are widely used in all sorts of terrestrial, marine and aerospace application fields. One of the typical examples is the release airbag system in a car. In addition, accelerometers are also used on a car for active suspension and brake control systems or in the fuel cut-off and engine knock systems [1]. Accelerometers are also widely used in the seismic science and other vibration measurement fields such as vibration of machines, vibration control of the hard disk in portable computers, shipping monitoring etc. Micromachined accelerometers are now being incorporated into products such as joysticks and 3-dimensional visual game systems, applications that were previously impossible due to sensor price and/or size. The applications of accelerometers in marine areas can be found in the navigation and guidance system, the Global Position System (GPS), submarines and etc. Micromachined accelerometers have special significance in aerospace applications because of their small size and light weight. They are used to sense micro-gravity, orbit and status of a satellite.

Types of accelerometers are:
a) Piezoelectric and piezoresistive accelerometers, piezoelectric (PE) accelerometers use the piezoelectric effect of quartz or ceramic crystals to generate an electrical output proportional to the applied acceleration [2].
b) Optical accelerometers, there are two basic sensing mechanisms for optical Accelerometers: the first one is by measuring the intensity of light coupling to the output fiber optic cable and the second one is by measuring the change of wavelength of the light, reflected from a surface [3].
c) Capacitive accelerometers, capacitive accelerometers convert the acceleration into a capacitance change. When acceleration is applied to the accelerometer, the seismic mass deflects from its rest position and changes the capacitance between the mass and the conductive stationary electrodes by a narrow gap. An electronic circuitry can easily measure this capacitance change. Capacitive accelerometers have several advantages, which make them very attractive for numerous applications. They have low temperature dependency unlike piezoresistive and piezoelectric accelerometers. Another important property of the capacitive accelerometers is their simple structure. However, its resolution in compare of tunneling accelerometer is low. Because in the tunneling accelerometer current change exponentially [4].
d) Tunneling accelerometer, tunneling accelerometers convert acceleration to a tunneling current.

There is always a possibility of electron tunneling between two conductive electrodes, if these electrodes are close enough to each other. The tunneling current is observable when the gap between the two conductive materials is about 10 Å. As the gap between the conductive materials decreases, the tunneling current increases. Two facts determining the tunneling current between two electrodes are the gap between the electrodes and the sharpness of the tip of the conductive material. As the tip of the conductive material is sharper, the probability of the electron tunneling increases. The change between the tip and the proof mass induces an exponential tunneling current, therefore in these models resolution increased. Since the gap between the two electrodes is in the order of few angstroms, open-loop accelerometers apply for small acceleration detection. Fig. 1 shows the structure and the operation principle of an open-loop tunneling accelerometer. By applying proper voltage, V_o to the bottom deflection electrode the tip of the electrode is brought sufficiently close to the tunneling counter-electrode, until this distance be about 10 Å. A constant tunneling current, I is established. This tunneling current is constant, if the proof mass is stationary and the tunneling voltage (V_{tunn}) is constant. Under acceleration the proof mass deflects from its rest position resulting in a change in the tunneling current. The readout circuit senses this change. With this mechanism, the tunneling current change and acceleration can be measured by this change [5].

The goal of this paper is to design an open-loop tunneling accelerometer based on the circular plate and tunneling effect. We will also discuss about governing differential equation of circular micro plate, sensing technology for this proposed model setup.

2. Model Description

A typical tunneling accelerometer has mechanical components and three electrodes. Mechanical components include a base plate with a tunneling tip on the center and a proof mass (flexible circular micro plate). The electrodes include a tip electrode, proof mass electrode, and deflection electrode. The metal of the electrode is a layer of Au film because of its inert chemical characteristics as well as its relatively high work function. When operating, the accelerometer maintains a constant tip-to-proof mass distance by applying an electrostatistic force on the proof mass. The cross section view of the tunneling accelerometer is illustrated in the Fig. 1. Usually, for normal performance, the distance between the tip and proof mass electrode is about 10 Å and the tunneling current is about nano ampere.

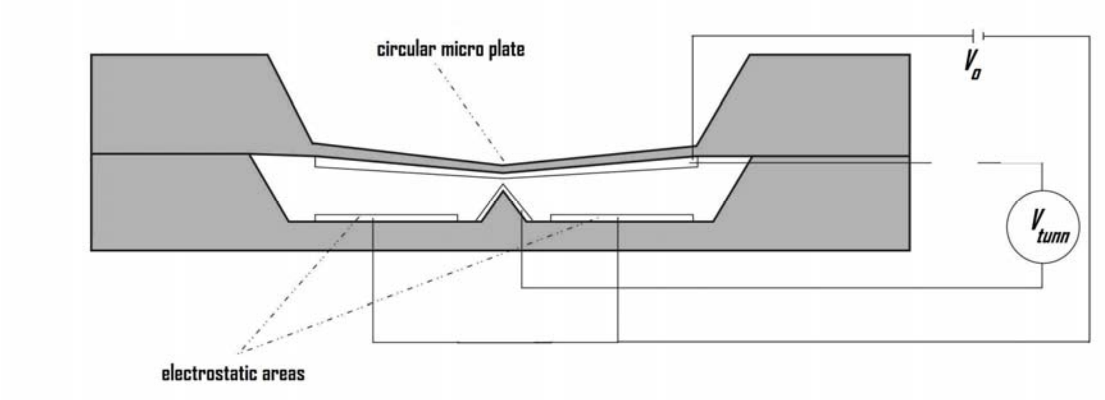


Fig.1. Tunneling accelerometer.

The change between the tip and the proof mass $w(r,t)$ induces an exponential change in the tunneling current. The tunneling current induced between the tunneling tip and proof mass electrode can be expressed as follow [6]

$$I = I_o \exp(-\alpha\sqrt{\Phi}\cdot w(r,t)), \tag{1}$$

where α is a constant, whose typical value is α=1.025 (Å^{-1}eV$^{-0.5}$) and Φ is the effective height of the tunneling barrier, and its typical value is 0.2 eV. I_0 is the initial tunneling current where its magnitude depends on initial distance of the tunneling tip and the proof mass electrode, tunneling voltage (V_{tunn}) and their materials.

In order to control the distance between the tip and proof mass electrode two electrostatic areas connected to a bias voltage are used with inducing an electrostatic force as below

$$q(w,V_o) = \frac{\varepsilon\, V_o^2}{2(g_0 - w(r,t))^2}, \tag{2}$$

where q is the electrostatic force per unit area of the deformed plate, ε, V_o and g_0 are the permittivity of free space in the air gap, applied bias voltage, and the air gap between two plates, respectively. In addition $w = w(r, t)$ is the deflection of the deformed thin micro-plate.

The proposed device employ a parallel-plate, in which one plate is actuated inertial and its motion is detected by tunneling current changes. In order to increase the efficiency of actuation and improve the sensitivity of detection, the distance between the plates is minimized and the area of the electrode is maximized. Under such conditions, the so-called squeeze-film damping is pronounced [7].

This phenomenon occurs as a result of the massive movement of the fluid underneath the plate, which is resisted by the viscosity of the fluid. This gives rise to a pressure distribution underneath the plate, which may act as a spring and/or a damping force. Recent studies show that the damping force dominates the spring force at low frequencies, whereas the spring force dominates the damping force at high frequencies. Therefore, viscous damping in many MEMS devices corresponds to squeeze-film damping. Damping Ratio in the circular plate can be given as [8]:

$$C = \frac{3\pi R^4}{2h^3}\mu_{eff}\left(1+\frac{0.8h\pi}{R}+\frac{32}{3\pi}\frac{h^3}{R^3}\right), \tag{3}$$

where R the plate radios and h is the plate thickness and μ_{eff} the effective viscosity of the gas, squeeze-film or other source of energy loss can be described quantitatively in terms of a corresponding quality factor. The quality factor Q can be expressed as follow:

$$Q = \frac{C_c}{2C} = \frac{1}{2\zeta} \tag{4}$$

where C_C is the critical damping ratio and ζ is the nondimensional damping coefficient.

3. Mathematical Modeling

Two major group of plate theory are used in scientific and practical applications: 1) Kirchhoff plate theory 2) Mindlin plate theory. The Kirchhoff thin plate theory is used when the thickness-to-length ratio (*h/2R*) of the plate is relatively low and so the effect of transverse shear strains is neglected in this classical theory. The Mindlin plate theory (1951) is used when the thickness-to-length ratio (*h/2R*) of the plate is relatively large and so the effect of transverse shear strains is considered [9].

Due to less thickness of plates in the proposed tunneling accelerometer in comparison with radius of the circular plate, the tunneling accelerometer plate can be modeled based on Kirchhoff classic thin plate theory. The load acting on the plate is axisymmetrically distributed therefore the deflection surface to which the middle plane of the plate is bent will also be axisymmetrical. In all points equally distant from the center of the plate the deflections will be the same, and it is sufficient to consider deflections in one diametric section throw axis of symmetry. Let us take the origin of coordinates at the center of the deflected plate and denote by r the redial distance of points in the middle plane of the micro plate and by $w(r, t)$ their deflections.

The nonlinear partial differential equation which is implemented in circular plate using Kirchhoff plate theory and assumption of plane strain condition is [10]:

$$\rho h\left(\frac{\partial^2 w}{\partial t^2}+a\right)+D\nabla^4 w+C\frac{\partial w}{\partial t}=q(w,V_o) \tag{5}$$

$$\nabla^4 w=\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}\right)\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right), \tag{6}$$

where a and ρ are the acceleration which must be measured and density of the deformed plate, respectively. In addition, D denotes the flexural rigidity of the deformed plate and can be derived based on fundamental mechanics as

$$D=\frac{Eh^3}{12(1-\upsilon^2)}, \tag{7}$$

where E and υ represent the Young modulus and Poisson ratio of the deformed micro circular plate.

Due to very small deflection of micro plate in the proposed tunneling accelerometers using of calculus of variation theory and Taylor's series and applying the truncation to first order can be linearized electrostatic forces as

$$q(w,V_o)=\frac{\varepsilon\, V_o^2}{2(g_0)^2}+\frac{\varepsilon\, V_o^2}{(g_0)^3}w(r,t)+O(2) \tag{8}$$

The linear form of Eq. (5) is

$$\begin{aligned}L(w(r,t))=\rho h\left(\frac{\partial^2 w}{\partial t^2}+a\right)+D\left(\frac{\partial^4 w}{\partial r^4}+\frac{2}{r}\frac{\partial^3 w}{\partial r^3}-\frac{1}{r^2}\frac{\partial^2 w}{\partial r^2}+\frac{1}{r^3}\frac{\partial w}{\partial r}\right)\\+C\frac{\partial w}{\partial t}-\frac{\varepsilon\, V_o^2}{(g_0)^3}w(r,t)-\frac{\varepsilon\, V_o^2}{2(g_0)^2}=0\end{aligned}, \tag{9}$$

where $L(w(r,t))$ a differential operator. The two spatial boundary conditions are determined from the requirement that the plate surround is clamped (zero displacement and zero slop). These boundary conditions are:

$$w(\pm R,t)=0,\quad \left.\frac{dw}{dr}\right|_{(\pm R,t)}=0 \tag{10}$$

4. Numerical Solution

The general discretization methods that can be applied directly to differential equation are finite difference approximations and the various weighted residual procedures (known alternately as the Galerkin procedure) or approximate techniques of determining the stationary of properly defined functional. It is important to remark that the well-known finite difference method of approximation is a particular case of weighted residual approximations, when the Delta function selected as weighting functions (Collocation method).

In the present article the weighted residual procedures to discretize governing equations in r direction was used. Let $w(r,t)$ is the solution of the governing nonlinear electro-mechanical coupling equation which is the continuous and smooth function on $[-R, R]$, so the $w(r,t)$ can be expanded with respect to base functions of $\varphi_n(r)$ as:

$$w(r,t) = \sum_{n=1}^{\infty} \Psi_n(t)\varphi_n(r) \tag{11}$$

It is clearly impossible to satisfy both the differential equation and the boundary conditions in a general case. So if the selected $\varphi_n(r)$ satisfy the existing geometrical boundary conditions, then $w(r,t)$ satisfies the same boundary conditions. An approximate solution for Eq. (9) can be expressed as the following sequence:

$$w_N(r,t) = \sum_{n=1}^{N} \Psi_n(t)\varphi_n(r) \tag{12}$$

The sequence $w_N(r,t)$ converges to the function $w(r,t)$ in the mean, in the other word there exist an $N > 0$ then [11]

$$\int_{-R}^{R} \left(w(r,t) - w_N(r,t)\right)^2 dr \prec \varepsilon(t)^2 \tag{13}$$

By substitution the forgoing approximated solution to equation (11) we have:

$$L(w_N(r,t)) = L(\sum_{n=1}^{N} \Psi_n(t)\varphi_n(r)) = \mathrm{E}r(r,t) \tag{14}$$

Where the $\mathrm{E}r(r,t)$ represents some residual obtained by substituting of the approximate solution into the differential equation. Using the $\varphi_n(r)$ as weighting functions and applying the Galerkin-Bubnov method, a set of N nonlinear ordinary differential equations with respect to time can be obtained as follow:

$$\int_{-R}^{R} \varphi_j(r) L\left(w_N(r,t)\right) dr = \int_{-R}^{R} \varphi_j(r) L\left(\sum_{n=1}^{N} \Psi_n(t)\varphi_n(r)\right) dr = 0 \qquad j = 1,\dots,N \tag{15}$$

The equation (13) can be rewritten in the following form:

$$\begin{aligned}
&\int_0^R 2\pi r\rho h\varphi_j(r)(\sum_{n=1}^{N} \ddot{\Psi}_n(t)\varphi_n(r))dr + C\int_0^R \varphi_j(r)(\sum_{n=1}^{N} \dot{\Psi}_n(t)\varphi_n(r))dr + \\
&\int_0^R \varphi_j(r)\sum_{n=1}^{N} 2\pi rD\left\{\left(\varphi^{IV}{}_n(r) + \frac{2}{r}\varphi^{III}{}_n(r) - \frac{1}{r^2}\varphi^{II}{}_n(r) + \frac{1}{r^3}\varphi^{I}{}_n(r) - \frac{\varepsilon V_o^2}{(g_0)^3})\varphi_n(r)\right)\right\}\Psi_n(t)dr \\
&-\int_0^R \frac{\pi\varepsilon V_o^2}{(g_0)^2}\varphi_j(r)rdr + \int_0^R 2\pi\rho ha\varphi_j(r)rdr = 0
\end{aligned} \tag{16}$$

The System of forgoing ordinary differential equations can be rewrite in the matrix form as follow:

$$\sum_{n=1}^{N} M_{jn}\ddot{\Psi}_n(t)+\sum_{n=1}^{N} C_{jn}\dot{\Psi}_n(t)+\sum_{n=1}^{N} K_{jn}\Psi_n(t)=F_j(t) \quad j=1,\dots,N, \tag{17}$$

where M_{jn}, C_{jn}, K_{jn} and F_j are the mass matrix, damping matrix, and stiffness matrix and force vector respectively and can be defined as follows:

$$M_{jn}=2\pi\rho h\int_{-R}^{R}\varphi_j(r)\varphi_n(r)rdr \tag{18}$$

$$K_{jn}=\int_{0}^{R}\varphi_j(r)2\pi rD\left\{\left(\left(\varphi^{IV}{}_n(r)+\frac{2}{r}\varphi^{III}{}_n(r)-\frac{1}{r^2}\varphi^{II}{}_n(r)+\frac{1}{r^3}\varphi^{I}{}_n(r)-\frac{k\varepsilon V_o^2}{(g_0)^3}\right)\varphi_n(r)\right)\right\}dr \tag{19}$$

$$C_{jn}=C\int_{0}^{R}\varphi_j(r)\varphi_n(r)dr \tag{20}$$

$$F_j(t)=\int_0^R\frac{\pi\varepsilon V_o^2}{(g_0)^2}\varphi_j(r)rdr+\int_0^R 2\pi\rho ha\varphi_j(r)rdr \tag{21}$$

5. Results and Discussion

The results presented are based on the following values of material and geometrical parameters. Table 1 shows these items.

Table 1. Material and geometrical parameters for the proposed model.

Parameter	**Value**
R (radius)	250 (μm)
h (thickness)	20 (μm)
E (young's modulus)	169 (GPa)
υ (Poisson's ratio)	0.3
g_0 (initial gap)	$10A^\circ$
ε (permittivity of air)	8.8541878×10^{-12} (F)
ρ (density)	$2331(Kg/m)^3$
μ_{eff} (air viscosity)	1.77×10^{-5}
Q (quality factor)	0.707
I_0	1.5 nA
V_o (Bias voltage)	120 v
V_{tunn} (tunneling voltage)	163 mV
$(\omega_n)_1$ (first natural frequency)	1.068 KHz
N	1

5.1 Response of the System to a Step Excitation

In this case a step excitation applied to the accelerometer at time t=0 and then kept fixed.

$$a = a_0 H(t), \tag{22}$$

where $H(t)$ is the unit step function. Fig. 2 shows the time history of the deflection of the center of the movable micro plate generated by different step excitation. The amplitude of the output decreases due to damping effects. Fig. 3 shows tunneling current changes for the system with respect to different applied external step excitation.

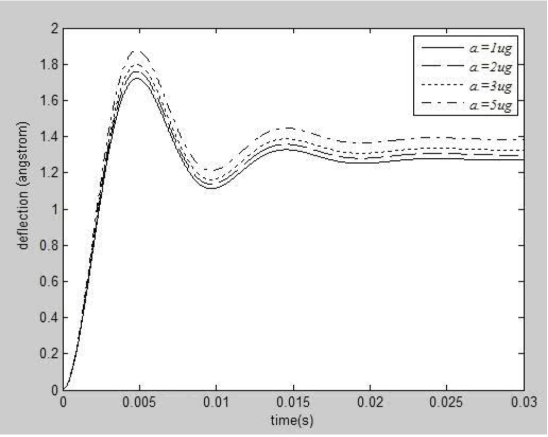


Fig.2. Deflection of center of micro plate due to different step excitation.

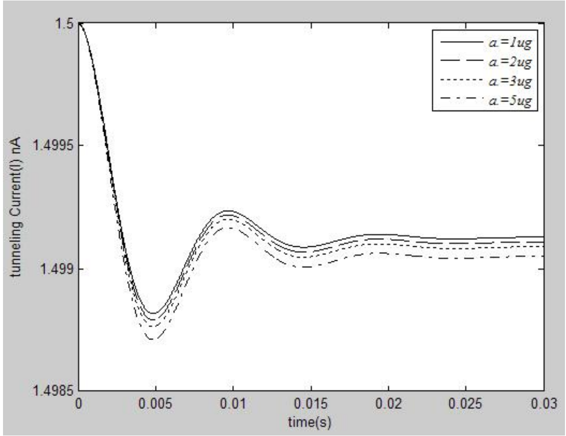


Fig.3. Tunneling current change due to different step excitation.

5.2 Response of System to a Harmonic Excitation

Harmonic response analysis gives you the ability to predict the sustained dynamic behavior of your structures, thus enabling you to verify whether or not your design will successfully overcome resonance, fatigue, and other harmful effects of forced vibration. Harmonic response used to determine the steady-state response of a linear structure to loads harmonically with time. Fig. 4 shows the harmonic response amplitude to applied harmonic acceleration (Eq. 23) in the proposed model and Fig. 5 shows tunneling current changes of the system to a harmonic excitation.

$$a = a_0 \sin(\omega t) \tag{23}$$

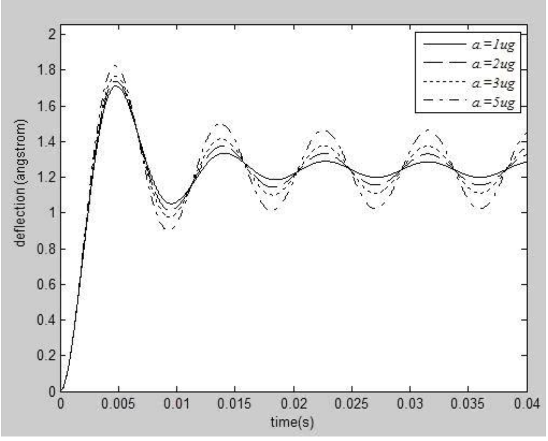


Fig.4. Deflection of micro plate due to different harmonic excitation in700Hz.

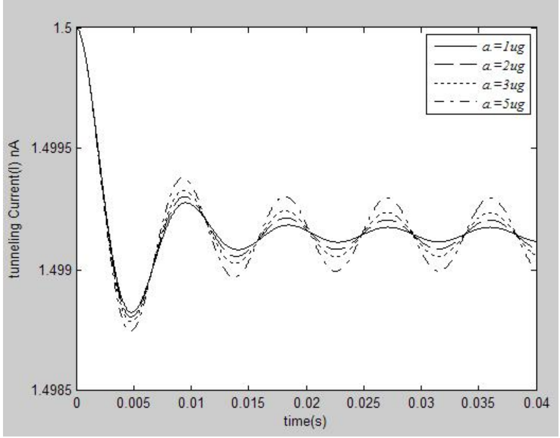


Fig.5. Tunneling current change due to different harmonic excitation in 700Hz.

5.2.1 Bandwidth and Quality Factor

We can see that quality factor also describes the sharpness of the resonance peak, the higher Q the narrow bandwidth. Fig. 6 shows response amplitude vs. excitation frequency in rate of various quality factor Q=0.707 and 0.5. We can see from the plot that the maximum response and tunneling current change is in around the natural frequency. Fig. 7 shows tunneling current change quantity due to the applied acceleration.

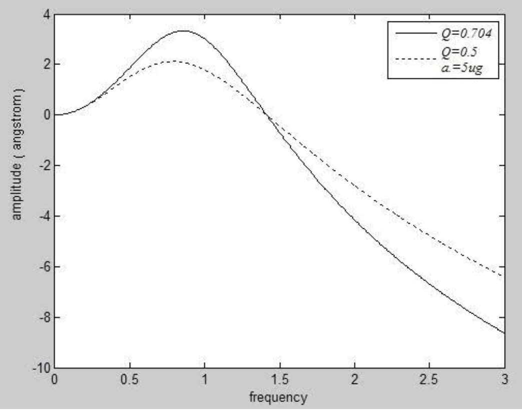


Fig.6. Response amplitude vs. excitation frequency in rate of various quality factors.

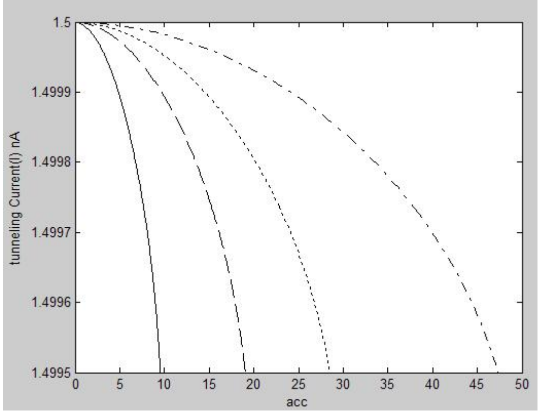


Fig.7. Applied acceleration and tunneling current change.

6. Conclusions

In this paper was described and modeled an open-loop NEMS tunneling accelerometer based-on circular micro plate and Kirchhoff thin plate theory. Galerkin-Bubnov method was used in order to discretize the governing equation. In the proposed model, by measuring tunneling current change, deflection of flexible micro plate and applied acceleration was determined. The response of proposed accelerometer due to harmonic and step excitation was examined. Results of This study can be used for close-loop accelerometer or in crash sensor design.

References

[1]. G. A**.** MacDonald. A review on low cost accelerometers for vehicle dynamics, *Sensors and Actuators*, A21-A23 (1990). p. 303-307.

[2]. G. Juraj Stein. Some recent developments in acceleration sensors, *Measurement Science Review*, vol. 1, (2001). p. 183-186

[3]. S. Wu and H. J. Frankena. Integrated optical sensors using micromechanical bridges and cantilevers, *SPIE*, vol. 1793, (1992).p. 83-89.

[4]. A. Garcia-Valenzuela , M. Tabib-Azar. Comparative study of piezoelectric, piezoresistive, electrostatic, magnetic, and optical sensors, In *Proceeding of SPIE*, July 1994, vol. 2291, p. 125–142.

[5]. W. Kenny, Cheng-Hsien Liu and Tomas. A high-precision, wide-bandwidth micromachined tunneling accelerometer, *Journal of Microelectromechanical Systems*, vol. 10, (2001). p. 425-433.

[6]. T. W. Kenny. Wide-Bandwidth elecromechanical actuators for tunneling displacement transducers, *Journal of Microelectromechanical Systems*, vol. 3, (2001). p. 97-104.

[7]. M. I. Younis. Modeling and simulation of microelectromechanical systems in multi-physics fields, *Virginia Polytechnic Institute and State University,* (2004). p. 18-19.

[8]. R. Sattler, G. Wachutka. Analytical compact models squeeze film damping, *DTIP of MEMS and MOEMS*, (2004). p.44-47.

[9]. S. Timoshenko, *Mechanics of Material.* Fourth Edition, PWS publishing co, Boston, MA(1997).

[10]. C-P. Chao, C-W. Chiu, C-Y. Tsai. A novel method to predict the pull-in voltage in a closed form for micro-plates actuated by a distributed electrostatic force, *Journal of Micromechanics and microengineering,* (2006). p. 987-988.

[11]. A. C. Baker, H. L. Porteous, *Linear Algebra and Differential Equation* NewYork: Ellis Horwood, 1990.

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.

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 4-12 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.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2007.PDF