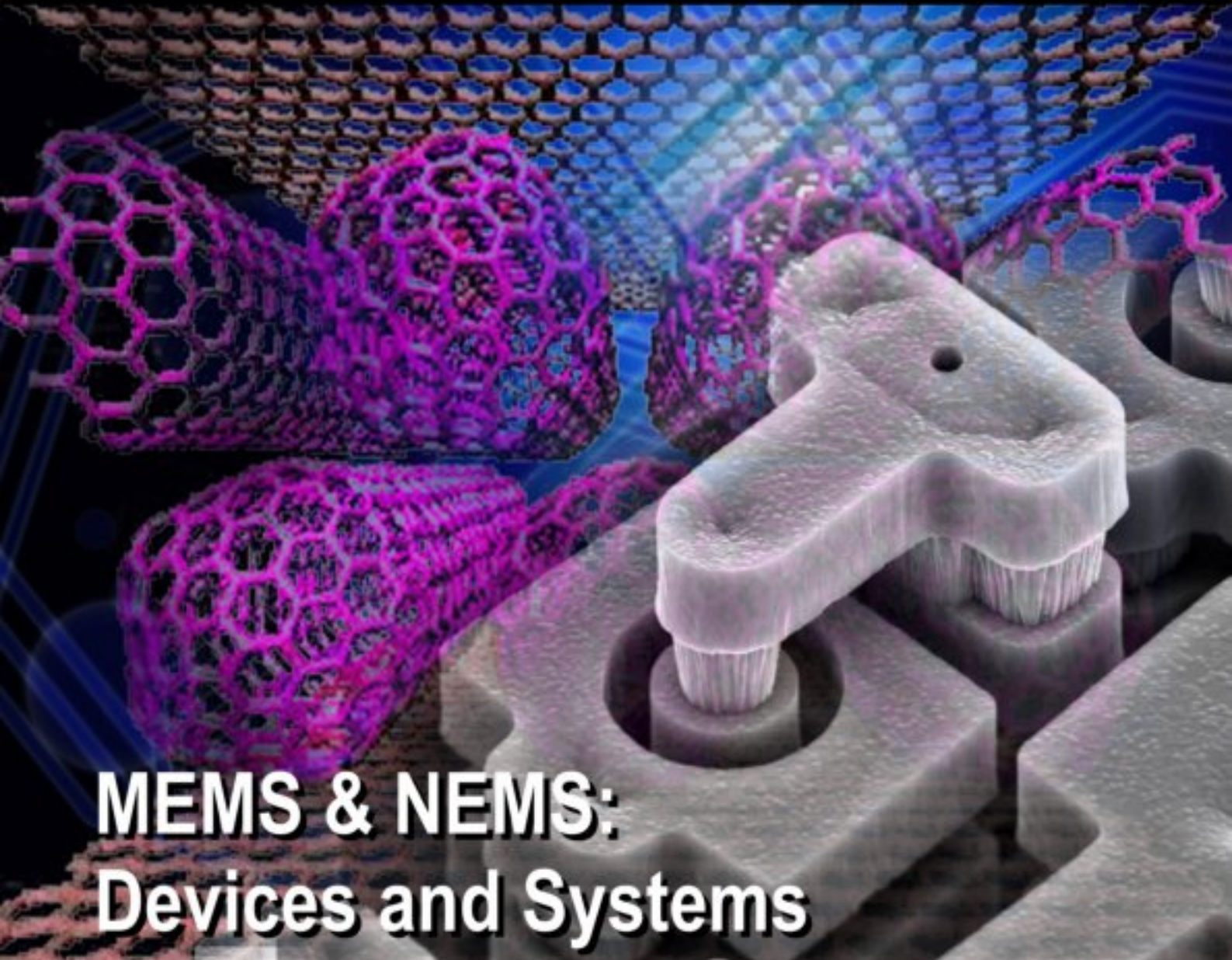


ISSN 1726-5749

SENSORS & TRANSDUCERS

10<sup>Special
Issue</sup>
/07



**MEMS & NEMS:
Devices and Systems**

International Frequency Sensor Association Publishing





Sensors & Transducers

Special Issue
October 2007

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: Sergey Y. Yurish

Guest Editors: Elena Gaura and James P. Brusey

Editors for Western Europe

Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vittorio, Università 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
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA

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
Granell, 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 Alcalá, 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
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK

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
Lee, Jun Su, Amkor Technology, Inc. South Korea
Lei, Hua, National Starch and Chemical Company, USA
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
Lukaszewicz, Jerzy Pawel, Nicholas Copernicus University, Poland
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
Mohamadi, 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 Lahoucine, 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 Seteбал, Portugal
Petsev, Dimitar, 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
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, Bhabha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemeni, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
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

Contents

Special Issue
October 2007

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Foreword

Elena Gaura and James P. Brusey..... 1

Nano-Structure or Nano-Systems: Opportunities and Pitfalls

P. J. French and C.-K. Yang..... 1

New Trends on MEMS Sensor Technology for Harsh Environment Applications

Patricia M. Nieva 10

Healthcare for the Healthy People: Miniaturization, Sensing and Actuation Trends and Needs in Preventive and Predictive Medicine

Alberto Sanna, Marco Nalin, Riccardo Serafin..... 21

Global Environmental Micro Sensors Test Operations in the Natural Environment (GEMSTONE)

Mark Adams, John Manobianco and Matthew Buza..... 30

Frequency Domain Modeling of SAW Devices for Aerospace Sensors

William Wilson, Gary Atkinson..... 42

Development of Materials and Sensors for the U.S. Army's Active Coatings Technology Program

James L. Zunino III 51

Microfabrication and Characterization of an Integrated 3-Axis CMOS-MEMS Accelerometer

Hongwei Qu, Deyou Fang and Huikai Xie..... 60

Characterization and Optimization Design of the Polymer-based Capacitive Micro-arrayed Ultrasonic Transducer

De-Yi Chiou, Mu-Yueh Chen, Hsu-Cheng Deng, Ming-Wei Chang..... 68

Fabry-Perot Diaphragm Fiber Optic Sensor (DFOS) for Acoustic Detection

Yan Sun, Guanhua Feng, George Georgiou, Edip Niver, Karen Noe and Ken Chin..... 76

Micromechanical GaAs Hot Plates for Gas Sensors

Jiri Jakovenko, Miroslav Husak, Tibor Lalinky, Milan Drzik..... 84

Integration of Microfluidics and Microacoustics Components for Miniature Flow Cytometry Systems

Surendra K. Ravula, Darren W. Branch, Jennifer Sigman, Paul G. Clem, Igal Brener..... 93

Design and Characterization of MEMS Thermal Converter

Jiri Jakovenko, Miroslav Husak, Tibor Lalinky..... 101

Fabrication of a Real Time Reactive Ion Etching Resonant Sensor Using a Low Temperature Sacrificial Polymer

Bryan G. Morris, Paul J. Joseph and Gary S. May..... 111

Perturbation Stochastic Finite Element Analysis of Thermoelastic Quality Factor of Micro-Resonators <i>S��verine Lepage and Jean-Claude Golinval</i>	124
A Semi-Analytical Model for Calculating Touch-Point Pressure and Pull-in Voltage for Clamped Diaphragms with Residual Stress <i>Anurekha Sharma and P. J. George</i>	131
The Development of Chemical Nanosensors <i>A. J. Jin, J. Li, Y. Lu</i>	140

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/Submission.htm>

Foreword

The 10th annual NSTI Nanotech Conference and Trade Show was held this year during 20-24 May at the Santa Clara Convention Center, in Santa Clara, California. The conference has grown this year to host 3000 attendees and 250 exhibitors, while the resulting proceedings boasts over 3000 pages of peer-reviewed micro and nanotechnology research.

A number of authors publishing in the Joint Electronics and Microsystems Symposia track were invited to submit a revised version of their papers to this special issue. Papers were selected from a number of symposia within the track, including: MEMS & NEMS, Sensors & Systems, Micro & Nano Fluidics, and MSM – Modeling Microsystems. These symposia brought together researchers from a number of disciplines to discuss topics ranging from theoretical developments, to design and fabrication, through to industrial applications of MEMS and NEMS sensors, devices and systems.

The joint symposia are motivated by the dream of smarter, smaller, and more complex systems that integrate micro and nano system technologies with intelligence, power and communication ability at the same micro or nano scale. The resulting increase in complexity poses an enormous challenge to engineers when designing, modeling, and fabricating such integrated micro and nano systems. The joint symposia aimed at bringing together researchers from different disciplines to exchange ideas about how to best develop such systems.

As with the joint symposia, this special issue includes papers ranging from those with a higher level focus to those covering low-level physical aspects of MEMS and NEMS devices and their modeling and fabrication. Four of the papers presented in this special issue correspond to invited talks: Sanna et al., examine miniaturization trends in preventative medicine and include some results from the EU project ANGEL; Adams et al., describe the results of the NASA funded GEMSTONE project, which involved creating and field-testing a small system of atmospheric probes; French and Yang explore the opportunities and pitfalls of scaling, whilst Nieva presents a number of new trends for using MEMS sensors in harsh environments.

We are very thankful both to the NSTI directors and Nanotech chairs (Dr. Matthew Laudon and Dr. Bart Romanovicz) and to the *Sensors & Transducers Journal* for offering the opportunity to publish this special issue.

Guest Editors:



Dr. Elena Gaura

Reader in Pervasive Computing
Director of Cogent Computing Applied Research Centre
Faculty of Engineering and Computing
Coventry University, UK
e.gaura@coventry.ac.uk
www.cogentcomputing.org



Dr. James P. Brusey

Senior Lecturer in Systems Engineering
Senior Research Fellow of Cogent Computing Applied
Research Centre
Faculty of Engineering and Computing
Coventry University, UK
j.brusey@coventry.ac.uk
www.cogentcomputing.org



Perturbation Stochastic Finite Element Analysis of Thermoelastic Quality Factor of Micro-Resonators

Séverine LEPAGE and Jean-Claude GOLINVAL

University of Liege, Aerospace and Mechanical Engineering Department, LTAS-VIS

E-mail: slepage@ulg.ac.be

Received: 17 September 2007 / Accepted: 19 September 2007 / Published: 8 October 2007

Abstract: In the design of micro-electromechanical systems (MEMS) such as micro-resonators, one of the major dissipation phenomena to be considered is thermoelastic damping. The performance of such MEMS is directly related to their thermoelastic quality factor which has to be predicted accurately. Moreover, the performance of MEMS depends on manufacturing processes which may cause substantial uncertainty in the geometry and in the material properties of the device. The aim of this paper is to provide a framework to account for uncertainties in the finite element analysis. Particularly, the influence of uncertainties on the performance of a micro-beam is studied using the perturbation stochastic finite element method. The developed method is applied on the analysis of the thermoelastic quality factor of a micro-beam whose elastic modulus is considered as random.
Copyright © 2007 IFSA.

Keywords: Stochastic finite element method, Thermoelastic damping, Micro-resonator, Uncertainty modeling

1. Introduction

Micro-electromechanical systems (MEMS) are subject to inevitable and inherent uncertainty in dimensional and material parameters that leads to variability in their performance and reliability. Manufacturing processes due to the small dimensions and high feature complexity leave substantial variability in the shape and geometry of the device while material properties of a component are inherently subject to scattering. The effects of these variations have to be considered and a modeling methodology is needed in order to ensure required MEMS performance under uncertainties.

In the literature, different works are carried out to quantify the effect of the uncertainties on electrostatically actuated MEMS [1-4]. These studies consider material and geometric parameters as random variables and use costly Monte-Carlo methods as well as first and second order reliability methods. Another approach to avoid the detrimental effect of these uncertainties is to design MEMS whose performances are not sensitive to the uncertain design parameters [5-7], but this is not always possible. In this paper, the Perturbation Stochastic Finite Element Method (PSFEM) is used to quantify the influence of uncertain geometric and material property variations on the thermoelastic quality factor of micro-resonators.

The paper is organized as follows. Firstly, the procedure to quantify the thermoelastic quality factor is exposed. An efficient thermoelastic finite element formulation is the key point in order to investigate the influence of uncertainties on the behavior of micro-systems. Then, the perturbation stochastic finite element method is extended to the study of the thermoelastic quality factor. Finally, the results of PSFEM simulations are presented and discussed.

2. Thermoelastic Finite Element Formulation

Thermoelastic damping represents the loss in energy from an entropy rise caused by the coupling between heat transfer and strain rate. Analytical models exist for simple configurations such as beams [8-9]. However, a numerical approach is required in order to take into account the spatial variation of the material properties. A thermoelastic finite element formulation is derived in [10] and shows efficiency in order to estimate the thermoelastic quality factor [11].

In order to determine the thermoelastic quality factor, the thermoelastic frequencies λ have to be computed. The eigenvalue problem corresponding to the thermoelastic problem is

$$\begin{pmatrix} -\mathbf{K}_{uu} & -\mathbf{K}_{u\theta} & \mathbf{0} \\ \mathbf{0} & -\mathbf{K}_{\theta\theta} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{uu} \end{pmatrix} \begin{pmatrix} \mathbf{x}_u \\ \mathbf{x}_\theta \\ \dot{\mathbf{x}}_u \end{pmatrix} = \lambda \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{M}_{uu} \\ \mathbf{C}_{\theta u} & \mathbf{C}_{\theta\theta} & \mathbf{0} \\ \mathbf{M}_{uu} & \mathbf{0} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \mathbf{x}_u \\ \mathbf{x}_\theta \\ \dot{\mathbf{x}}_u \end{pmatrix}, \quad (1)$$

where subscripts u and θ refer respectively to the mechanical and thermal degrees of freedom. \mathbf{M} , \mathbf{C} and \mathbf{K} are respectively mass, damping and stiffness matrices.

If the number of mechanical and thermal degrees of freedom is denoted by n_u and n_θ , respectively, the eigenvalue problem (1) has $2 n_u$ conjugate complex eigenvalues and n_θ real eigenvalues. The $2 n_u$ eigenvalues correspond to the mechanical frequencies and the n_θ ones to the thermal frequencies. Solving the thermoelastic eigenvalue problem with a non-symmetric block Lanczos algorithm allows the calculation of the complex eigenvalues of the thermoelastic structure and hence, the determination of the quality factor of the corresponding mode. The quality factor of the n th mode is given by

$$Q = \frac{1}{2} \left| \frac{\Im(\lambda)}{\Re(\lambda)} \right|. \quad (2)$$

3. Perturbation Stochastic Finite Element Method

Stochastic Finite Element Method (SFEM) can be applied to the thermoelastic problem. The present work focuses on second moment approaches, in which the first two statistical moments, i.e. the mean and the variance, are estimated. The perturbation SFEM is used in order to determine the mean and the

variance of the thermoelastic quality factor of MEMS. The perturbation SFEM [12] consists in a deterministic analysis complemented by a sensitivity analysis with respect to the random parameters. This enables the development of a Taylor series expansion of the response, from which the mean and variance of the response can be derived knowing the mean and variance of the random parameters.

The perturbation method considers that the random design variables b_i are perturbed from their expectation \bar{b}_i , so that the random variables b_i are written as the sum of a deterministic value \bar{b}_i and a zero mean random variable Δb_i .

The second order Taylor expansion about the nominal value $\bar{\mathbf{b}}$ with respect to the random variables b_i is given by

$$Q(\bar{\mathbf{b}}) \approx \bar{Q} + \sum_{i=1}^n Q_{,i} \Delta b_i + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n Q_{,ij} \Delta b_i \Delta b_j . \quad (3)$$

where the subscripts, i and, ij respectively denote the first and second order partial derivative with respect to b_i and b_j computed at the nominal value $\bar{\mathbf{b}}$.

Since the random variables Δb_i are zero-mean random variables of known covariance, the expectation of the quality factor is

$$E[Q(\bar{\mathbf{b}})] \approx \bar{Q} + \sum_{i=1}^n Q_{,i} E[\Delta b_i] + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n Q_{,ij} E[\Delta b_i \Delta b_j] \quad (4)$$

$$= \bar{Q} + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n Q_{,ij} Cov(b_i, b_j) \quad (5)$$

while the variance of the quality factor has the following expression:

$$Var[Q(\bar{\mathbf{b}})] = E\left[\left(Q(\bar{\mathbf{b}}) - E[Q(\bar{\mathbf{b}})]\right)^2\right] \quad (6)$$

$$\approx \sum_{i=1}^n \sum_{j=1}^n Q_{,i} Q_{,j} E[\Delta b_i \Delta b_j] \quad (7)$$

$$= \sum_{i=1}^n \sum_{j=1}^n Q_{,i} Q_{,j} Cov(b_i, b_j) \quad (8)$$

The mean is second-order accurate, while the variance is first-order accurate since the second-order terms vanish. The first and second order derivatives of the quality factor are expressed in terms of the first and second order derivatives of the eigenvalue. Due to the nature of the thermoelastic eigenproblem, this study involves the calculation of eigenvalue sensitivities of a non-symmetric damped system.

Many eigenpair sensitivity methods are restricted to systems whose characteristic matrices are symmetric. However, the thermoelastic damping and stiffness matrices are asymmetric and the eigenpair sensitivity analysis can not be carried out using the previous methods. Many authors [13-15] extend the method of Fox and Kapoor to asymmetric matrices. Murthy and Haftka [16] expose an excellent review on the calculation of the eigenpair sensitivity of asymmetric systems. Brandon [17] presents the modal method for asymmetric damped systems. This method solves the problems due to

asymmetric matrices by using the left eigenvector. However, it has disadvantages in CPU time and storage capacity because it uses state space form to consider damping of systems and requires a lot of eigenpair information to find eigenpair sensitivity. In [18], an N-space method is exposed where the first order eigenvalue and eigenvector sensitivities are simultaneously obtained from one single equation, which is therefore very efficient in CPU time and storage capacity. This method is extended to the computation of second order sensitivities of asymmetric damped systems in order to be applied to the thermoelastic damping case. Its main advantage is that to compute the second order derivatives of the right eigenpair it requires only corresponding right eigenpair information without use of the left eigenvector information so that the computation of the left eigenvector derivatives is avoided.

4. Applications

In numerous micro-resonators, the vibrating part consists in a clamped-clamped silicon beam. In this section, the test case beam has the following dimensions: a length L of 90 μm , a height h of 4.5 μm and a width w of 4.5 μm (Fig. 1). The thermal and mechanical properties of silicon at $T_0=298$ K are: $\rho=2300$ kg/m³, $\eta=0.2$, $c_v=711$ J/kgK, $\alpha=2.5e-6$ K⁻¹ and $k=170$ W/mK. The thermoelastic quality factor is determined for the first bending mode in plane OYZ .

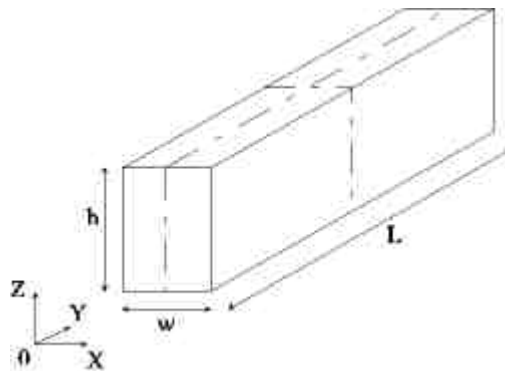


Fig. 1. Beam geometry.

Young's modulus is considered as a Gaussian random variable. Its mean is equal to 158 GPa and its coefficient of variation, i.e. the ratio between the standard deviation and the mean, is set to 6 %, which is a typical value encountered in polysilicon. Direct Monte-Carlo simulations are carried out in order to get a reference solution. 2000 samples are generated.

Table 1 lists the means and standard deviations of the quality factor obtained by different methods. Monte-Carlo results, denoted MC, are considered as reference solutions. First and second order perturbation stochastic finite element methods, denoted PSFEM 1st and PSFEM 2nd, are applied to study the thermoelastic quality factor of the test case. Since the determination of the second order derivative of the eigenvalue can be too computationally demanding, a second order PSFEM in terms of the quality factor but only taking into account the first order derivative of the eigenvalue, denoted PSFEM p2nd, is also investigated. The CPU times for each method are normalized with respect to the CPU time required for one deterministic finite element resolution and are presented in Table 1. MC simulations are a lot more CPU time costly than PSFEM and as the order of PSFEM increases, the CPU time increases. Since the approximation of the standard deviation of the quality factor is first order accurate (Equation 7), the standard deviation has the same value whatever the order of the PSFEM and the relative error with respect to MC standard deviation is less than 1 %. The first order PSFEM gives a mean equal to the deterministic quality factor, i.e. 12967, while MC simulations yield

a higher mean. This is due to the fact that the quality factor is a non-linear function of Young's modulus as shown in Fig. 2 (b). Moreover, due to this non-linear variation, the probability density function of the quality factor is not strictly Gaussian as shown in Fig. 2 (a). In this figure, the bars represent the distribution of the output samples obtained by MC simulations and the solid line plots the Gaussian distribution with a mean and a standard deviation equal to the values of the MC samples. The second order PSFEM approximation of the mean is really good (0.02 % relative error) and the pseudo second order PSFEM approximation has also a good accuracy (0.026 % relative error) at a less computational effort.

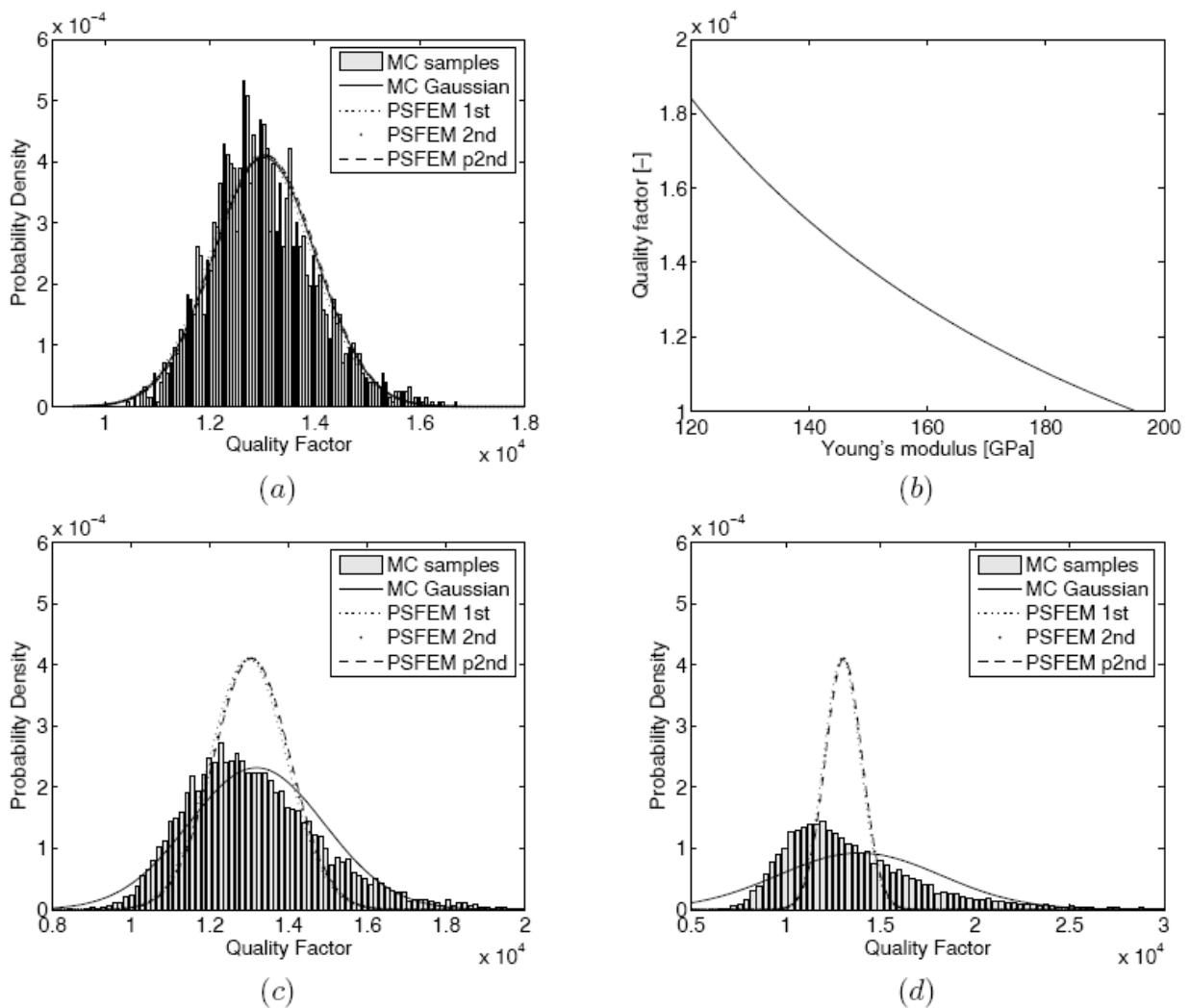


Fig. 2. Probability density function of the quality factor (CoV(E)=0.06 (a), CoV(E)=10 % (c) and CoV(E)=20 % (d)), (b) Variation of the quality factor with respect to Young's modulus.

Table 1 also compares the means and standard deviations of the quality factor corresponding to three different coefficients of variation of Young's modulus, i.e. 6 %, 10 % and 20 %. As the coefficient of variation of Young's modulus increases, the approximations of the mean and standard deviation of the quality factor by PSFEM become less accurate. The second order PSFEM is more accurate than the pseudo-second order PSFEM at the price of a considerably larger computational effort. Figs. 2 (a,c,d) show that as the coefficient of variation of Young's modulus increases, the probability density function drifts away from the Gaussian distribution and PSFEM approximations get worse. Note that as the coefficient of variation increases, the required number of samples in MC simulations increases leading to a larger CPU time ($n_{\text{samples}}=5000$ for CoV=10% and $n_{\text{samples}}=10000$ for CoV=20%).

These analyses show that PSFEM is adequate in order to determine the mean and standard deviation of the quality factor when Young's modulus variation is small (i.e. in this application, a coefficient of variation lower than 10 %). The second order and the pseudo-second order perturbation stochastic finite element methods provide more information than the first order one. Indeed, the first order method does not take into account the variation of the mean due to the non-linear characteristic of the response with respect to the random variable. Moreover, the increase in accuracy from PSFEM p2nd to PSFEM 2nd is not sufficient to justify the increase in computational effort.

Table 1. Variation of the mean and coefficient of variation of the quality factor with respect to the coefficient of variation of Young's modulus.

Method	CoV(E) [%]	Mean(Q) [-]	$\sigma(Q)$ [-]	CoV(Q) [%]	t^*_{CPU} [-]
MC	6	13035	980	7.52	2005
PSFEM 1st	6	12967	971	7.49	1.02
PSFEM 2nd	6	13037	971	7.45	1.16
PSFEM p2nd	6	13069	971	7.43	1.04
MC	10	13181	1720	13.05	5015
PSFEM 1st	10	12967	1619	12.49	1.02
PSFEM 2nd	10	13161	1619	12.30	1.16
PSFEM p2nd	10	13250	1619	12.22	1.04
MC	20	13895	4313	31.05	10062
PSFEM 1st	20	12967	3238	24.97	1.02
PSFEM 2nd	20	13744	3238	23.56	1.16
PSFEM p2nd	20	14099	3238	22.97	1.04

5. Conclusions

The Perturbation Stochastic Finite Element Method has been extended to the analysis of a strongly coupled multiphysic phenomenon: thermoelastic damping. The methodology has been validated and its efficiency has been proved on 1-D cases. Therefore, using PSFEM, a numerical method is available to quantify the influence of uncertain property variations on the thermoelastic quality factor of micro-resonators, making available a new efficient numerical tool to MEMS designers.

Acknowledgements

The author S. Lepage is supported by the Belgian National Fund for Scientific Research (FNRS), which is gratefully acknowledged. This work is also supported by the Communauté Française de Belgique - Direction Générale de la Recherche Scientifique in the framework Actions de Recherches Concertées (convention ARC 03/08-298).

References

- [1]. M. Allen, M. Raulli, K. Maute and D. Frangopol, Reliability-based Analysis and Design Optimization of Electrostatically Actuated MEMS, *Computers and Structures*, 82, 2004, pp. 1007-1020.
- [2]. J. S. Kong, D. M. Frangopol, M. Raulli, K. Maute, R. A. Saravanan, L. A. Liew and R. Raj, A methodology for Analyzing the Variability in the Performance of a MEMS Actuator Made from a Novel Ceramic, *Sensors and Actuators A*, 116, 2004, pp. 336-244.
- [3]. K. Maute and D. M. Frangopol, Reliability-based Design of MEMS Mechanisms by Topology Optimization, *Computers and Structures*, 81, 2003, pp. 813-824.

- [4]. S. Reh, P. Lethbridge and D. Ostergaard, Quality Based Design and Design for Reliability of Micro-electro-mechanical Systems (MEMS) using Probabilistic Methods, In *Technical proceedings of the 2000 International Conference on Modeling and Simulation of Microsystems*, 2000, pp. 708-711.
 - [5]. R. Liu, B. Paden and K. Turner, MEMS Resonators That Are Robust to Process-induced Feature Width Variations, *Journal of Microelectromechanical Systems*, 11, 5, 2002, pp. 505-511.
 - [6]. A. Mawardi and R. Pitchumani, Design of Microresonators under Uncertainty, *Journal of Microelectromechanical Systems*, 14, 1, 2005.
 - [7]. A. Mawardi and R. Pitchumani, Optimal Design of a Micromachined Force Gauge under Uncertainty, *Journal of Micromechanics and Microengineering*, 15, 2005, pp. 2353-2365.
 - [8]. R. Lifshitz and M. L. Roukes, Thermoelastic Damping in Micro-and Nano-mechanical Systems, *Physical Review B*, 61, 8, 2000, pp. 5600-5609.
 - [9]. C. Zener, Internal Friction in Solids, *Physical Review*, 52, 1937, pp. 230-235.
 - [10]. S. Lepage and J. C. Golinval, Finite Element Modeling of the Thermoelastic Damping in Micro-Electromechanical Systems, In *Acomen 2005, Third International Conference on Advanced Computational Methods in Engineering*, Ghent, Belgium, 30 May-2 June 2005.
 - [11]. S. Lepage, O. Le Traon, I. Klapka, S. Masson and J. C. Golinval, Thermoelastic Damping in Vibrating Beam Accelerometer: A New Thermoelastic Finite Element Approach, In *Caneus 2006*, Toulouse, France, 27 August-1 September 2006.
 - [12]. M. Kleiber and T. D. Hien, The Stochastic Finite Element Method - Basic Perturbation Technique and Computer Implementation, *John Wiley and sons*, 1992.
 - [13]. R. H. Plaut and K. Huseyin, Derivative of Eigenvalues and Eigenvectors in Non-self Adjoint Systems, *AIAA Journal*, 11, 2, 1973, pp. 250-251.
 - [14]. L. C. Rogers, Derivatives of Eigenvalues and Eigenvectors, *AIAA Journal*, 8, 5, 1970, pp. 943-944.
 - [15]. S. Garg, Derivative of Eigensolutions for a General Matrix, *AIAA Journal*, 11, 8, 1973, pp. 1191-1194.
 - [16]. D. V. Murthy and R. T. Haftka, Derivatives of Eigenvalues and Eigenvectors for a General Complex Matrix, *International Journal for Numerical Methods in Engineering*, 26, 1988, pp. 293-311.
 - [17]. J. A. Brandon, Second-order Design Sensitivities to Assess the Applicability of Sensitivity Analysis, *AIAA Journal*, 29, 1, 1991, pp. 135-139.
 - [18]. K. M. Choi, H. K. Jo, W. H. Kim and I. W. Lee, Sensitivity Analysis of Non-conservative Eigensystems, *Journal of Sound and Vibration*, 274, 2004, pp. 997-1011.
-

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 addition, 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 6-14 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/Submission.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

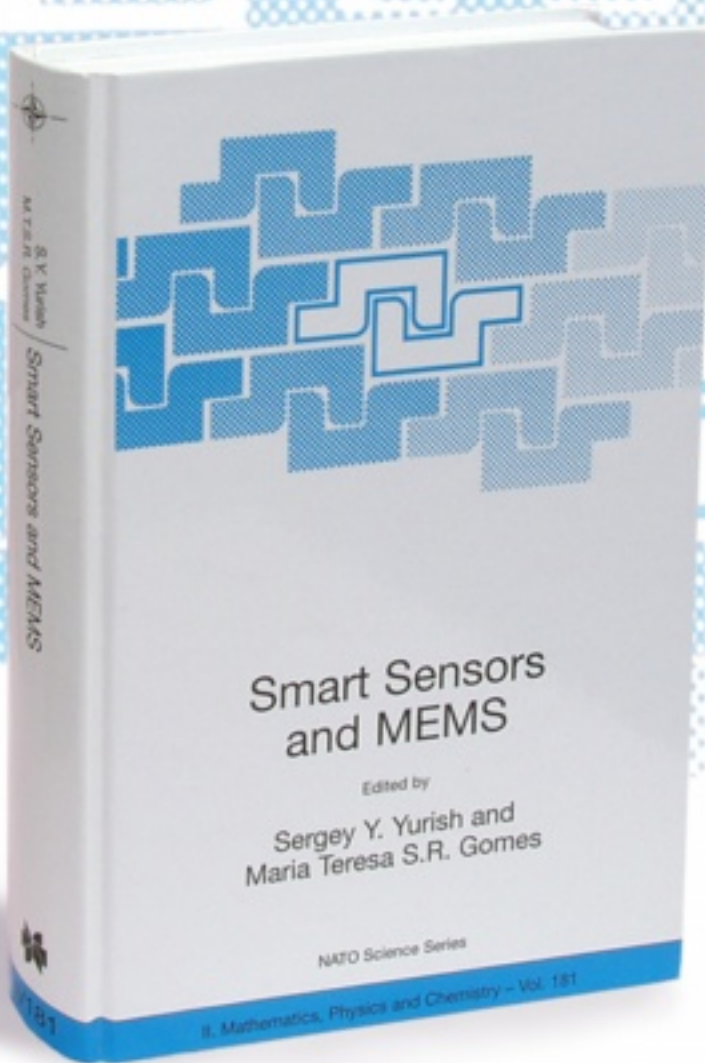
Smart Sensors and MEMS

Edited by

Sergey Y. Yurish and
Maria Teresa S.R. Gomes

The book provides an unique collection of contributions on latest achievements in sensors area and technologies that have made by eleven internationally recognized leading experts ...and gives an excellent opportunity to provide a systematic, in-depth treatment of the new and rapidly developing field of smart sensors and MEMS.

The volume is an excellent guide for practicing engineers, researchers and students interested in this crucial aspect of actual smart sensor design.



Kluwer Academic Publishers

Order online:

www.sensorsportal.com/HTML/BOOKSTORE/Smart_Sensors_and_MEMS.htm

www.sensorsportal.com