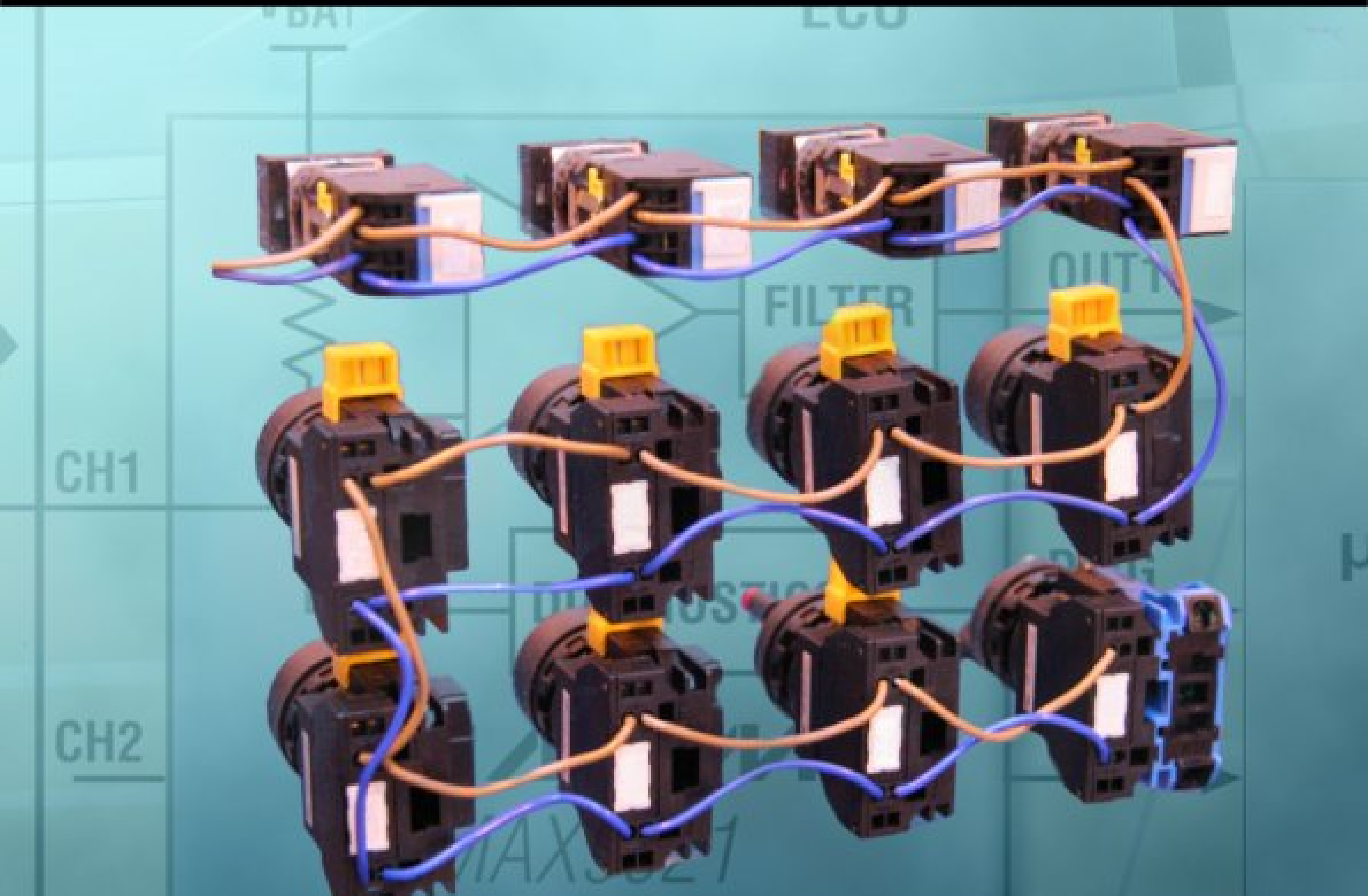
ISSN 1726-5479

SENSORS & TRANSDUCERS

5/10
vol. 116



Sensor Buses and Interfaces

International Frequency Sensor Association Publishing
IFSA

Sensors & Transducers

Volume 116, Issue 5,
May 2010

www.sensorsportal.com

ISSN 1726-5479

Editors-in-Chief: professor Sergey Y. Yurish, tel.: +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, Vittorio, Universitá di Brescia, Italy

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

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

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

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

Editor for Asia-Pacific
Mukhopadhyay, Subhas, Massey University, New Zealand

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
Baliga, Shankar, B., General Monitors Transnational, USA
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, RF Arrays Systems, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Benachaiba, Chellali, Universitaire de Bechar, Algeria
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
Chavali, Murthy, VIT University, Tamil Nadu, India
Chen, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiang, Jeffrey (Cheng-Ta), Industrial Technol. Research Institute, 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 Nacional de Colombia, 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
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding, Jianning, Jiangsu Polytechnic University, China
Kim, Min Young, Kyungpook National University, Korea South
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, Univ.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
Francis, Laurent, University Catholique de Louvain, Belgium
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 Rosa, 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
Haider, Mohammad R., Sonoma State University, USA
Hashsham, Syed, Michigan State University, USA
Hasni, Abdelhafid, Bechar University, Algeria
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
Jiang, Wei, University of Virginia, USA
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Kang, Moonho, Sunmoon University, Korea South
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
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhbha Atomic Research Centre, Mumbai, India

Ko, Sang Choon, Electronics. and Telecom. Research Inst., 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
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, University of Oklahoma, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, University of Vigo, Spain
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
Melnyk, Ivan, Photon Control Inc., Canada
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, Benemérita Universidad Autónoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mulla, Imtiaz Sirajuddin, National Chemical Laboratory, Pune, India
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucine, Cherif, 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
Penza, Michele, ENEA C.R., Italy
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
Raoof, Kosai, Joseph Fourier University of Grenoble, France
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Robert, Michel, University Henri Poincare, France
Rezazadeh, Ghader, Urmia University, Iran
Royo, Santiago, Universitat Politecnica de Catalunya, Spain
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK
Sadana, Ajit, University of Mississippi, USA
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sandacci, Serghei, Sensor Technology Ltd., UK
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Shah, Kriyang, La Trobe University, Australia
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmaliy, Yuriy, Kharkiv National Univ. of Radio Electronics, Ukraine
Silva Girao, Pedro, Technical University of Lisbon, Portugal
Singh, V. R., National Physical Laboratory, India
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technol., India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University, USA
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 Inst. 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
Teker, Kasif, Frostburg State University, USA
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tian, Gui Yun, University of Newcastle, UK
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
Vanga, Raghav Rao, Summit Technology Services, Inc., USA
Vaseashta, Ashok, Marshall University, USA
Vazquez, 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, Pacific Northwest National Laboratory, 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 Univ. of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Lisheng, The Chinese University of Hong Kong, Hong Kong
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Yang, Xiaoling, University of Georgia, Athens, GA, USA
Yaping Dan, Harvard University, USA
Ymeti, Aurel, University of Twente, Netherland
Yong Zhao, Northeastern University, China
Yu, Haihu, Wuhan University of Technology, China
Yuan, Yong, Massey University, New Zealand
Yufera Garcia, Alberto, Seville University, Spain
Zakaria, Zulkarnay, University Malaysia Perlis, Malaysia
Zagnoni, Michele, University of Southampton, UK
Zamani, Cyrus, Universitat de Barcelona, Spain
Zeni, Luigi, Second University of Naples, Italy
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
Zhang, Xueji, World Precision Instruments, Inc., USA
Zhong, Haoxiang, Henan Normal University, China
Zhu, Qing, Fujifilm Dimatix, Inc., USA
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 on CD. Copyright © 2009 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 116
Issue 5
May 2010

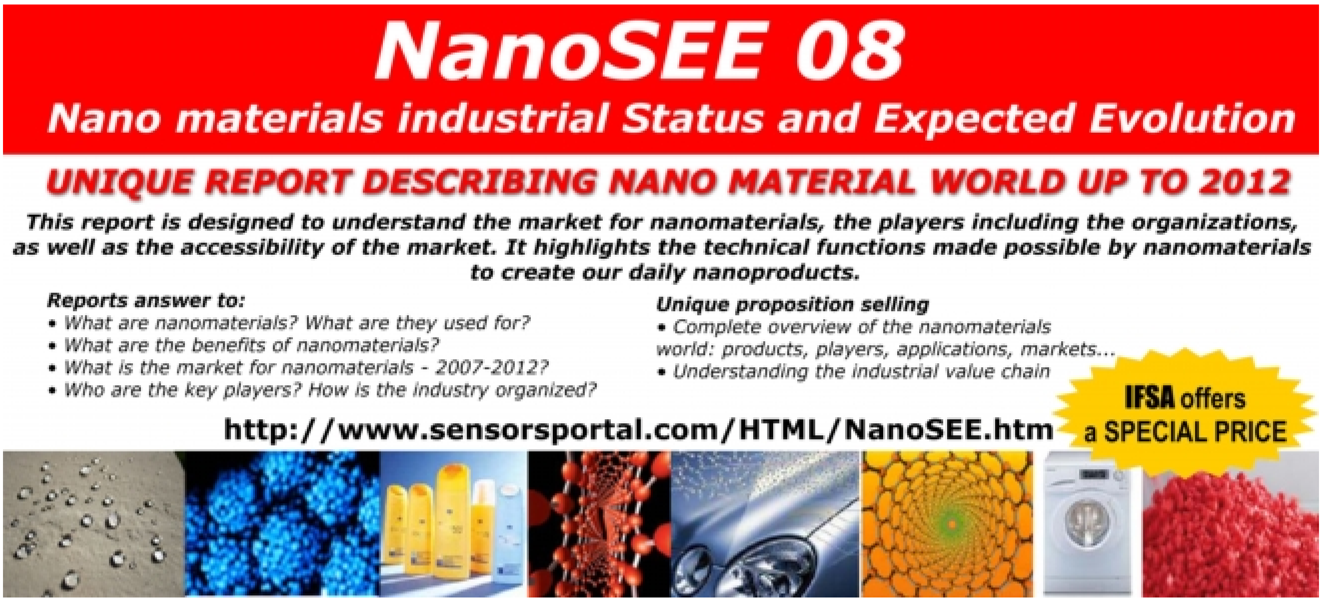
www.sensorsportal.com

ISSN 1726-5479

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

International Frequency Sensor Association (IFSA).



Sensors & Transducers Journal, Vol. 116, Issue 5, May 2010, pp. 89-103

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Harmonic Response of Magneto-electro-elastic Sensors Bonded to Cylindrical Shells

B. Biju, N. Ganesan and #K. Shankar
Machine Design Section, Department of Mechanical Engineering
Indian Institute of Technology Madras, Chennai 600 036, India
Tel.: +91 44 22574701
E-mail: skris@iitm.ac.in

Received: 18 March 2010 /Accepted: 24 May 2010 /Published: 31 May 2010

Abstract: This paper deals with semi analytical finite element formulation for coupled magneto-electro-elastic sensor bonded to a mild steel cylindrical shell. The cylinder is subjected to harmonically varying internal pressure with clamped free and clamped-clamped boundary condition. Numerical results are presented for the first three axial modes associated with the axisymmetric mode of the shell with different sensor locations. The sensor response is controlled mainly by its radial displacement in all the modes. The third mode response becomes significant when the sensor is placed at the free end of the mild steel cylinder for clamped free boundary condition. *Copyright © 2010 IFSA.*

Keywords: Magneto-electro-elastic, Sensor, Harmonic response, Semi analytical finite element

---

1. Introduction

Composite materials that possess simultaneously piezoelectric, piezomagnetic and magneto electric effects are classified as Magneto-electro-elastic (MEE) materials. The composite consisting of piezoelectric phase shows a coupling between mechanical and electric field where as the piezomagnetic phase shows the coupling between mechanical and magnetic field. Magneto-electric coupling effect which is absent in the constituent phases is also exhibited by these class of magneto-electro-elastic materials. On application of either mechanical, electric or magnetic loads, these materials will respond in such a way to convert one form of energy into another. These materials are widely used in acoustic devices, magnetic field probes, medical ultrasonic imaging, sensors and actuators etc. Harmonic response analysis helps to predict the sustained dynamic behavior of the structure, thus enabling to predict whether the structure will overcome resonance, fatigue and other harmful effects of forced vibration. Response characteristics of MEE sensors under dynamic loading will help to determine the best operating conditions of MEE devices which in turn will lead to emerging areas for application of magneto-electro-elastic materials as sensors and actuators.

Fibrous composites consisting of piezomagnetic cobalt iron oxide $CoFe_2O_4$ matrix reinforced by piezoelectric barium titanate $BaTiO_3$ fibers (Buchanan, 2004) are analyzed for the sensory response. The composite is transversely isotropic with plane of symmetry oriented in the radial direction. Aboudi (2001) has employed a homogenization method assuming that the composites have a periodic structure, for predicting the effective moduli of magneto-electro-elastic composites. Ramirez *et al* (2006) presented approximate solution to a free vibration problem of a two dimensional MEE laminate assuming perfect bonding between each interface. Analytical solution for transient response of MEE hollow cylinder was presented by Hou *et al* (2004) where plain strain condition with axisymmetric loading was used so that radial displacement only is considered to derive the solution. Transient responses of displacements, stresses, electric and magnetic potentials, electric displacements, magnetic induction are obtained by the study. Dai *et al* (2006) has presented an analytical solution for magneto-thermo-electro-elastic transient response of a piezoelectric hollow cylinder placed in an axial magnetic field subjected to arbitrary thermal shock, mechanical load and transient electric excitation. Sirohi *et al* (2000) investigated the piezoelectric strain sensor in which strain is measured in terms of charge developed by direct piezoelectric effect. Huang *et al* (2000) examined the dynamic electromechanical response of piezoelectric sensors and actuators which are modeled as rectangular plate and the variation of electric potential, stresses and electric displacements across the thickness were evaluated. Galopin *et al* (2008) has done finite element modeling of magneto electric sensors and the magneto electric effect stemming from piezoelectric and magnetostrictive composite was studied. Daga *et al* (2009) has studied the behavior of MEE sensors bonded to beam under transient mechanical loading.

This paper deals with harmonic response of magneto-electro-elastic sensor bonded to an axisymmetric cylindrical shell. The sensor is bonded on the outer surface of a shell structure. Semi analytical finite element method is used to model the entire structure. Dynamic response of the sensor is studied when the cylinder is subjected to harmonically varying internal pressure. Numerical studies are carried out for clamped-free and clamped-clamped boundary conditions with the sensor placed at different locations on the top surface of the cylinder. These studies will be highly useful when we use MEE sensors and actuators for active vibration control of structures. Ansys 10.1 is used to validate the computer code developed for the study. Ansys cannot model fully coupled magneto-electro-elastic materials but it can model piezoelectric material *PZT-5* which is used to compare with the results of the code.

2. Constitutive Equations

The constitutive equations for the MEE medium relating stress σ_j, electric displacement D_l and magnetic induction B_l to strain S_k, electric field E_m and magnetic field H_m, exhibiting linear coupling between magnetic, electric and elastic field can be written as (Daga *et al* (2008))

$$\sigma_j = C_{jk}S_k - e_{jm}E_m - q_{jm}H_m \tag{1}$$

$$D_l = e_{lj}S_k + \varepsilon_{lm}E_m + m_{lm}H_m \tag{2}$$

$$B_l = q_{lj}S_k + m_{lm}E_m + \mu_{lm}H_m, \tag{3}$$

where C_{jk}, ε_{lm} and μ_{lm} are elastic, dielectric and magnetic permeability coefficients respectively and e_{lj}, q_{lj} and m_{lm} are the piezoelectric, piezomagnetic and magnetoelectric material coefficients. Here $j,k = 1,\ldots,6$ and $l,m = 1,..,3$.

2.2. Finite Element Modeling of the Shell

In the axi-symmetric cylindrical shell, the geometry and material properties do not vary along circumferential (θ) direction and semi analytical finite element approach can be used for a simplified solution. The displacements, electric scalar potential and magnetic scalar potential are expressed using Fourier series in the circumferential direction.

$$u_r = \sum u_r^n \cos n\theta \tag{2.1}$$

$$u_\theta = \sum u_\theta^n \sin n\theta \tag{2.2}$$

$$u_z = \sum u_z^n \cos n\theta \tag{2.3}$$

$$\phi = \sum \phi^n \cos n\theta \tag{2.4}$$

$$\psi = \sum \psi^n \cos n\theta , \tag{2.5}$$

where u_r, u_θ, u_z are the radial, circumferential and axial displacements, ϕ and ψ are the electric and magnetic scalar potentials respectively.

The displacements $\{u\} = \{u_r\, u_\theta\, u_z\}^T$, electric potential (ϕ) and magnetic potential (ψ) within the element can be expressed in terms of suitable shape functions and the corresponding nodal quantities.

$$\{u\} = [N_u]\{u^e\}; \phi = [N_\phi]\{\phi^e\};\ \psi = [N_\psi]\{\psi^e\} \tag{3}$$

The strains can be related to the nodal degree of freedom by the following expression

$$\{S\} = [B_u]\{u^e\}, \tag{4}$$

where $[B_u]$, the strain displacement matrix can be written as

$$[B_u] = [L_u][N_u] \tag{5}$$

$$= \begin{bmatrix} \frac{\partial}{\partial r} & 0 & 0 \\ \frac{1}{r} & \frac{1}{r}\frac{\partial}{\partial \theta} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial z} & \frac{1}{r}\frac{\partial}{\partial \theta} \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial r} \\ \frac{1}{r}\frac{\partial}{\partial \theta} & \frac{\partial}{\partial r} - \frac{1}{r} & 0 \end{bmatrix} \begin{bmatrix} N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 & N_4 & 0 & 0 \\ 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 & N_4 & 0 \\ 0 & 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 & N_4 \end{bmatrix}$$

$$[B_u] = \begin{bmatrix} \dfrac{\partial N_1}{\partial r} & 0 & 0 & .... \\ \dfrac{N_1}{r} & \dfrac{nN_1}{r} & 0 & .... \\ 0 & 0 & \dfrac{\partial N_1}{\partial z} & .... \\ 0 & \dfrac{\partial N_1}{\partial z} & -\dfrac{nN_1}{r} & .... \\ \dfrac{\partial N_1}{\partial z} & 0 & \dfrac{\partial N_1}{\partial r} & .... \\ -\dfrac{nN_1}{r} & \dfrac{\partial N_1}{\partial r} - \dfrac{N_1}{r} & 0 & .... \end{bmatrix} \tag{6}$$

In the present formulation body forces, free charge density and free current density are absent. In the absence of free charge density, Gauss law can be reduced as $C.D = 0$ where D is the electric displacement vector. The electric potential f which satisfies the above relation is defined so that the electric field E can be written as $E = - Cf$ .The relation between electric field (E_m) related to electric potential (ϕ) can be written as

$$E_r = -\frac{\partial \phi}{\partial r}, \quad E_\theta = -\frac{1}{r}\frac{\partial \phi}{\partial \theta}, \quad E_z = -\frac{\partial \phi}{\partial z} \tag{7}$$

The array of electric field vector is given by

$$\{E\} = \left\{ -\frac{\partial \phi}{\partial r} \quad -\frac{1}{r}\frac{\partial \phi}{\partial \theta} \quad -\frac{\partial \phi}{\partial z} \right\} \tag{8}$$

The electric field vector can be related to the electric potential as a nodal degree of freedom using the following expression as

$$\{E\} = \left[B_\phi\right]\left\{\phi^e\right\} \tag{9}$$

The derivative of shape function matrix $[B_\phi]$ matrix is given below as

$$[B_\phi] = [L_\phi][N_\phi]$$

$$= \begin{bmatrix} -\dfrac{\partial}{\partial r} \\ -\dfrac{1}{r}\dfrac{\partial}{\partial \theta} \\ -\dfrac{\partial}{\partial z} \end{bmatrix} \begin{bmatrix} N_1 & N_2 & N_3 & N_4 \end{bmatrix} \tag{10}$$

$$[B_\phi] = \begin{bmatrix} -\frac{\partial N_1}{\partial r} & -\frac{\partial N_2}{\partial r} & -\frac{\partial N_3}{\partial r} & -\frac{\partial N_4}{\partial r} \\ \frac{nN_1}{r} & \frac{nN_2}{r} & \frac{nN_3}{r} & \frac{nN_4}{r} \\ -\frac{\partial N_1}{\partial z} & -\frac{\partial N_2}{\partial z} & -\frac{\partial N_3}{\partial z} & -\frac{\partial N_4}{\partial z} \end{bmatrix} \tag{11}$$

The magnetic field is formulated using scalar potential approach. In the absence of free current density, Gauss law for magnetic field can be written as $C.B= 0$ where B is the magnetic induction vector. The magnetic scalar potential ψ which satisfies the above relation is defined so that the magnetic field H can be written as $H = -\nabla \psi$. The magnetic field (H_m) related to magnetic potential (ψ) can be written as

$$H_r = -\frac{\partial \psi}{\partial r}, \quad H_\theta = -\frac{1}{r}\frac{\partial \psi}{\partial \theta}, \quad H_z = -\frac{\partial \psi}{\partial z} \tag{12}$$

The array of magnetic field vector is given by

$$\{H\} = \left\{ -\frac{\partial \psi}{\partial r} \quad -\frac{1}{r}\frac{\partial \psi}{\partial \theta} \quad -\frac{\partial \psi}{\partial z} \right\} \tag{13}$$

The magnetic field vector $\{H\}$ can be related to the magnetic potential as a nodal degree of freedom the following expression

$$\{H\} = \left[B_\psi\right]\left\{\psi^e\right\} \tag{14}$$

The derivative of shape function matrix $[B_\psi]$ matrix is given below as

$$[B_\psi] = [L_\psi][N_\psi]$$

$$= \begin{bmatrix} -\frac{\partial}{\partial r} \\ -\frac{1}{r}\frac{\partial}{\partial \theta} \\ -\frac{\partial}{\partial z} \end{bmatrix} \begin{bmatrix} N_1 & N_2 & N_3 & N_4 \end{bmatrix} \tag{15}$$

$$[B_\psi] = \begin{bmatrix} -\frac{\partial N_1}{\partial r} & -\frac{\partial N_2}{\partial r} & -\frac{\partial N_3}{\partial r} & -\frac{\partial N_4}{\partial r} \\ \frac{nN_1}{r} & \frac{nN_2}{r} & \frac{nN_3}{r} & \frac{nN_4}{r} \\ -\frac{\partial N_1}{\partial z} & -\frac{\partial N_2}{\partial z} & -\frac{\partial N_3}{\partial z} & -\frac{\partial N_4}{\partial z} \end{bmatrix} \tag{16}$$

2.3. Evaluation of Elemental Matrices

The finite element equations for MEE cylinder can be written as

$$\begin{aligned}&[M^e_{uu}]\{\ddot{u}^e\}+[K^e_{uu}]\{u^e\}+[K^e_{u\phi}]\{\phi^e\}+[K^e_{u\psi}]\{\psi^e\}=\{F^e\}\\&[K^e_{u\phi}]^T\{u^e\}-[K^e_{\phi\phi}]\{\phi^e\}-[K^e_{\phi\psi}]\{\psi^e\}=\{G^e\}\\&[K^e_{u\psi}]^T\{u^e\}-[K^e_{\phi\psi}]^T\{\phi^e\}-[K^e_{\psi\psi}]\{\psi^e\}=\{M^e\}\end{aligned}\quad , \tag{17}$$

where F, G and M correspond to elemental load vectors of applied mechanical force, electric charge and magnetic current respectively.

Different elemental matrices in Equation (17) for n$^{\text{th}}$ harmonic are defined as

$$[M^e_{uu}]=P\int_A[N_u]^T[\rho][N_u]rdrdz$$

$$[K^e_{uu}]=P\int_A[B_u]^T[c][B_u]rdrdz$$

$$[K^e_{u\phi}]=P\int_A[B_u]^T[e][B_\phi]rdrdz$$

$$[K^e_{u\psi}]=P\int_A[B_u]^T[q][B_\psi]rdrdz$$

$$[K^e_{\phi\phi}]=P\int_A[B_\phi]^T[\varepsilon][B_\phi]rdrdz$$

$$[K^e_{\psi\psi}]=P\int_A[B_\psi]^T[\mu][B_\psi]rdrdz$$

$$[K^e_{\phi\psi}]=P\int_A[B_\phi]^T[m][B_\psi]rdrdz\,, \tag{18}$$

where $P=2\pi$ for $n=0$ and $P=\pi$ for $n>0$, n is circumferential harmonic number.

When electric and magnetic loading are absent, using standard condensation techniques, the equivalent stiffness matrix $[K_{eq}]$ is derived by eliminating the electric potential (ϕ) and magnetic potential (ψ) from Equation (17). For harmonic mechanical loading equation (17) can be rewritten as

$$[M_{uu}]\{\ddot{u}\}+[K_{eq}]\{u\}=\{Fe^{i\omega t}\}\,, \tag{19}$$

where

$$[K_{eq}]=[K_{uu}]+[K_{u\phi}][K_{II}]^{-1}[K_I]+[K_{u\psi}][K_{IV}]^{-1}[K_{III}]\,, \tag{20}$$

where

$$[K_I]=[K_{u\phi}]^T-[K_{\phi\psi}][K_{\psi\psi}]^{-1}[K_{u\psi}]^T$$
$$[K_{II}]=[K_{\phi\phi}]-[K_{\phi\psi}][K_{\psi\psi}]^{-1}[K_{\phi\psi}]^T$$
$$[K_{III}]=[K_{u\psi}]^T-[K_{\phi\psi}]^T[K_{\phi\phi}]^{-1}[K_{u\phi}]^T$$

$$[K_{IV}]=[K_{\psi\psi}]-[K_{\phi\psi}]^T[K_{\phi\phi}]^{-1}[K_{\phi\psi}] \quad (21)$$

After evaluating the nodal displacements, the electric potential (ϕ) and magnetic potential (ψ) can be derived at each nodal points using the following equations

$$\text{Electric potential } \{\phi\}=[K_{II}]^{-1}[K_I]\{u\} \quad (22)$$

$$\text{Magnetic potential } \{\psi\}=[K_{IV}]^{-1}[K_{III}]\{u\} \quad (23)$$

3. Results and Discussions

3.1. Validation

A computer code has been developed to study the harmonic response of magneto-electro-elastic sensor bonded on the outer surface of a mild steel cylindrical shell while the cylinder is subjected to a harmonic pressuring load (Fig. 1). Constant damping ratio of 0.01 is assumed and full method is used as the solution technique. The study is carried out for axisymmetric model of the shell structure with $n=0$. The circumferential displacement (u_θ) will be suppressed when $n=0$ and the model will simplify to a 2D axisymmetric model.

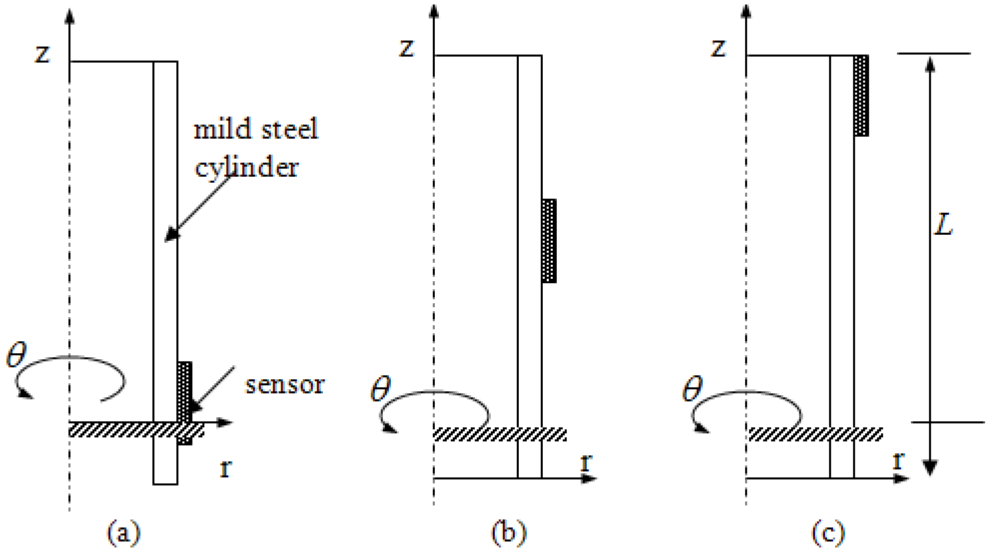


Fig. 1. Schematic diagram of a mild steel cylinder with sensor patch placed at (a) clamped end; (b) middle; and (c) free end.

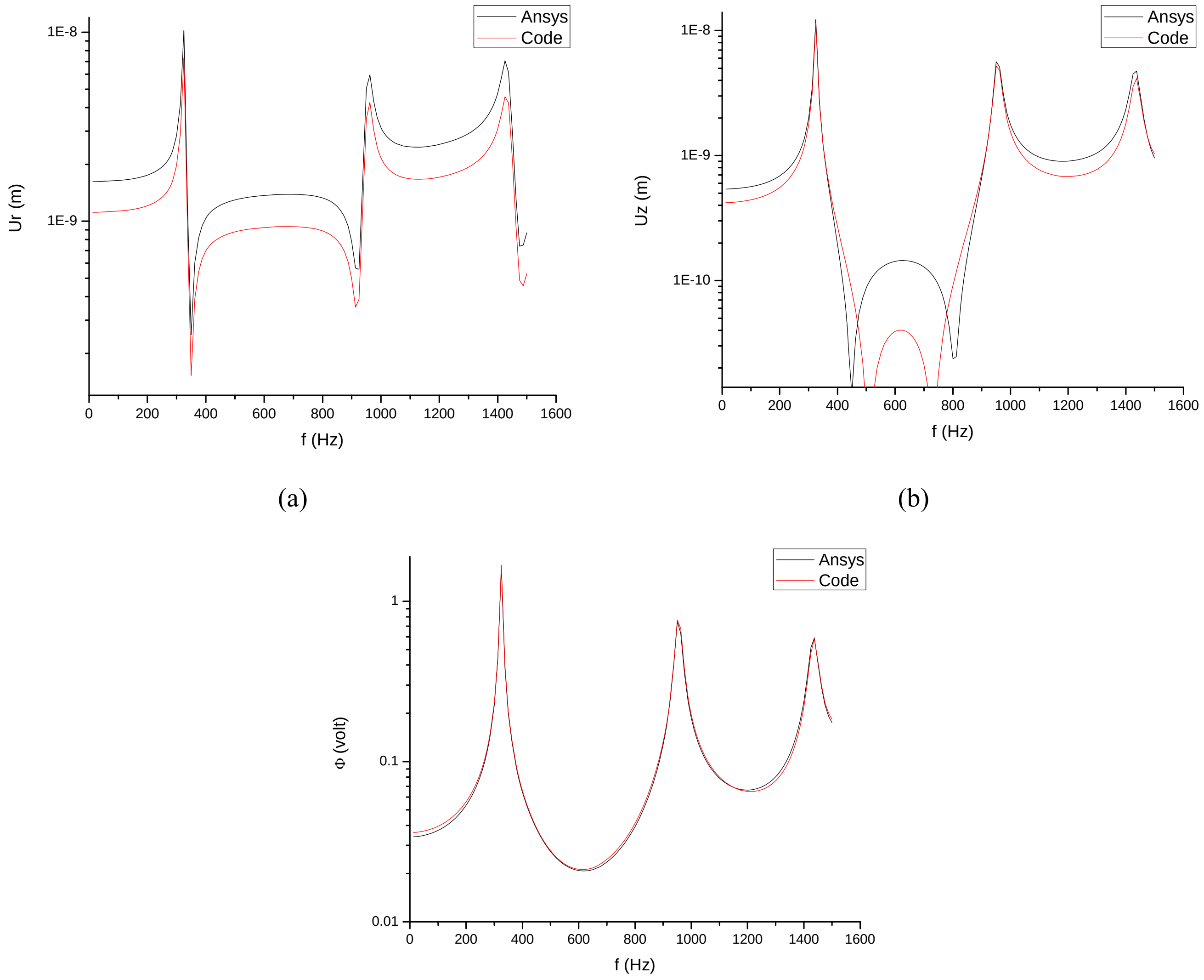
The commercial finite element package Ansys 10.1 cannot model fully coupled magneto-electro-elastic materials but it can model piezoelectric materials. The present code is validated using piezoelectric material PZT-5 whose material properties (Chen *et al* (2007)) are given in Table 1. The dimensions of the cylinder used for the analysis are L = 4.0m, Ri = 0.5 m and Ro = 0.51 m. The cylinder is subjected to a uniform internal pressure of 100 N/m^2 with clamped-free and clamped-clamped boundary condition.

Table 1. Material properties of PZT-5 and different volume fraction v_f of multiphase magneto-electro-elastic $BaTiO_3$-$CoFe_2O_4$ for radial plane of symmetry.

	0.0 *vf*	0.2 *vf*	0.4 *vf*	0.6 *vf*	0.8 *vf*	1.0 *vf*	PZT-5
Elastic constants							
C_{11}	269.5	240	220	190	170	162	86.85
C_{12}	170	145	125	110	100	78	54.01
C_{23}	173	146	125	110	100	77	50.77
$C_{22}= C_{33}$	286	250	225	200	175	166	99.2
$C_{44}=C_{66}$	45.3	45	45	45	50	43	21.1
Piezoelectric constants							
e_{11}	0	4.0	7.0	11.0	14.0	18.6	15.1
e_{12}	0	-2.0	-3.0	-3.5	-4.0	-4.4	-7.2
e_{35}	0	0	0	0	0	11.6	12.32
Dielectric constants							
e_{11}	0.093	2.5	5.0	7.5	10.0	12.6	1.5
$e_{22} = e_{33}$	0.08	0.33	0.8	0.9	1.0	11.2	1.53
Magnetic permeability constants							
m_{11}	1.57	1.33	1.0	0.75	0.5	0.1	0
$m_{22} = m_{33}$	-5.9	-3.9	-2.5	-1.5	-0.8	0.05	0
Piezomagnetic constants							
q_{11}	700	550	380	260	120	0	0
q_{12}	580	410	300	200	100	0	0
q_{35}	560	340	220	180	80	0	0
Magnetoelectric constants							
m_{11}	0	2000	2750	2500	1500	0	0
m_{33}	0	2.8	4.8	6.0	6.8	0	0
Density							
r	5300	5400	5500	5600	5700	5800	7750

C_{jk} in 10^9N/m^2, e_{lj} in C/m^2, e_{lm} in 10^{-9}C/Vm, q_{lj} in N/Am, m_{lm} in 10^{-4}Ns^2/C^2, m_{lm} in 10^{-12}Ns/VC, r in kg/m^3

The radial displacement (u_r), axial displacement (u_z) and electric potential (ϕ) of a node on the sensor which gives maximum electric response is plotted in Fig. 2 using both the code and Ansys. The results are found to be in good agreement.



(a)

(b)

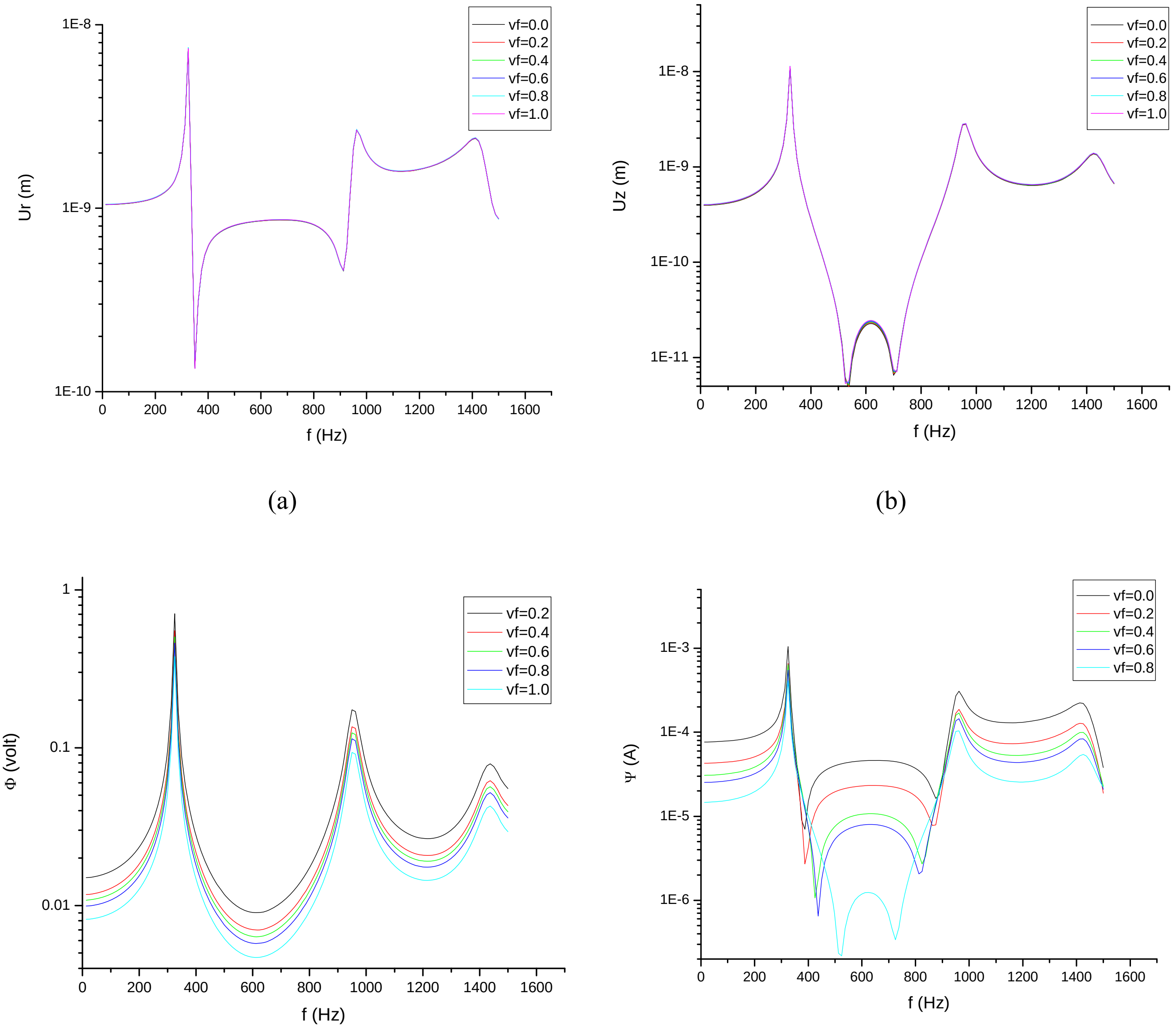
(c)

Fig. 2. Validation of the code for (a) radial displacement (u_r); (b) axial displacement (u_z); and (c) electric potential (ϕ).

3.2. Clamped-free Boundary Condition of the Shell

3.2.1. Sensor at Clamped End

The radial displacement (u_r), axial displacement (u_z), electric potential (ϕ) and magnetic potential (ψ) of a node on the sensor when the sensor is placed at the clamped end is shown in Fig. 3. The study is carried out for different volume fractions of $BaTiO_3$ in a composite of $BaTiO_3$-$CoFe_2O_4$ as shown in Table 1. It is seen that the electric potential (ϕ) is maximum when *vf=0.2* which can be attributed to the induced strain because of the high elastic constants for *vf=0.2*. The magnetic potential (ψ) is maximum when *vf=0.0* which corresponds to pure piezomagnetic composite having maximum value of piezomagnetic coupling constants. The first mode is dominating the response when the sensor is placed at the clamped end.



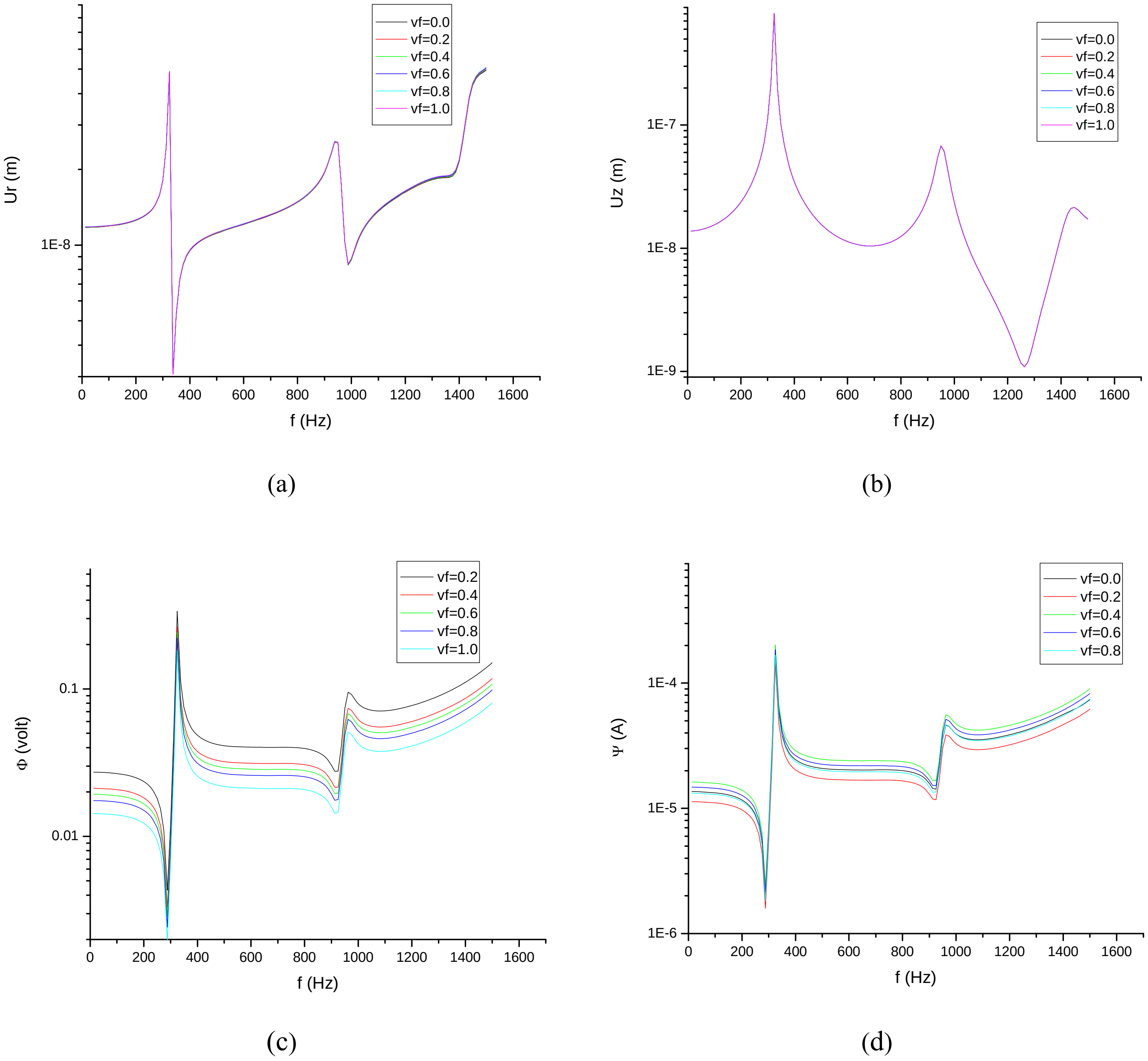
(a) (b)

(c) (d)

Fig. 3. (a) Radial displacement (u_r); (b) axial displacement (u_z); (c) electric potential (ϕ); and (d) magnetic potential (ψ) when sensor at clamped end.

3.2.2. Sensor at Middle

Fig. 4 shows the radial displacement (u_r), axial displacement (u_z), electric potential (ϕ) and magnetic potential (ψ) of a node on the sensor when the sensor is placed at the middle of the cylinder. The absolute value of response decreases and the response is controlled by the radial component of displacement when the sensor is placed at the middle of the shell.



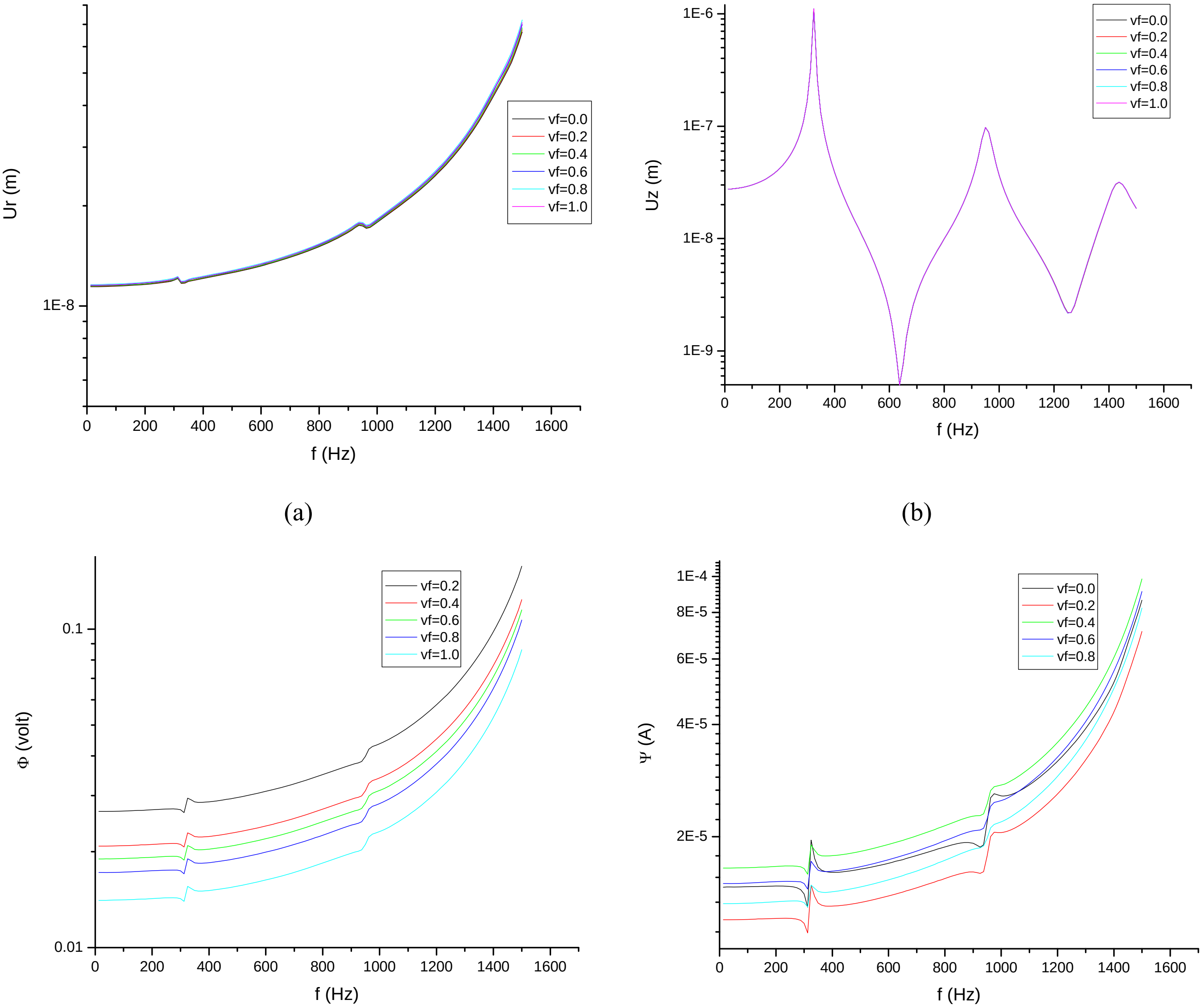
(a) (b)

(c) (d)

Fig. 4. (a) Radial displacement (u_r); (b) axial displacement (u_z); (c) electric potential (ϕ); and (d) magnetic potential (ψ) when sensor at middle.

3.2.3. Sensor at Free End

The radial displacement (u_r), axial displacement (u_z), electric potential (ϕ) and magnetic potential (ψ) of a node on the sensor when sensor is placed at the free end is shown in Fig. 5. The radial displacement is high during the third axisymmetric mode. The electric and magnetic potential is high for the third mode and it can be concluded that the response is significantly controlled by the radial displacement.



(a) (b)

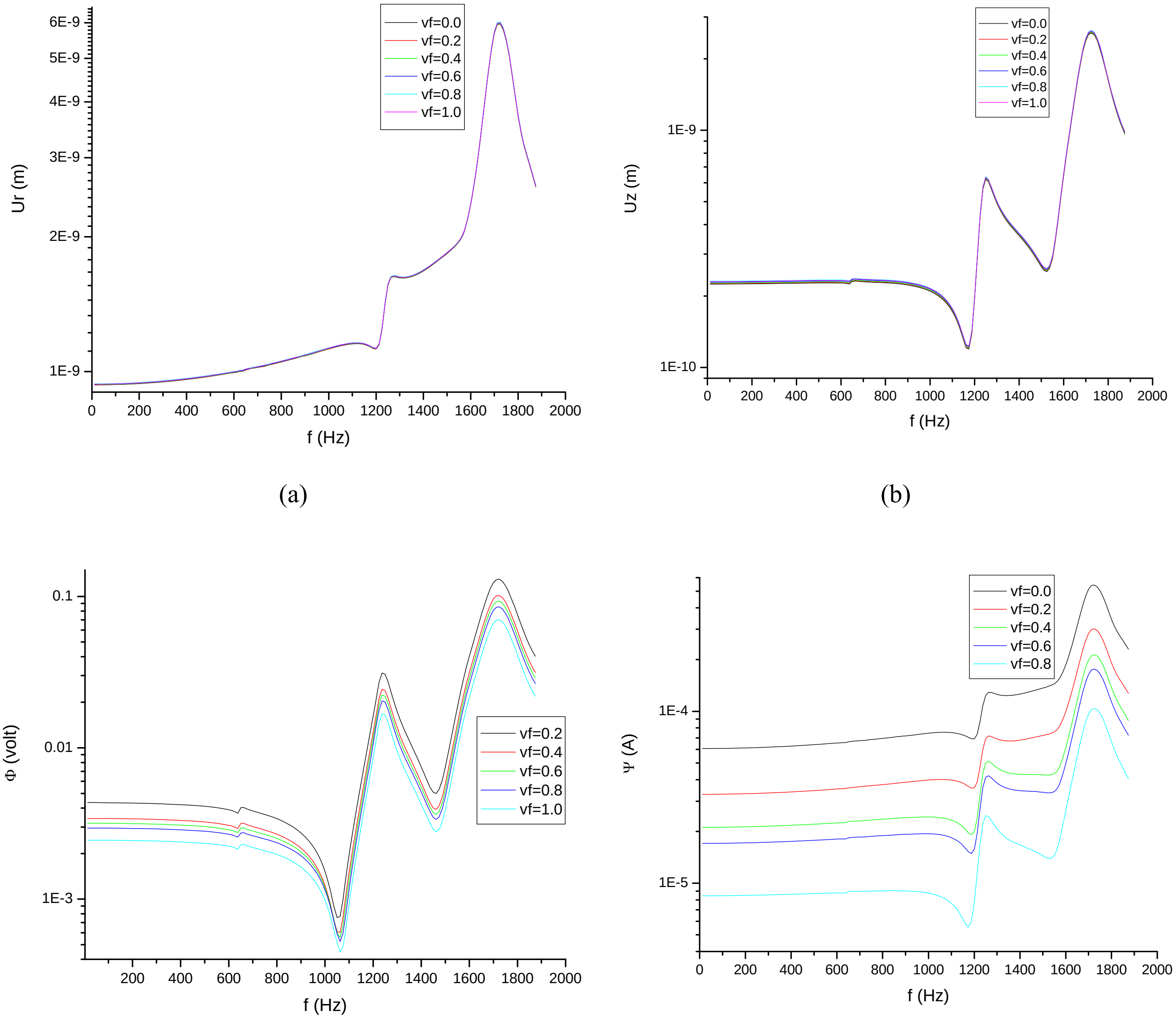
(c) (d)

Fig. 5. (a) Radial displacement (u_r); (b) axial displacement (u_z); (c) electric potential (ϕ); and (d) magnetic potential (ψ) when sensor at free end.

3.3. Clamped-clamped Boundary Condition of the Shell

3.3.1. Sensor at Clamped End

The radial displacement (u_r), axial displacement (u_z), electric potential (ϕ) and magnetic potential (ψ) of a node on the sensor when sensor is placed at the clamped end is plotted in Fig. 6. The response is marginal for first mode of vibration where as it peaks high during second and third mode. The effect of volume fraction on magnetic response is clearly visible when the sensor is located at the clamped end with clamped-clamped boundary condition.



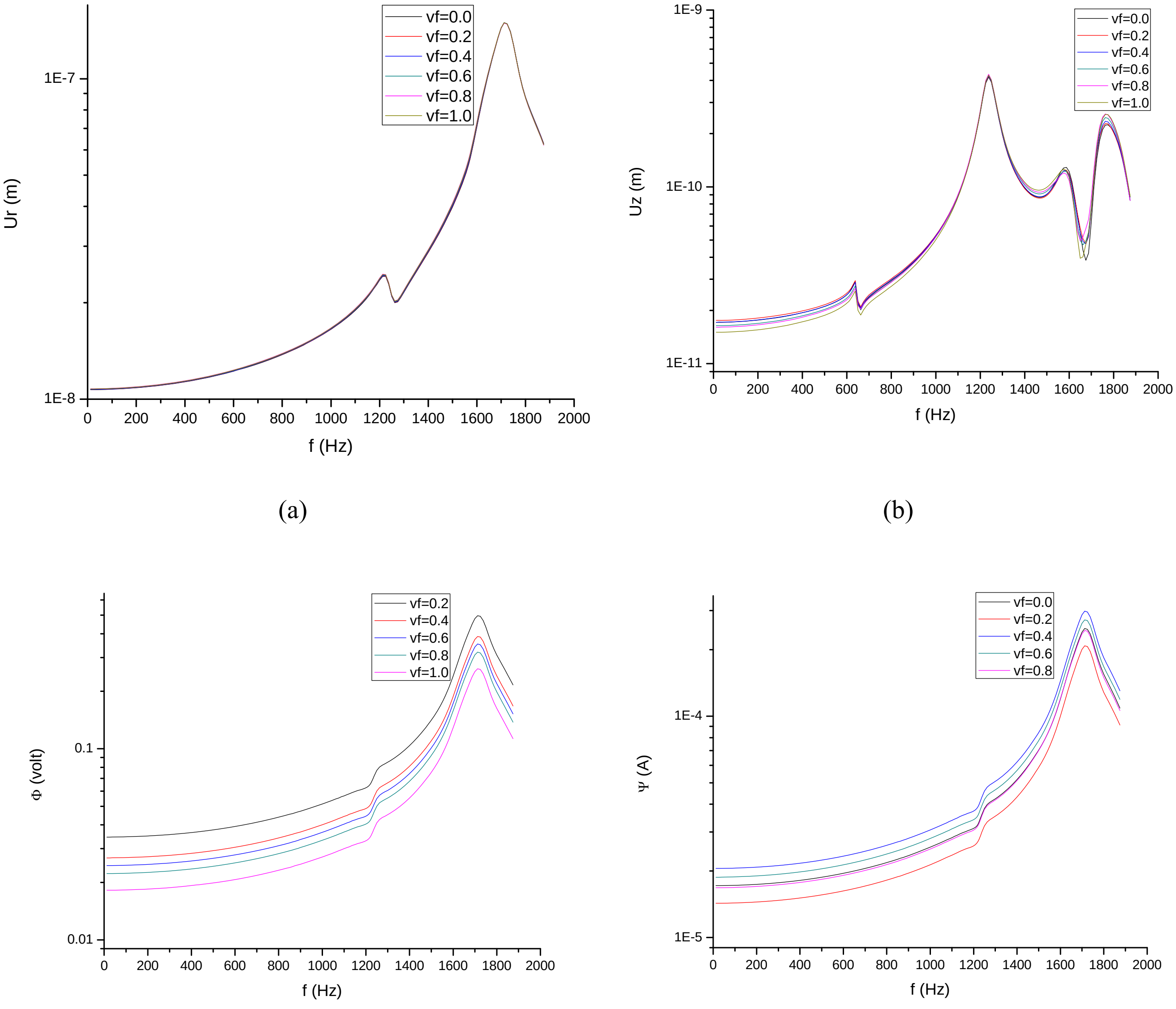
(a) (b)

(c) (d)

Fig. 6. (a) Radial displacement (u_r); (b) axial displacement (u_z); (c) electric potential (ϕ); and (d) magnetic potential (ψ) when sensor at clamped end.

3.3.2. Sensor at Middle

Fig. 7 shows the radial displacement (u_r), axial displacement (u_z), electric potential (ϕ) and magnetic potential (ψ) when sensor is placed at the middle of the shell. The radial displacement is seen maximum during the third mode. The electric and magnetic response follows the same pattern of radial displacement. It is unlikely to see that when *vf=0.4* the magnetic potential (ψ) is found maximum.



(a) (b)

(c) (d)

Fig. 7. (a) Radial displacement (u_r); (b) axial displacement (u_z); (c) electric potential (ϕ); and (d) magnetic potential (ψ) when sensor at middle.

4. Conclusions

Harmonic response of magneto-electro-elastic sensor bonded to a cylindrical shell is evaluated using semi analytical finite element method. The electric and magnetic response of the sensor for various sensor locations and boundary conditions are studied. The sensor response is controlled mainly by its radial displacement in all the modes. It is seen that the sensor response is maximum during the first mode when the sensor is placed at the clamped end and middle of the mild steel cylinder for clamped free boundary condition. The third mode response becomes significant when the sensor is placed at the free end for clamped free boundary condition. For clamped-clamped boundary condition the third mode response is significant for both the sensor locations.

References

[1]. Aboudi J., Micromechanical analysis of fully coupled electro-magneto-thermo-elastic multiphase composites, *Smart Materials and Structures*, 10, 2001, pp. 867-877.

[2]. Anandkumar, R. Annigeri, N. Ganesan, and S. Swarnamani, Free vibration of simply supported layered and multiphase magneto-electro-elastic cylindrical shells, *Smart Materials and Structures*, 15, 2006, pp. 459-467.

[3]. Buchanan, G. R., Free vibration of an infinite magneto-electro-elastic cylinder, *Journal of Sound and Vibration*, 268, 2003, pp. 413-426.

[4]. J. M. Bakhashwain, M. Sunar, S. J. Hyder, Finite Element modeling of magnetostrictive smart structures, *The Arabic journal of Science and Engineering,* 29, 2004, pp. 27-138.

[5]. Hadjali M, Besbes M and Bouillault F., Modeling of magneto-mechanical phenomena using shell elements, *IEEE Transactions on Magnetics*, 40, 2004, pp. 569-572.

[6]. Buchanan, George R., Layered versus multiphase magneto-electro-elastic composites, *Composites Part B*, 35, 2004, pp. 413-420.

[7]. Ghosh, D. P. and S. Gopalakrishnan, Coupled analysis of composite laminate with embedded magnetostrictive patches *Smart Materials and Structures* 14, 2005, pp. 1462-1473.

[8]. Jiang Aimin and Hao Jiang Ding, Analytical solutions to magneto-electro-elastic beams, *Structural Engineering and Mechanics,* 18, 2, 2004, pp. 195-209.

[9]. Ramirez, Fernando., Paul R. Heyliger and E. Pan, Free vibration response of two-dimensional magneto-electro-elastic laminated plates, *Journal of Sound and Vibration*, 292, 2006, pp. 626-644.

[10].Hou, Peng-Fei. and Andrew. Y. T. Leung**,** The transient responses of magneto-electro-elastic hollow cylinders, *Smart Material systems and Structures,* 13, 2004, pp. 762-776.

[11].Chen Jiangyi, Pan E. and Chen Hualing, Wave propagation in magneto-electro-elastic multilayered plates, *International Journal of Solids and Structures,* 44, 2007, pp. 1073-1085.

[12].Wang, X. and Z. Zhong, A finitely long circular cylindrical shell of piezoelectric/ piezomagnetic composite under pressuring and temperature change, *International journal of Engineering Science*, 41, 2003a, pp. 2429-2445.

[13].Sirohi J. and Copra I., Fundamental understanding of piezoelectric strain sensors, *Journal of Intelligent Systems and Structures,* 11, 2000, pp. 246-257.

[14].Daga Atul, Ganesan N. and Shankar K., Behaviour of magneto-electro-elastic sensors under transient mechanical loading, *Sensors and Actuators A: Physical,* 150, 2009, pp. 46-55.

[15].Zienkiewicz O. C., Lyness John and Owen D. R. J., Three dimensional magnetic field determination using a scalar potential- A finite element solution, *IEEE Transactions on Magnetics*, 13, 1977, pp. 1649-1656.

[16].Dai H. l. and Wang X., Magneto-thermo-electro-elastic transient response in a piezoelectric hollow cylinder subjected to complex loading, *International Journal of Solids and Structures,* 43, 2006, pp. 5628-5646.

[17].Galopin Nocolas, Mininger Xavier, Bouillault Frederic and Daniel Laurent, Finite Element modeling of magnetoelectric sensors, *IEEE Transactions on Magnetics*, 44, 2008, pp. 834-837.

Guide for Contributors

Aims and Scope

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

Topics Covered

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

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

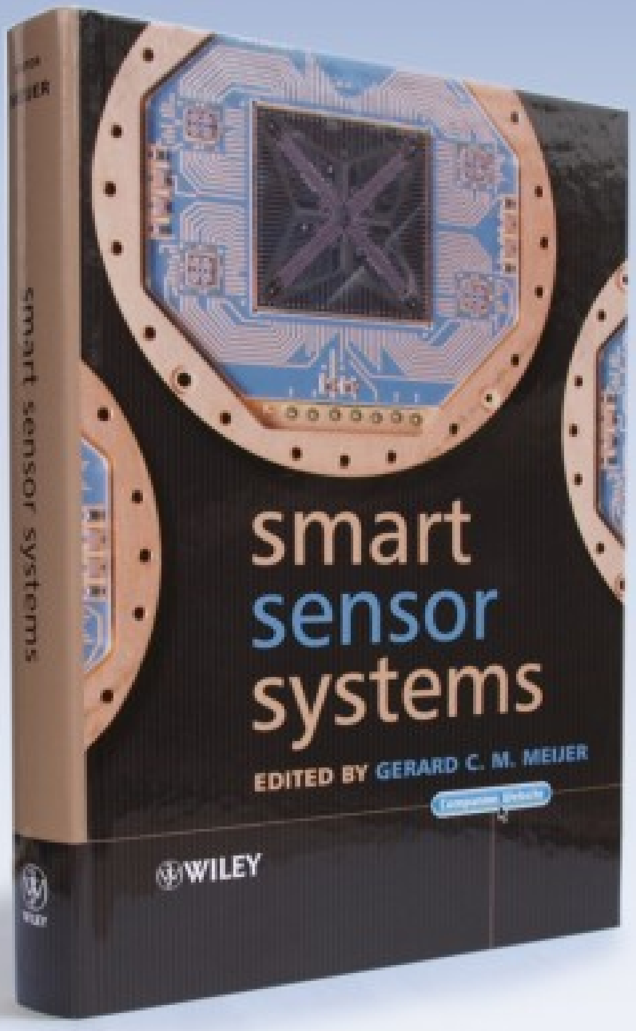
Submission of papers

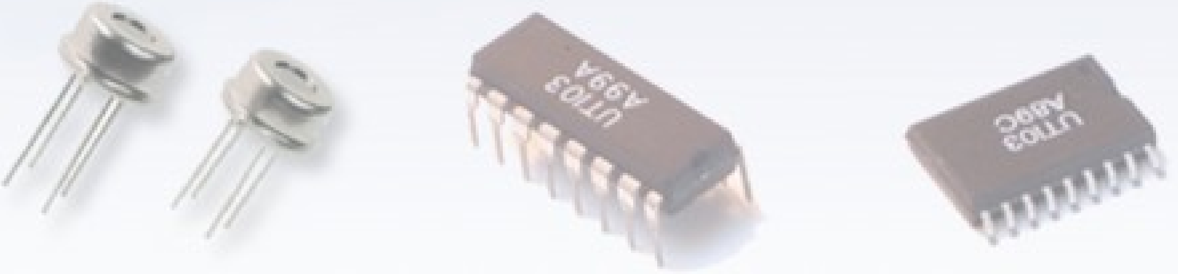
Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example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

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_2009.pdf


A380


smart
sensor
systems
EDITED BY GERARD C. M. MEIJER
WILEY


UTI03
A99A
UTI03
A89C