

ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 107
8/09



**Sensors and Transducers
Applications**

International Frequency Sensor Association Publishing





Sensors & Transducers

Volume 107, Issue 8
August 2009

www.sensorsportal.com

ISSN 1726-5479

Editors-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, Vittorio, Università 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, Northern 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, Vyngantas, 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 Motors 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
Djordjevic, Alexander, 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 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
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

Kim, Min Young, Kyungpook National University, 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
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, 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
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
Raouf, 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 Politècnica de Catalunya, Spain
Rodriguez, Angel, Universidad Politécnica de Catalunya, 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
Saxena, Vibha, Bhabha 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
Sengupta, Deepak, Advance Bio-Photonics, India
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
Soleymannpour, 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
Sunriddetchka, 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
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, 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 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
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, Quintao, 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

Contents

Volume 107
Issue 8
August 2009

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Precise Frequency and Period Measurements for Slow Slew Rate Signals Based on the Modified Method of the Dependent Count Sergey Y. Yurish	1
Electronic Nose Technology and its Applications <i>Esmail Mahmoudi</i>	17
Electronic Nose Study of Powdered Garlic <i>Rosa E. Baby, María M. Sance, Mónica Bauzá, Valeria M. Messina, Alvaro R. Gómez, José L. Burba, Noemí E. Walsøe de Reca</i>	26
Effects of Radiation on Silicon Pressure Sensor <i>Jaspreet Singh, M. M. Nayak, K. Nagachenchaiyah, K. Rajanna</i>	35
Design of a PC Based Pressure Indicator Using Inductive Pick-up type Transducer and Bourdon Tube Sensor <i>S. C. Bera, N. Mandal, R. Sarkar and S. Maity</i>	42
Problem of Piezoelectric Sensitivity of 1–3-type Composites <i>Vitaly Yu. Topolov and Anatoly E. Panich</i>	52
Development of a Surface Micromachined On-Chip Flat Disk Micropump <i>M. I. Kilani, A. T. Al-Halhouli, P. C. Galambos, Y. S. Haik, A. Al-Salaymeh and S. Üttgenbach</i>	64
Humidity Sensing Behavior of Polyaniline / Strontium Arsenate Composites <i>Machappa T., M. Sasikala, Koppalkar R. Anilkumar, M. V. N. Ambika Prasad</i>	77
Oxygen Sensing Properties of the WO₃ Thick Films <i>R. S. Khadayate, S. K. Disawal and P. P. Patil</i>	86
Optimization of Firing Temperature of PbO-doped SnO₂ Sensor for Detection of Acetone, Methanol, Propanol <i>J. K. Srivastava, Preeti Pandey, V. N. Mishra and R. Dwivedi</i>	92
Sol gel Synthesis of Tungsten Oxide Thin Film in Presence of Surfactant for NO₂ Detection <i>Vibha Srivastava, A. K. Srivastava, K. N. Sood, Kiran Jain</i>	99
Epinephrine Biosensor Using Tyrosinase Immobilized Eggshell Membrane <i>Sanket Tembe, Sudha Kulkarni, Meena Karve, S. F. D'Souza</i>	111
Finite Element Analyses of a Flat Spring for use in an Electromagnetic Microgenerator <i>Nibras Awaja, Dinesh Sood, Thurai Vinay</i>	119
Design and Development of a Step Climbing Wheeled Robot <i>Srijan Bhattacharya, Sagarika Pal, Subrata Chattopadhyay</i>	133

Enhancement of Heat Exchanger Control using Improved PID Controller <i>Gopalakrishna G., Sivakumaran N. and *Sivashanmugam P.</i>	144
Speech Disability Threshold Determination by Graphical and DSP Techniques <i>Anandthirtha. B. Gudi and H. C. Nagaraj</i>	157
Smart Wireless Sensors Integrated in Clothing: an Electrocardiography System in a Shirt Powered Using Human Body Heat <i>Vladimir Leonov, Tom Torfs, Chris Van Hoof and Ruud J. M. Vullers</i>	165

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>

Problem of Piezoelectric Sensitivity of 1–3-type Composites

¹Vitaly Yu. TOPOLOV and ²Anatoly E. PANICH

¹Department of Physics, Southern Federal University, 5 Zorge street, 344090 Rostov-on-Don, Russia
Tel.: +007-(863)-2975127, fax +007-(863)-2975120

²Department of High Technologies and Innovations, Southern Federal University,
10 Milchakov street, 344090 Rostov-on-Don, Russia
Tel.: +007-(863)-2223401, fax +007-(863)-2434844
E-mail: vutoplov@sfedu.ru, piezo@sfedu.ru

Received: 11 June 2009 / Accepted: 15 August 2009 / Published: 25 August 2009

Abstract: A new structure of the anisotropic high-sensitive 1–3-type piezo-active composite is put forward. Effective piezoelectric coefficients d_{33}^* and g_{33}^* , squared figure of merit $d_{33}^* g_{33}^*$ and related hydrostatic parameters d_h^* , g_h^* and $d_h^* g_h^*$ are studied within the framework of the proposed model of the ferroelectric ceramic / porous polymer composite with 1–3–0 connectivity. Effects of porosity, microgeometry of pores and their orientation on the aforementioned piezoelectric coefficients and figures of merit of the 1–3–0 composite are studied to show its piezoelectric performance and high piezoelectric sensitivity. A comparison of the effective parameters to those known for the related 1–3-type composites based on ferroelectric ceramics is carried out, and some advantages concerning high piezoelectric sensitivity of the studied 1–3–0 composite are emphasized. *Copyright © 2009 IFSA.*

Keywords: Piezo-active Composite, Piezoelectric sensitivity, Piezoelectric coefficients, Figures of Merit

1. Introduction

Piezo-active composites are smart materials [1] that are characterised by coupled electromechanical properties and often used as elements of piezoelectric transducers, sensors, actuators, hydrophones, devices for acoustics, medical diagnostics, etc. The electromechanical properties of these materials depend [2–6] on microgeometry, volume fraction of components, their electromechanical properties, poling conditions, and other factors. An arrangement of the components, connectivity of the composite [1, 2, 5] and an electromechanical interaction between its components [3, 4, 7] considerably influence

the piezoelectric coefficients and their anisotropy. To describe piezoelectric sensitivity (PS) of the composite, one can consider its piezoelectric coefficients g_{ij}^* (voltage coefficients), d_{ij}^* (charge coefficients) and figures of merit that depend on g_{ij}^* and d_{ij}^* [2, 3]. In hydrophone and hydroacoustic applications, the hydrostatic piezoelectric coefficients g_h^* and d_h^* and figures of merit play the key role when describing PS [3, 8, 9]. In the last decades, a problem of PS of the ferroelectric ceramic (FC) / polymer composites has been important in connection with sensor and acoustic applications of these materials [1, 10, 11]. A study on PS of the two-component composite with α - β connectivity (e.g., 2-2, 1-3, 0-3 or 3-3) is concerned, as a rule, with modelling of the effective electromechanical properties and related effective parameters [3-6, 12]. It is known [1, 3, 8, 10, 13] that the piezoelectric coefficients g_{ij}^* or d_{ij}^* of the FC / polymer composites can be several tens of times larger than the similar piezoelectric coefficients related to the FC. An increase in PS needs a modification of the composite structure [14], an addition of the third component [15] or auxetic polymer [16], or forming a porous structure in polymer components [8]. These and other possibilities were studied for the transversely isotropic 1-3-type composites comprising a system of FC rods (being continuous in one direction) that are surrounded by a polymer matrix (being continuous in three directions). In our present work, we put forward a new structure of the anisotropic 1-3-type composite and study trends in increasing its PS. The aim of this paper is to analyse microgeometric and physical factors that promote increasing PS of the anisotropic FC-based composite and attaining maximum values of a series of its effective parameters.

2. Structure and Effective Properties of the 1-3-type Composite

The composite to be considered (Fig. 1) contains a system of FC rods that are continuous in the OX_3 direction, having a square base and characterized by a square arrangement in the (X_1OX_2) plane. It is assumed that the remanent polarization vector of each rod is $\mathbf{P}_r^{(1)} \uparrow \uparrow OX_3$. The polymer matrix surrounding the FC rods contains spheroidal air inclusions (pores) that are described by

$$(x_1^0 / a_1)^2 + (x_2^0 / a_1)^2 + (x_3^0 / a_3)^2 = 1 \quad (1)$$

in the axes of the rectangular co-ordinate system $(X_1^0 X_2^0 X_3^0)$. Semiaxes of the spheroid from Eq. (1) are $a_1 = a_2$ and a_3 . The spheroidal pores with $a_k = \text{const}$ are regularly distributed in the polymer medium and occupy the sites of a simple tetragonal lattice. A shape of the pore is concerned with an aspect ratio $\rho = a_1 / a_3$ that is assumed to be fixed over the composite sample. The radius or the largest semiaxis of these pores (e.g., $a_1 = a_2$ for oblate pores) should be considerably less than the length of the side of the square being the intersection of the rod by the (X_1OX_2) plane. The above-described FC / porous polymer composite (Fig. 1) is described by 1-3-0 connectivity in terms of paper [2]. As in the case for the 1-3 FC composites manufactured in the last years [10, 11], it is assumed that the poling procedure is carried out after inserting the aligned rods into the matrix and covering the composite sample with electrodes parallel to the (X_1OX_2) plane.

The determination of the effective electromechanical (i.e., elastic, piezoelectric and dielectric) properties of the system "FC rods – porous polymer matrix" is carried in two stages. First, we determine the effective properties of the polymer matrix with aligned spheroidal pores and its dependence on porosity m_p , where m_p is the ratio of the total volume of the pores to the volume of the matrix in the composite sample. The corresponding averaging procedure is carried out within the framework of the effective field method [3, 4] based on Eshelby's concept of spheroidal inclusions [4]. As follows from this averaging, the matrix with the system of the regularly distributed spheroidal pores (Fig. 1, inset) is characterized by ∞mm symmetry in the co-ordinate system $(X_1^0 X_2^0 X_3^0)$. Second, the determination of the effective electromechanical properties of the composite (Fig. 1) with the regularly

distributed parallelepiped-shaped rods is carried out using the matrix approach [17, 18]. It means an averaging of the electromechanical constants of the FC rod and the polymer matrix in the OX_1 and OX_2 directions, in which the periodical arrangement of the rods is observed. For this averaging procedure, full sets of elastic compliances $s_{ij}^{(n),E}$ (measured at electric field $E = \text{const}$), piezoelectric coefficients $d_{kl}^{(n)}$ and dielectric permittivities $\varepsilon_{ff}^{(n),\sigma}$ (measured at mechanical stress $\sigma = \text{const}$) of FC ($n = 1$) and porous polymer ($n = 2$) are used. These electromechanical constants are written in the axes of the $(X_1X_2X_3)$ system (Fig. 1). Preliminarily, a transition from the constants determined for the porous matrix in the $(X_1^0 X_2^0 X_3^0)$ system to the constants related to the $(X_1X_2X_3)$ system is carried out using conventional formulae [19] for tensor components and taking into account the rotation angle θ (Fig. 1, inset). The properties are averaged taking into account boundary conditions [17, 18] for the electric and mechanical fields. These boundary conditions at the interfaces $x_a = \text{const}$ (Fig. 1) correspond to the continuity of the electric and mechanical fields as follows:

- (i) three normal components of mechanical stress σ_{av} (i.e., $\sigma_{11} = \text{const}$, $\sigma_{12} = \text{const}$ and $\sigma_{13} = \text{const}$ for $x_1 = \text{const}$ or $\sigma_{21} = \text{const}$, $\sigma_{22} = \text{const}$ and $\sigma_{23} = \text{const}$ for $x_2 = \text{const}$),
- (ii) three tangential components of mechanical strain ξ_{rt} (i.e., $\xi_{22} = \text{const}$, $\xi_{23} = \text{const}$ and $\xi_{33} = \text{const}$ for $x_1 = \text{const}$ or $\xi_{11} = \text{const}$, $\xi_{13} = \text{const}$ and $\xi_{33} = \text{const}$ for $x_2 = \text{const}$),
- (iii) one normal component of electric displacement D_q (i.e., $D_1 = \text{const}$ for $x_1 = \text{const}$ or $D_2 = \text{const}$ for $x_2 = \text{const}$), and
- (iv) two tangential components of electric field E_p (i.e., $E_2 = \text{const}$ and $E_3 = \text{const}$ for $x_1 = \text{const}$ or $E_1 = \text{const}$ and $E_3 = \text{const}$ for $x_2 = \text{const}$).

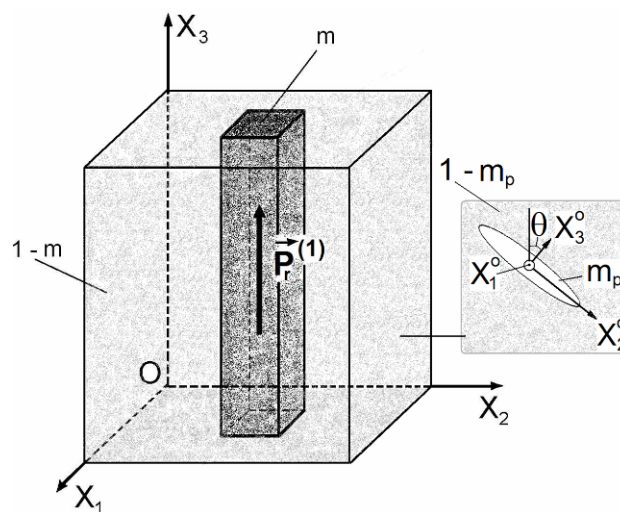


Fig. 1. Schematic of the 1–3–0 FC / porous polymer composite. $(X_1X_2X_3)$ is the rectangular co-ordinate system concerned with the composite sample, $(X_1^0 X_2^0 X_3^0)$ is the rectangular co-ordinate system concerned with the orientation of the spheroidal pore in the polymer matrix. m and $1 - m$ are volume fractions of FC and porous polymer, respectively, m_p is the volume fraction of air in the porous matrix, θ is the rotation angle, and $\mathbf{P}_r^{(1)}$ is the remanent polarization vector of FC.

The electromechanical properties of the composite are described by the full set of s_{ij}^{*E} , d_{kl}^* and $\varepsilon_{ff}^{*\sigma}$ and regarded as homogenised (effective) properties in a long-wave approximation. It means that the wavelength of an external acoustic field is to be much longer than the size of the rod in the composite sample. Evaluations of the effective electromechanical properties and related parameters $X^*(m, m_p, \rho, \theta)$ of the composite are carried out using the room-temperature electromechanical constants of the FC and polymer components (Table 1). Among FC materials we have chosen the “soft” PCR-7M composition based on $\text{Pb}(\text{Zr}, \text{Ti})\text{O}_3$ with high piezoelectric and dielectric properties [20]. As follows

from our analysis of matrices of elastic, piezoelectric and dielectric constants of the 1–3-type composite poled along the OX_3 axis, this material is characterized by point symmetry m where the mirror plane is perpendicular to the OX_1 axis (Fig. 1). The matrix of the effective piezoelectric coefficients d_{kl}^* in this case is written as

$$\|d^*\| = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15}^* & d_{16}^* \\ d_{21}^* & d_{22}^* & d_{23}^* & d_{24}^* & 0 & 0 \\ d_{31}^* & d_{32}^* & d_{33}^* & d_{34}^* & 0 & 0 \end{pmatrix}, \quad (2)$$

and the piezoelectric coefficients g_{33}^* are represented by the matrix that has the form shown in Eq. (2). However, at $\theta = 90^\circ b$ ($b = 0, 1, 2, \dots$), the form of matrix from Eq. (2) becomes simpler due to vanishing the matrix elements d_{kl}^* and g_{kl}^* with $kl = 16, 21, 22, 23$, and 34.

To describe PS of the 1–3-type composite with m symmetry, we consider the following effective parameters: the effective piezoelectric coefficients d_{33}^* and g_{33}^* that are interconnected [19] in accordance with a matrix equation

$$\|g^*\| = \|\varepsilon^{*\sigma}\|^{-1} \|d^*\|, \quad (3)$$

squared figure of merit

$$(Q_{33}^*)^2 = d_{33}^* g_{33}^*, \quad (4)$$

the hydrostatic piezoelectric coefficients

$$d_h^* = d_{21}^* + d_{22}^* + d_{23}^* + d_{31}^* + d_{32}^* + d_{33}^* \text{ and } g_h^* = g_{21}^* + g_{22}^* + g_{23}^* + g_{31}^* + g_{32}^* + g_{33}^*, \quad (5)$$

and squared hydrostatic figure of merit

$$(Q_h^*)^2 = d_h^* g_h^*. \quad (6)$$

Table 1. Room-temperature elastic compliances s_{ij}^E (in 10^{-12} Pa $^{-1}$), piezoelectric coefficients d_{kl} (in pC / N) and dielectric permittivities $\varepsilon_{ff}^\sigma / \varepsilon_0$ of FC and polymer components.

Components	s_{11}^E	s_{12}^E	s_{13}^E	s_{33}^E	s_{44}^E	d_{31}	d_{33}	d_{15}	$\varepsilon_{11}^\sigma / \varepsilon_0$	$\varepsilon_{33}^\sigma / \varepsilon_0$
PCR-7M [20]	17.5	-6.7	-7.9	19.6	43.8	-350	760	880	3990	5000
Polyurethane [8]	401	-149	-149	401	1100	0	0	0	3.5	3.5

Note. PCR is the abbreviation “piezoelectric ceramics from Rostov-on-Don”, Russia [20]. The PCR-7M FC has been manufactured by means of hot pressing. According to results [8], this FC composition is characterized by the largest e_{33}/c_{33}^E ratio that promotes high PS of the 1–3-type PCR-7M-based composite.

In Eq. (3), $\|\varepsilon^{*\sigma}\|$ is the matrix of dielectric permittivities of the composite at constant stress.

The piezoelectric coefficients d_{33}^* and g_{33}^* characterize the piezoelectric response along the poling axis OX_3 axis at an electric or mechanical action along the same axis. Squared figures of merit from Eqs. (4) and (6) are used [3, 8, 9] to describe the sensor signal-to-noise ratio of a piezoelectric element. The hydrostatic parameters from Eqs. (5) and (6) characterize a piezoelectric response and PS of the composite under a hydrostatic pressure. Below we consider behaviour of the effective parameters and changes in PS of the 1–3-type FC / porous polymer composite (Fig. 1) when varying the volume fractions m , m_p , the aspect ratio ρ , and the orientation angle θ .

3. Maxima of Effective Parameters and Piezoelectric Sensitivity

3.1. Volume Fraction (m), Aspect Ratio (ρ) and Porosity (m_p) Dependences

In this section we consider a dependence of the effective parameters d_{33}^* , g_{33}^* , $(Q_{33}^*)^2$, d_h^* , g_h^* , and $(Q_h^*)^2$ on one of the variables at the orientation angle $\theta = 0$. The volume fraction (m) dependence of the effective parameters shows that only the piezoelectric coefficient d_{33}^* monotonically depends on m at fixed values of m_p and ρ from ranges $0 < m_p \leq 0.3$ and $1 \leq \rho \leq 100$, respectively. It is typical of the $d_{33}^*(m)$ dependence predicted [3, 4, 7] and experimentally studied [13, 21] for the 1–3 FC / polymer composite. The piezoelectric coefficients g_{33}^* , d_h^* and g_h^* and squared figures of merit $(Q_{33}^*)^2$ and $(Q_h^*)^2$ have maxima (see, for example, Fig. 2). These maxima are caused by a balance of d_{3j}^* from Eq. (5) and by a considerable influence of dielectric permittivity $\varepsilon_{33}^{*\sigma}$ on g_{33}^* and g_h^* owing to relations $g_{33}^* = d_{33}^* / \varepsilon_{33}^{*\sigma}$ and $g_h^* = d_h^* / \varepsilon_{33}^{*\sigma}$ that are derived from Eq. (3) at $\theta = 0$. As a consequence, dielectric permittivity $\varepsilon_{33}^{*\sigma}$ pre-determines non-monotonic behaviour of $(Q_{33}^*)^2$ and $(Q_h^*)^2$ (see Eqs. (4) and (6)). The sharp maxima of g_{33}^* , g_h^* , $(Q_{33}^*)^2$, and $(Q_h^*)^2$ appear at relatively small volume fractions of FC ($m < 0.03$) while d_h^* has a diffuse maximum at $0.1 < m < 0.2$ (Fig. 2). As follows from our results, the volume fractions m corresponding to maxima of g_{33}^* , g_h^* , $(Q_{33}^*)^2$, and $(Q_h^*)^2$ considerably depend on elastic properties of the matrix. Comparison of curves from Fig. 2 enables us to conclude that the volume fraction (m) dependence of squared figures of merit $(Q_{33}^*)^2$ and $(Q_h^*)^2$ follows the volume fraction dependence of the piezoelectric coefficients g_{33}^* and g_h^* , respectively, and the configuration of the curves is similar (see, e.g., curves 2 and 3 in Fig. 2 (a) or 2 (b)).

The effective parameters of the composite differently depend on the aspect ratio ρ of pores in the polymer matrix. Varying ρ , we change ratios of elastic module $c_{11}^{(2)} / c_{13}^{(2)}$ and $c_{11}^{(2)} / c_{33}^{(2)}$ of the porous matrix, and this change influences PS of the composite. Fig. 3 shows that all local maxima of the effective parameters $(X^*)_m$ increase monotonically on increasing the aspect ratio ρ of pores, i.e., when elastic module $c_{13}^{(2)}$ and $c_{33}^{(2)}$ of the matrix decrease in the presence of more oblate pores therein. The like tendency was analyzed [8] for the 1–3-type composite with a matrix containing a system of parallelepiped-shaped pores distributed regularly.

An example of the porosity (m_p) dependence of the effective parameters of the composite is given in Fig. 4 for relatively small volume fractions of FC m . It should be mentioned that Choy et al. [22] manufactured the 1–3 FC / polymer composite with $m \approx 0.033$, 0.066, etc., and we can consider the volume fractions $m > 0.03$ without additional restrictions. A monotonic increase in the effective parameters (Fig. 4) is associated with a decrease in elastic moduli $c_{ij}^{(2)}$ of the porous matrix, and this

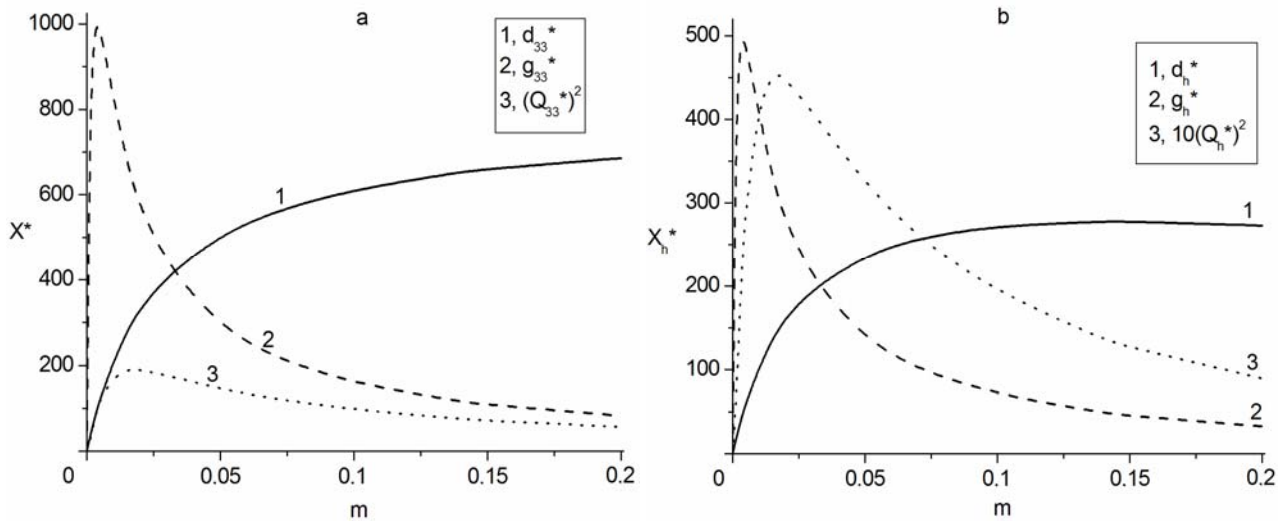


Fig. 2. Volume fraction dependences of the piezoelectric coefficients d_{33}^* (in pC / N), g_{33}^* (in mV m / N) and squared figure of merit $(Q_{33}^*)^2$ (in 10^{-12} Pa $^{-1}$, graph a) and related hydrostatic parameters d_h^* (in pC / N), g_h^* (in mV m / N) and squared figure of merit $(Q_h^*)^2$ (in 10^{-12} Pa $^{-1}$, graph b). The effective parameters were calculated for the 1–3–0 PCR-7M / porous polyurethane composite at $m_p = 0.1$, $\rho = 10$ and $\theta = 0$.

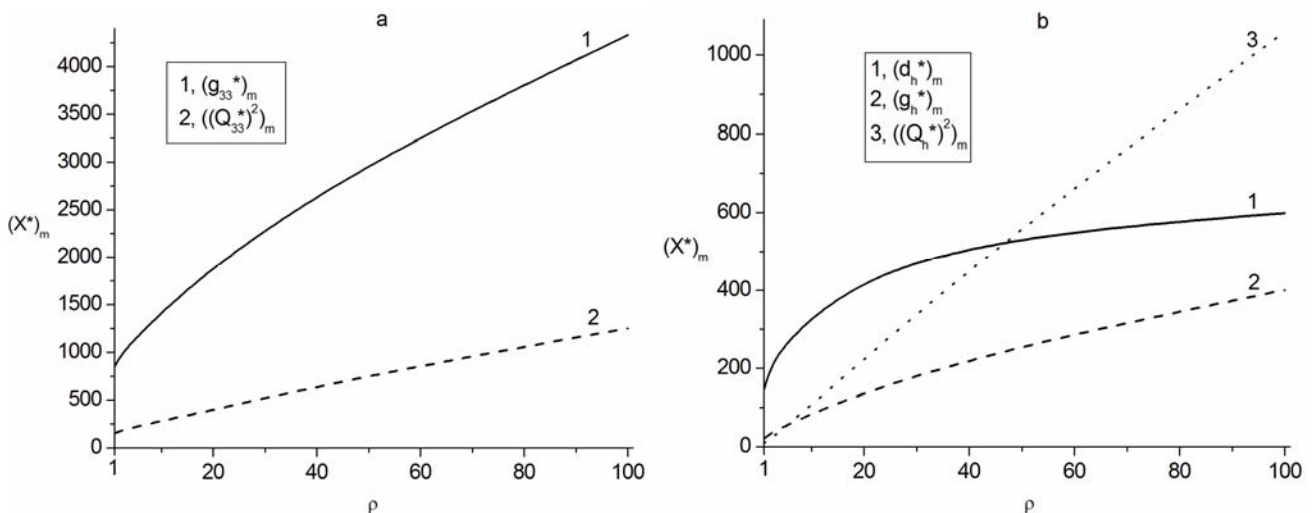


Fig. 3. Local maxima of the piezoelectric coefficient $(g_{33}^*)_m$ (in mV m / N) and squared figure of merit $((Q_{33}^*)^2)_m$ (in 10^{-12} Pa $^{-1}$, graph a) and the hydrostatic piezoelectric coefficients $(d_h^*)_m$ (in pC / N), $(g_h^*)_m$ (in mV m / N) and squared figure of merit $((Q_h^*)^2)_m$ (in 10^{-12} Pa $^{-1}$, graph b). The effective parameters were calculated for the 1–3–0 PCR-7M / porous polyurethane composite at $m_p = 0.2$, $\theta = 0$ and $1 \leq \rho \leq 100$.

decrease promotes increasing the piezoelectric activity of the composite at $m = \text{const}$. We also see that the piezoelectric coefficient d_{33}^* at $m_p = \text{const}$ increases on increasing m (curves 1, 4 and 7 in Fig. 4) while g_{33}^* and $(Q_{33}^*)^2$ at $m_p = \text{const}$ decrease (curves 2, 5 and 8 or 3, 6 and 9 in Fig. 4). Such a distinction is concerned with a fact that g_{33}^* and $(Q_{33}^*)^2$ pass maximum points at $m < 0.03$ (see, e.g., curves 2 and 3 in Fig. 2 (a)) and undergo appreciable decreasing on increasing m . In particular, curves 8 and 9 in Fig. 4 suggest that g_{33}^* and $(Q_{33}^*)^2$ increase at $m = 0.10$ (i.e., far from the maximum points) very slowly, and this circumstance is to be taken into account when manufacturing the 1–3-type high-sensitive composites.

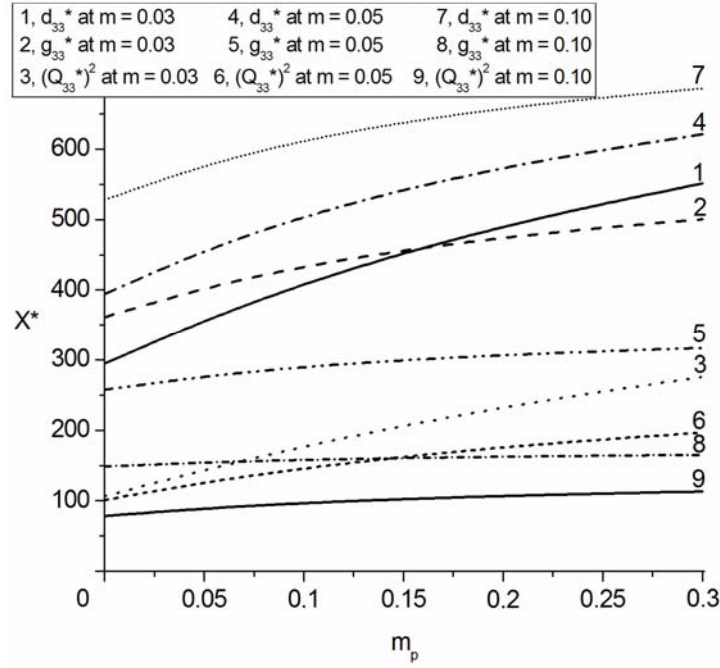


Fig. 4. Calculated dependences of the piezoelectric coefficients d_{33}^* (in pC / N), g_{33}^* (in mV·m / N) and squared figure of merit $(Q_{33}^*)^2$ (in 10^{-12} Pa $^{-1}$) on porosity m_p of the polymer matrix in the 1–3–0 PCR-7M / porous polyurethane composite at $\rho = 10$ and $\theta = 0$.

Changes in values of local maxima of the effective parameters $(X^*)_m$ of the composite are shown in Fig. 5. $(g_{33}^*)_m$ and $(g_h^*)_m$ considerably increase on increasing porosity m_p of the matrix (curves 1 and 4 in Fig. 5), and such behaviour is concerned with a decrease in $\varepsilon_{33}^{(2)}$ of the porous matrix and $\varepsilon_{33}^{*\sigma}$ of the composite. As a consequence, $\max g_{33}^*$ and $\max g_h^*$ are attained at volume fractions of FC $m \approx 0.01$ or less. The local maximum $(d_h^*)_m$ increases slowly (curve 3 in Fig. 5) as compared to $(g_h^*)_m$ (curve 4 in Fig. 5). It is accounted for by a slight influence of the piezoelectric coefficients d_{31}^* and d_{32}^* on the hydrostatic piezoelectric coefficient d_h^* from Eq. (5) in the presence of the spheroidal pores at $\theta = 0$.

3.2. Orientation Effect

Now we consider an effect of the orientation of pores (Fig. 1, inset) on PS and vary the orientation angle θ along with the volume fraction of FC m at $m_p = \text{const}$ and $\rho = \text{const}$. An interesting example of the $X^*(m, \theta)$ dependence is shown in Fig. 6. The corresponding composite at $\theta \neq 90^\circ$ is characterized by point symmetry m . Elastic compliances $s_{ij}^{(2)}$ of the porous matrix are given by

$$\|s^{(2)}\| = \begin{pmatrix} s_{11}^{(2)} & s_{12}^{(2)} & s_{13}^{(2)} & s_{14}^{(2)} & 0 & 0 \\ s_{12}^{(2)} & s_{22}^{(2)} & s_{23}^{(2)} & s_{24}^{(2)} & 0 & 0 \\ s_{13}^{(2)} & s_{23}^{(2)} & s_{33}^{(2)} & s_{34}^{(2)} & 0 & 0 \\ s_{14}^{(2)} & s_{24}^{(2)} & s_{34}^{(2)} & s_{44}^{(2)} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^{(2)} & s_{56}^{(2)} \\ 0 & 0 & 0 & 0 & s_{56}^{(2)} & s_{66}^{(2)} \end{pmatrix}, \quad (7)$$

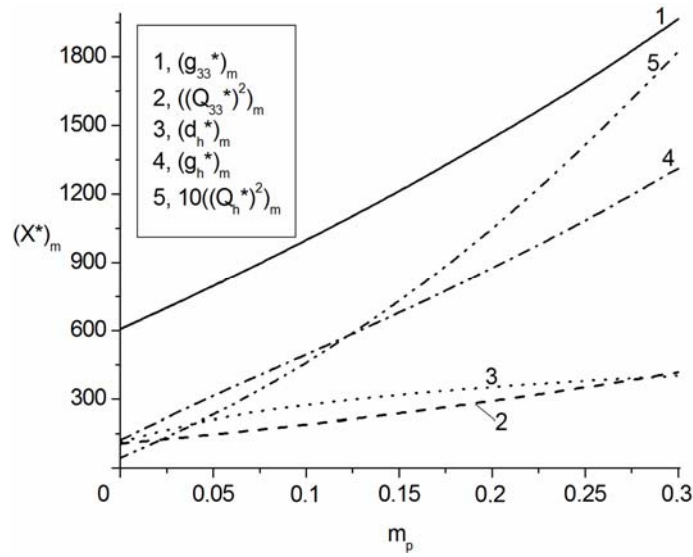


Fig. 5. Local maxima of the piezoelectric coefficient $(g_{33}^*)_m$ (in $\text{mV}\cdot\text{m}/\text{N}$) and squared figure of merit $((Q_{33}^*)^2)_m$ (in 10^{-12} Pa^{-1} , graph a) and the hydrostatic piezoelectric coefficients $(d_h^*)_m$ (in pC/N), $(g_h^*)_m$ (in $\text{mV}\cdot\text{m}/\text{N}$) and squared figure of merit $((Q_h^*)^2)_m$ (in 10^{-12} Pa^{-1} , graph b). The effective parameters were calculated for the 1–3–0 PCR-7M / porous polyurethane composite at $\rho = 10$, $\theta = 0$ and $0 < m_p \leq 0.3$.

however at $\theta = 0$, elastic compliances $s_{ij}^{(2)}$ from Eq. (7) obey conditions

$$s_{i4}^{(2)} = 0 \quad (i = 1, 2 \text{ and } 3), \quad s_{56}^{(2)} = 0, \quad s_{13}^{(2)} = s_{23}^{(2)}, \quad s_{11}^{(2)} = s_{22}^{(2)}, \quad s_{44}^{(2)} = s_{55}^{(2)}, \quad \text{and} \quad s_{66}^{(2)} = 2(s_{11}^{(2)} - s_{12}^{(2)}). \quad (8)$$

Irrespectively of the θ angle, dielectric properties of the porous matrix are varied in a relatively narrow range so that an inequality $\varepsilon_{ff}^{(2)} \ll \varepsilon_{ff}^{(1),\sigma}$ holds. The graphs in Fig. 6 have been built for volume fractions of FC $m \leq 0.2$ because of lack of extreme points of the effective parameters and obvious decreasing PS of the composite at $m > 0.2$.

As follows from results shown in Fig. 6, non-monotonic behaviour of the hydrostatic parameters d_h^* , g_h^* and $(Q_h^*)^2$ is observed on increasing θ at $m = \text{const}$. A violation of conditions from Eqs. (8) and the appreciable elastic anisotropy of the porous matrix with elastic compliances $s_{ij}^{(2)}$ from Eq. (7) promote a considerable re-distribution of internal electric and mechanical fields in the composite sample. This re-distribution results in an increase of the hydrostatic parameters d_h^* , g_h^* and $(Q_h^*)^2$ due to an improved balance of the piezoelectric coefficients d_{ij}^* and g_{ij}^* from Eq. (5). It means that at relatively small volume fractions of FC ($m < 0.10$), the piezoelectric coefficients $d_{3j}^* > 0$ ($j = 1, 2$ and 3) provide a main contribution into d_h^* from Eq. (5) and promote considerable values of d_h^* as compared to those calculated for cases of $\theta = 0$ or 90° . The piezoelectric coefficients $g_{3j}^* > 0$ ($j = 1, 2$ and 3) analogously favour PS and considerable hydrostatic response of the composite. The matrix with inclined pores (Fig. 1, inset) and elastic compliances from Eq. (7) plays the crucial role like that of the auxetic polymer matrix in the high-performance 1–3-type composites studied earlier [16, 23]. For example, the composite with $m_p = 0.2$, $\rho = 100$ and $\theta = 0$ is characterized by $\max d_h^* \approx 10 d_h^{(1)}$ that corresponds to the volume fraction of FC $m = 0.049$ (Fig. 6 (d)). At this volume fraction we have

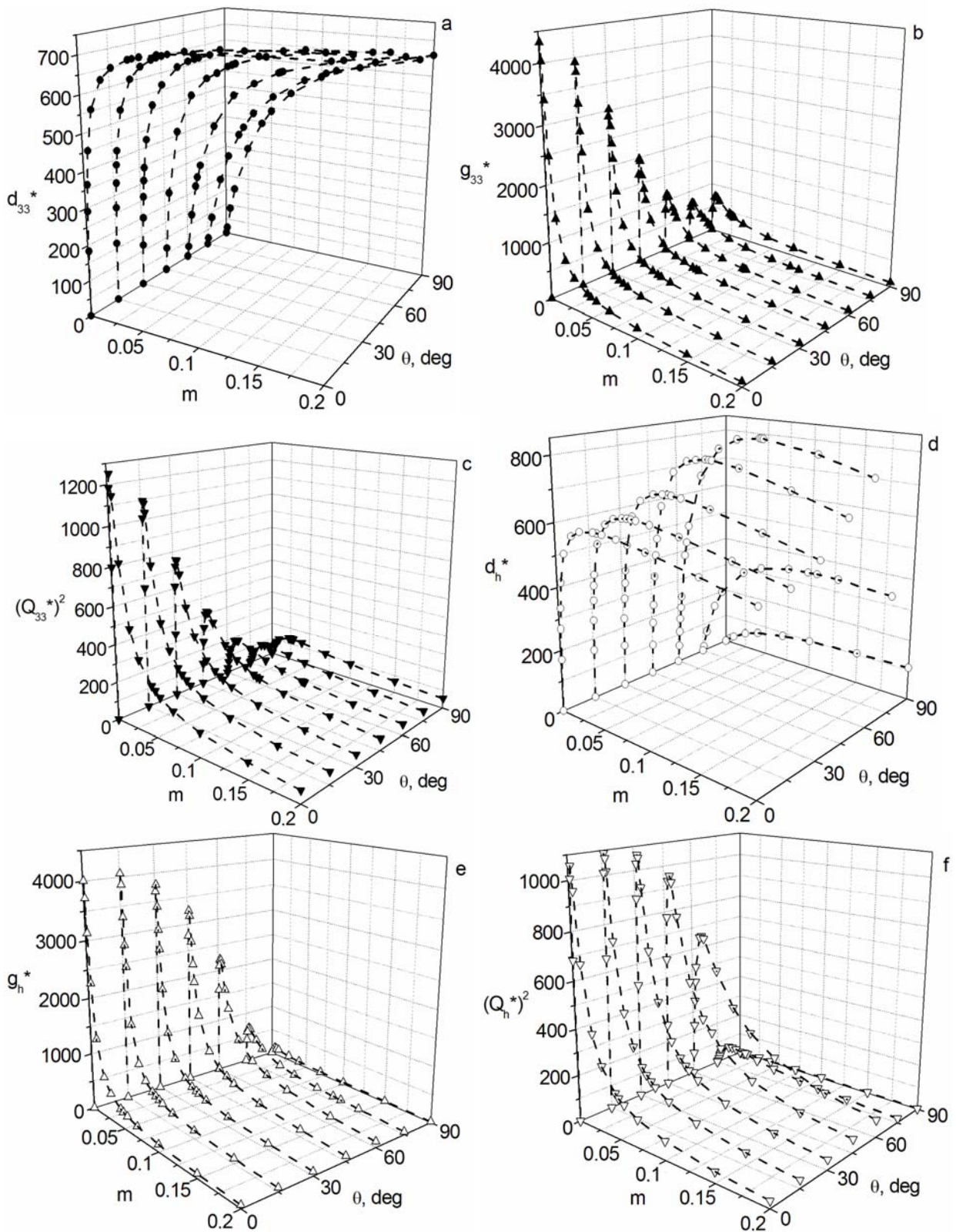


Fig. 6. Dependences of the piezoelectric coefficients d_{33}^* (a, in pC / N), g_{33}^* (b, in mV m / N), squared figure of merit $(Q_{33}^*)^2$ (c, in 10^{-12} Pa $^{-1}$, graph a) and related hydrostatic parameters d_h^* (d, in pC / N), g_h^* (e, in mV m / N) and $(Q_h^*)^2$ (f, in 10^{-12} Pa $^{-1}$). The effective parameters were calculated for the 1–3–0 PCR-7M / porous polyurethane composite at $m_p = 0.2$ and $\rho = 100$.

$$g_{33}^* \approx 26 g_{33}^{(1)}, g_h^* \approx 210 g_h^{(1)}, (Q_{33}^*)^2 \approx 18 (Q_{33}^{(1)})^2, \text{ and } (Q_h^*)^2 \approx 2120 (Q_h^{(1)})^2. \quad (9)$$

In the related composite with pores at $\theta = 60^\circ$ (Fig. 1, inset), $\max d_h^* \approx 14 d_h^{(1)}$ is attained at the volume fraction of FC $m = 0.093$ (Fig. 6 (d)). At the same m_p , ρ , θ , and m values, the composite is characterized by the following parameters: $g_{33}^* \approx 9.9 g_{33}^{(1)}$, $g_h^* \approx 185 g_h^{(1)}$, $(Q_{33}^*)^2 \approx 8.0 (Q_{33}^{(1)})^2$, and $(Q_h^*)^2 \approx 2560 (Q_h^{(1)})^2$. However, at the volume fraction $m = 0.049$ (as in case of $\theta = 0$) in the presence of inclined pores at $\theta = 60^\circ$, we have the following effective parameters of the composite:

$$g_{33}^* \approx 17 g_{33}^{(1)}, g_h^* \approx 360 g_h^{(1)}, (Q_{33}^*)^2 \approx 12 (Q_{33}^{(1)})^2, \text{ and } (Q_h^*)^2 \approx 4900 (Q_h^{(1)})^2. \quad (10)$$

As is seen from comparison of data from Eqs. (9) and (10), the composite with inclined pores demonstrates high PS and larger hydrostatic parameters g_h^* and $(Q_h^*)^2$. At the same time, the presence of the porous matrix at $\theta = 90^\circ$ leads to the appreciable decrease in the piezoelectric coefficient d_h^* and other effective parameters of the composite (Fig. 6) mainly due to a change in the balance of elastic compliances $s_{ij}^{(2)}$ from Eq. (7). The spheroidal pores at $\theta = 90^\circ$ do not provide considerable ratios of elastic moduli $c_{11}^{(2)} / c_{13}^{(2)}$ and $c_{11}^{(2)} / c_{33}^{(2)}$ in the matrix and, as a consequence, promote lower PS of the corresponding composite. To the best of our knowledge, such an orientation effect was not studied in earlier works on the 1–3-type composites and is to be taken into consideration in future applications of materials with high PS.

We note for comparison that the related 1–3 PCR-7M / polyurethane composite is characterized by the maximum values of the effective parameters [8] as follows: $\max g_{33}^* \approx 34 g_{33}^{(1)}$, $\max g_h^* \approx 91 g_h^{(1)}$, $\max[(Q_{33}^*)^2] \approx 8.3 (Q_{33}^{(1)})^2$, and $\max[(Q_h^*)^2] \approx 54 (Q_h^{(1)})^2$. However, these maximum values are attained at different volume fractions m of FC (on analogy with maximum points of curves 2 and 3 in Fig. 2 (a) and curves 1 – 3 in Fig. 2 (b)) that does not promote high PS being comparable to PS of the composite with parameters from Eqs. (9) or (10). According to experimental data [24], the 1–3-type PZT / porous epoxy composite with the volume fraction of FC $m = 0.06$ is characterized by hydrostatic parameters $d_h^* = 220$ pC / N, $g_h^* = 228$ mV·m / N and $(Q_h^*)^2 = 50.2 \cdot 10^{-12}$ Pa⁻¹ at porosity of the matrix $m_p = 0.20$ and $d_h^* = 284$ pC / N, $g_h^* = 294$ mV·m / N and $(Q_h^*)^2 = 83.5 \cdot 10^{-12}$ Pa⁻¹ at $m_p = 0.40$. Our results shown in Figs. 6 (d) – (f) testify to higher PS of the composite at $m = 0.06$ and various values of the orientation angle θ .

Comparison of data on the hydrostatic piezoelectric coefficient d_h^* from Fig. 6 (d) to data from paper [23] on the 1–3-type FC / auxetic polymer composites enable us to emphasize the more active role of the anisotropic porous structure (Fig. 1, inset) in comparison with the auxetic structure of the polymer matrix. In our current study and Ref. 23, different examples of the inequality $d_h^* > d_{33}^*$ were analyzed to improve hydrostatic performance of the 1–3-type composites. However at $m = 0.05 \dots 0.10$, values of d_h^* of the composite studied in the present work are about 2 – 3 times more than those evaluated [23] for the FC / auxetic polymer composites based on either PZT or BaTiO₃. Undoubtedly, this advantage of the composite with the inclined spheroidal pores favours high PS and large values of such parameters, as g_h^* and $(Q_h^*)^2$.

4. Conclusions

Results on the effective electromechanical properties and PS of novel piezo-active 1–3-type composites with a regular distribution of components are presented. The important role of

microgeometry of pores, the orientation effect and features of the piezoelectric response of the composite with point symmetry m are to be taken in consideration when manufacturing the high-sensitive composites and predicting the effective parameters that describe PS. The increase in the hydrostatic piezoelectric coefficients d_h^* and g_h^* and squared figure of merit $(Q_h^*)^2$ of the 1–3–0 composite is attained in different ways (see Figs. 2 – 6) due to variations of volume fractions of FC and pores, changes in the aspect ratio and / or orientation of pores, the elastic anisotropy of the porous matrix, and other factors. It has been shown that the orientation of the spheroidal pores in the polymer matrix can improve PS and hydrostatic parameters of the composite due to a more favourable balance of the piezoelectric coefficients d_{3j}^* and g_{3j}^* . The results reported in this paper can promote manufacture and design of the anisotropic 1–3-type composites with high PS. These composites are to be used as elements of sensors, hydrophones, transducers, and other piezoelectric devices for which PS characteristics play the key role. Calculated dependences of the effective parameters of the composites on a series of variables (Figs. 2 – 6) show in which ranges one can attain the maxima of different piezoelectric coefficients and squared figures of merit. Data on the maximum points and non-monotonous behaviour of the effective parameters can be of benefit for the optimization and exploitation of the piezoelectric response, PS and other characteristics of the 1–3-type composites based on FC.

Acknowledgements


The authors would like to thank Dr C R Bowen and Professor R Stevens (University of Bath, UK) and Professor P. Bisegna (University of Rome “Tor Vergata”, Italy) for their interest in the research problems. This work has been supported by the grant K-08-T-18 of the Department of High Technologies and Innovations at the Southern Federal University (Russia), and this financial support is gratefully acknowledged.

References

- [1]. R. E. Newnham, Molecular mechanisms in smart materials, *Mater. Res. Soc. Bull.*, Vol. 22, Issue 5, 1997, pp. 20–34.
- [2]. R. E. Newnham, D. P. Skinner, L. E. Cross, Connectivity and piezoelectric – pyroelectric composites, *Mater. Res. Bull.*, Vol. 13, Issue 5, 1978, pp. 525–536.
- [3]. A. A. Grekov, S. O. Kramarov, A. A. Kuprienko, Effective properties of a transversely isotropic piezoelectric composite with cylindrical inclusions, *Mech. Compos. Mater.*, Vol. 25, Issue 1, 1989, pp. 54–61.
- [4]. V. M. Levin, M. I. Rakovskaja, W. S. Kreher, The effective thermoelectroelastic properties of microinhomogeneous materials, *Int. J. Solids. Struct.*, Vol. 36, Issue 18, 1999, pp. 2683–2705.
- [5]. V. Yu. Topolov, S. V. Glushanin, Evolution of connectivity patterns and links between interfaces and piezoelectric properties of two-component composites, *J. Phys. D: Appl. Phys.*, Vol. 35, Issue 16, 2002, pp. 2008–2014.
- [6]. R. Kar-Gupta, T. A. Venkatesh, Electromechanical response of 1–3 piezoelectric composites: Effect of poling characteristics, *J. Appl. Phys.*, Vol. 98, Issue 5, 2005, pp. 054102–14 p.
- [7]. V. Yu. Topolov, A. V. Turik, Nonmonotonic concentration dependence of piezoelectric coefficients of 1–3 composites, *J. Appl. Phys.*, Vol. 85, Issue 1, 1999, pp. 372–379.
- [8]. V. Yu. Topolov, A. V. Turik, Porous piezoelectric composites with extremely high reception parameters, *Tech. Phys.*, Vol. 46, Issue 9, 2001, pp. 1093–1100.
- [9]. A. S. Bhalla, R. Y. Ting, Hydrophone figure of merit, *Sensors Mater.*, Vol. 4, Issue 1, 1988, pp. 181–185.
- [10]. E. K. Akdogan, M. Allahverdi, A. Safari, Piezoelectric composites for sensor and actuator applications, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, Vol. 52, Issue 5, pp. 746–775.
- [11]. A. Safari, E. K. Akdogan, Rapid prototyping of novel piezoelectric composites, *Ferroelectrics*, Vol. 331, 2006, pp. 153–179.

- [12].C. R. Bowen, V. Yu. Topolov, Piezoelectric sensitivity of PbTiO₃-based ceramic / polymer composites with 0–3 and 3–3 connectivity, *Acta Mater.*, Vol. 51, Issue 17, 2003, pp. 4965–4976.
- [13].K. A. Klicker, J. V. Biggers, R. E. Newnham, Composites of PZT and epoxy for hydrostatic transducer applications, *J. Am. Ceram. Soc.*, Vol. 64, Issue 1, 1981, pp. 5–9.
- [14].V. Yu. Topolov, S. V. Glushanin, A. E. Panich, Features of the piezoelectric response for a novel four-component composite structure, *Ferroelectrics*, Vol. 308, 2004, pp. 53–65.
- [15].V. Yu. Topolov, A. V. Turik, On increasing the hydrostatic sensitivity of three-component piezocomposites, *Tech. Phys. Lett.*, Vol. 27, Issue 1, 2001, pp. 81–83.
- [16].O. Sigmund, S. Torquato, I. A. Aksay, On the design of 1–3 piezocomposites using topology optimization, *J. Mater. Res.*, Vol. 13, Issue 4, 1998, pp. 1038–1048.
- [17].F. Levassort, M. Lethiecq, D. Certon, F. Patat, A matrix method for modeling electroelastic moduli of 0–3 piezocomposites, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, Vol. 44, Issue 2, 1997, pp. 445–452.
- [18].S. V. Glushanin, V. Yu. Topolov, Features of electromechanical properties of piezoelectric composites with elements of connectivity 1–1, *J. Phys. D: Appl. Phys.*, Vol. 34, Issue 16, 2001, pp. 2518–2529.
- [19].A. V. Gorish, V. P. Dudkevich, M. F. Kupriyanov, A. E. Panich, A. V. Turik, Piezoelectric Device-making. Vol. 1. Physics of Ferroelectric Ceramics, Moscow, *Radiotekhnika*, 1999 (in Russian).
- [20].A. Ya. Dantsiger, O. N. Razumovskaya, L. A. Reznichenko, L. D. Grineva, R. U. Devlikanova, S. I. Dudkina, S. V. Gavriyatchenko, N. V. Dergunova, A. N. Klevtsov, Highly Effective Piezoceramic Materials (Handbook), Rostov-on-Don, *Kniga*, 1994 (in Russian).
- [21].H. L. W. Chan, J. Unsworth, Simple model for piezoelectric ceramic / polymer 1–3 composites used in ultrasonic transducer applications, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, Vol. 36, Issue 4, 1989, pp. 434–441.
- [22].S. H. Choy, H. L. W. Chan, M. W. Ng, P. C. K. Liu, Study of 1–3 PZT fibre / epoxy composites with low volume fraction of ceramics, *Integr. Ferroelectrics*, Vol. 63, 2004, pp. 109–115.
- [23].V. Yu. Topolov, C. R. Bowen, Characteristics of 1–3-type ferroelectric ceramic / auxetic polymer composites, *Modelling Simul. Mater. Sci. Eng.*, Vol. 16, Issue 1, 2008, pp. 015007–12 p.
- [24].M. J. Haun, R. E. Newnham, An experimental and theoretical study of 1–3 and 1–3–0 piezoelectric PZT-polymer composites for hydrophone applications, *Ferroelectrics*, Vol. 68, 1986, pp. 123–139.

2009 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.
(<http://www.sensorsportal.com>)



Universal Frequency-to-Digital Converter (UFDC-1)

- 16 measuring modes: frequency, period, its difference and ratio, duty-cycle, duty-off factor, time interval, pulse width and space, phase shift, events counting, rotation speed
- 2 channels
- Programmable accuracy up to 0.001 %
- Wide frequency range: 0.05 Hz ... 7.5 MHz (120 MHz with prescaling)
- Non-redundant conversion time
- RS-232, SPI and I²C interfaces
- Operating temperature range -40 °C... +85 °C

www.sensorsportal.com info@sensorsportal.com SWP, Inc., Canada

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. *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

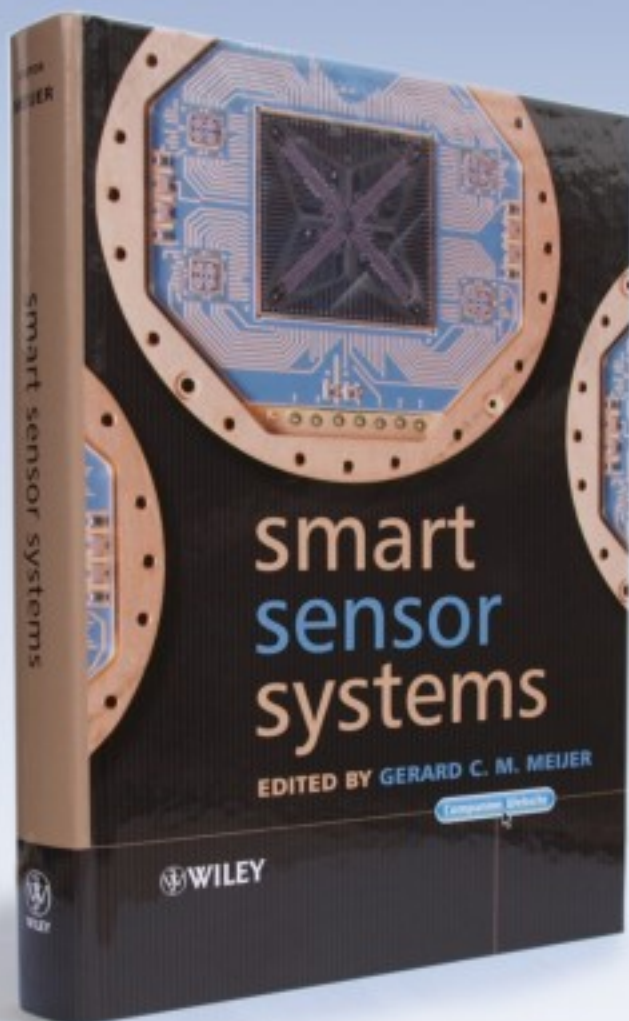
Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: <http://www.sensorsportal.com/HTML/DIGEST/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_2009.pdf

 **WILEY**
1807-2007

KNOWLEDGE FOR GENERATIONS



'Written by an internationally-recognized team of experts, this book reviews recent developments in the field of smart sensors systems, providing complete coverage of all important systems aspects. It takes a multidisciplinary approach to the understanding, design and use of smart sensor systems, their building blocks and methods of signal processing.'



Order online:

http://www.sensorsportal.com/HTML/BOOKSTORE/Smart_Sensor_Systems.htm

www.sensorsportal.com