Numerical modeling of 3-D comb drive electrostatic accelerometers structure (method of levitation force reduction)

Sławomir Wiak and Krzysztof Smółka
Institute of Mechatronics and Information Systems, Technical University of Lodz, Lodz, Poland

Abstract

Purpose – The purpose of this paper is to discuss the numerical modelling of 3D structure of micro-electro-mechanical systems (MEMS) accelerometers. The general idea being discussed is the method of levitation force reduction, as the main source of incorrect mathematical model of comb drive structure.

Design/methodology/approach – Accelerometers design is a highly interdisciplinary area and, therefore, different methods and tools have to be exploited. Dynamic accelerometer behaviour modelling has been performed by use of a new object-oriented model (NOOM), based on complex computer field and mechanical models.

Findings – The paper describes methods of levitation force reduction in electrostatic comb drive structures based on electrostatic structural models and finite elements method.

Research limitations/implications – In the present work, the authors limit themselves to the electrostatic energy domains.

Practical implications – Both, mechanical and electric models of accelerometers give the input data for defining the object-oriented model, based on Matlab-Simulink platform, fulfilling the general demand of dynamic behaviour simulation of comb drive structure. The proposed by authors methodology could give valuable contribution to MEMS design methodology.

Originality/value – A new methodology has been successfully applied to calculation of levitation force in different geometries of comb drive. This methodology could be useful for multidisciplinary MEMS systems.

Keywords Object-oriented methods, Modelling, Vectors, Force measurement

Paper type Research paper

Introduction

Actually, the task of the designer is complicated by the evidence that different energy domains, in general being mutually coupled, are involved when modelling micro-electro-mechanical devices, in the frame of more general micro-electro-mechanical systems (MEMS). Some specific codes based on finite element method (FEM) could be successfully applied to MEMS designing while microdomain physics are also taken into account. This paper deals with the methods of analysis of electrostatic accelerometers with comb drive structure. In surface micromachining, comb drives are the most commonly used actuators for moderate in-plane micro-displacements and micro-forces (van Spengen and Heeres, 2007). They are also often used as motion sensing in accelerometers. Accelerometers are important devices in the range of variety applications such as air bag actuation (by Analog and Sandia), microrobots, etc. The comb-drive accelerometers,

COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering
Vol. 28 No. 3, 2009
pp. 593-602

0332-1649
DOI 10.1108/03321640910940864

shown in Figure 1, are very popular devices in the MEMS community and have been well characterized (Kraft, 1997; Iyer *et al.*, 1998).

The capacitive accelerometer consists of the moving comb teeth, suspended by spring beams on both sides, and fixed teeth.

The suspension is designed to be in the *x*-direction of motion and to be stiff in the orthogonal direction (*y*) to keep the comb fingers aligned. Owing to phenomena complexity only field models are fully acceptable in 3D structure designing. Movable part displacement into desired direction "could even destroy" mathematical model, due to introducing to equivalent circuit model additional capacitances. Therefore, authors' effort is focused on establishing such a modelling strategy leading to levitation force reduction.

Solid modeling of micro-accelerometer 3D structures

The base method of the proposed strategy is solid modelling. It is rapidly emerging as a central area of research and development in such diverse applications as engineering and product design, computer-aided manufacturing, electronic typing, etc. The solid model, which contains the external surfaces, edges and internal volume information, could be used for design representation, verification, simulation, analysis for processing, manufacturability and costing, and for both rapid prototyping and rapid tooling.

Levitation

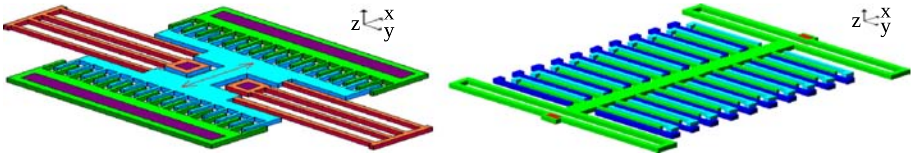
An effect to be reckoned with is comb drive levitation (van Spengen, 2007). Owing to the fact that there is ground plane under the comb drive, the pattern of electrostatic filed is not symmetric (Figure 2), which causes the fingers to move upwards as well as sideways. This start already at low voltages (van Spengen, 2007). Tang *et al.* (1992) observed that the levitation force linearly decreases with the vertical displacement of the movable finger till it equals zero at a displacement z_0. This means that z_0 is an upper limit for the use of this actuation under quasistatic conditions. This relationship can be described as follows:

$$f_z = \alpha(z - z_0)V^2 \quad (1)$$

where f_z is the force for unit length, α is constant of proportionality, V is the applied DC bias. Unfortunately, the parameters α and z_0 cannot be easily determined by theoretical analysis of the electrostatic problem. FEM electrostatic simulations (with the Matlab/Simulink together with finite element method magnetics (FEMM) software package), were used to predict the structure behaviour.

Field models

The parallel plate capacitor is the most fundamental configuration of comb drives. The stored energy is expressed by the following formula (C – capacitance, U – voltage):



Note: Computer models

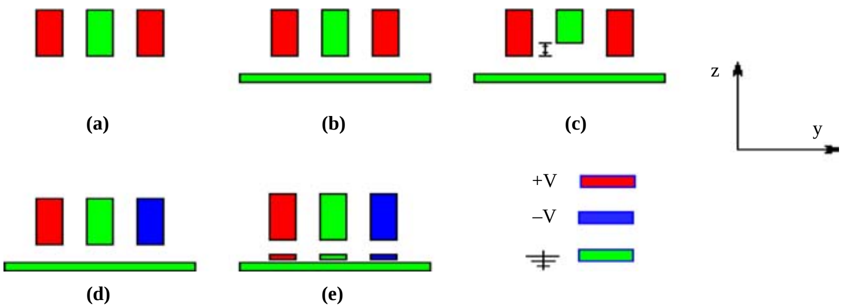
Figure 1.
Two types of electrostatic accelerometers

$$W = \frac{1}{2} CU^2 \tag{2}$$

When the plates of the capacitor move towards each other, the work done by the attractive force between them can be computed as the change in W (stored energy) versus displacement (x). Levitation force exists in polysilicon comb drives because of the ground plane under the comb fingers. Comb fingers with a Si ground layer can generate vertical electrostatic force and have been used for vertical actuation. Figure 3(b) shows a lateral-axis comb drive. The Si layer is grounded. When a voltage is applied as shown in Figure 3(b), the *z*-axis force as well as the *x*-axis force is generated.

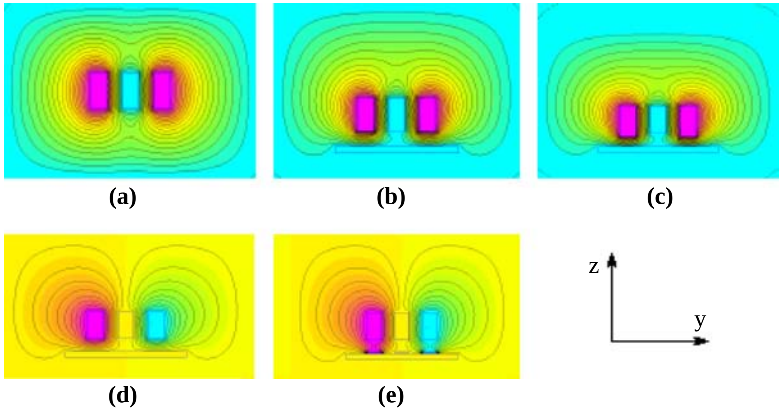
Levitation of the several micrometers is possible, leading to in-plane nonlinearities, reduced lateral stability, etc. – for critical applications levitation force must be minimized (Tang *et al.*, 1992).

In Figure 4, the levitation force is shown as a function of the rotor's vertical displacement. Values are calculated by use of finite-element software. In the accelerometer, the electrostatic levitation force equals the spring's restoring force. Some methods, leading to levitation force reduction, even elimination are shown in Figure 2.



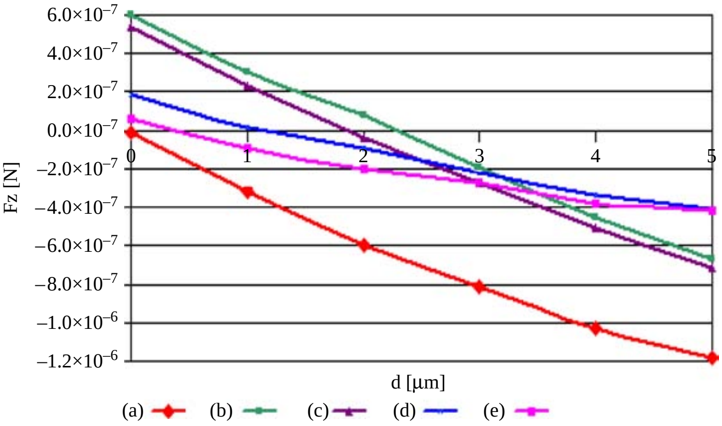
Note: Reproduced from the only available original

Figure 2. Different structures comb-drives: (a) remove substrate below comb drive; (b) substrate and comb drive; (c) change height finger of comb drive; (d) differential bias on adjacent comb fingers; (e) add striped ground conductors



Note: The boundary conditions are the Dirichlet (V = 0)

Figure 3. Electric field equipotential lines for different structures comb-drives from Figure 3



Note: Reproduced from the only available original

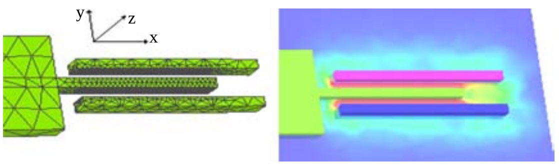
Figure 4.
Plot of the vertical force versus rotor vertical displacement for the structures are shown in Figure 2(a)-(e)

Figure 5 shows mesh and electric field for 3D structures and Figure 6 shows model comb-drives (Matlab/Simulink).

In the case of removing substrate below comb drive, we eliminate levitation force, but it could complicate manufacturing, and moreover it is not commonly used. Methods such as "differential bias on adjacent comb fingers" or "add striped ground conductors" (Figures 2 and 3) are easier to implement, but they only reduce levitation by around 10x (Tang *et al.*, 1992).

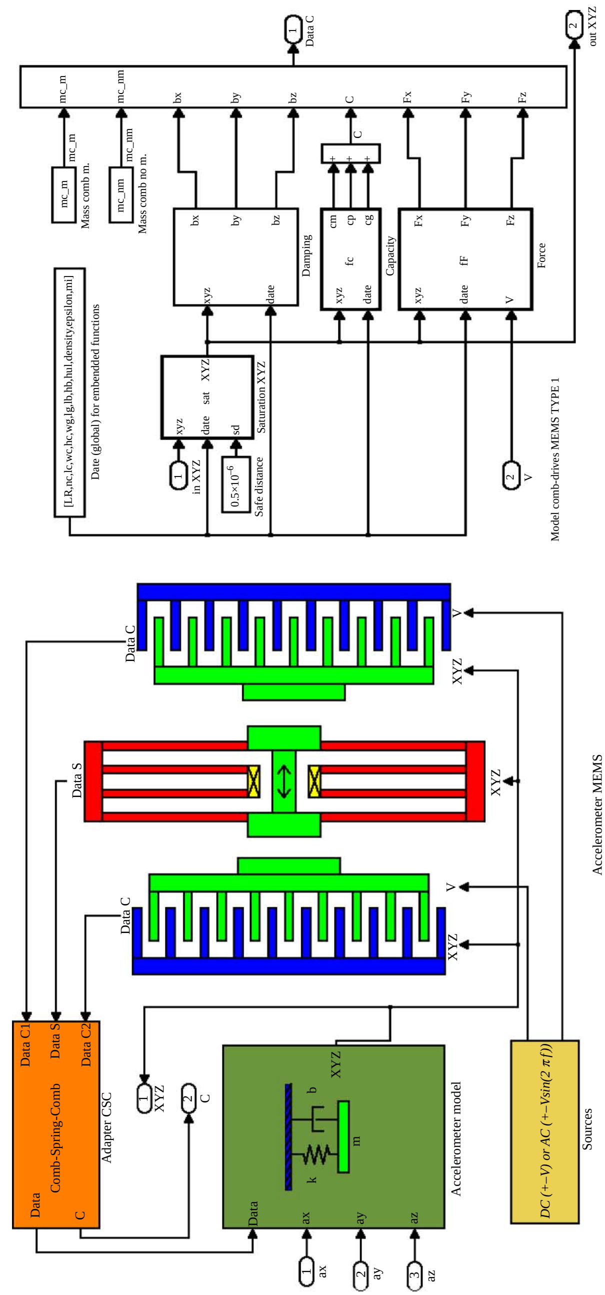
Object-oriented modelling

Simulation is a very important method to gain insight in complex systems, to make virtual experiments to get deeper understanding, and to verify new designs (Schwarz *et al.*, 2004). Modelling, simulation and analysis tools are needed to support the MEMS designer during these activities. In the design of microsystems, sophisticated CAD systems, based on FEM, like OPERA from Vector Fields, COSMOS and ANSYS, are exploited for modelling and simulation the behaviour of the system components with high accuracy. Finite element analyses are the most commonly used methods for numerical mechanical and electrostatic simulations. These methods are accurate for fine meshes. However, as they are layout-based, any change to the geometric sizes requires a new mesh, leading to inconvenient design iteration (Jing *et al.*, 2002). Unfortunately, FEM simulations are time consuming.



Note: Reproduced from the only available original

Figure 5.
Mesh and electric field for 3D structures



Note: MATLAB/Simulink

Figure 6.
Model comb-drives

Levitation modelling by used object-oriented methods

Subject of calculations of the levitation forces and balance point in comb structures was taken up frequently. The analytical calculations based on the circuit modelling of capacitances were presented by van Spengen (2007) and Molfese *et al.* (2006). The another methods were presented in Liao *et al.* (2004) and Chyuan *et al.* (2005). In these cases, FEM and boundary element method were applied. Authors recommended the BEM for studying the electrostatic field of the levitation of MEMS comb drives, because the BEM's discretisations are restricted only to boundaries, and it makes data generation much easier than FEM. Boundary element method is very efficient method, but for problems having degenerate boundary and degenerate scale problems, conventional BEM cannot be used directly, and many external numerical techniques were needed. Therefore, the FEM is most useful and simplest method for modelling of the MEMS, because there is no laborious artificial boundary technique needed (Chyuan *et al.*, 2005).

In this work, the authors were introduced FEMs combined with object oriented methods in Matlab/Simulink. This strategy enable changes the all parameters of the comb drive. On the other hand, this strategy allowed to take advantage of FEM, what is possibility calculations of complicated geometries without additional operations.

The following software tools were used:

- *MATLAB*. It is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation (The MathWoks, 2005).
- *MATLAB\Simulink*. It is software for modelling, simulating, and analysing dynamic systems. It supports linear and non-linear systems, modelled in continuous time, sampled time, or a hybrid of the two (The MathWoks, 2005).
- *FEMM*. It is a suite of programs (freeware software) for solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. The program currently addresses linear/nonlinear magnetostatic problems, linear/nonlinear time harmonic magnetic problems, and linear electrostatic problems (Meeker, 2006b).
- *Lua*. The Lua extension language has been used to add scripting/batch processing facilities to FEMM (Meeker, 2006b).
- *OctaveFEMM*. It is an Octave/MATLAB toolbox that allows for the operation of FEMM via a set of Octave/MATLAB functions. Since there are not many options for interactive interprocess communications with MATLAB, the toolbox works by trading messages between MATLAB and FEMM via temporary files. Although this method of exchanging messages between processes is very slow relative to ActiveX or MathLink, it has the virtue of working. When programs starts up a FEMM process, the usual FEMM user interface is displayed and is fully functional. The syntax of the OctaveFEMM toolbox closely mirrors that of FEMM's existing Lua scripting language interface associated with FEMM v4 (Meeker, 2006a).

Figure 7 is universal MATLAB/Simulink block, which included different models of vertical cross section of three electrostatic fingers. Owing to parameters change,

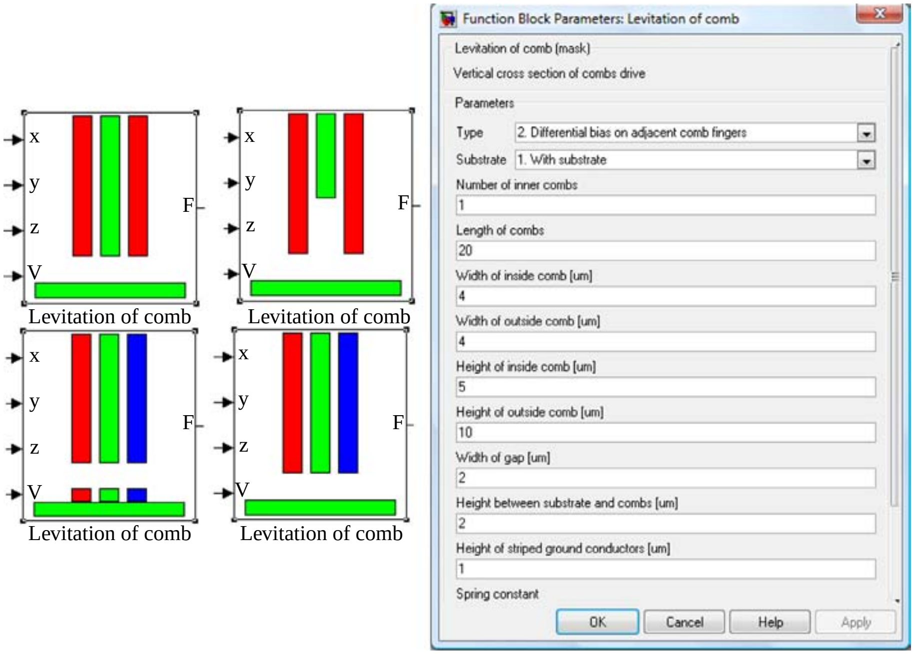


Figure 7. Different kinds of the same universal MATLAB/Simulink block and function block parameters

structural changes were obtained. However, Figure 8 shows examples diagrams and the results of calculations. Figure 9 shows calculation of balance point used by algebraic constant block.

Complex strategy

Authors propose (their own) a complex strategy of modelling and the optimisation technique, based on the circuit methodology and the vector field model of accelerometer MEMS. This strategy is fully satisfactory in order to simulate the electromechanical characteristics of different structure accelerometers, and dynamic behaviour of the object.

A novel complex strategy in computer modelling of accelerometer MEMS, based on the solid modelling, is proposed by the authors in this paper. This strategy is fully

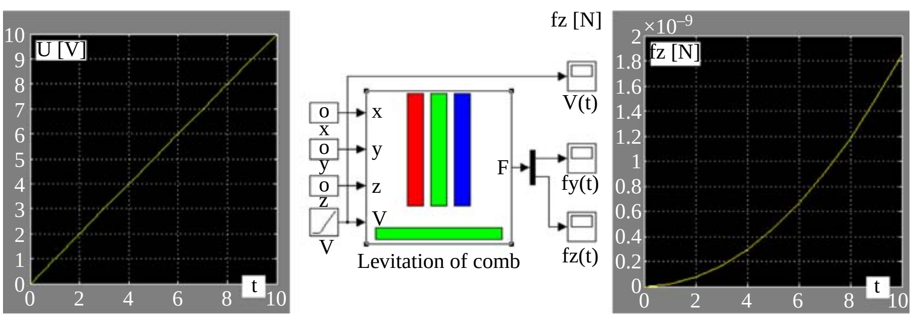
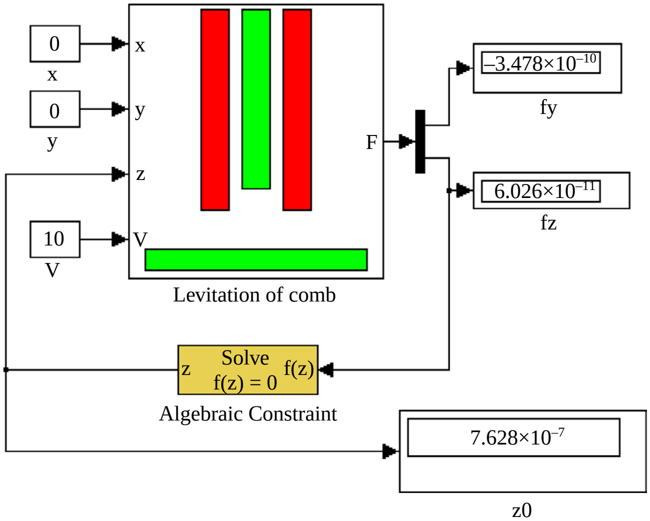


Figure 8. The levitation force f_z in the function of the voltage U



Notes: Heights fingers: 10 and 9 µm, widths finger: 5 µm, widths of gaps between fingers 2 µm and lengths of the all fingers: 10 µm

Figure 9.
Calculation of balance point

satisfactory in order to simulate the electromechanical characteristics of different accelerometer structures (MEMS). This methodology consists of the following general steps: solid modelling of 3D structure of inertial devices, parameterised model to speed up geometry introducing, creation of the mathematical model of 3D structure, creation of the complex electromechanical models of MEMS dynamic behaviour (system of electric and mechanical partial differential equations – based on lumped parameters models), creation of the library of object-oriented MEMS components (Matlab/Simulink Figure 6).

In authors' opinion, only such new methodology makes the complex simulation of device dynamic behaviour and MEMS optimal design possible, leading to levitation force reduction as well.

Conclusion

The vector field analysis (mechanical and electrical) has given the knowledge about the structures of the micro accelerometer, as well as the dynamic behavior of the analyzed object.

On the base of this research a following conclusion could be drawn that:

- only the 3D design with the application of the solid modeling delivers the full view of the phenomena occurring in the accelerometers; and
- such complex, object-oriented solution makes possible the full simulation of device and optimization MEMS devices.

The above-mentioned methodology determines a two-fold benefit:

(1) the decrease in the total time between the device idea and its implementation as a marketable product; and

(2) the reduction in the costly experiments number with the real prototypes.

The new object-oriented Matlab/Simulink elements may be use to different MEMS design – for example resonators and gyroscopes.

References

Chyuan, S.-W., Liao, Y.-S. and Chen, J.-T. (2005), "Computational study of the effect of finger width and aspect ratios for the electrostatic levitating force of MEMS comb drive", *IEEE Journal of Microelectromechanical Systems*, Vol. 14 No. 2, pp. 305-12.

Iyer, S., Mukherjee, T. and Fedder, G.K. (1998), "Multi-mode sensitive layout synthesis of microresonator", paper presented at International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, Santa Clara, CA, April.

Jing, Q., Mukherjee, T. and Fedder, G.K. (2002), "Schematic-based lumped parameterized behavioral modeling for suspended MEMS", paper presented at Technical Digest of the ACM/IEEE International Conference on Computer-Aided Design, San Jose, CA, November 10-14, pp. 367-73.

Kraft, M. (1997), "Closed loop digital accelerometer employing oversampling conversion", PhD dissertation, Coventry University, Coventry.

Liao, Y.-S., Chynan, S.-W. and Chen, J.-T. (2004), "An alternatively efficient method (DBEM) for simulating the electrostatic field and levitating force of a MEMS combdrive", *Journal of Micromechanics and Microengineering*, Vol. 14, pp. 1258-69.

(The) MathWorks (2005), "Matlab 7.1. Getting started guide", *User Manual*, The MathWorks, Natick, MA.

Meeker, D. (2006a), "Finite element method magnetics: OctaveFEMM", *Version 1.0, User's Manual*, 2 October.

Meeker, D. (2006b), "Finite element method magnetics", *Version 4.0, User's Manual*, 8 January.

Molfese, A., Nannini, A., Pennelli, G. and Pieri, F. (2006), "Analysis, testing and optimisation of electrostatic comb-drive levitational actuators", *Analog Integrated Circuits and Signal Processing*, Vol. 48 No. 1, pp. 33-40.

Schwarz, P., Clauß, Chr., Diener, K.-H., Elst, G., Haufe, J., Jancke, R., Schneider, A. and Schneider, P. (2004), "Web-based, simulation-oriented training courses in electronics and microsystems technology", *Proceedings of the 5th EUROSIM Congress on Modelling and Simulation, Paris, France, 6-10 September*.

Tang, W.C., Lim, M.G. and Howe, R.T. (1992), "Electrostatic comb drive levitation and control method", *The Journal of Microelectromechanical Systems*, Vol. 1 No. 4, pp. 170-8.

van Spengen, W.M. (2007), "A 'nano-battering ram' for measuring surface forces: obtaining force-distance curves and sidewall stiction data with a MEMS device", *Journal of Micromechanics and Microengineering*, Vol. 17, pp. S91-7.

van Spengen, W.M. and Heeres, E.C. (2007), "A method to extract the lateral and normal component of the motion from the capacitance change of a moving MEMS comb drive", *Journal of Micromechanics and Microengineering*, Vol. 17, p. 447.

Further reading

Chyuan, S.-W., Liao, Y.-S. and Chen, J.-T. (2004), "Computational study of variations in gap size for the electrostatic levitating force of MEMS device using dual BEM", *Microelectronics Journal*, Vol. 35, pp. 739-48.

Iyer, S. (1999), "Numerical spring models for behavioral simulation of MEMS inertial sensors", in Mukherjee, T. (Ed.), *Proceedings of SPIE – The International Society for Optical Engineering, Paris, France*, Vol. 4019, pp. 55-62.

Zhang, G. (1998), "Design and simulation of a CMOS-MEMS accelerometer", project report, Carnegie Mellon University, Pittsburgh, PA, May.

Zhou, Y. (1998), "Layout synthesis of accelerometers", MS Project Report (advisor: Prof. Gary K. Fedder, Co-advisor: Dr Tamal Mukherjee), Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, August.

About the authors

Sławomir Wiak, DSc, PhD, MEng., MIEEE, MICS, is a Dean of Faculty of Electrical, Electronic, Computer and Control Engineering, Technical University of Lodz, Poland. He is specialized in computer science and electrical engineering (computer-aided design, computer modeling and simulation, data base and expert systems, mechatronics, engineering knowledge). He was invited to give lectures at University of Southampton (Great Britain), National Technical University of Athens (Greece), University of West Bohemia – Plzen, University of Prague, Czech Academy of Sciences, University of d'Artois (France), University of Maribor, University of Pavia, Italy, University of Vigo, Spain. He is holding a membership in the societies: IEEE, ICS, ICS IEEE, Polish Society of Applied Electromagnetics and membership of International Steering Committees: SMC, COMPUMAG as well, Chairman of ISEF, Editorial Board of CEFC, ICEM, EWOIPE, ACEMP, ELECTROMOTION, ICEMS (China), ICREPQ (Spanish, Portuguese), ICEFHE, Editorial Board of *IJEET*, *ICAISC*. Sławomir Wiak is the corresponding author and can be contacted at: wiakslaw@p.lodz.pl

Krzysztof Smółka was born in Łask in 1975. He obtained Master of Science degree (2000) in Computer Methods in Engineering. Now, he works in Institute of Mechatronics and Information Systems Technical University of Lodz in Poland. His researches are on the design of mechatronics devices (MEMS also), methods of optimisation, application methods of artificial intelligence, numerical models and languages of programming.