26th International Conference
ENGINEERING MECHANICS 2020
Brno, Czech Republic, November 24 – 25, 2020

CONCEPT OF METAMATERIAL WITH PIEZOELECTRIC ELEMENTS FOR CYBER-PHYSICAL SYSTEM APPLICATIONS

Hadas Z.*, Marcian P., Rubes O.***, Hrstka M.******

Abstract: *This paper deals with a metamaterial for sensing purposes under Industry 4.0 applications. The presented of metamaterial is based on an auxetic structure which is made by Direct Metal Laser Sintering technology. The stain steel auxetic structure could integrate smart material elements or systems for electromechanical conversions. The proposed concept of metamaterial uses the auxetic structure with piezoelectric elements or stacks to transduce external load of structure into electric signal. The auxetic structure could provide uniform mechanical load on several smart piezoelectric elements in middle layers due to negative Poisson ration. The paper presents a FEM simulation of this concept and analysis of coupled electromechanical system under harmonic excitation. Deformation of auxetic structure with piezoceramic PZT plates is presented and the voltage response is analyzed. The assembly of metamaterial system with piezoelectric PVDF in case of soft application is also presented and it will be tested under future development.*

Keywords: Metamaterial, Auxetic structure, PZT, PVDF, Cyber-physical system.

1. Introduction

This contribution deals with a concept of a metamaterial for sensing purposes under Industry 4.0 applications. Recent development of modern manufacturing application expects higher availability and affordability of sensors, data acquisition systems and big data technologies (Lee et al., 2015). This cyber-physical system with proposed metamaterial could be integrated in modern devices and it provides electrical signal on the base of operation and structure loads. Employed metamaterials in engineering application could provide transformative technologies between physical and cybernetical system for sensing purposes and provide integrated smart system in design of machines and devices.

Metamaterials are artificial materials which have extraordinary mechanical or electro-mechanical properties not observed in nature (Li et al., 2017). The presented metamaterial structure includes the periodic pattern cells with negative Poisson ratio (Koudelka et al., 2016) and smart elements are inserted inside individual cells (Hu et al., 2017). The used smart elements cloud be in form of piezoceramic plates, piezoceramic or piezopolymer stack. The auxetic structure converts external mechanical loads to press of piezoelectric elements or stack due to negative Poisson ration. Smart elements are forced by structural loads to achieve expected electrical signal, which provide metamaterial with required electro-mechanical properties. The generated electrical signal is proportional with the dynamic loads and it also depends on geometry of structure pattern (Giorgio et al., 2015).

2. Used Auxetic Structure of Proposed Metamaterial with Piezoelectric Elements

The used structural pattern could integrate electrically isolated piezoelectric plate, see Fig 1a, or piezoelectric stack, see Fig. 1b. The presented and analyzed metamaterial is based on a planar periodic

* Assoc. Prof. Zdenek Hadas, PhD.: Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2; 616 69, Brno; CZ, hadas@fme.vutbr.cz

** Petr Marcián, PhD.: Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2; 616 69, Brno; CZ, marcian@fme.vutbr.cz

*** Ondrej Rubes: Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2; 616 69, Brno; CZ, ondrej.rubes@vutbr.cz

**** Miroslav Hrstka, PhD.: Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2; 616 69, Brno; CZ, miroslav.hrstka1@vutbr.cz

auxetic structure with these patterns. Both piezoelectric systems (grey boxes) could be integrated in auxetic structure (bounded blue area) under load and it is shown in Fig. 1c. Such metamaterial with piezoelectric systems for electromechanical conversions (Bowen et al., 2014) could provide cyber-physical system for sensing purposes in modern applications and devices (Herterich et al., 2015).

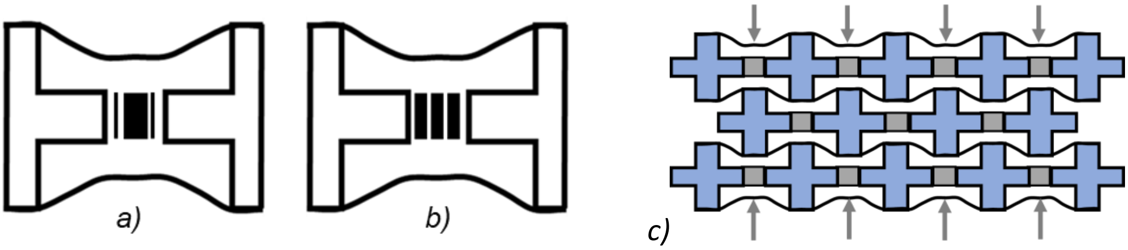
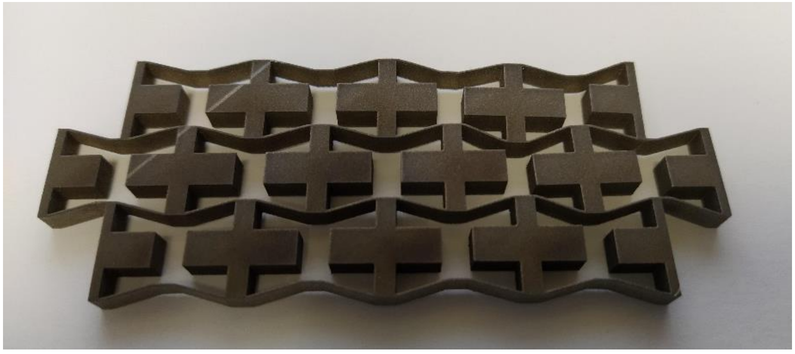


Fig. 1: Patterns of structure with smart elements in form of a) isolated piezoceramic plates; b) piezoceramic or piezopolymer stack; c) planar metamaterial structure under load.

The presented auxetic structure is manufactured by additive technology (Direct Metal Laser Sintering) from stainless steel powder and it could provide uniform mechanical load on three smart piezoelectric elements in middle layers. Dimensions of this structure is 90 x 36 x 5 mm, thickness of cell borders is 0.4 mm. The Poisson ratio is analyzed for pure auxetic structure in value -0.46 and parameter of stiffness is 4.6 kN/mm.

a)



b)

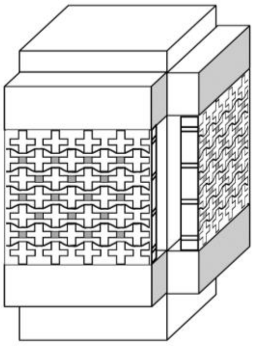


Fig. 2: Prototype of stain steel structure and proposed metamaterial application.

3. FEM Simulation of Metamaterial with Piezoelectric PZT Plates

Plastic jaws could be included in all pattern cell for electric isolation of used piezoelectric elements. For a uniform load only three PZT piezoceramic plates 5 x 5 x 1 mm (Noliac NCE51) are integrated in middle layer in used FEM simulation. Included PZT plates changed properties of metamaterial and the value of Poisson ratio is -0.38 and the stiffness of metamaterial is 7.2 kN/mm. The analyzed stress of metamaterial structure is shown in Fig. 3 for maximal amplitude 0.1 mm. The operation with significantly lower vibration amplitude is assumed. The metamaterial system is designed for sensing purposes and the performance of individual piezoceramic plates under this metamaterial is 1050 mV/N.

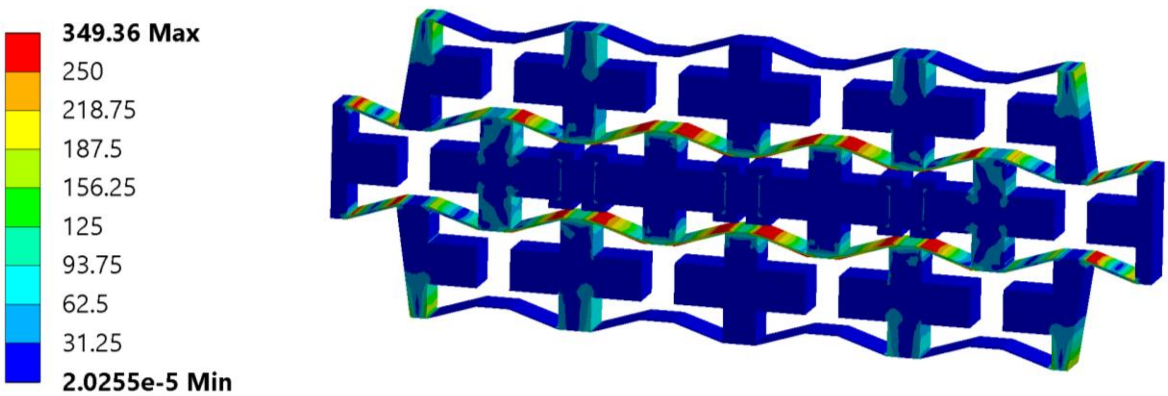


Fig. 3: Equivalent stress [MPa] of metamaterial structure with piezoceramic PZT plates under excitation with amplitude 0.1 mm.

4. Concept of Metamaterial with PVDF Piezoelectric Stack

PVDF is piezoelectric polymer which has significantly lower piezoelectric properties. However, this material is very flexible in form of foil and PVDF could be also used for layered structure of piezoelectric stack, Fig. 4a. In this case the utilization of the PVDF (Dong et al., 2017) or PVDF-based copolymers PVDF-co-HFP (Mrlik et al., 2017) seems to be a promising solution for sensing application. The piezoelectric PVDF stack was manufactured for implementation in middle layer of proposed auxetic structure, Fig. 4b. This PVDF piezoelectric stack consists of 18 layers of PVDF foil (thickness 0.14 mm) with dimensions 5 x 5 mm. Conductive layers are created aluminum foil and individually isolated and total width is 5 mm and it provides a compliant smart element which does not increase total stiffness of the proposed metamaterial. The stiffness will be very similar as the pure auxetic structure and it provides opportunity to use this PVDF material in soft applications.

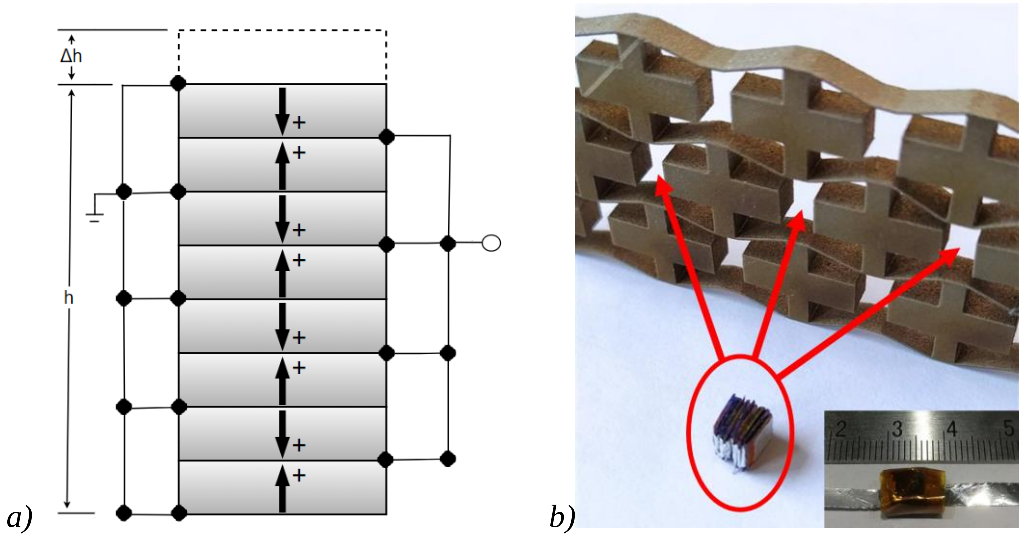


Fig. 4: Metamaterial structure: a) common topology of piezoelectric stack; b) PVDF piezoelectric stack for implementation in middle layer of auxetic structure.

The assembled piezoelectric PVDF stack, detail in Fig. 4b, was tested in lab conditions and the voltage response of this sensing system was analyzed. The voltage response is proportional with a rate of stack deformation. The piezoelectric stack assembly was loaded by force impulses, which were created by modal hammer and the force impulse was recorded, see Fig. 5a. The voltage response is proportional with force peak and it was measured on oscilloscope with a probe 1 MΩ. The voltage response on the force impulse 150 N is shown in Fig. 5b. The voltage response around 30 V peak to peak correspond with this force level. Due to elimination of oscillation peaks in voltage signal which could be caused by self-oscillation of PVDF and aluminum foils a tip mass 150 grams was added for this laboratory experiment. The response and oscillation effect in mass-spring system will be further analyzed for future sensing applications.

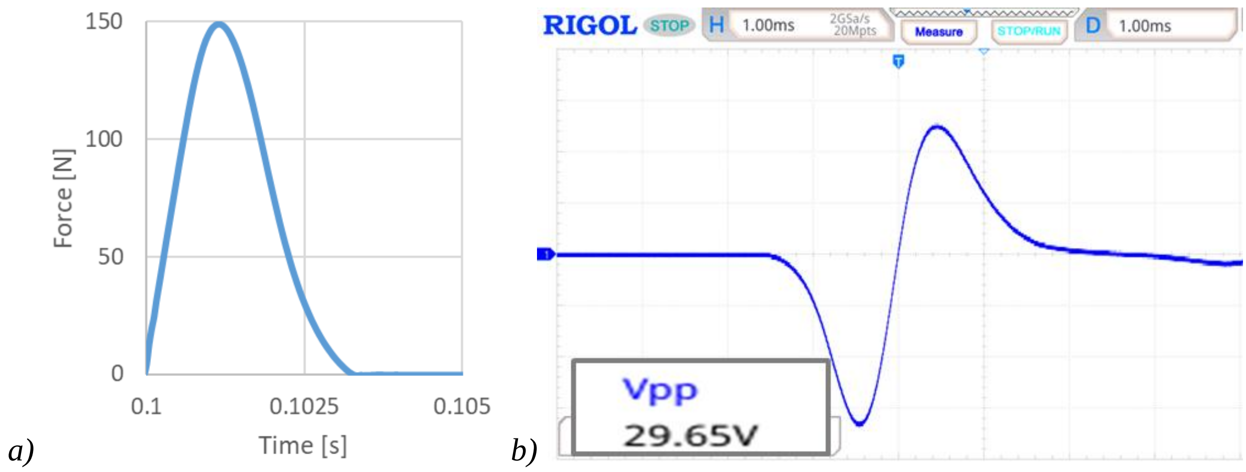


Fig. 5: a) External impulse force; b) Oscilloscope screenshot of PVDF stack voltage response.

5. Conclusions

The main aim of this paper was to present the proposed concept of metamaterial for energy harvesting (Hadas et al., 2018) and sensing purposes (Ksica et al., 2019). The used concept of metamaterial uses the stain steel auxetic structure with smart materials in middle layer of structure. This metamaterial can convert input forces of vibrating structure into electric signal, which are observed on included smart elements. The contribution presents finite element model of the basic concept of metamaterial with PZT plates. Simulation results of auxetic structure with piezoceramic PZT plates and the voltage response are analyzed. Furthermore, the concept of PVDF piezoelectric stack is presented for metamaterial with lower stiffness. The individual PVDF stack was manufactured and the voltage response is presented. It provides potential for future sensing applications. The assembly of metamaterial system with PZT plates and piezoelectric PVDF stack will be tested under future development and integration in engineering application is expected.

The proposed metamaterial provides smart solution of design for future devices and machines which could integrate design and sensing function together. A combination of additive technologies, smart material manufacturing and printed electronics allows to provide modern cyber-physical system for Industry 4.0 application.

Acknowledgement

The presented development and publishing of this paper was supported provided via the Czech Science Foundation project GA19-17457S „Manufacturing and analysis of flexible piezoelectric layers for smart engineering“.

References

Bowen, C. R., Kim, H., Weaver, P. M., and Dunn, S. (2014) Piezoelectric and ferroelectric materials and structures for energy harvesting applications. Energy and Environmental Science, 7(1), 25.

Dong, C., Fu, Y., Zang, W., He, H., Xing, L., and Xue, X. (2017) Self-powering/self-cleaning electronic-skin basing on PVDF/TiO 2 nanofibers for actively detecting body motion and degrading organic pollutants. Applied Surface Science, 416, pp. 424-431.

Giorgio, I., Galantucci, L., Della Corte, A., and Del Vescovo, D. (2015) Piezo-electromechanical smart materials with distributed arrays of piezoelectric transducers: Current and upcoming applications. International Journal of Applied Electromagnetics and Mechanics, 47(4), pp. 1051-1084.

Hadas, Z., Janak, L., and Smilek, J. (2018). Virtual prototypes of energy harvesting systems for industrial applications. Mechanical Systems and Signal Processing, 110, pp. 152-164.

Herterich, M. M., Uebernickel, F., and Brenner, W. (2015) The Impact of Cyber-physical Systems on Industrial Services in Manufacturing. Procedia CIRP, 30, pp. 323-328.

Hu, G., Tang, L., Banerjee, A., and Das, R. (2017) Metastructure with Piezoelectric Element for Simultaneous Vibration Suppression and Energy Harvesting. Journal of Vibration and Acoustics, Transactions of the ASME, 139(1).

Koudelka, P., Neuhauserova, M., Fíla, T., and Kytýř, D. (2016) Deformation Mechanisms of Auxetic Microstructures for Energy Absorption Applications. Applied Mechanics and Materials, 821, pp. 428-434.

Ksica, F., Hadas, Z., and Hlinka, J. (2019) Integration and test of piezocomposite sensors for structure health monitoring in aerospace. Measurement, 147, 106861.

Lee, J., Bagheri, B., and Kao, H. A. (2015) A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters, 3, pp. 18-23.

Li, Y., Baker, E., Reissman, T., Sun, C., and Liu, W. K. (2017) Design of mechanical metamaterials for simultaneous vibration isolation and energy harvesting. Applied Physics Letters, 111(25).

Mrlik, M., Osicka, J., Ilcikova, M., Pavlinek, V., and Mosnacek, J. (2017) Smart composites based on controllably grafted graphene oxide particles and elastomeric matrix with sensing capability. In G. Park (Ed.) (p. 1016417).