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EXPERIMENTAL INVESTIGATION AND MODELING OF PIEZOELECTRIC ACTUATOR BEHAVIOUR FOR TRANSPORT APPLICATIONS

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Abstract

Today piezoelectric materials are widely used in transport vehicles as actuators, sensors, for vibration suppression, energy harvesting and in many more applications. In this paper, the behavior of the trimorph piezoelectric actuator is investigated. The trimorph piezoelectric actuator consists of two active piezoelectric layers separated by one passive (isolation) layer. The finite element method analysis (FEM) is used to investigate deformation behavior of the piezoelectric actuator when different values of input voltage are applied.

The simulation results are experimentally verified. Moreover, the dynamic behavior of piezoelectric actuator (output displacement of piezoelectric beam end) is experimentally investigated when the input voltage is applied with different frequencies. The presented results can be used to better understand the properties of piezoelectric materials and to optimally design trimorph piezoelectric actuators for different applications in transport vehicles.

***Key words**: piezoelectric beam, FEM, actuators, dynamics*

1 INTRODUCTION

Today piezoelectric materials are widely used in transport vehicles [1,2] as actuators [3-5], sensors, for vibration suppression [6], energy harvesting [7-15] and many more. Piezoelectric materials exhibit a property such that they mechanically deformed when the electrical voltage is applied or they generate electricity due to deformation (when the external pressure is applied). In the paper [16] finite element model of the composite beams with integrated piezoelectric layers is presented. Papers [17-20] introduced a model for piezoelectric shell elements and piezoelectric active thin-walled structures. Most of these papers investigate thin piezoelectric materials or bimorph piezoelectric actuators, but investigation of trimorph actuators (containing two active layers and one passive layer) remain very few in the literature.

In this paper, the behavior of trimorph piezoelectric actuator is investigated and presented, with regard to its applicability in transport applications. Trimorph piezoelectric actuators achieve active stroke by realizing bending when the input voltage is applied. The deformation behavior of the trimorph piezoelectric actuator is investigated by using finite element method (FEM). The deformation behavior is investigated for different values of the input voltage. The results obtained by FEM simulations are verified via experimental investigation of the piezoelectric actuator deformation (by applying different values of input voltage). The dynamic behavior of the piezoelectric actuator is also experimentally investigated when the input voltage is applied with different frequencies.

2 TRIMORPH PIEZOELECTRIC ACTUATOR CHARACTERISTICS

In this paper, the trimorph piezoelectric actuator of the company *Johnson Matthey* is investigated. The trimorph piezoelectric actuator consists of three layers: two piezoelectric (active) layers separated by one isolation carbon-fiber layer (Fig. 1a). The upper and bottom piezoelectric layers are additionally coated with the thin protecting layer. To provide electric connection, the isolation carbon fiber layer is coated with Cu (at one end and on one side) – Cu foil (Fig. 1b).

The trimorph piezoelectric beam realizes actuation by bending (Fig. 1). To activate the piezoelectric beam, at the upper piezoelectric layer constant value of voltage need to be applied (V_{in1}=0÷230 V) while the bottom layer need to be grounded (V_{in2}=0), see Fig. 2. By additionally applying input voltage (V_{in3}=1÷230 V) at the middle Cu-foil, piezoelectric actuator realizes actuation/bending in one direction (Fig. 2). By applying input voltage V_{in3}=0 at the Cu-foil, piezoelectric actuator realizes being in the opposite direction (Fig. 2). The dimensions and material characteristic of the trimorph piezoelectric actuator that is investigated in this paper are given in Table 1 and Table 2, respectively.

Table 1 Dimensions of the trimorph piezoelectric actuator

Length (mm)	49.95
Length of piezoelectric layers (mm)	45
Width (mm)	7.2
Thickness of piezoelectric layers (mm)	0.27
Thickness of carbon-fiber layer (mm)	0.24
Thickness of carbon-fiber layer with Cu-foil (mm)	0.28
Thickness of piezoelectric actuators with protecting layers (mm)	0.80

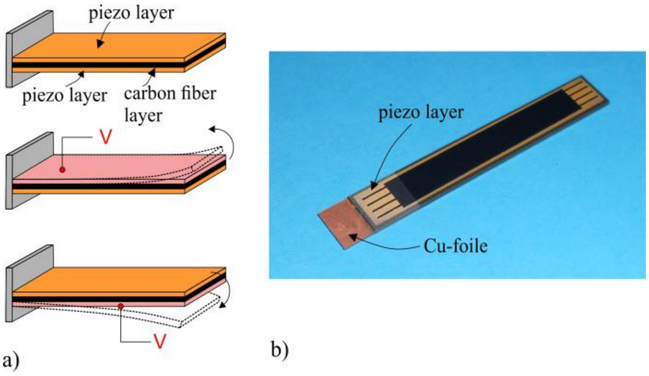

Fig. 1 *Trimorph piezoelectric actuator: a) Working principle; b) physical model of the actuator*

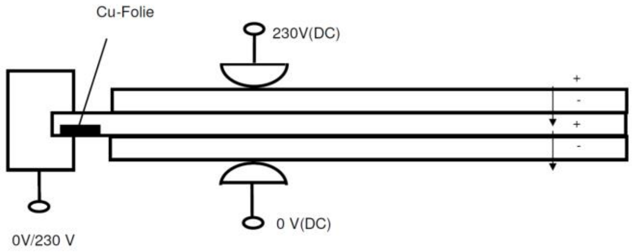

Fig. 2 *Actuation principle and electric connections*

Table 2 Material characteristics of the trimorph piezoelectric actuator

Piezo ceramic material		M1100
Relative dielectric constant	εr^T_{11} εr^T_{33}	4750 4500
Piezoelectrical charge constant (10^{-12}C/N)	d_{31} d_{33} d_{15}	-315 640 895
Compliance (10^{-12}1/Pa)	s^E_{11} s^E_{12} s^E_{13} s^E_{33} s^E_{55}	14.20 -3.70 -6.50 20.60 43.00
Density of piezo ceramic (kg/m^3)	ρ_{PZT}	8100
Young modulus of Carbon-fiber layer (Pa)	E_{cf}	$2*10^{10}$
Density of Carbon-fiber layer (kg/m^3)	ρ_C	1900
Poisson ratio of carbon-fiber layer	ν_C	0.2

3 NONLINEAR FEM ANALISYS OF THE THRIMORPH PIEZOELECTRIC ACTUATOR DEFORMATION BEHAVIOUR

The deformation behavior of the trimorph piezoelectric actuator is investigated by using commercially available FEM software (Fig. 3). For the FEM analysis and simulations coupled structural – electrostatics analysis is used; two-way structural – electrostatics interaction analysis is performed. For the FEM analysis, the piezoelectric actuator is fixed at one end i.e. as boundary condition fixed support is applied at the bottom part of the actuator (Fig. 3b). FEM analysis is done for two cases: when piezoelectric layer 1 (upper layer) is active and when piezoelectric layer 2 (bottom layer) is active (Fig. 3a). In the first case, as an input electric potential (V_{in}) is applied to the upper surface and ground is applied to the bottom surface of piezoelectric layer 1 (Fig. 3b); at the piezo layer 2 electric potential of 0 V is applied. For the second case of the FEM analysis electric potential (V_{in}) is applied to the upper surface and ground is applied to the bottom surface of the piezoelectric layer 2 (opposite from the first case of analysis); the piezoelectric layer 1 is inactive (0 V is applied). The piezoelectric actuator model is discretized with a total number of 11619 tetrahedral finite elements (Fig. 3c). To investigate the behavior of the trimorphic piezoelectric actuator when different values of input voltage are applied, nonlinear time-dependent finite element analysis is done. The applied voltage ranges from 0 to 230 V, with an increment value of 5, i.e. Vin=0:5:230 V (for both investigated cases). Some of the results of FEM analysis for first and second investigated cases are shown in Fig. 4 and Fig. 6 respectively. The obtained values of piezoelectric actuator tip displacement with respect to applied input voltage are shown in form of graph (Fig. 5 for first and Fig. 7 for the second investigated case); the displacement values are shown for evaluation point (Fig. 3b). Based on the results it could be concluded that the behavior of the piezoelectric trimorph actuator is nearly linear i.e. that the output displacement represents the nearly linear function of the applied input voltage.

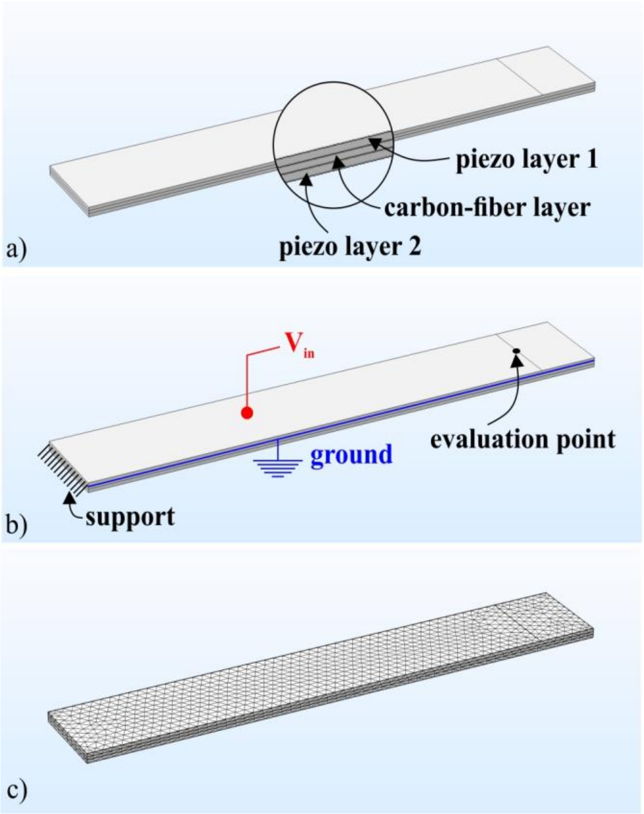

Fig. 3 *3D model of piezoelectric trimorph actuator for FEM analysis: a) arrangements of piezoelectric actuator layers; b) boundary conditions (for activating piezo layer 1); c) discrete model*

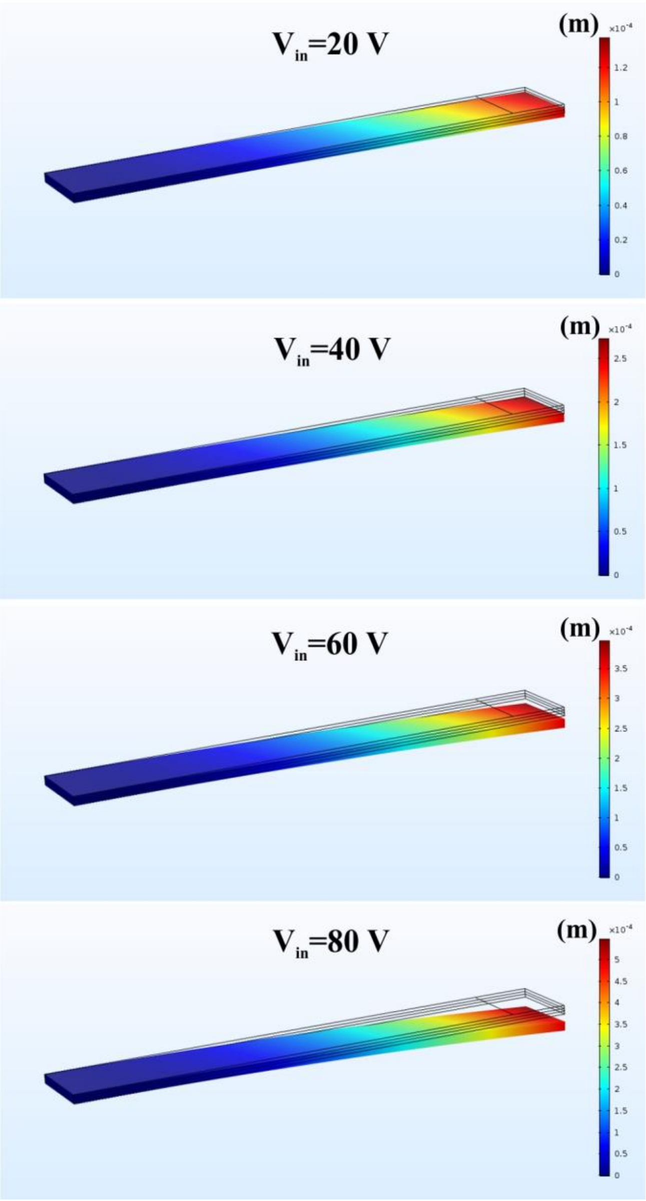

Fig. 4 *FEM results of deformation behavior of the trimorph piezoelectric actuator when different values of input voltage are applied at piezoelectric layer 1*

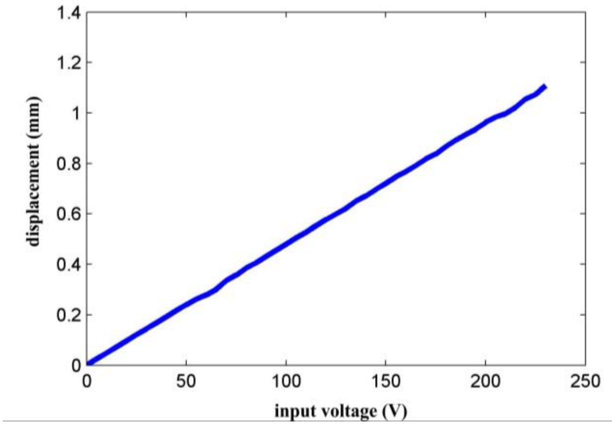

Fig. 5 *FEM results for obtained values of piezoelectric actuator tip displacement (evaluation point) with respect to applied input voltage at piezoelectric layer 1*

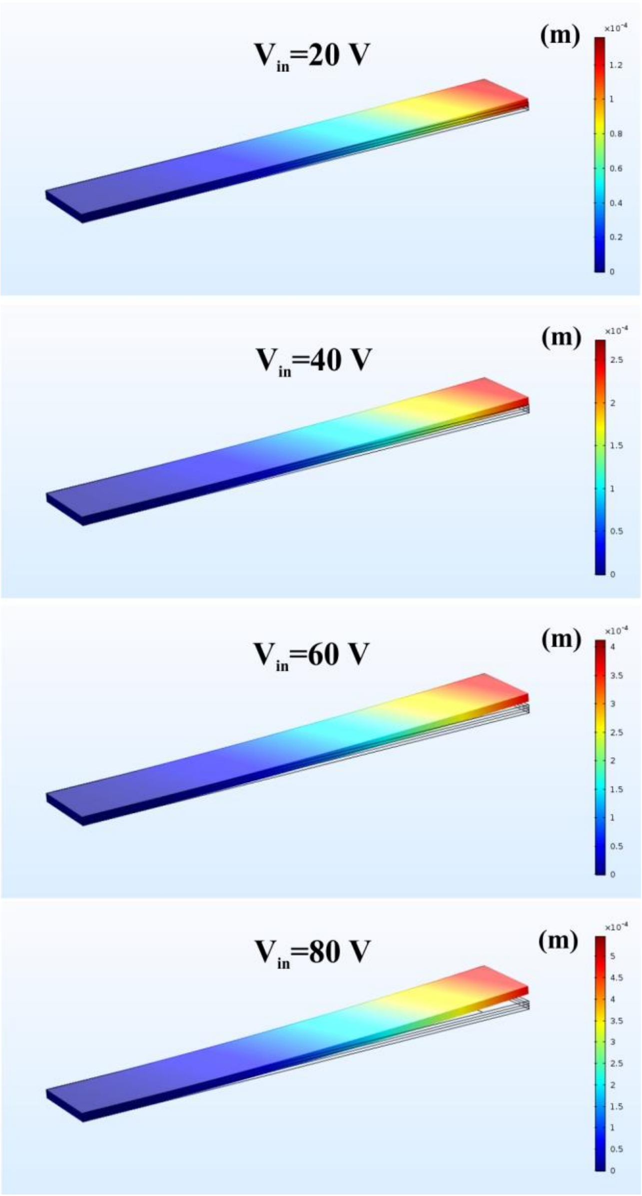

Fig. 6 *FEM results of deformation behavior of the trimorph piezoelectric actuator when different values of input voltage are applied at piezoelectric layer 2*

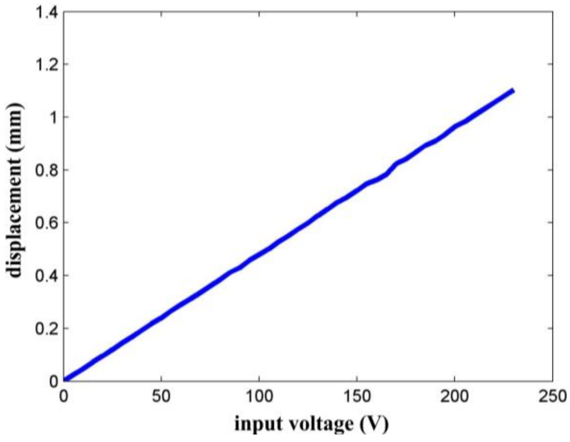

Fig. 7 *FEM results for obtained values of piezoelectric actuator tip displacement (evaluation point) with respect to applied input voltage at piezoelectric layer 2*

4 EXPERIMENTAL INVESTIGATION OF THE THRIMORPH PIEZOELECTRIC ACTUATOR DEFORMATION BEHAVIOUR

To verify the FEM model and analysis results, deformation behavior of the trimorph piezoelectric actuator has been experimentally investigated (Fig. 8). The experimental set up included: piezoelectric actuator, displacement sensor, power supply and data acquisition device (HBM Spider) to obtain the measurement data. The piezoelectric actuator was fixed at one end and displacement sensor was placed at the actuator tip (Fig. 8), where displacement was measured in direction of actuator deformation (perpendicular to actuator width). The displacement of the piezoelectric actuator was measured at the same location as the evaluation point in the FEM analysis (Fig. 3b) where the experimental investigations correspond to FEM simulations shown in Fig. 4. Measurement was done for different values of input voltage: 20 V, 40 V, 60 V and 80 V. The results of measurement are shown in Fig. 9 in form of a graph. The experimental results confirm that the behavior of the trimorph piezoelectric actuator is nearly linear i.e. that the output displacement of the actuator tip is a linear function of the applied input voltage. Fig. 10 shows a comparison between results obtained with FEM analysis and experimental investigations. Although there is some moderate difference between results it could be concluded that the FEM model is accurate enough.

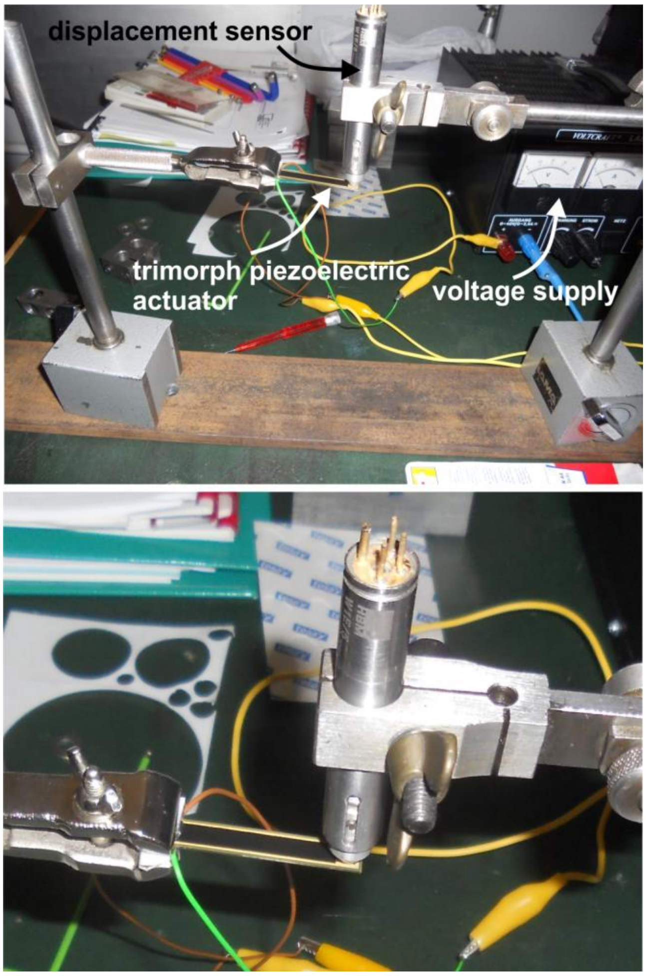

Fig. 8 *Experimental measurements of the trimorph piezoelectric actuator output displacement when different constant values of input voltage are applied*

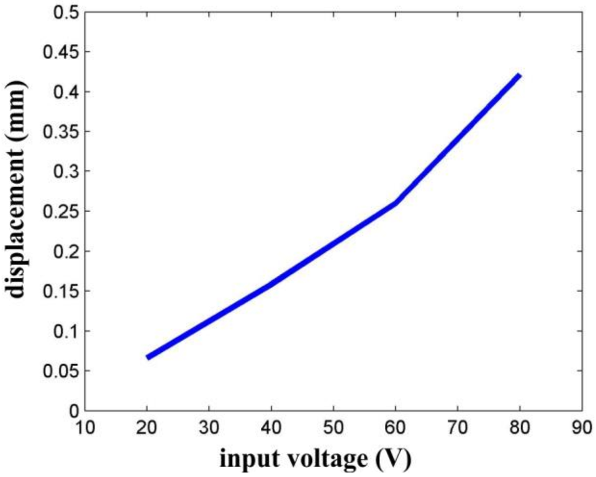

Fig. 9 *Experimentally obtained values of trimorph piezoelectric actuator tip displacement with respect to applied input voltage at piezoelectric layer 1*

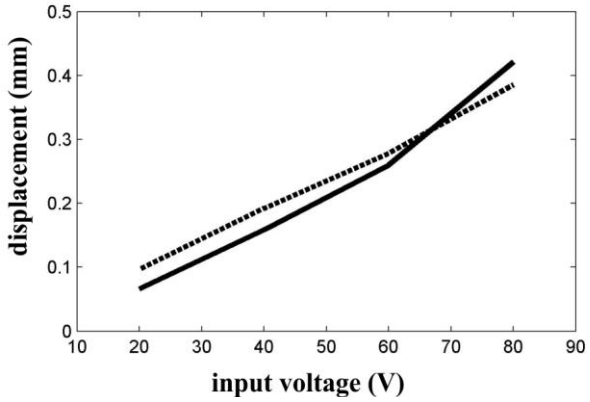

Fig. 10 *Comparison between measured and results obtained with FEM analysis for displacement of piezoelectric actuator tip*

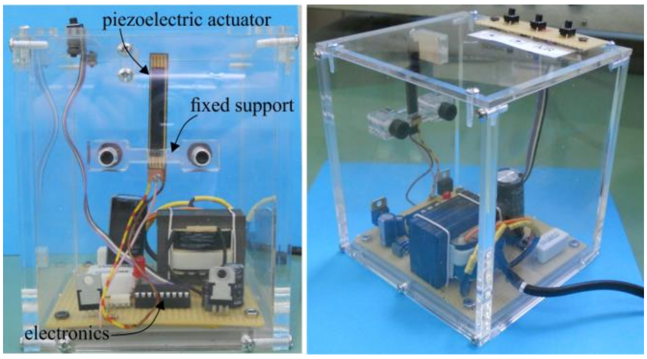

Fig. 11 *Trimorph piezoelectric actuator with electronics for applying the input voltage with different frequencies*

Additionally, the dynamic behavior of the trimorph piezoelectric actuator has been experimentally investigated when the input voltage is applied with different frequencies. The piezoelectric actuator was fixed at one end and additional electronics was built to apply the input voltage with desired frequencies (Fig. 11). The experimental set up included: piezoelectric actuator with electronics (Fig. 12a), vibrometer for frequent measurement of actuator tip displacement (Fig. 12b), amplifier for signal conditioning

(Fig. 12c), NI DAQ card for signal acquisition and PC with virtual instrumentation to display and save the measurement data (Fig. 12d). Fig. 13 show the dynamic response of the piezoelectric actuator when the input voltage is applied at 1Hz (Fig. 13a) and 13 Hz (Fig. 13b).

Fig. 12 *Experimental investigation of piezoelectric dynamic behavior: a) measurement set-up b) vibrometer; c) amplifier for signal conditioning with data acquisition card; d) virtual instrumentation for display of measuring results and saving the data*

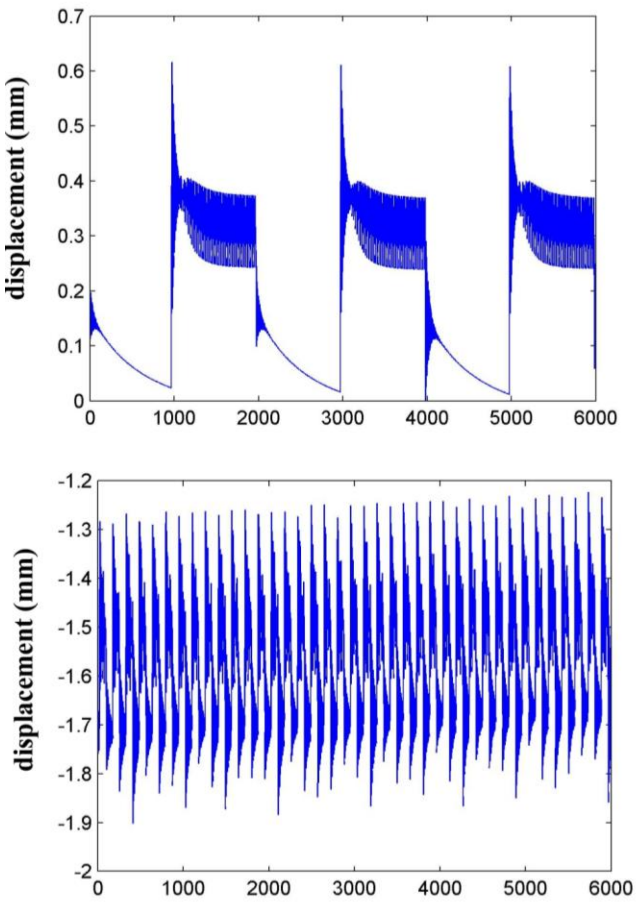

Fig. 13 *Dynamic response of the piezoelectric actuator when input voltage is applied at: a) 1 Hz; b) 13 Hz*

5 CONCLUSIONS

In this paper, the deformation behaviors of the trimorph piezoelectric actuator is investigated for different values of the input voltage (ranging from 0 to 230 V). The FEM analysis is done and it was shown that the actuator has nearly linear characteristic; the relation of output deformation to applied input voltage is approximately linear.

The experimental investigations also showed similar linearity where the results obtain by FEM and experimental measurement are in good agreement. Additionaly, the dynamic behavior of the piezo actuator was investigated by applying input voltage at different frequencies. Analytical analysis of the piezoelectric beam dynamic behavior can be sometimes complex, thus one possibility for prediction of the piezoelectric cantilever beam dynamic behavior is to use artificial neural network (ANN). The ANN can be trained with experimental data sets to predict accurately the trimorph piezoelectric actuator dynamic behavior. This method could provide a useful tool for easier design of piezoelectric elements for application in engineering systems, which will be explored in the future.

The presented results and model, in this paper, can be further used and applied to better understand the properties of piezoelectric materials and to optimally design trimorph piezoelectric actuators for different applications in transport vehicles.

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