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# PERFORMANCE ANALYSIS OF CONTINUOUS LINEAR MOTION OF SINGLE AND SERIES CONNECTED PIEZOELECTRIC ELEMENTS BY USING METHOD OF IMPACT DRIVE MECHANISM

**Kuscu Hilmi*, Kaya Ulas**

*Trakya University, Edirne, Turkiye*

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ABSTRACT

*IDMcan be defined as thetransformation ofsmall vibrations of a piezo element into continuous linear motion on a frictional surface by controlling the extension and contraction speed thus the impact force.In most of previous studies, longitudinal vibrations of piezo elements are employed as in [1], [2], [3] to obtain a continuous linear motion.*

*In this study, linear continuous motion characteristics of series connected piezoelectric (PZT) crystals are investigated both numerically and experimentally, when the method of the impact drive mechanism applied was driven by coupled transverse and torsional vibrations. For the experiments, PZT rectangular crystal bars are series connected with a neodymium magnet glued to the bottom end, and then positioned to a grinded smooth steel surface. The three test specimens were series connected one, two, and three-elements PZT-5X military grade single crystals, and the neodymium magnets were N38 grade coated with nickel. Before starting the tests, resonant frequencies of test specimens are calculated numerically by making harmonic analysis employing a finite element software (ANSYS) and tested experimentally by using the sweep characteristics of the signal generator. Triangular,and sine signal waves at resonance frequencies are applied for each test specimen at 220 Volts. Both the numerical and experimental results showed that the top-end deflection, strain energy, the impact force thus the linear velocity increases by increasing the number of PZT crystal elements of a test specimen.*

*The research conducted herecould be supportive when designing nano/micro-scale positioning actuators anddriving systems for different kinds of high technology applications.*



## 1. INTRODUCTION

Piezoelectric materials (PEM) are frequently used in micro-robotics applications to position or move intended objects with micro-scale accuracy. The mechanisms for large stroke linear actuation of PEM's includes inchworm type actuators, and the actuators driven by employing method of impact drive mechanism (IDM).

The inchworm-type actuators are the combination of three or more PZT elements electrically isolated from each other in which some of them is the driving unit and the others are the clamping units. The simplest form of the inchworm mechanism and its electricity order is shown in Fig. 1 [1].

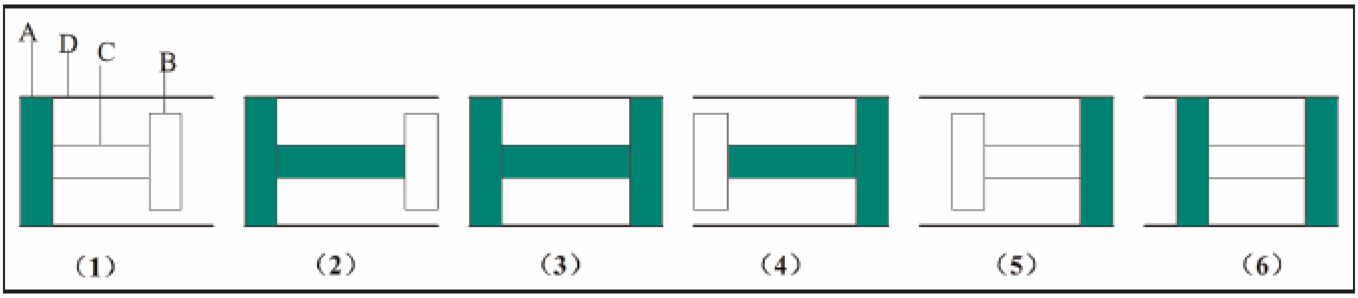


*Fig. 1. The inchworm mechanism and electricity order in one cycle [1]*

* Corresponding author. E-mail: taskintez@gmail.com

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Here, three PZT elements are connected or glued to form an H-shape and positioned to a precisely machined channel that has wideness of several μm's more than the vertical two elements. The two vertical elements are the clamping units while the horizontal one is the driving unit. When the first vertical or clamping element elongates with induced electricity, it touches the walls of the channel and creates a friction thus fixes itself. It follows with the horizontal or the driving one elongation with electricity which changes the position of second clamping element. Then, the electricity is applied to the second clamping unit to fix itself in its new position, and finally, the first clamping unit and driving unit are freed from electricity, thus both move in the direction of the second clamping unit. This cycle provides linear movement of an inchworm actuator through precise machined channel. The disadvantage of the inchworm actuators is the precisely machined channel will be deviate from its dimension with temperature fluctuation, that can prevent clamping units to fix themselves.

On the other hand, the mechanisms which works based on the IDM principle areutilizing friction and inertial force caused by rapid deformations of piezoelectric elements [2]. A mechanism based on IDM includes a piezo element, the main object, and a weight glued to each other and placed on a flat surface as in Fig. 2. By controlling the contraction and extension speed of a piezo element an impact force which is larger than the frictional force between the flat surface and the main object can be created and this provides the movement of complete body.

In literature IDM based mechanisms are driven by longitudinal vibrations as in Fig. 2 [2]. In this study the transverse vibrations and bending induced forces are employed to actuate the complete IDM based mechanism.PZT bars are combined with a frictional element (Neodymium magnet) and placed on a fixed and grinded steel surface. The important point is that to provide a smooth linear motion of the test specimen, the reaction forces created by the magnet must have an optimum value; If below the optimum value then the impact of vibrations separates the contact of the magnet and smooth steel surface thus prevent the motion of test specimen if above the optimum value this time the impact of vibrations could not be able to move the specimen or limits the motion.

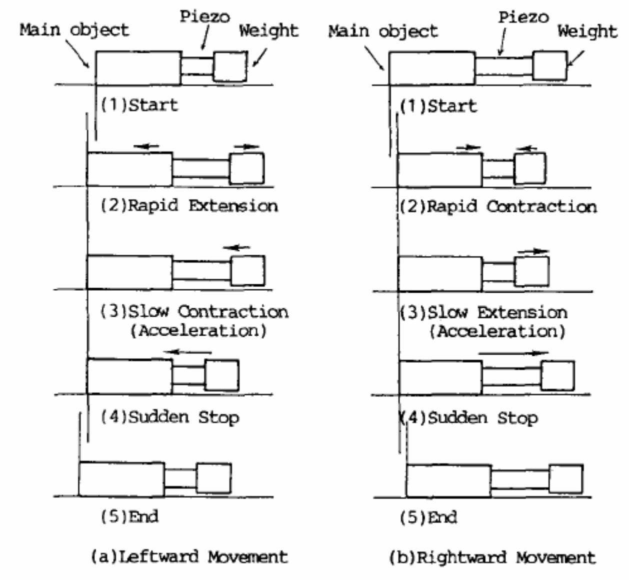



*Fig. 2. IDM based mechanism movement principle [2].*


*Fig. 3. Test Setup*

## 2. THE EXPERIMENTAL SETUP

Based on the method of IDM principle andtransverse vibrations actuated linear positioner concept, a test model is constructed which is shown in Fig. 3. The main components are:

a) Flat steel bar: An AISI-1040 steel bar with a dimension of Width=40, Height=20 mm, and Length=150 mm is prepared as a rail. First of all, its one of surface that has dimension of 40x20x150 mm is grinded to decrease surface roughness, and to provide a smooth movement of test specimens.

b) Test specimens: Three test specimens with neodymium magnet at one end are prepared for the tests. These are with,single PZT-5X grade PZT material, series connected double PZT-5X grade materials and triple PZT-5X grade materials as shown in Fig. 5. The dimensions of each PZT crystalare 4x4x10 mm rectangular bar.

c) Electrical supply components: Signal generator, Amplifier, operational amplifier, and transformer. The flow diagram of current to test specimens are defined in Fig. 4.

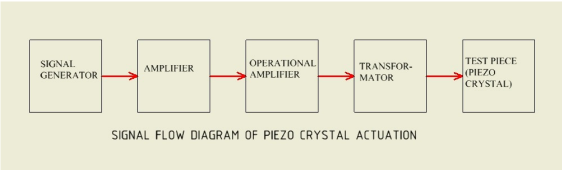
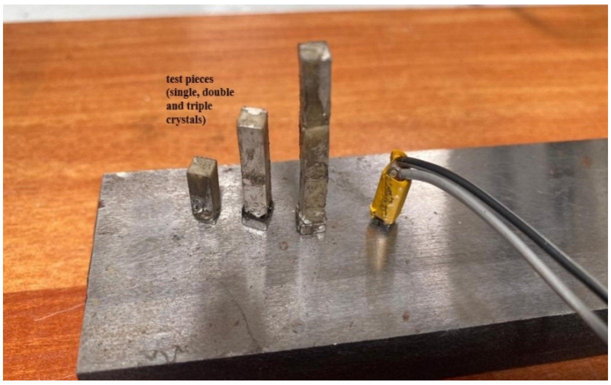



*Fig. 4. Signal flow diagram for PZT material actuation*



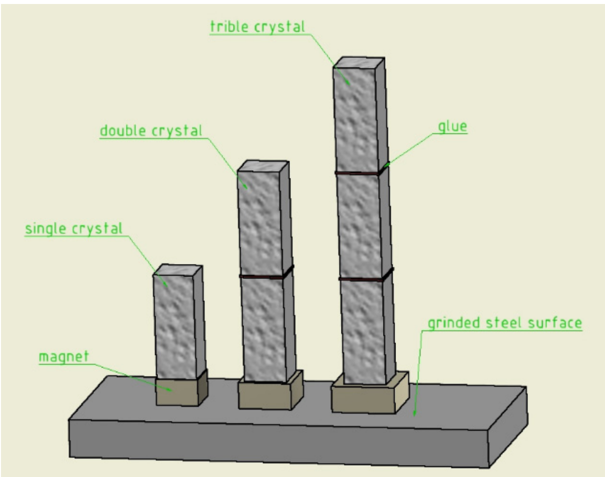




*Fig. 5. Test specimens: single crystal, double crystals, and triple crystals*

The signal generator has the ability to generate signals with frequency range of 0-25 MHz, and voltage range 2-20 Volts. It has sweep characteristics which is valuable to find the resonance frequency, and also has the arbitrary signal waves generation capability. The amplifier adds 35 Watts of energy to signal by increasing the current to 3 Amperes, and the voltage to 12 Volts. Then the operational amplifier increases voltage value to supply the Transformer input. Transformer has two options for the output: 110 Volts and 220 Volts. In these experiments 220 Volts is applied to the test specimens.

d) Measurement Unit: Laser sensor, Programming logic controller (PLC), and PC are employed for measurement as in Fig. 6.

For the measurement of displacement, a laser distance sensor (Fig. 7) is employed. The technical specifications of the laser sensor can be investigated from Table 1.

e) Oscilloscope: An oscilloscope measures the supplied voltage and frequency to the test specimens.

***Table 1** Laser Sensor Properties*

| | |
|---|---|
| ***Measuring range*** | *10 mm ... 20 mm* |
| ***Target*** | *Natural objects* |
| ***Repeatability*** | *1 µm 1) 2)* |
| ***Linearity*** | *± 10 µm 3)* |
| ***Response time*** | *≥ 2 ms 4)* |
| ***Measuring frequency*** | *≤ 2 kHz* |
| ***Output time*** | *≥ 0.5 ms* |
| ***Light source*** | *Laser, red visible red light* |

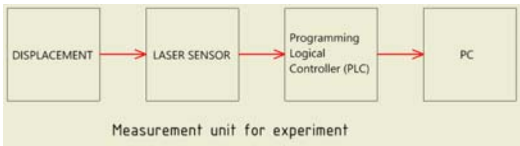



*Fig. 6. Measurement unit's signal flow diagram for the experiment*


*Fig. 7. Laser Sensor*

### 3. FEM CALCULATION AND EXPERİMENTAL RESULTS

The calculated results by using FEM Software for triple PZT crystal test specimen presented in Fig. 8, and Fig. 9. Harmonic analysis result is defined in Fig. 8, and the resonance frequency is 24 KHz. Finally, Fig. 10 shows the measured displacement-time graph on the test rig. It travels 7 mm in 980 milliseconds.

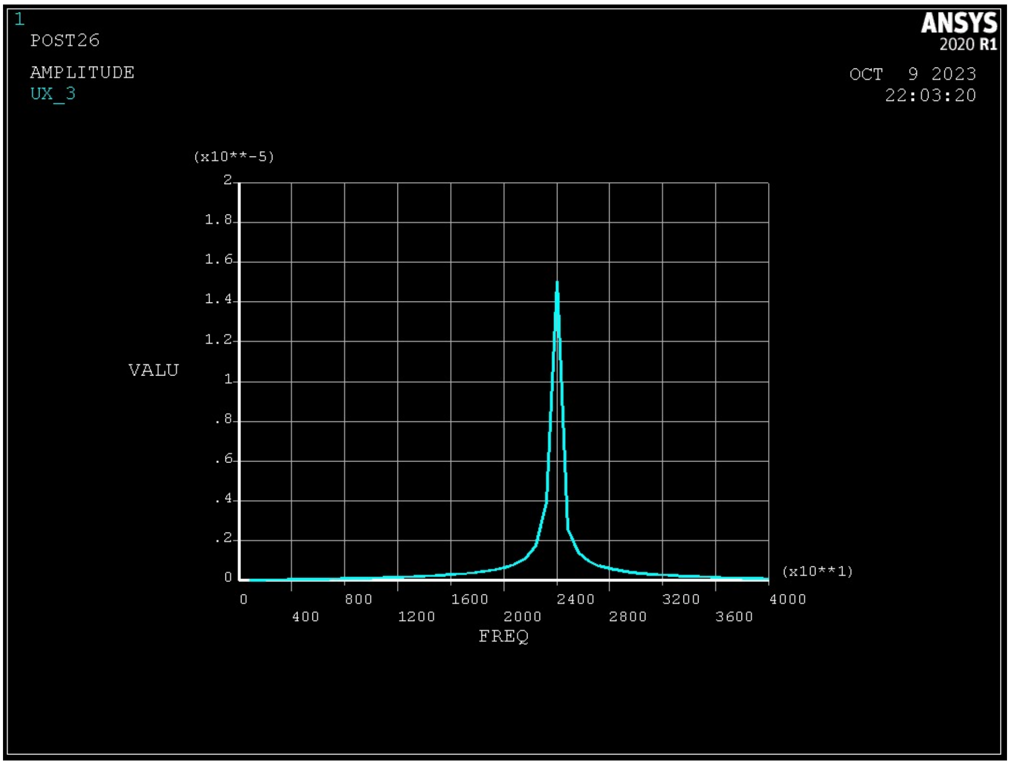



*Fig. 8. Series connected three PZT crystal harmonic analysis in FEM software at 220 V Voltage*

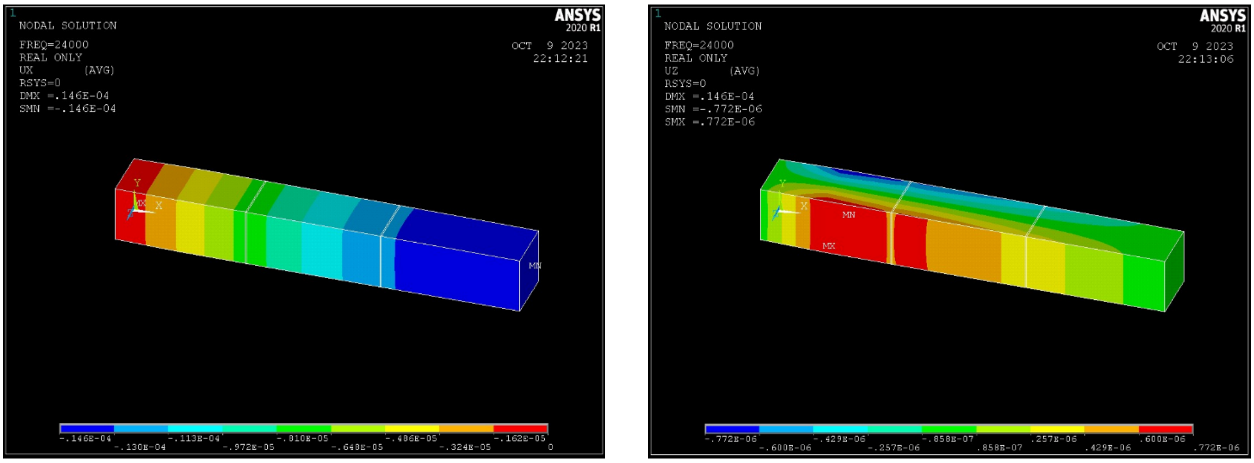



*Fig. 9. Longitudinal (x-direction) and transverse deflection (z-direction) analysis of triple PZT crystal test specimen at resonance frequency and 220 V Voltage*

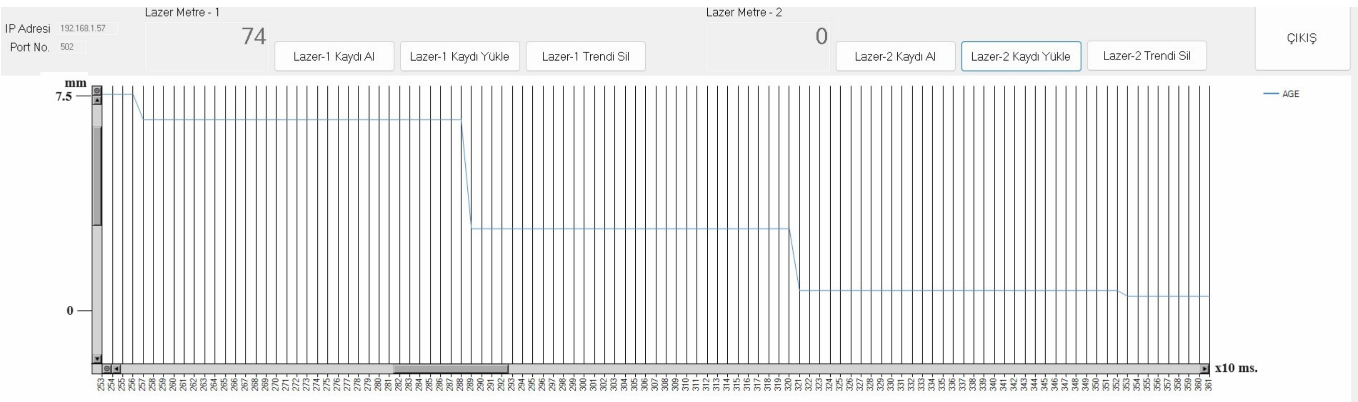



*Fig. 10. Triple PZT crystal test specimen's Experimental linear displacement-time result at 220 V Voltage*

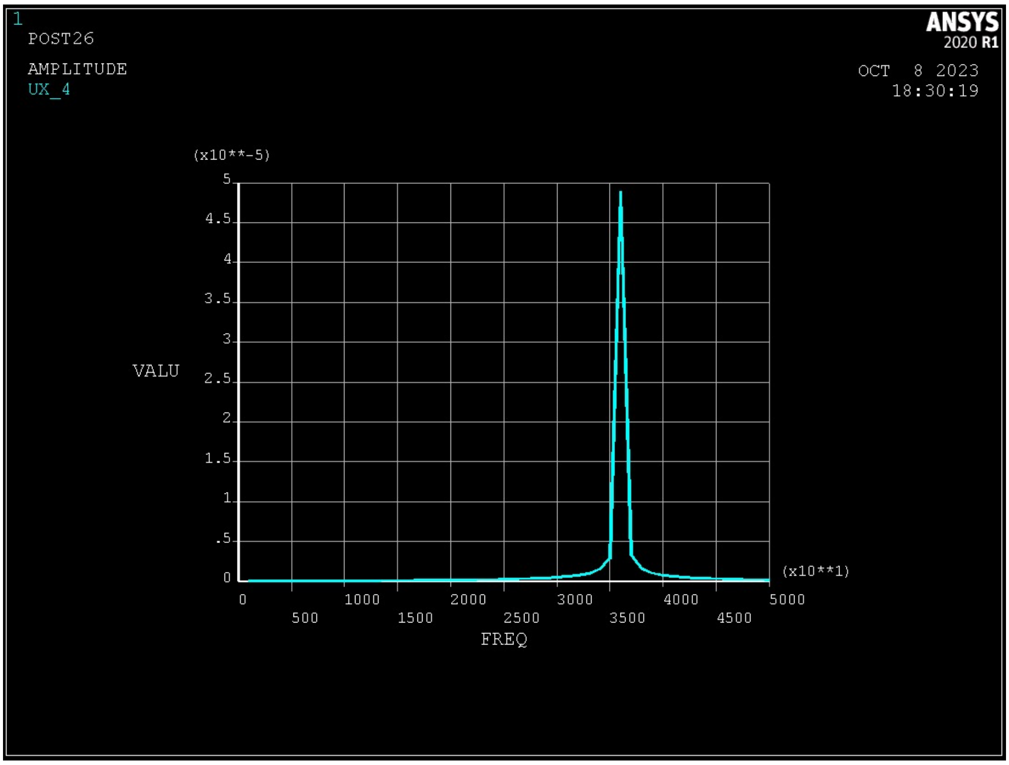



*Fig. 11. Series connected double PZT crystal harmonic analysis in FEM software at 220 V*

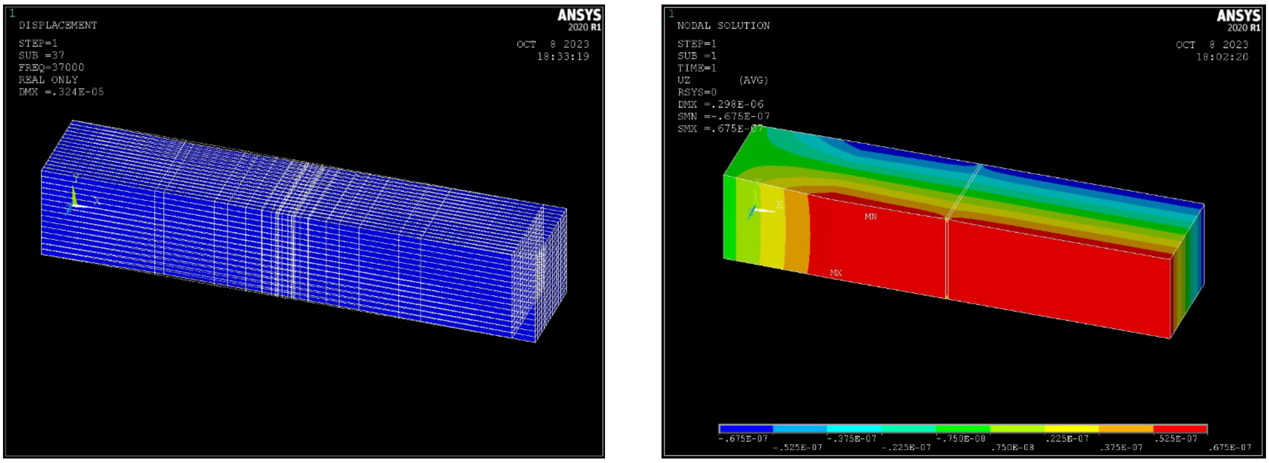



*Fig. 12. Longitudinal (x-direction) and transverse deflection (z-direction) analysis of double PZT crystal test specimen at resonance frequency and 220 V Voltage*

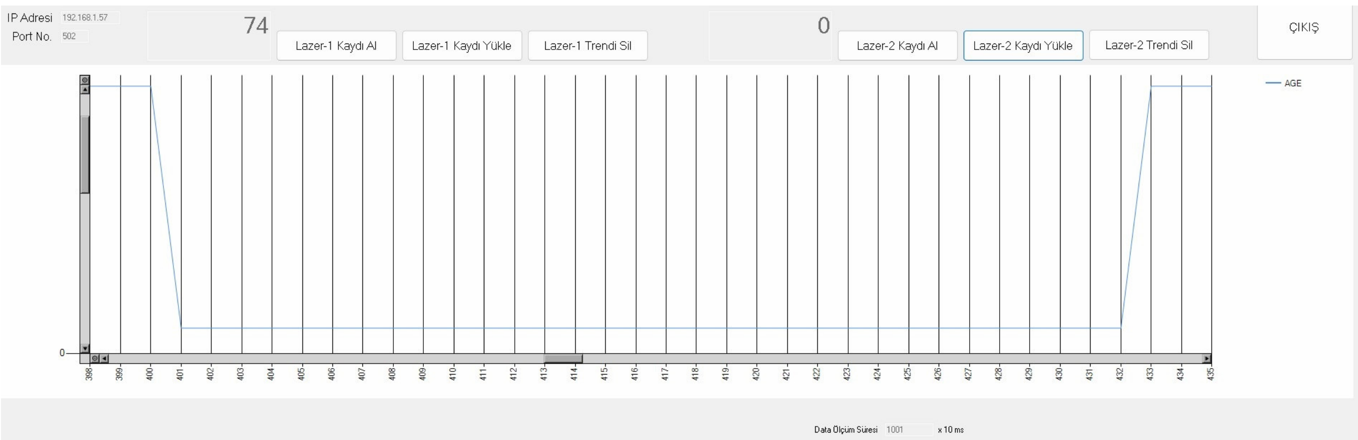



*Fig. 13. Double PZT crystal test specimen's Experimental linear displacement-time result at 220 V Voltage*

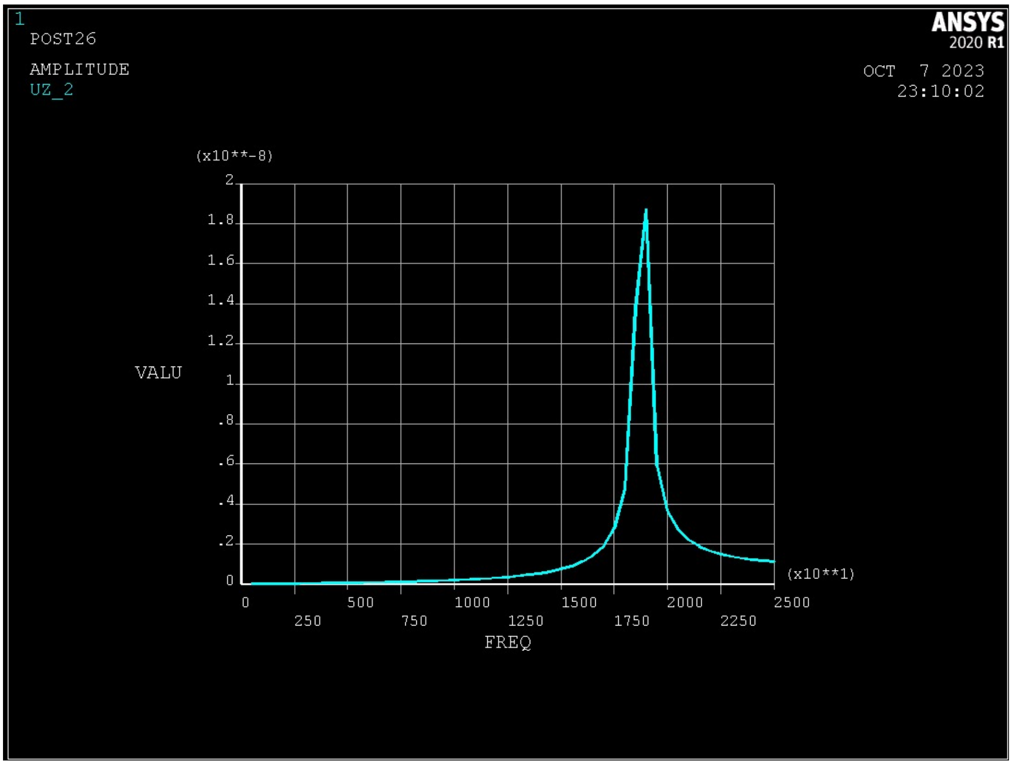



*Fig. 14. Single PZT crystal harmonic analysis in FEM software*

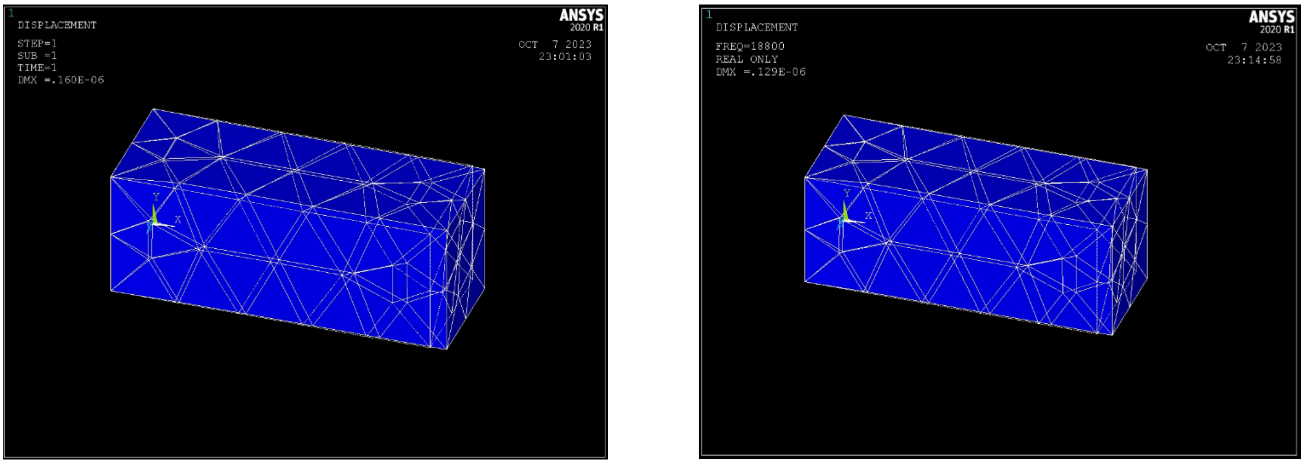



*Fig. 15. Longitudinal (x-direction) and transverse deflection (z-direction) analysis of single PZT crystal test specimen at resonance frequencyand 220 V Voltage*

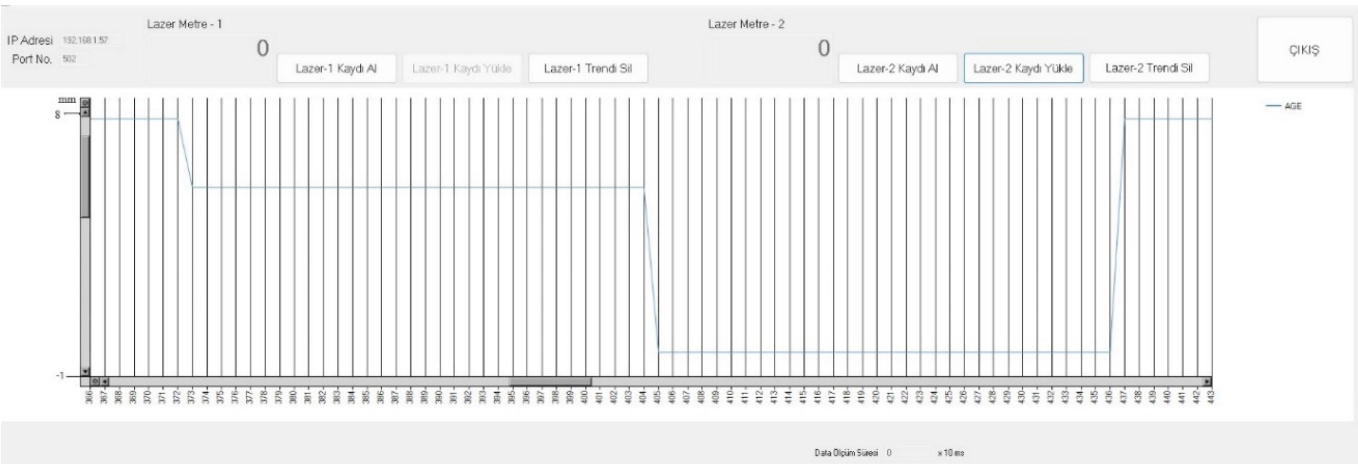



*Fig. 16. Single PZT crystal test specimen's Experimental linear displacement-time result at 220*

The calculated resonance frequency of double crystal test specimen in Fig. 11 is 36 KHz. But the sweep characteristics of signal generator showed that the resonance frequency is around 22 KHz. From Fig. 12, it can be concluded that the deflection in x- or z-directions decreases with decreasing the number of PZT crystals in a test specimen.

The most remarkable point is that the displacement-time graph in Fig. 13 indicates that linear speed of double crystal test specimen is faster than the triple one.

The FEM calculated resonance frequency of single crystal test specimen is around 18 KHz. as in Fig. 14. The experimental result for resonance frequency is around 16 KHz. In Fig. 15 the deflections in x- and z-directions at resonance frequency are shown. It indicates that the deflection decreases with decreasing the number of PZT crystals in a test specimen.

Fig. 16 shows that the linear speed of single PZT crystal is lower than the double one, but higher than the triple one.

## 4. CONCLUSION

Each test specimen is numerically analyzed to determine the resonance frequency, then at the resonance frequency the longitudinal and transverse deflections are calculated by using the FEM software. Finally, all three-type test specimenlinear displacement-time graph is measured based on the method of IDM. The measured and FEM solutions arepresented in Table 2-4.

***Table 2*** *Triple crystal test specimen results*

| *Triple Crystal Experimental and FEM Solutions* | | | |
|---|---|---|---|
| *Resonance Frequency (fem result-Experimental Result)* | *Longitudinal Deflection in x-dir. (fem result)* | *Transverse Deflection in z-dir. (fem result)* | *Linear Velocity on test rig* |
| *23 KHz-24 KHz* | *0.0146 mm* | *0.772 μm* | *7.14 mm/s* |

***Table 3*** *Double crystal test specimen*

| *Double Crystal Experimental and FEM Solutions* | | | |
|---|---|---|---|
| *Resonance Frequency (fem result-Experimental Result)* | *Longitudinal Deflection in x-dir. (fem result)* | *Transverse Deflection in z-dir. (fem result)* | *Linear Velocity on test rig* |
| *36 KHz-22 KHz* | *0.0324 mm* | *0.0675 μm* | *20 mm/s* |

***Table 4*** *Single crystal test specimen results*

| *Double Crystal Experimental and FEM Solutions* | | | |
|---|---|---|---|
| *Resonance Frequency (fem result-Experimental Result)* | *Longitudinal Deflection in x-dir. (fem result)* | *Longitudinal Deflection in z-dir. (fem result)* | *Linear Velocity on test rig* |
| *18 KHz-16 KHz* | *0.00019 μm* | *0.000129 μm* | *9.3 mm/s* |

The experimental and FEM calculation results concludethat with increasing the number of PZT crystals in a test specimen, the deflection and the resonance frequency increases.And the remarkable point is that the linear speed of double PZT test specimen is faster than the single and triple PZT test specimens on the test rig. This means the vibration of PZT crystals damps each other, when there are more than 2 PZT crystalsin a test specimen. Finally, the longitudinal deflection is far more than the transverse ones.Thus, it is clear from the results, for IDM based mechanisms Longitudinal vibration is more efficient than the transverse ones.But in case of precise positioning, transverse vibrations could be more accurate, because of small deflections.

## 5. REFERENCES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