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INCREMENTAL PIEZOELECTRIC MOTOR, WITH ACTIVE FORCE IN NORMAL STATE – POSITIONING ERROR STUDY

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Această lucrare prezintă rezultatele unor teste asupra unui motor piezoelectric de tip „inchworm" cu scopul acumulării de date privind erorile de poziţionare generate în cursul funcţionării, pentru a putea fi determinate strategiile optime de conducere. Au fost emise ipoteze privind fenomenele descoperite şi au fost formulate strategii de conducere care să poată compensa abaterile cât mai eficient. Motorul realizat în cadrul unei teze de doctorat a fost patentat în România [1]. Acţionarea se face cu ajutorul a trei stive piezoelectrice comandate într-o secvenţă specifică. Privind caracteristicile acestui motor sunt de menţionat următoarele: domeniu de deplasare 20mm, pas de lungime variabilă 0..20µm, forţă de ~70N în mişcare şi ~140N în stare normală (nealimentat), viteză de deplasare peste 13500µm/s.

This paper presents the results of a set of tests on a piezoelectric "inchworm" motor with the purpose of accumulation of data concerning the positioning errors generated while moving, in order to devise optimal command and control strategies. Hypotheses were postulated concerning the found phenomena and appropriate command and control strategies were formulated in order to best compensate for errors. The motor, designed and built as part of a PhD thesis, received a Romanian patent [1]. The motor is run by three primary piezoelectric stacks through a specific command sequence. Concerning the characteristics of this motor are worth mentioning: 20mm movement domain, variable step length 0..20µm, ~70N movement force and ~140N in normal state (not powered), over 13500µm/s speed.

Key words: piezoelectric actuator, linear motor, incremental movement, positioning errors

1. Introduction

In precise positioning, various methods and constructive solutions are used in order to obtain the highest accuracy of positioning on the longest possible positioning domain and with the largest active force. The present paper presents the results of a movement test on a prototype incremental motor of "inchworm"

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type that contains three primary piezoelectric stacks and an interpretation of the results is given.

Movement principle for this type of motor is known for a long time, pattents being issued since 1975, such as the one of William G. May [2]. Recent studies on this type of movement are being conducted at the current time, such as the ones published by Jian Li [3] in 2005, Chanwoo Moon [4] in 2006 and Haiwei Lu [5] in 2009.

The movement of these devices is obtained as the consequence of a sequence of clamping, releasing and advancing and retracting of sub-assemblies contained within.

2. The motor's internal structure and the way of generating movement

This prototype motor was designed and built as part of a PhD thesis called "Advanced mechatronic positioning system with piezoelectric actuators" and for which a patent was applied to and given by O.S.I.M. [1].

Inside the motor's shell there are two clamping systems implemented by two clamps squeezing the motor's shaft, one of them fixed to the shell and a mobile one who can move also dragging a shaft, movement obtained through displacement generated by one of the piezoelectric stacks contained within.

A section through this motor can be seen in figure 1. The mobile clamping system is formed by the piezoelectric stack (1), the four jaws clamp (2) that is maintained closed by the stack (3) of disc-springs and the cup (4) inside of which are all assembled. The clamp can be opened by the displacement of the piezoelectric stack (supplied with a voltage of up to 1000V) that pushes against the spring stack. When these are compressed, the force that maintains the clamp closed decreases and it opens. The advantage of this motor comes from this very fact, claimed in the patent, that an active force is maintained when no power is applied.

Two more piezoelectric stacks (5) and (6) have the purpose of opening the immobile clamping system and correspondingly to ensure the advance of the mobile system when commanded. The three primary stacks type „P-016.15H " are supplied by high voltage and high power amplifiers type "E-472.20" (1000V/550W). Three command signals are applied in an established order, as seen in Figs 2 and 3 in order to obtain an incremental movement of the motor's shaft (7) with respect to the motor's shell. In order to change the direction of the movement, the reversal of commands generation order is required.

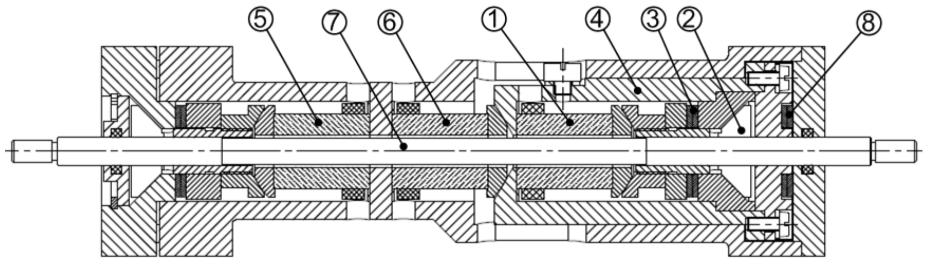

Fig. 1. Longitudinal section through the incremental piezoelectric motor with active force in normal state

The mobile clamping system as a sub-assembly moves inside the motor's shell with the help of the piezoelectric stack (6) who pushes the cup (4) against the spring-disc stack (8), these ensuring the return to the initial position when the command stops.

The stationary clamping system is constructive by similar to the mobile one, having the same working principle. The difference is that it cannot move and thus can maintain the shaft's position.

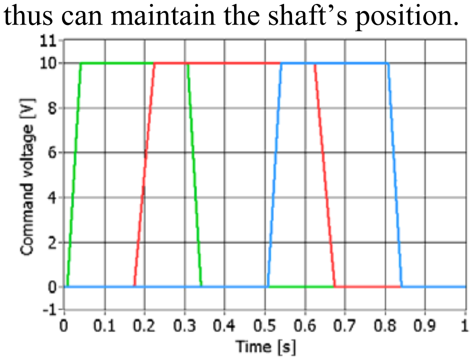

Fig. 2. Advance movement commands

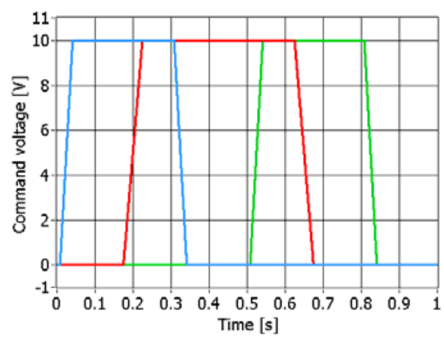

Fig. 3. Reverse movement commands

The generated commands have a maximum value of 10V because this is the level required by the amplifiers in order to give the 1000V output for the stacks. These signals can be seen in Figs. 2 and 3, green for the stationary clamping system stack, red for advance and blue for the mobile clamping system stack. As seen, the difference consists only in the reversal of the commands order.

3. The experimental setup for the motor prototype and the experimental results

The experimental setup, as seen in figure 4, is made of the motor (1) locked on a base and a digital comparator (Millitron 1202D) (2) with it's inductive probe (3).

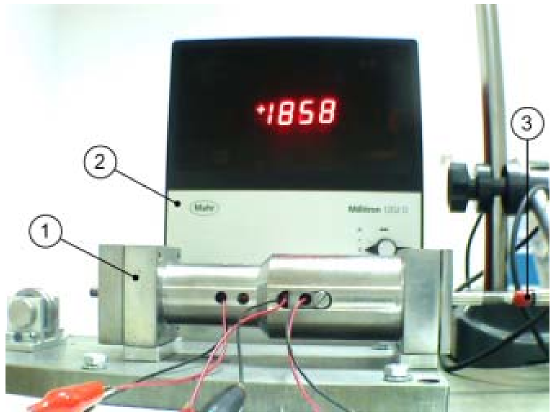

Fig. 4. The experimental setup for the incremental piezoelectric motor with active force in normal state

The generation and acquisition of the signals was made through a specially designed program in the LabView development environment and some data acquisition boards [7].

The motor was not loaded during the tests and was allowed to run as such.

In figures 5 and 7 are shown stepping sequences for forward and backward movement, respectively, and in Figs. 6 and 8 are presented selections of these movements, corresponding to a single step.

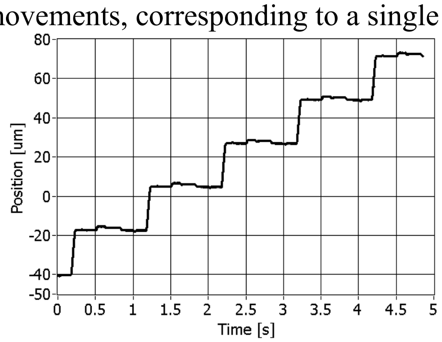

Fig. 5. Five steps forward

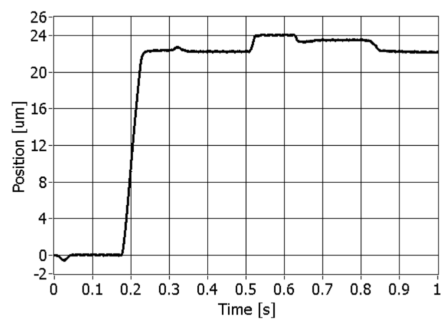

Fig. 6. One step forward

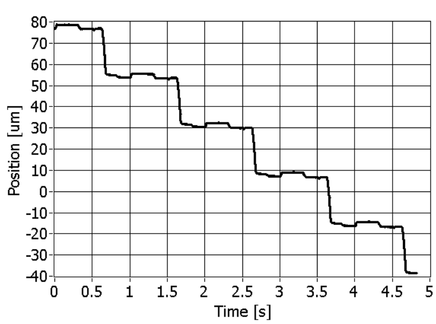

Fig. 7. Five steps backwards

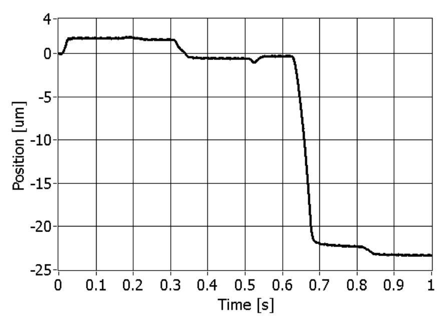

Fig. 8. One step backwards

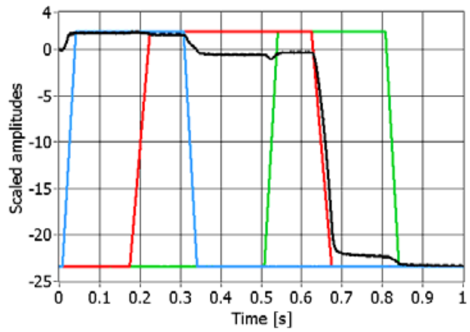

Fig. 9. One step backwards and the correspondent commands

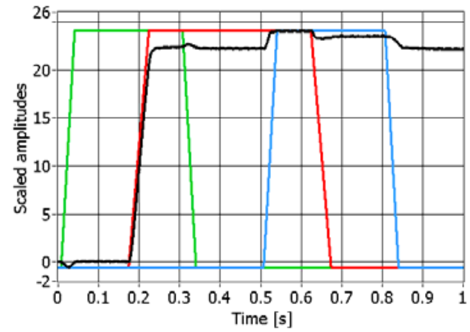

Fig. 10. One step forward and the corresponding commands

Another set of measurements was made for the purpose of determining the relation between the level of the voltage used to command the advance piezoelectric stack and the final step size.

For the purpose of obtaining the most relevant data with a minimum of test trials, a restricted set of command values was chosen. The set of voltage values used in order to supply the motor is: 0, 5, 10, 25, 50, 100, 250, 500, 1000 V and it allows for a better study of the motor's behavior at small step sizes comparable with expected play between the parts.

In Figs. 11 and 12 is shown the correlation between the voltage values used to supply the advance stack and the values of the motion steps in two ranges: 0-1000V and 0-50V.

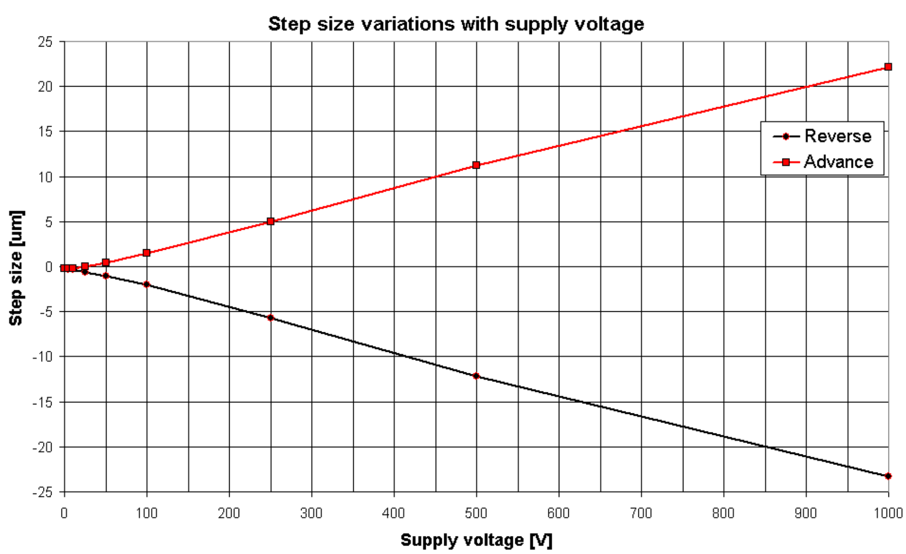

Fig. 11. Step value variations for forward and backward movement in 0-1000V range

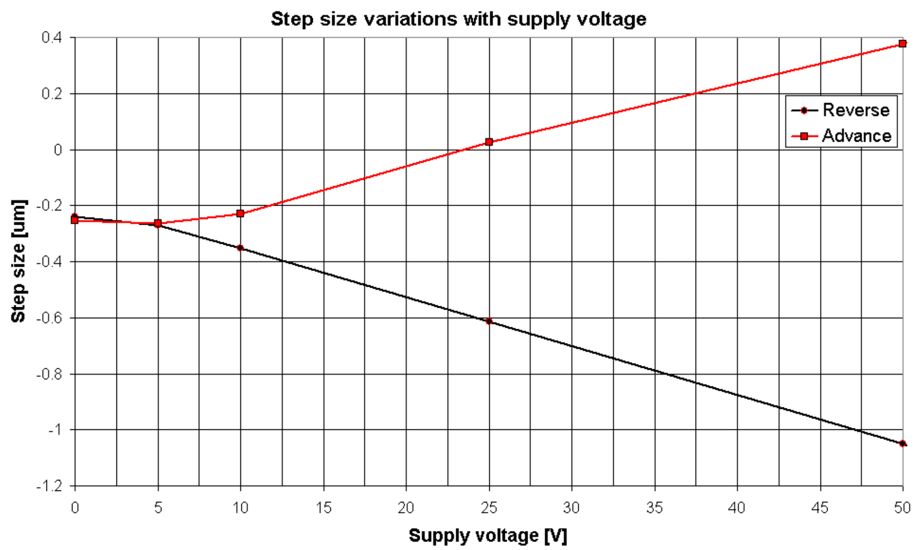

Fig. 12. Step value variations for forward and backward movement in 0-50V range

4. Interpretation of the experimental results

As seen in figures 9 and 10, the closing and opening actions of the clamps have an effect on the shaft's position. It can be noted also that the effect is stronger in the case of the mobile clamping system. The modification of the shaft position during clamping/unclamping is detrimental, but the value of this displacement also matters.

The differences in the effects of the two clamping systems on positioning could be explained by deficient parts manufacturing, assembly errors, or can simply be caused by wear of the materials. Also, the much larger influence on the mobile clamping system's side could be caused by its mobility as there is a small but important (by way of magnitude compared to the movement increment) play between the cup and its guide.

In the graphical representation of the figures 11 and 12 it can be seen that:

- the variation of the step size with command voltage is almost linear,
- size of steps on forward and backward movement for the same command voltage level are similar but slightly larger for backward movement,
- for a zero value of the forward command signal, regardless of the sense of the command, the motor is showing a residual backward movement.

The cause for the motor's residual movement could not be determined, but the following are taken into consideration:

- minor manufacturing defects of the motor's shaft, as seen in figure 13, or for other components,
- expected wear as result of the intermittent contact between moving parts,
- the existence of a mechanical hysteresis in the process of clamping/unclamping

Fig. 13. Defects on the surface of the motor's shaft, caused by the manufacturing process and visible as transversal striations

Taking into consideration the working principle of this motor and the particular constructive solution, two main command and control strategies can be imagined:

- one in which the target position is reached generating steps of constant appropriate length, steps calculated on the base of the results presented in figure 11,
- another where steps of any length are executed until the position of the shaft is in the vicinity of the target point and then, maintaining the mobile clamping system clamped and the stationary one open, the final precise positioning can be achieved by means of classical active

control such as a PID algorithm applied to the advance piezoelectric stack.

The first command and control strategy allows for energy saving because none of the piezoelectric stacks are powered when in position, but precision is sure to be less than optimal. The second strategy does offer better precision but requires permanent control of the power supplied to the motor.

5. Conclusions

The motor prototype works according to William G. May's [2] claims.

Motor movement is affected by other phenomena whose precise causes are to be determined by future research.

By implementing an appropriate command and control algorithm, very high positioning precision can be achieved (estimated at better than ±20nm using the particular instruments available for the testing of this prototype), the value of this precision being limited in practice only by the quality of the components, selected algorithm and the signal to noise ration that is to be found in the control system's reaction.

R E F E R E N C E S

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