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Main page
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EXPERIMENTAL STUDIES OF PRECISION DRIVES.

EXEMPLARY RESULTS OF NEW STUDIES

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Abstract:
The paper describes exemplary results of experimental studies of kinematic accuracy and efficiency of miniature linear drives. There was studied a unit of linear drive consisting of two-stage fine-pitch toothed gear and fine-thread screw gear, as well as a miniature drive with plunger electromagnet designed for valves. The presented results of the experimental studies allow one to evaluate the metrological properties of the applied testing devices as well as a complex evaluation of our own research abilities. However, measurements of the efficiency cannot be performed directly. It is necessary, in that case, to measure the powers, what is achieved by measuring the loads and displacements at the same time. This will be emphasised and developed in the paper.

Keywords: *testing of miniature drives, kinematic accuracy, miniature electromagnet, efficiency, precision drives*

1. Introduction

In the process of designing drives for precision and mechatronic devices, problems of kinematic accuracy, efficiency and resistance to motion of a whole drive or its units are very significant, yet hard to be evaluated in a quantitative way. It should be emphasised that the quantities mentioned here are varying together with the parameters of the drive operation; this mainly refers to the load and the speed. Reliable information concerning this subject can be obtained only thanks to experimental studies.

One of the research fields dealt with in the *Division of Design of Precision Devices* is studying kinematic accuracy of design members and units, which are used for building drive systems. The information achieved this way makes it possible to optimise design of these units, what can influence the operating parameters of the entire drive only in a positive way. The last few years, one studied, among other things, kinematic accuracy of miniature clutches [1], roller screws [2] and fine-pitch toothed gears [3,4]. However, studies of kinematic accuracy and efficiency of the entire drive unit have been carried out just recently, making use of the available testing equipment. The unit is a miniature linear drive.

Miniature plunger electromagnets can be also using as actuator in miniature drives. Studying dynamic characteristics of these electromagnets is very important from point of view of design of miniature fast linear actuators, but requires using of a lot of number

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measurements non-influence techniques. The general problem is elimination of interactions between test stand and miniature actuator under test.

2. Experimental studies – DC linear drive

While designing, the required design features of the drives are being formed with a full awareness. It is easy to prove that values of these features are only evaluated at this stage; the real values can be obtained exclusively by means of measurements performed on manufactured models of the drives. It is so, mainly due to the fact that it is very hard to foreseen the real values of friction coefficients, as existing in a mechanism. And these vary in a significant way, with respect to the surface quality of the collaborating members, developed velocity, load, etc. Screw gear, often applied in our drives, is a unit extremely sensitive to variations of the friction coefficient. It is a self-locking gear and it is applied to ensure a high resolution of the drive. Here is applied a fine thread with a small helix angle γ. In the linear drives manufactured by us, values of the angle γ were found within the range of *1,5° – 2,5°*.

One should be aware of high values of the friction coefficients in screw gears of linear drives. It is, among other things, due to the fact that their motion is reversible and intermittent. Our experience proves that the coefficient of kinematic sliding friction of a screw collaborating with a nut is of *0,1 – 0,2*, while the coefficient of static friction is of about *0,3*. As resulted by the above values, the efficiency of the screw gear practically does not exceed *0,2*, and can be even lower than *0,1*. It points out to the significant influence of the screw gear on the resistance to motion of the entire linear drive.

So, during operation of the gear, there can be observed variations of instantaneous efficiencies, mainly caused by variations of the friction coefficient (also by variation of locations of the points of direct collaboration in the drive mechanism). These can be relatively high changes of the instantaneous efficiency.

In tested unit, a *DC* motor drives a two-stage fine-pitch toothed gear ($z_1 = 10$; $z_2 = 42$; $z_3 = 9$; $z_4 = 50$; total velocity ratio $i_c = 4{,}2\times 5{,}56 = 23{,}3$; pitch module $m = 0{,}4\ mm$). The last wheel of the gear z_4 is seated on a cylindrical surface, coaxial with respect to the thread of a nut of the fine-thread screw gear. These two rotate together. A screw with the thread *M4×0,35*, collaborating with the nut, cannot rotate. It is due to a grooved shaft placed next to the screw in parallel. There is a pin fixed in a cylindrical part of the screw. Its axis is orthogonal with respect to the screw. This pin slides within the groove of the shaft. The range of linear displacement of the screw is of about *25 mm*.

In the first version of the drive (*A*), the screw thread was made by means of a screw die. There was no additional finishing applied. Since it was foreseen that in the case of such a technology, deviation of the screw positions could be considerably large, one manufactured also a second linear drive *(B),* where the screw thread was ground. A testing program for both units was identical, and it covered:

- measurement of kinematic deviation of the screw position in linear motion, for both direction of its displacement,
- measurement of average efficiency of the drive mechanism.

The kinematic deviation of the screw position was measured in function of the rotation angle (number of revolutions) of the *DC* motor. This means that inaccuracies of the whole kinematic chain of the drive, starting at the motor shaft, were the source of this deviation. Because of the reduction rate of the drive, the last members of the kinematic chain should have the biggest influence on the value of the kinematic deviation of the screw position. Therefore, it seems that assembly and manufacturing errors of the screw gear and the second stage of the toothed gear are the most significant. During measurements the screw was loaded with a force of $F = 2\ N$.

The kinematic deviation of the screw position in drive *A* (Fig. 1) varies over a large range, of about *90 μm* – while moving the screw out (course 1), and of about *140 μm* –while moving the screw in (course 2). Large values of the deviation are not surprise. However, the course of the chart seems to be surprising, since values of the deviation oscillate around a certain component, whose value varies over a large range along with variations of the screw displacements. Additionally, the charts intersect in few points. This results in a quite surprising chart of hysteresis, i.e. a deviation calculated as a difference between screw positions reached during both motion directions (forward and backward), corresponding to the same number of motor revolutions.

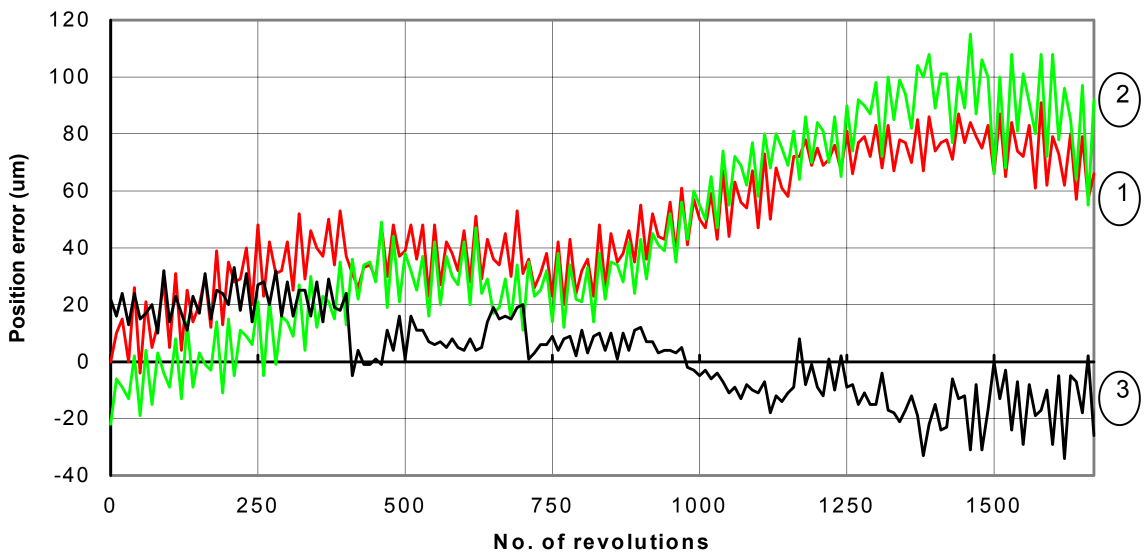


Fig. 1. Kinematic deviation of the screw position and hysteresis for drive unit *A*

The hysteresis has both positive and negative values form the range of *±30 μm* (*course 3*). One cannot observe oscillations of instantaneous values of the deviation around any constant component either. Only over the range of the screw displacements from about *6* to *20 mm* (from about *400* to *1250* revolutions of the motor), values of the hysteresis are concentrated around zero-value, however in a quite considerable range of variations of *±20 μm*. Such results are probably the effect of inaccuracy of threads manufacturing since it is evident from the comparison with the results obtained for the model *B*.

Course of the kinematic deviation of the screw position is totally different in the case of drive model *B* (Fig. 2). While moving the screw out (course 1), values of the deviations vary over the range of about *32 μm* (form *+12 μm* to *-20 μm*), and while moving the screw in (course 2), over the range of about *28 μm* (form *-10 μm* to *-38 μm*). So, this range is considerably smaller with respect to drive *A*. Instantaneous values of deviations concentrate around a certain component, which changes its value only by few μm over the whole studied range of the screw motion. As the result, hysteresis (course 3) varies also within a range much smaller, i.e. form *+12 μm* to *+32 μm*. Additionally, in function of the motor revolutions, its values oscillate around a component, which changes its value also only by few *μm* over the studied range. These results point out to the fact, that the screw in drive *B* is precisely manufactured, whereas deviations of the toothed gear are revealed more clearly.

This is indicated by the measurements of the deviation of the screw position performed for every revolution of the motor (Fig. 3). The deviation varies cyclically, along with the period corresponding to the number of motor revolutions being close to velocity ratio of the toothed gear.

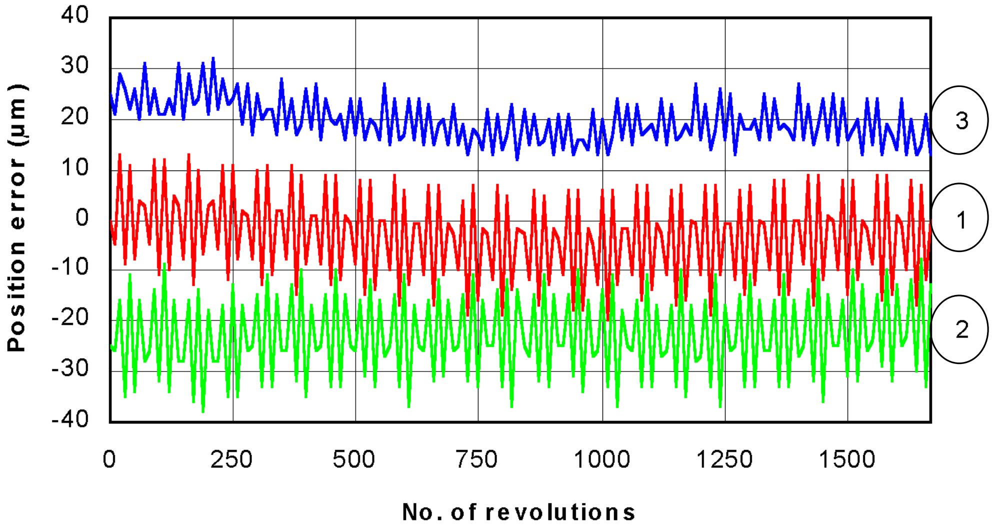


Fig. 2. Kinematic deviation of the screw position and hysteresis for drive unit *B*

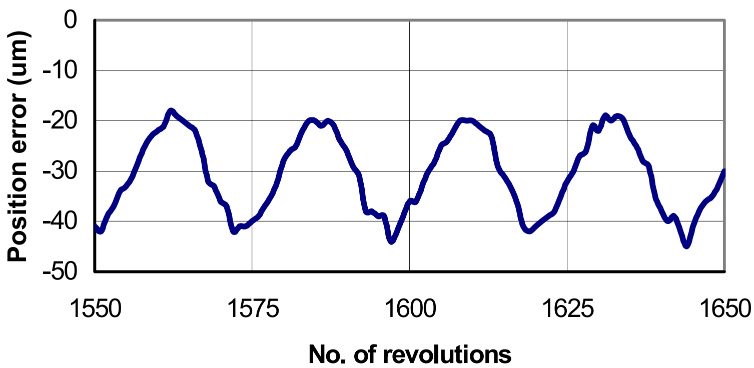


Fig. 3. Cyclical variations of the kinematic deviation of the screw position for drive unit *B*

Efficiency of the linear drive was studied by applying various loads on the output member (the screw) and various supplying voltages. The drive was fixed as having vertical position, and the screw was loaded with an axial force over the range of *0-25 N* by means of suspending weights on it. The motor was supplied with a voltage of *2, 4* and *6 V*. The following were measured: motor current, rotational speed of the rotor (in a non-contact way, by means of an optoelectronic tachometer).

On the basis of the applied load and the velocity of the screw motion, one determined the output power, whereas the input power was determined on the basis of parameters of motor supply (supply voltage and current). The efficiency of the drive, calculated as a ratio of these two powers, (so, it is efficiency of the entire drive, including the motor) did not exceed *2-3%* for the supply voltage of *6 V* (Fig. 4, series 1). Similar courses were obtained for lower supply voltages.

So, it was decided to determine efficiency of the mechanical units of the drive (excluding the motor), i.e. two-stage fine-pitch toothed gear coupled with the screw gear. In order to do this, there are needed values of the torque at the gear input (pinion fixed to the motor shaft). One determined experimentally torque characteristics in function of the rotational speed of the motor, for various supply voltages, using a test station for studying *DC* micromotors [5]. Then, one recorded values of the torque corresponding to a given rotational speed of the motor (measured during the tests), and calculated power transmitted to the gear input. Efficiency of the toothed gear coupled with the screw gear was determined as a ratio of the power at the screw to the power at the gear input, i.e. at the motor shaft. Values of the efficiency determined this way are of about *6-7%* (Fig. 4, series 2).

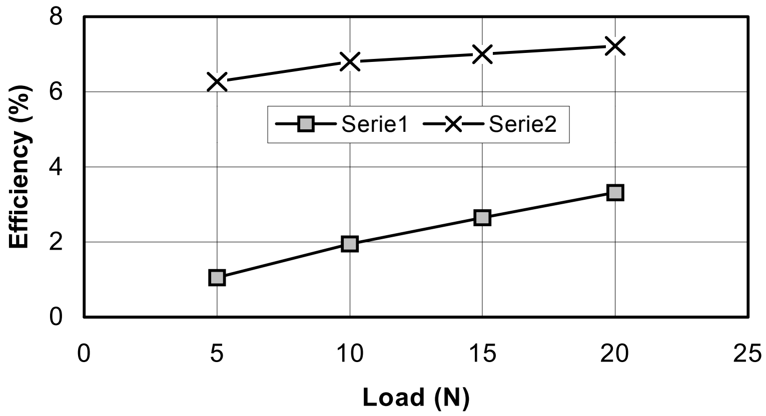


Fig. 4. Efficiency of the linear drive (Series 1) and toothed gear coupled with screw gear (Series 2)

3. Testing of the dynamic characteristics of the miniature direct linear actuator

There is presented in Fig. 5 (block diagram and view of mechanical part) an integrated measuring system for studying dynamic characteristics of miniature plunger electromagnets designed for application in valves. In the presented test station, there is applied the photoelectric system described above, in order to perform non-contact measurements of linear displacements (measurement of the plunger motion) and circuits for measuring the electromagnetic force (with a piezoelectric transducer by *KISTLER* company) and supply parameters. The dynamic force of the plunger attraction is determined on the basis of measurement of the reactive force of the electromagnet casing – this idea is presented in paper [6]. A digital oscilloscope coupled with a microcomputer was applied for recording the signals.

Is necessary to indicate general problems in presented test of direct linear actuator:

- rapid changes of quantities characterizing their functioning, which result from small electrical and electromechanical time-constants,
- small thermal time-constants, creating the need to apply measuring methods that eliminate the influence of temperature on research results (test is made practically in constant thermal conditions),
- small dimensions of object (specially plunger) as well as other elements, causing technical problems during selection and installation of measuring transducers,
- small mass of plunger, often causing an interaction of the object of research and mechanical units of measuring system,

The obtained results give as possibility to calculate efficiency of drive – for example for optimising of supply procedures (e. g. with using forcing of current).

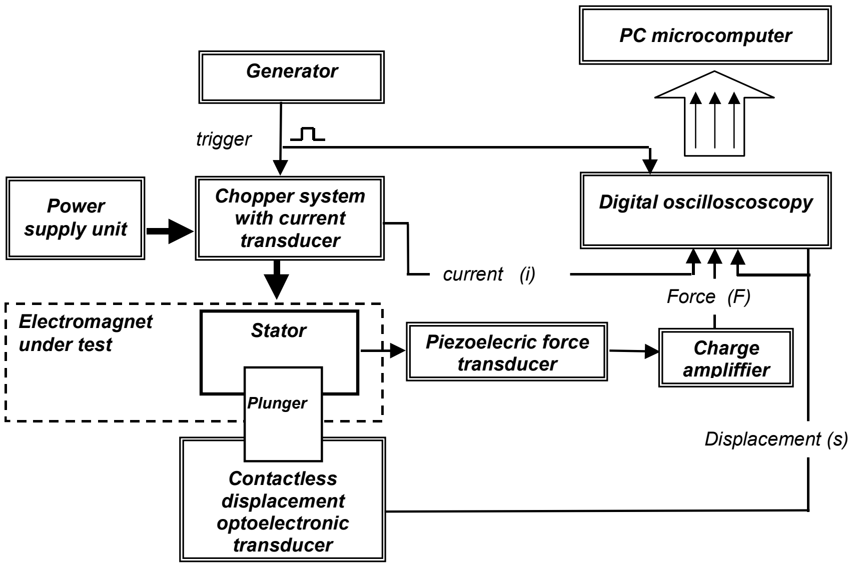
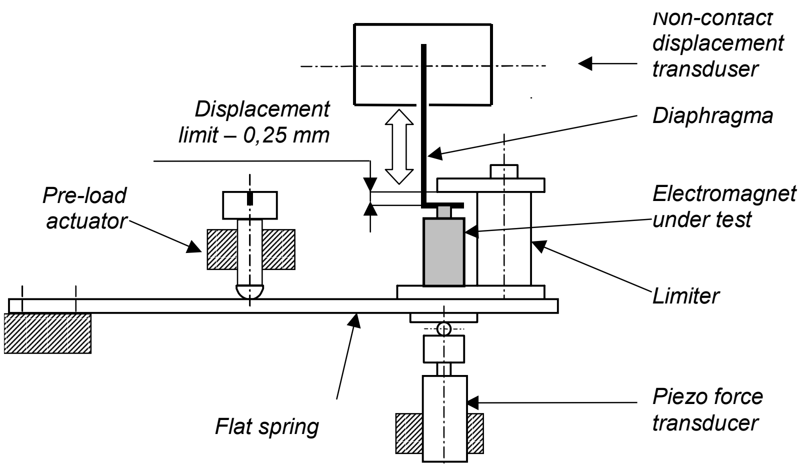


Fig. 5. Testing of the dynamic characteristics of the miniature linear electromagnet

a) block diagram of the system



b) structure of the mechanical unit of the test station

Exemplary dynamic characteristics of a miniature plunger electromagnet are presented in Fig. 6.

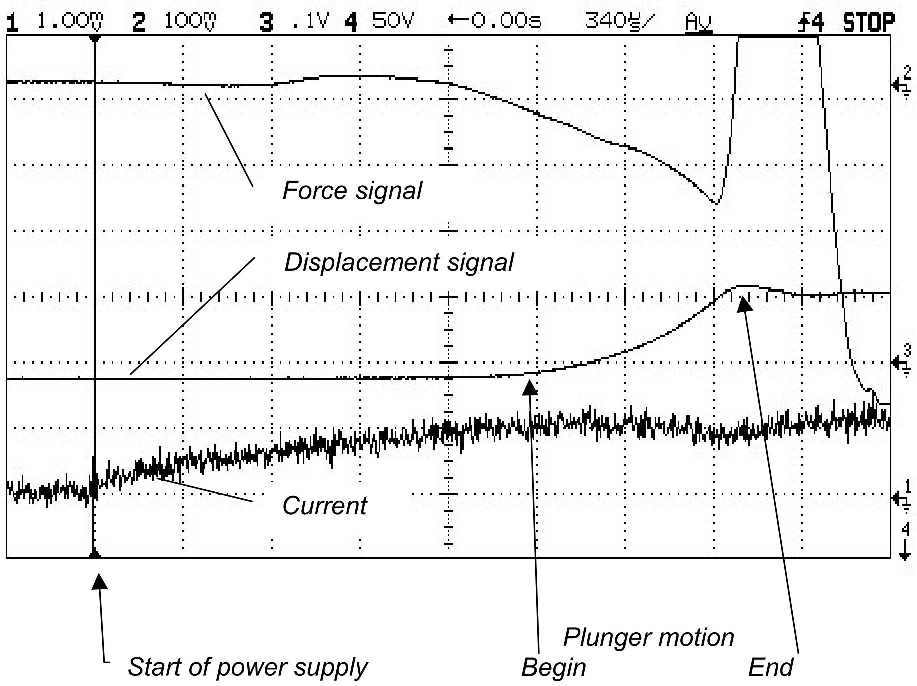


Fig. 6. Dynamic characteristics of small plunger electromagnet.

4. Conclusions

One can observe a dependency of the load, applied to the unit of the *DC* linear drive, on the calculated efficiency. It is probably connected with the accepted parameters of motor operation as found within the range of small torque, and with characteristics of the applied motor. For during measurements, one observed non-linear dependency of the power supply on the current of the motor loaded by the gear, i.e. for the same values of the torque, the supply currents were different for various rotational speeds. Explanation of such behaviour requires further studies.

The presented results of the experimental studies allow one to evaluate the metrological properties of the applied testing devices as well as a complex evaluation of our own research abilities.

5. References

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