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Electromagnetic angular positioner based on DC micromotor

Maciej Bodnicki[1,*], *Jakub* Wierciak[1], *Wojciech* Credo[1], *Karol* Bagiński[1],
Leszek Wawrzyniuk[1]

[1]Warsaw University of Technology, Faculty of Mechatronics, Institute of Micromechanics and Photonics, ul. Boboli 8, 02-525 Warszawa, Poland

Abstract. The presented works concerned launching of an angular positioner powered by an electromagnetic actuator, designed for performing angular micromovements within a range of few microradians. The principle of operation is based on balancing the electromagnetic torque of the motor with a torque that is twisting a compliant element. As electrodynamic actuators have no distinguished controlled positions, therefore in typical positioning systems desired positions are obtained applying a closed-loop position control. Usually, such systems employ also a feedback (dumping) related to velocity of the moving elements, what simplifies forming of dynamics of the system. The design of the physical model employs a DC micromotor, whose rotor is coupled with a torsional torquemeter. A feedback signal is generated by resistive strain gauges. The paper presents a mathematical model of the positioning system, results of simulation study as well as results of experimental study. The simulation study indicates that it is possible to select such design features and such type of the micoromotor that a high dynamics of positioning is ensured.

Keywords: angular positioning, DC micromotor, torque meter, simulation tests, test stand

1 Introduction

Miniature positioning drives that implement angular displacement with respect to one or more axes are used primarily in optical positioning systems. They are used for accurate, often quick positioning of mirrors or other optical elements. For systems with low dynamics, it is possible to use drives with classic rotary motors with gears characterized by high accuracy and high ratios. Both DC and stepping motors are used in such drives. An advantage of stepping motors is their ability to operate in open loop control. . SMA actuators are also used in low dynamic systems.

Often, however, the requirements for movement ranges include several dozen mrad, with the dynamics of work of, for example several hundred Hz. The use of piezoelectric elements makes it possible to achieve such parameters (these are often line actuators operating on an arm relative to the axis of rotation). Such positioners are also built as the electromagnetic actuators (VCM motors) with specially designed excitation combinations

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[*] Corresponding author: m.bodnicki@mchtr.pw.edu.pl

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(permanent magnets) and windings, supplemented by suspension (often air gap suspension).

2 Idea of the positioner with torque balance

It was considered possible to build an electrodynamic positioner. The concept of mechanical structure of such a system and versions of its control has been developed. The use of an electrodynamic actuator, such as a typical, commercial DC micromotor with a coreless rotor, requires a high resolution rotor angular position transducer, far beyond the capabilities of conventional incremental converters.

For this reason, it has been proposed to use strain gauges measuring the deformation of a twisted mechanical element rigidly coupled to an rotor. The driven element (e.g. mirror) is attached to the torsion element at the location where its largest angular displacement occurs.

The ability to shape the correct torsional rigidity and high bending stiffness is guaranteed by the so called “drilled cross” elements known from the torque transducers' construction. The scheme of the proposed solution is shown in Figure 1.

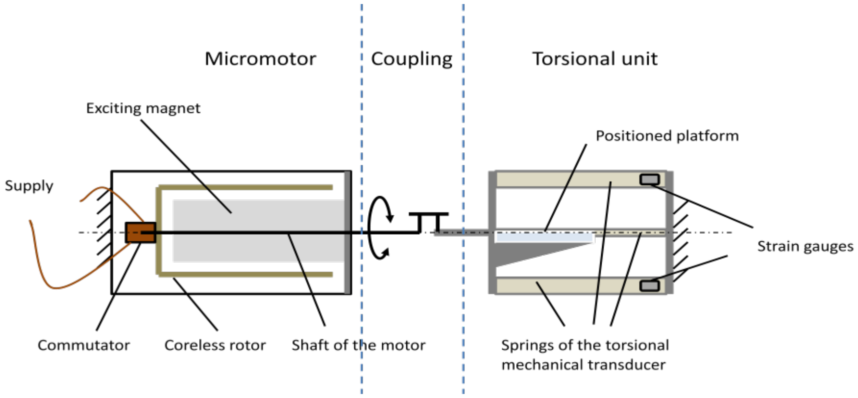


Fig. 1. Scheme of the positioner with electromagnetic activation on basis DC micromotor

According to the above assumptions, this system has the functional structure shown in Figure 2. The micromotor tracks the position by twisting the mechanical element to which the scanner table is connected. The amplified differential signal is the result of subtracting the load from the load cell transducers from the position signal. The load of the motor is the sum of the static torque (originating from twisting the element) and dynamic torque (originating from acceleration of the displaced parts). Preliminary selection of system parameters based on drive and measurement drive catalogue data leads to an estimate of the approximate native vibration frequencies of the uninhibited system, which is approximately 200 Hz.

Two types of scanner operation are possible with the proposed system:

- with feedback from the deformation signal of the torsion spring,
- without feedback, based on the linear dependence of the torque developed by the motor against the current flowing in its winding. In the latter case, it is based on the linear mechanical characteristics of the twisted element.

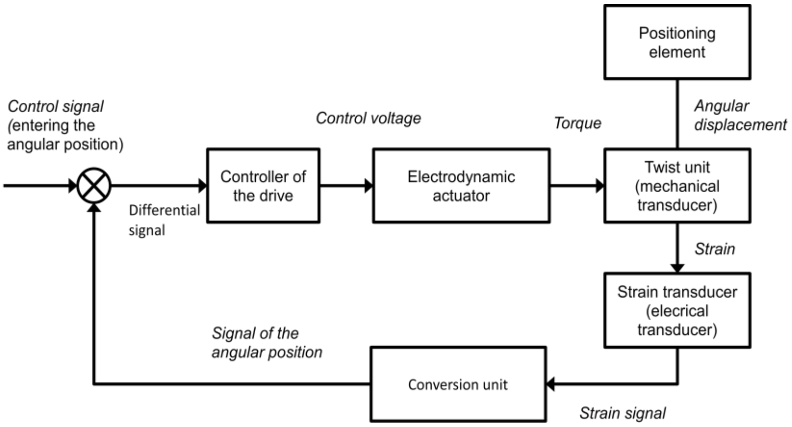


Fig. 2. Functional block diagram of the analyzed system

3 Test stand and physically experiments

For preliminary experimental research, a test stand was assembled using a DC micromotor with permanent magnet in stator and an ironless rotor in form of a cylinder, characterised by a rapid mechanical response.

The shaft of the micromotor was coupled by a bellows coupling (with significant torsion stiffness) with a flexible element. As a susceptible flexible element, a system of 4 flat springs, constituting a mechanical transducer of a stationary torque meter (SPM type, developed at the Institute), was used. The torque generated by the micromotor forces the mechanical transducer to be converted by an electric transducer (strain gauge bridge) into an electrical signal which is registered in the measurement system.

Due to the proportionality of the mechanical structure and processing circuit, the voltage at the output of the bridge is the information about the twisting of the spring system and the angular displacement of the shaft of the micro motor. There is also the possibility to control the output of the angular positioner.

The block diagram of the stand is shown in Fig. 3, its view in Fig. 4. Figure 5 shows the close-up of the spring system and its schematic view with marked places of strain gauge.

The micromotor used in experiments was characterized by a startup torque of 0.054 N·m (when the rotation speed is zero) at 12 V supply voltage. The voltage reduction resulted in a proportional reduction in the startup torque.

A SPM-100 stationary torque-meter (design in IM&P) with a measuring range of 0.1 N·m and a torsional stiffness of mechanical transducer c_{SPM} = 54 N·m/rad was used in the test stand. In the case of the applied micromotor, it was possible to achieve the maximum angle of twist of the mechanical transducer φ_{SPM} = 1 mrad (3.4'). This is not, however, the value of twisting of the modelled positioner. Due to the use of bellows coupling, the resulting rigidity value of the serial system results from the formula:

$$c = \frac{c_{SPM} \cdot c_C}{c_{SPM} + c_C} = 45{,}76 \text{ N·m/rad} \tag{1}$$

Where: c - torsional stiffness, c_{SPM} - torsion stiffness, c_C - bellows coupling torsion rigidity (300 N·m/rad).

The net maximum angle of the positioner model (with 12 V supply of the used DC micromotor) was therefore φ_{max} = 1.18 mrad (4.06').

The torque conversion processing constant is $A_T = 0.381$ Nm / V, with respect to the angular movement of the positioner, the processing constant has the value $A_\varphi = 8.36$ mrad/V (28.74'/V)

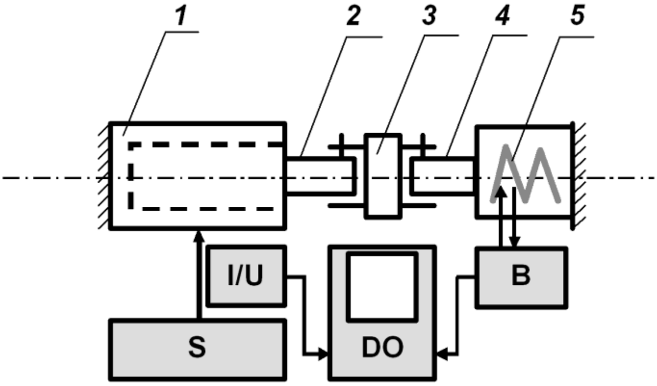


Fig. 3. Block diagram of the test stand – model of the positioner

1 – DC micromotor, 2 – shaft of the micromotor, 3 – coupling (spring bellow type), 4 – shaft of the stationary torque meter, 5 – mechanical transducer of the torque meter, S – supply, I/O – non contact, Hall – effect current/voltage transducer, D) – digitally oscilloscope, B – strain gauge bridge

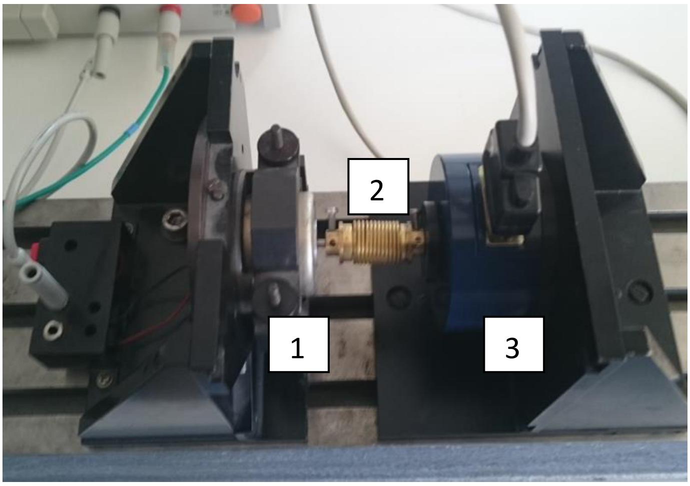


Fig. 4. View of electromechanical components of the test stand (model of the positioned)

1 – DC micromotor, 2 – coupling, 3 –stationary torque meter

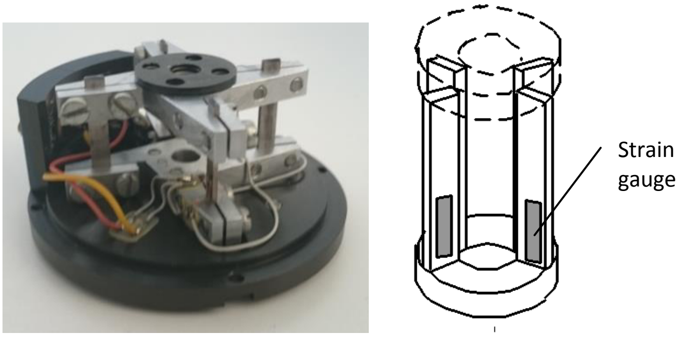


Fig. 5. System of 4 flat springs, constituting a mechanical transducer of a stationary torque meter (SPM type)

Figure 6 shows the time waveform of the current in the winding of the micromotor after stepped voltage supply with the visualisation of the time constant of the process. By properly selecting the electrical system parameters and operating mode of the power supply, it is possible to significantly shorten the time constant value. Fig. 7 shows the positioning leading to selected angular positions.

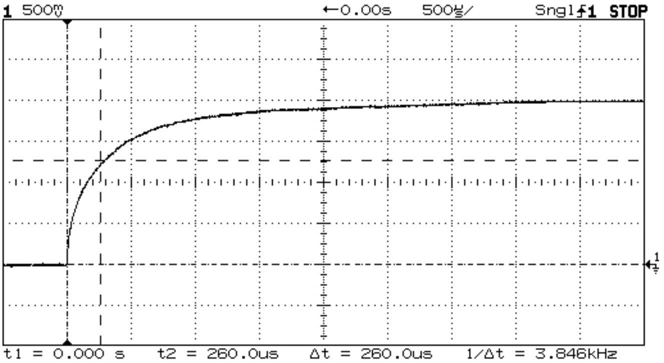
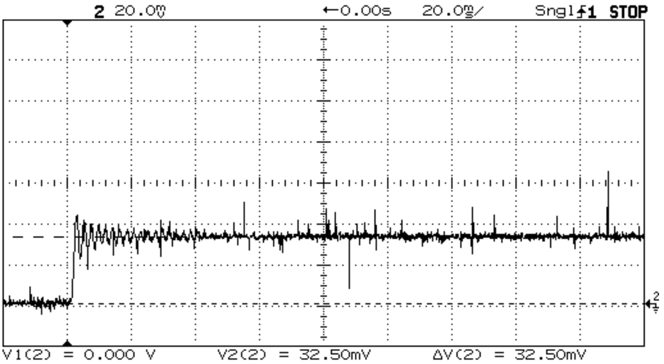


Fig. 6. Current course during step of the voltage supply (12 V; the time constant value is 280 µs)

a)



b)

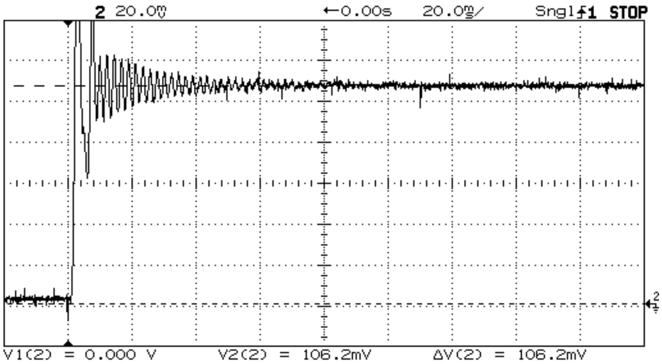


Fig. 7. Positioning

a) from position 0 to 0.295 mrad, b) from position 0 to 0,885 mrad

Fig. 8 shows cyclic switching between zero level and maximum angular deviation (1.18 mrad)

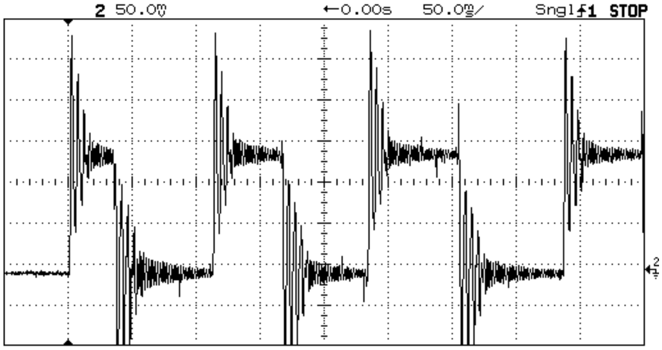


Fig. 8. Sequence of jumps between zero and max position of the positioner

4 Mathematical model

A mathematical model has been developed and includes: a classic DC motor model (which consists of two equations: balance of torque (2) and balance of voltages (3)), a torsion model in the form of a force torque linearly dependent on the angular displacement of the element and the damping moment proportional to the velocity of motion (4) and the control system model consists of equation of the strain gauge bridge channel dynamics (5) and equation of controller and the power amplifier (modeled as a PID regulator) – (6):

$$K_T i = (J_s + J_L)\frac{\mathrm{d}^2\varphi}{\mathrm{d}t^2} + K_D\frac{\mathrm{d}\varphi}{\mathrm{d}t} + (M_F \cdot sgn(\frac{\mathrm{d}\varphi}{\mathrm{d}t}) + M_L)\ , \qquad (2)$$

$$u = R_t i + L\frac{\mathrm{d}i}{\mathrm{d}t} + K_E\frac{\mathrm{d}\varphi}{\mathrm{d}t}\ , \qquad (3)$$

$$M_L = C_{SPM}\cdot\varphi + B_{SPM}\frac{\mathrm{d}\varphi}{\mathrm{d}t} \tag{4}$$

$$\tau\frac{\mathrm{d}U_\mathrm{B}}{\mathrm{d}t}+U_B=k\cdot\varphi \tag{5}$$

$$u(t)=k_p\left[\varsigma(t)+\frac{1}{T_i}\int_0^t\varsigma(t)\,dt+T_d\frac{d\varsigma(t)}{dt}\right] \tag{6}$$

where the symbols mean following: i - armature current, J_L - moment of inertia of positioning elements, J_s - moment of inertia of rotor of micromotor, K_D - constant of viscous damping in the motor, K_E - voltage constant, , K_T - torque constant, L - inductance of armature windings, M_F - motor friction torque, M_L - load torque, R_t - total resistance of armature circuit, u - supply voltage, φ - angular displacement of motor rotor, C_{SPM} – torsional stiffness of the spring system, B_{SPM} – constant of viscous damping in the spring system, U_B – voltage signal from strain gauges bridge (angular position signal), τ – time constant in low-pass filtering system, k – coefficient in the strain gauge bridge, k_p – gain coefficient, T^i - integral time, T_d - derivative time, ζ - the difference signal.

5 Simulation tests

Simulation models are written parallel in two software environments/languages: Matlab/Simulink (see Fig. 9) and AMIL.

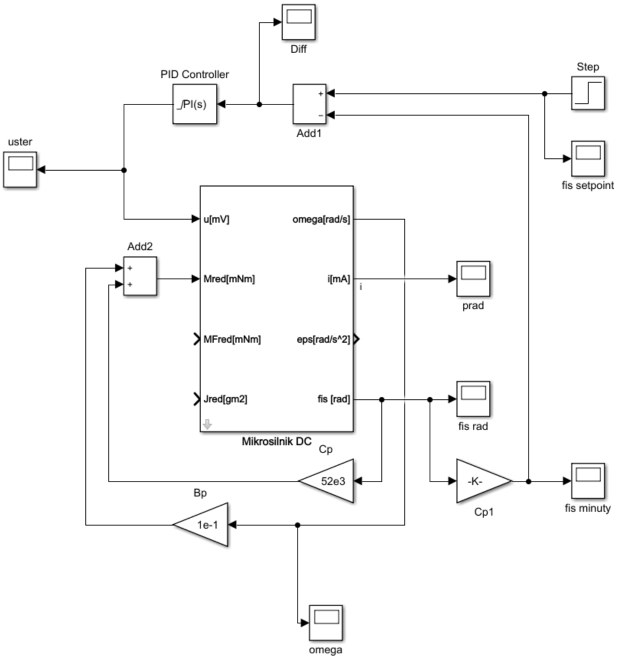


Fig. 8. Simulink model of the positioner

Sample results showing the effect of changes of dumping coefficient are shown in Fig. 9.

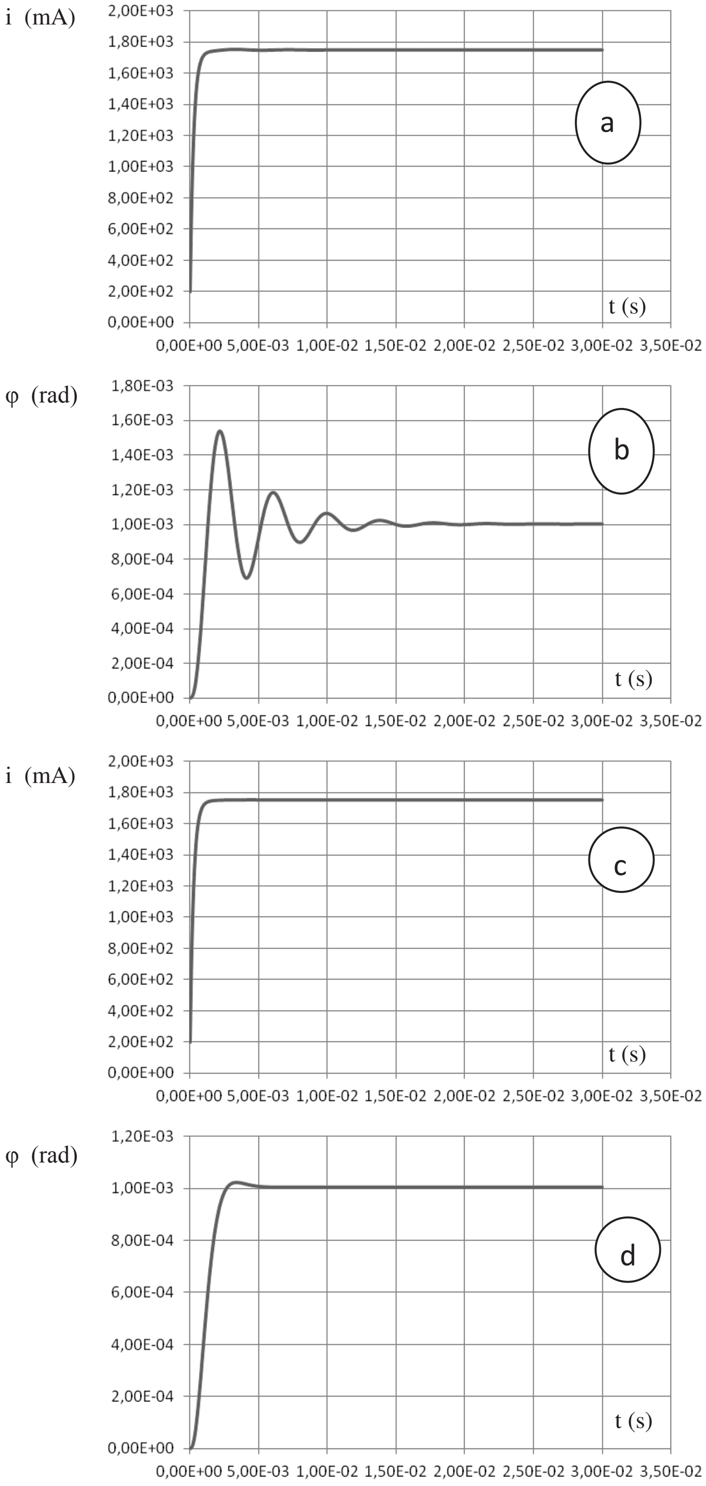


Fig. 9. Simulation of the positioning: a, c – current, b, d – angle of twist; c, d - change of dumping coefficient (multiplication by 10)

Conclusions

Design of an angular positioner with a range of single mrad has been proposed. The demonstrator (physical model) as assembled and tested in test stand -. An example of a DC motor and a strain gauge torquemeter were used. However, the parameters of the applied micromotor were not optimized. Experiments have been performed indicating the positioning capability of up to 1 mrad, with positioning time up to 40 ms.

The developed mathematical model and simulation software allow for optimization of the positioner and give the possibility e.g. of selection of the micromotor from the catalog proposals and the design of a dedicated spring system. The development of the model is anticipated by taking into account thermal phenomena.

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