Measurement problems of miniature electrical machines

M Bodnicki
Warsaw University of Technology, Faculty of Mechatronics, Warsaw, Poland
maciej.bodnicki@pw.edu.pl

Abstract. The article presents the issue related to experimental research on the determination of static and dynamic properties of miniature electrical machines. The tested objects are, for example, micromotors with body diameters in the order of single millimetres, or linear drives with millimetre dimensions. The main measurement problems were presented and the specificity of these measurements was characterized. First of all, electromechanical time constants have small values due to small values of masses or mass moments of inertia. The force quantities (forces and torques) generated by such actuators also require the use of unconventional measuring transducers. The research may concern the identification of static and dynamic characteristics, but also methods of dynamic measurement of the quantities used in the control of such micromachines are presented. Practical examples of original measurement methods and systems are presented.

1. Miniature electrical machines

An important direction of work carried out at the Department of Precision Equipment Design (DPED) at Institute of Micromechanics and Photonics Warsaw University of Technology is the creation of new methods and tools (transducers and stands) for dynamic measurements of mechanical quantities characterizing the work of miniature activators and electric motors. The work is focused on methods and devices that will not interfere with the operation of the facility and will be useful for research, diagnostics or control.

An example of such DC micromotors is shown in Figure 1.

Figure 1. An example of miniature DC motors

The classic definition of "electric micro-machines" no longer sufficiently differentiates this category of motors. At present, in addition to introducing actuators created in the silicon microsystem technique, miniature electric motors operating on the principle of classical electromagnetic conversion of electrical energy into mechanical one are becoming available on the market. Miniaturization of
these engines is possible, among others, thanks to advances in the technology of magnetic materials and electronic circuits used in contactless commutation.

After 2000, the results of work on further unconventional micromotor solutions based on various physical phenomena are published, e.g.:

A. Piezoelectric rotary motor of the "traveling" wave type [1]:
   - The dimensions of this motor are 4 to 2 mm in body housing diameter;
   - The maximum torque of such a motor is 1.4 mN·m, and the maximum speed is 4 rpm;

B. Ultrasonic cylindrical micromotor using a miniature PZT transducer [2]:
   - The motor diameter with the preload mechanism is 2 mm and the height is 5.9 mm, the rotor diameter is 0.8 mm;
   - A rotational speed of approx. 2400 rpm was achieved.

C. Ultrasonic micromotor of the "standing" wave type: (Suzuki, designed for additional functions of watches) [3]:
   - Dimensions 2 mm in diameter and 0.3 mm in height;
   - The starting torque of this micromotor is 3.2 μN·m. depending on the size, it develops a speed of 100-300 rpm;

D. Synchronous micro-pump micromotor [4]:
   - Maximum rotational speed 7000 rpm;
   - Diameter <5 mm;

E. High speed synchronous micromotor (Kinetron's micromotor) [5]:
   - It is a two-phase, four-pole synchronous motor with a two-pole permanent magnet rotor and a printed flexible winding;
   - The diameter of this micromotor is 1 mm and the height is 2 mm;
   - Maximum rotational speed 3200 rpm.

Also at DPED, own designs of miniature electromagnetic activators with new generation permanent magnets are developed according to technologies developed by the Faculty of Materials Science and Engineering, Warsaw University of Technology.

This technology implements the concept of manufacturing disc magnets for stepper motors as magnets composed of two oppositely magnetized elements with a structure gradient. The tested structure provides an effect such as multipolar magnetization, which is difficult to carry out, especially for magnets with small dimensions. Magnets were obtained from Nd-Fe-B powder bonded with chemically hardened epoxy resin. An innovative idea was to use centrifugal casting so that the powder particles were only in the active area of the magnet, i.e. in the part cooperating with the magnet guide. In the process used, an oblong, axially symmetrical piece with a cross-section similar to the assumed shape of a magnet was obtained. The magnets were obtained by cutting the shaped piece perpendicular to its axis [6].

An example of the use of such a construction magnet is a stepping micromotor with a disc rotor with a diameter of 8 mm. In the first phase of the work, a "technology demonstrator" was developed (Figure 2), then a prototype was made. In the demonstrator, the coils are wound on ferrite cores (l = 8, Ø1.6) with a winding wire Ø 0.15, selecting the number of turns 500. The demonstrator's structure has an open structure - enabling the change of the magnetic core design features - using elements made of polymethacrylate and duralumin. The construction of the prototype is already closed - the 3D printing method made of ABS plastic was used [7].

2. Measured mechanical values
The directly measured or indirectly determined quantities are usually the linear / angular position and its derivatives, as well as forces and moments. Measurements, during which it is necessary to simultaneously determine many characteristic quantities, are important. A typical example of such tests are the procedures for determining the load characteristics of micromotors or microactivators.
The dimensions of the test objects determine small values of mass / mass moments of inertia, which in turn forces the designer of the measurement system to carefully consider the possibility of attaching any additional elements to them. Also, the values of the parasitic loss moments of typical measuring transducers and load groups of stations (e.g. brakes) exceed the maximum values of torques developed by miniature activators.

If the values of linear accelerations and the masses of the moving elements are known, it is possible to calculate the dynamic forces. Accelerometers MEMS are currently used to measure accelerations, the dimensions of which enable testing of miniature actuators [8,9]. However, one should pay attention to the changes of transducer parameters as a function of time [10].

Moreover, for example, the smallest DC micromotors are characterized by very high rotor speeds (in the order of several dozen to over one hundred thousand rpm) and small electromechanical time constants (even in the order of several milliseconds). Classic designs of force / torque meters with measuring ranges useful in the considered applications often exclude dynamic measurements.

The equipment presented in the article has been designed for testing miniature motors with rotating shafts and linear actuators (e.g. fast-acting electromagnets).

3. System for non-contact measurement of positioning accuracy.
When testing miniature linear actuators, we deal with a small working movement and low generated forces. The use of standard gauges that require connection, or at least a momentary contact of the measuring head with the actuator, may disturb the working movement or even prevent its execution - especially when the force with which the activator works is only a few mN. Therefore, it was assumed from the very beginning that the research would be conducted without contact, preferably with the use of an optoelectronic transducer. Another problem was the acceleration and speed of operation of the said drives. If you want to measure the position dynamically and enter data into the microprocessor system, it is necessary to register the appropriate number of samples.

Good results are obtained when measuring changes in the degree of optical coupling in an open optoelectronic link caused by the displacement of a moving element of the drive (e.g. an activator tip). However, the presented system is based on a line detector - CCD photo line. Linear photoelement arrays have a number of applications, but they are most often used to scan the surface of data carriers (both documents and, for example, fingerprints of the fingertips), or to monitor technological processes by checking the geometry of moving details. Here they play the role of ordinary cameras, but more economical and, most importantly, much faster. They can also be used, just like photodiodes arranged in series, to study linear displacements [11].

Using the matrix of photoelements, the test can be carried out in two ways - either by comparing the obscuration of the next pixel, thus determining the position of the edge of the tested element, or by additionally testing the level of its exposure. The second technique, although much more complex and requiring edge recognition algorithms, allows for greater accuracy by interpolating adjacent pixels (artificially increasing the number). As a result, the resolution can be increased many times, depending...
on the voltage resolution of the analogue-to-digital converter that measures the degree of exposure of subsequent pixels.

Figure 3. Demonstrator of system for contactless measurement of linear displacement

The illuminator uses a simple collimator analogous to those used in nuclear physics (there are used diaphragms in the form of long channels emitting a beam of radiation with a specific direction in line with the channel axis). This method was transferred to the developed illuminator system by placing the diode in a long, narrow sleeve shaded in the middle. The part of the rays running at an angle to the axis is scattered and absorbed on the sleeve walls. This solution is also often used as the sensor’s input diaphragm, but it works only where a single photodiode is sampled that measures only light intensity. When using a diode with a wide beam angle and a large half-angle, an even distribution of intensity is guaranteed throughout the spot.

In the constructed device [8] the following technical and operational parameters were achieved: measuring range 8 mm; measurement accuracy: 8 μm, static measurement resolution: 900 nm, maximum dynamic measurement resolution with the dynamics of the tested object equal to 1 m/s: 1.65 mm; maximum dynamics of the tested object with a dynamic measurement resolution of 50 μm: 0.03 m/s.

4. Force / torque measurement system

The presented apparatus was designed for testing miniature motors with a rotating rotor motion (torque measurement) and measuring forces [12].

In the developed system, it was decided to use the optoelectronic technique to measure the displacements of a typical mechanical element, the formal description of which allows for unambiguous determination of the relationships between mechanical quantities changing during the measurement. One such element is a flat beam rigidly fixed at one end. In the design process, the relationship between the displacement of the selected spot on the beam surface (and the displacement of the radiation beam reflected from this spot on the surface of the detection element) was calculated when it was loaded with a bending force or a bending moment.

The system works on the principle of triangulation. After reflection from the surface of the measuring element, the light beam hits the PSD sensor. The measuring element is a prismatic beam bricked up at one end and loaded at the other by a measured torque or force. The beam deflection caused by the applied load changes the reflection angle of the light beam and thus the position of the light spot on the sensor surface.

The illustrated system can measure both torque and force applied to the end of the beam. The beam curvature will be different for both types of load, but it is possible to determine mathematically in both cases. It has been verified that it is possible to transform the equations describing the beam deflection curvature in such a way that one calibration process allows for the determination of the actual
measurement characteristics of the device measuring both torque and force. The rationale for this type of operation is that it is relatively easy to produce a known value force with high accuracy compared to producing a small torque with great accuracy.

The geometry of the stand is shown in Figure 4. The advantage of the system is the possibility of calibrating the torque measurement path by setting a specific force value - for which mass standards loading the transducer by gravity can be used. We do not have the appropriate standards of this size that do not cause additional deformation of the torque converter. Therefore, the technical implementation of the calibration of torque meters with extremely low measuring ranges is often unsolvable.

The use of optoelectronic technology (illuminator: infrared diode and PSD detector), in addition to non-contact measurement, also allows the designer to choose the parameters of the measuring beam - unlike, for example, strain gauges whose dimensions are limited.

In the case of testing the torque developed by the micromotor, it is mounted by the body at the point where the torque \( M \) is applied.

![Figure 4. Scheme of the optoelectronic system for measuring torques with a semi-beam subjected to bending](image)

- **a)** idea of measurement of force/torque, b) plain view
  1 – illuminator in holder, 2 – photodetector in holder, 3 – stands plate, 4 – semi-beam, 5 – micromotor, \( L \) – length of the beam, \( x \) – distance of reflection point

The task of the illuminator is to create a light beam which, after reflection from the measuring beam, is to hit the sensor surface. The beam should be as focused as possible so that the light point formed on the sensor surface is small and of the same shape during the entire measurement cycle. The illuminator cannot be a source of divergent light, so that the light does not reflect from other surfaces
of the device than the beam and does not illuminate the sensor beyond the measuring point. The best solution is a laser illuminator.

In the work [5] the ADL65075 laser diode was used, the beam of which is focused with the CAX100 collimator. The diode creates a beam of light with a wavelength of 650 nm (red light), has a power of 7 mW. Laser diodes are powered by a current source, their luminous power depends on the value of the supplied current.

The PSD Hamamatsu S3931 (Position Sensitive Detector) sensor is made of a semiconductor resistive layer (p-type) applied to a high-resistance n-type substrate. There are electrodes at both ends of the resistive layer, which is the active surface of the sensor. When the surface of the sensor is illuminated, an electric charge is created at the point where the photons of light are hit by the photovoltaic effect. This charge then flows through the resistive layer to both electrodes, dividing into two parts proportional to the distance of the point of incidence of light from the electrodes (the greater the distance, the greater the material resistance and the lower the current). Knowing the values of both currents and the sensor length, it is possible to determine the position of the point of incidence of light in relation to the centre of the active surface of the sensor.

The PSD sensor, illuminated with light at a given point, generates two current signals resulting in the recalculation of the position of the light point in relation to the centre of the sensor. The sensor current signals are fed to the measuring amplifiers U1 and U2 (separate amplifiers for both sensor signals). The amplifier works in a current-voltage converter system. The current signal is fed to the input of the inverting amplifier. This input is connected to the output of the amplifier via a resistor. The ratio of the output voltage of the amplifier to the input current depends on the value of this resistor.

The device (Figure 5.) enables: measurement of dynamic forces in the range of ± 0.02 N and the micromotor torque (by measuring the stator reaction torque) in the range of ± 0.005 Nm with an accuracy of 1%.

![Figure 5. View of the stand with the cover removed (left) and components of the system (right): 1 – cable unit, 2 – data acquisition card (NI), 3 – connection unit](image)

Measurements of the starting torque of the micromotor in the motor mounted at the end of the measuring beam come down to registering the instantaneous step response to the power supply voltage jump of the motor. When the supply voltage is applied, the motor torque increases to the maximum value - this is the starting torque of the motor. The speed of the torque increase depends on the speed of the current increase in the motor winding - this relationship is described by the parameter of the
motor voltage constant $K_e$. After reaching the start-up value, the torque drops to the value balancing the resistance to rotor movement.

Since the measuring beam at the end of which the tested engine is mounted is quite long and thin - it starts to vibrate at its own frequency due to the engine start-up. These vibrations are quite strong and slowly dampen. In order to record the engine start-up, the frequency of these vibrations had to be measured and then filtered from the signal. The LabView environment offers many possibilities of analysing and processing analog signals. With its help, it was found that the beam vibration frequency is 20.5 Hz. Additionally, after filtering this component, a frequency of 296 Hz was detected, which was also filtered out.

During dynamic tests, the acquisition card worked in the continuous measurement mode with a set sampling frequency. The measurement signals from the sensor were processed with the previously derived equations to obtain the actual torque value. The processed signal was then filtered. First, by means of a band-stop filter, the natural frequency of the beam was eliminated - 20.5 Hz. After this operation, the signal was subjected to low-pass filtration - the value of the cut-off frequency was experimentally set at 150 Hz. This allowed to eliminate higher frequencies (the aforementioned 296 Hz component and noise), without affecting the measurement signal at the same time.

The filtered signal was then saved to a text file for archiving and presented on the screen in the form of a time waveform.

Figure 6 shows the waveforms of the starting torque of the micromotor (the object from Figure 1 was tested), recorded in the test stand at different supply voltages. The results confirm the linear dependence of starting torque on the voltage.

![Figure 6](image)

**Figure 6.** Exemplary results – starting torque obtained at different supply voltages of the micromotor

5. **Summary and conclusions**

The presented devices, developed in DPED, are only technology demonstrators. Only single devices were made. They enable measurements of mechanical quantities while determining the static and dynamic properties of miniature activators. The measuring ranges can be from a few to several mN·m / mN with an uncertainty above 1% f.s., but less than 2.5%. The non-contact linear displacement transducer with a range of 8 mm is characterized by an astatic resolution of 0.9 micrometers and a dynamic frequency response of 0.6 kHz. Concepts of measurement systems and adopted design solutions may be the basis for the construction of similar systems by other laboratories.
The common feature of both presented systems is the use of optoelectronic technology - laser diodes as illuminators and as detectors of CCD matrices and PSD elements. From the point of view of photonic systems, these are simple schemes, but they allow for non-contact measurement or (torque meter, force transducer) to reduce the mechanical interactions of the test bench and the tested object.

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