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Method of Measurement of Angular Velocity in Miniature Devices

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The method and system for measuring angular velocity, particularly suitable for use in miniature drive systems, are presented. This applies, for example, to drive systems with direct current micromotors with mass moments of inertia of rotating assemblies up to several tens $\mathrm{g \cdot cm^2}$ and electromechanical time constants of the order of several tens of milliseconds. This is without the need to connect additional rotating elements to the mechanical structure of the drive. The analogue output signal is obtained by loading the input of the integrating two-port network with rectangular pulses of constant length, obtained after detecting radiation reflected from a rotating surface. The paper presents the performance of the physical model of the transducer and simulation studies indicating the possibility of optimizing the dynamic parameters of the system. Reducing the time constant of the two-port network resulted in a reduction of the time constant of the transducer (for example, a two-fold reduction of the quad constant resulted in a five-fold reduction of the transducer response time constant). Increasing the number of pulses per revolution while reducing their amplitude results in a reduction of the pulsation level in the output signal.

topics: angular velocity measurement, optoelectronic transducer, dynamic measurement, miniature drive systems

1. Introduction

Knowledge of instantaneous values of an angular velocity signal is often an important element in controlling the drive and actuator systems of mechatronic devices. Angular velocity measurement is also included in the scope of determining the static and dynamic properties of such systems.

In the area of mechatronic devices and systems, an important group are small and miniature devices, which we define as micromechatronic systems. Methods, transducers, and test rigs useful in the case of classic electric machines may disturb the correct operation of miniature actuators used in such systems, therefore special transducers of mechanical quantities and unconventional measurement methods should be used. The dimensions of the objects tested determine small values of the mass moments of inertia of rotating elements, which in turn forces the designer of the device or a measuring system to carefully consider the possibility of attaching any additional elements to them. Also, the values of parasitic loss torques of typical measuring transducers often exceed the maximum values of torques developed by miniature motors (most often used as actuators). The smallest direct current (DC) micromotors are also 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 ms) [1, 2].

Rotational speed measurements are typically performed in two ways, i.e., using tachometric generators (small electrical machines) or by digitally processing the signal from a rotational pulse-angle transducer (encoder) [3–6], or even absolute encoders [10].

Tachometric generators (mainly synchronous or DC) are permanently connected to the tested drive system. The range of the measured angular speeds in this case is up to ≈ 1000 rad/s. The continuous (analogue) signal of the DC generator is parasitically modulated by pulsations caused by commutation phenomena and changes in air gap parameters due to the eccentricity of the rotor mounting relative to the stator. Synchronous generators additionally introduce a pulsating loading torque into the system as a result of an interaction of the rotor and the stator teeth.

Digital methods require the use of rotational encoders. The method of generating a discrete output signal from this transducer (e.g., using optoelectronic, inductive, Hall sensor technology) is not important, neither is the accepted design solution (a system with its own rotor attached to the device

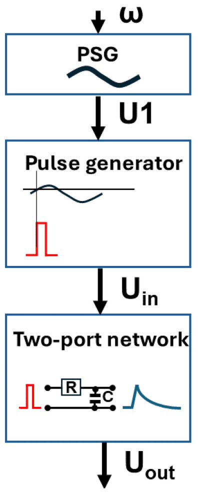

Fig. 1. The transducer block diagram. Here, PSG is quasi-sinusoidal pulse generator, and U_1 — quasi-sinusoidal voltage, U_{in} — input voltage of RC integrating two-port network, U_{out} — output signal of transducer.

structure, i.e., a commercial component or using a rotating drive element to generate a series of pulses). Digital methods allow to be determined the average value of the angular velocity. Two basic processing algorithms are used [7, 9]:

(i) Counting the pulses of the rotary-pulse transducer (angle measurement) in a set time interval;

(ii) Measurement of the time of rotation of the rotating element by an assumed constant angle value; this is done by counting the pulses of the reference generator.

2. The concept of the measurement system and its demonstrator (physical model)

The following assumptions were made regarding the technical and operational features and structure of the transducer (block diagram is shown in Fig. 1):

- Use of an open optoelectronic coupling to generate a quasi-sinusoidal signal [11],
- Generation of rectangular pulses of a fixed length (independent of the measured speed, i.e., frequency of the quasi-sinusoidal signal) with a fixed edge level from the voltage link,
- Supplying the above rectangular pulses to the input of an analogue energy-accumulating circuit, i.e., resistor–capacitor (RC) integrating two-port network; the output signal from the two-port network will be proportional to the number of pulses generated in time and will carry information about the angular velocity of the rotational movement,
- In the case of a need to eliminate pulsations in the signal at the two-port network output, adding a low-pass filter system.

Due to the possibility of direct integration with the device (using a rotating element of the drive system for minimally invasive installation of elements used to generate a series of voltage pulses), it is advantageous to use an open optoelectronic coupling whose operation principle is based on radiation reflected from the surface of the shaft.

The task of the system designer is to select the length of the rectangular pulse and its voltage and to select the time constant of the integrating two-port network, while sticking to the rule of a significant difference in the length of the pulse duration (short) in relation to the time constant of the two-port network. Ultimately, such a system should not determine the constant component of the rectangular waveform, but the aforementioned total value of the accumulated voltage.

The level of input pulses should be selected taking into account the assumed range of measured speeds and the measurement range of the data acquisition system (e.g., 5 or 10 V).

3. Physical model and its tests

The physical system of the integrating two-port network was built. A monostable flip-flop triggered by the rising edge of the signal from the optoelectronic converter to reflected light was used to generate input pulses charging the input. To simplify the system, one marker was used on the circumference of the rotating shaft. The converter shaft was connected to a DC micromotor with a speed control range from 0 to 3000 rpm. A classic speed transducer was added to this drive, namely a DC tachometric generator, which was a reference transducer. This drive system was used for static calibration of the transducer and allowed the dynamics of the system to be tested. Due to the electromechanical

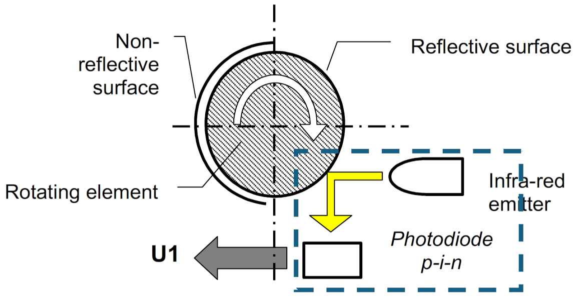

Fig. 2. Diagram of the encoder system for radiation reflected from a rotating element; one marker per revolution; “U1” — input signal denoted as U_1 in Fig. 1.

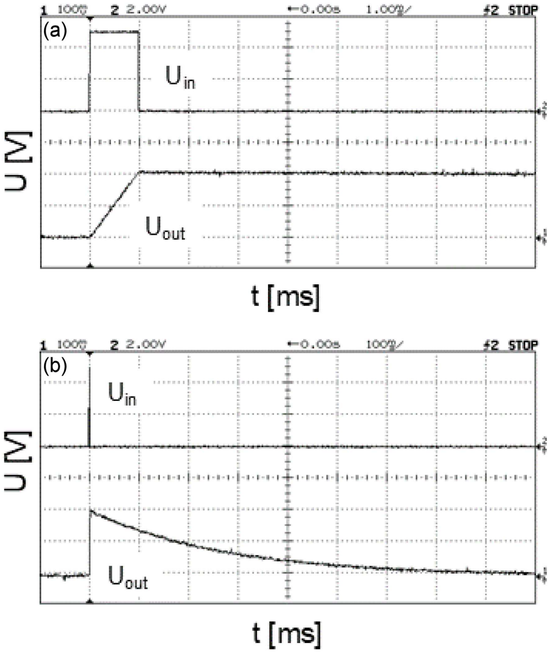

Fig. 3. Input charging TTL pulse U_{in}(1 V/div) and output signal U_{out}(0.1 V/div): (a) 1 ms/div time scale, (b) 100 ms/div time scale.

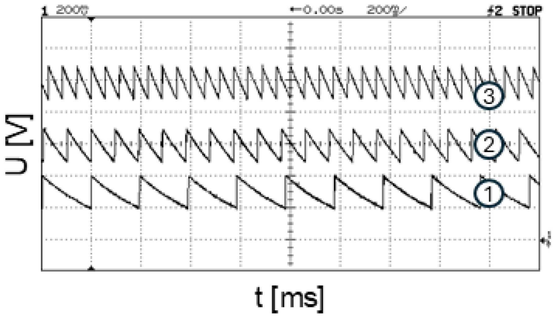

Fig. 4. Output signals at various angular speeds: 1 — 400 rpm, 2 – 900 rpm, 3 — 1500 rpm.

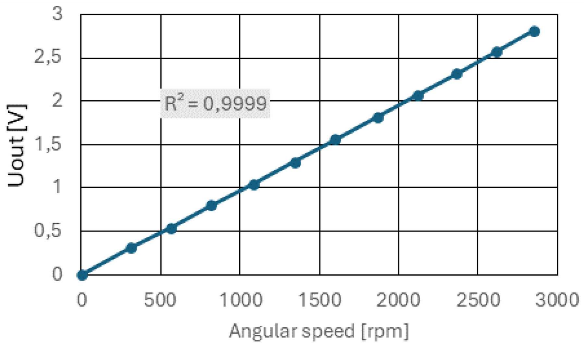

Fig. 5. Static characteristics of the transducer.

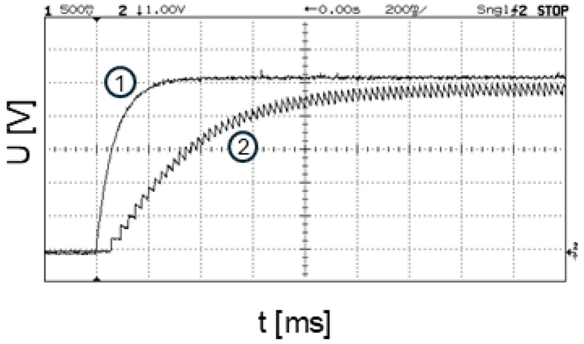

Fig. 6. Start-up of the DC miniature drive: 1 — reference signal from DC tachogenerator (1 V/div) (indicates the time constant of the drive), 2 — output signal of the transducer (0.5 V/div).

time constants of the drive system, it is almost impossible to determine the dynamic response of the transducer to the excitation of a pure speed step in experimental studies [12]. The dynamics of the drive system corresponds to the time constant of the tachometric generator signal recorded in parallel with the signal of the tested transducer. A digital oscilloscope was used to record time waveforms.

The critical settings of the measurement system are: charging pulse duration of 1 ms; two-port network input pulse amplitude of 0.2 V, RC two-port network time constant of 160 ms. Figure 2 shows a diagram of the mechanical part of the rotary-pulse converter structure.

Figure 3a shows the output waveform, i.e., the system's response to a single charging pulse, and Fig. 3b its initial phase against the background of the charging pulse duration (the charging pulse amplitude is reduced by a voltage divider from the TTL-level signal, where TTL reads transistor–transistor logic).

Figure 4 shows the waveforms, i.e., signal levels obtained at different angular speeds of the rotating system.

Figure 5 shows a graph illustrating the quality of the static measurement (steady speed). A low-pass filter system was added to the measurement circuit (a classic universal meter was used).

Figure 6 shows the system's response to a voltage step in the micro-engine supply (i.e., during start-up of the assembled drive system) in comparison with the reference waveform recorded with a tachometric generator. The frequency limitation is visible — the transducer's response has a much larger time constant.

4. Optimisation — simulation tests

In many applications, the dynamic limitations of the transducer are not decisive, since some analyses can be performed to improve the dynamic measurement capabilities.

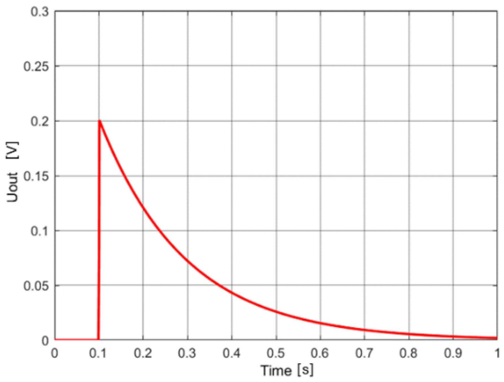

Fig. 7. Single output pulse in a simulation model of the demonstrator (see Fig. 3b).

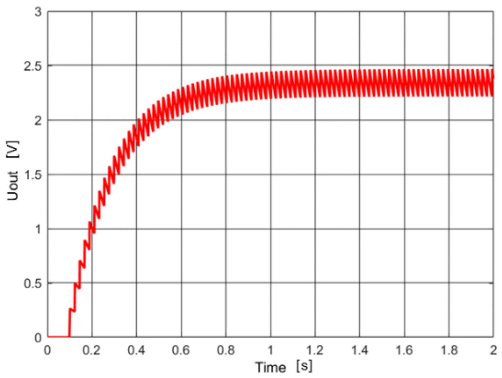

Fig. 8. Simulation of the demonstrator with the output signal at 2400 rpm.

For this purpose, a simulation model of the transducer system was developed in the MATLAB-Simulink environment. The key element of the measurement chain — the RC integrating two-port network — is described by the classic equation [13]

$$U_{in} = \tau \frac{\mathrm{d}U_{in}}{\mathrm{d}t} + U_{out}, \tag{1}$$

where: τ = RC is the time constant of the relaxation function, U_{in} — the level of "charging" pulses selected arbitrarily to the conditions of the experiment, U_{in} — output signal of two-port network.

A Simulink block was used as a monostable flip-flop with an adjustable pulse duration, and a low-pass block was used to eliminate the output signal pulsations [14].

The flip-flop input is initiated either by a clock signal from the generator or, in the case of experiments involving a specific drive system with a rotating element, by using the *Compare to Function* (*Simulink block*), initiated by a value of the function equal to 1.2,

$$z(\varphi) = \sin(n\varphi) + \cos(n\varphi), \tag{2}$$

where: φ — angular position, n — number of initial markers on the surface of the rotating shaft.

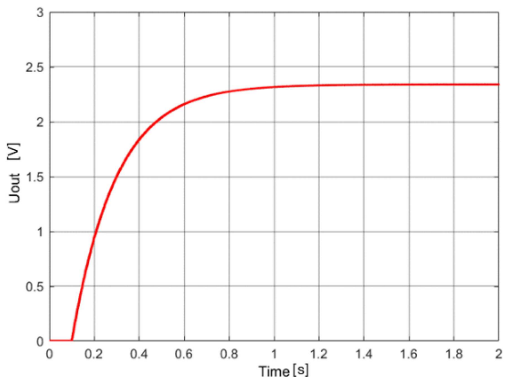

Fig. 9. Simulation details: output signal at 2400 rpm, 10 pulses/rev, increasing amplitude of pulses, RC time constant the same as in the demonstrator.

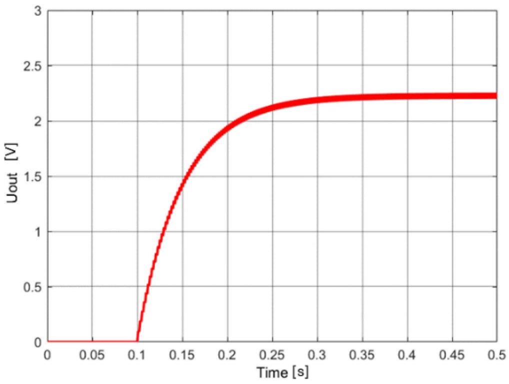

Fig. 10. Simulation details: output signal at 2400 rpm, 10 pulses/rev, pulse amplitude reduced 10 times, RC time constant = 1/2 as in the demonstrator.

In order to verify the simulation model, the presented demonstrator was modelled. The response of the system to a single pulse is shown in Fig. 7, and the signal generated at 2400 rpm (pulsing frequency 40 Hz) in Fig. 8.

In the simulation studies, the focus was on the analysis of the dynamic properties of the transducer. It was possible to test the time response to a rectangular step of the measured velocity.

During simulation tests, the changes in the transducer parameters included changes in the number of pulses per revolution and changes in the time constant of the RC network. The target was to achieve beneficial changes in the output signal character (increased response dynamics and elimination of pulsations).

The following sample simulation results show the effects of changes in the transducer structure. Figure 9 shows the effect of increasing the number of charging pulses (from 1 to 10 per one revolution). In order to maintain the output signal level, it was necessary to reduce the pulse amplitude.

Reducing the time constant of the RC circuit leads to an improvement in the dynamics of the transducer. The course presented in Fig. 10 corresponds to a two-fold reduction of the time constant of the RC two-port network and 10 pulses per one revolution, the amplitude of which was reduced in the same proportion. A reduction in the response time constant is visible with the reduction of pulsation. As a result, a significant reduction in the transducer time constant was obtained from ≈ 250 ms (Fig. 8) to ≈ 50 ms (Fig. 10) with a simultaneous reduction of the pulsation component level from 0.2 V to 20 mV.

5. Conclusions

Increasing the number of pulses (e.g., by increasing the number of markers on the rotating element) while simultaneously reducing the amplitude of the charging pulses is a way to reduce the variable component of the signal. However, it does not lead to a reduction in the response time constant. In order to improve the dynamics and reduce the response time constant to a step of speed, reduced values of the two-port network time constant should be adopted — preferably as low as possible. By simultaneously increasing the number of pulses per revolution, small time constants of the system and a small pulsation value can be obtained. At the same time, increasing the pulsation frequency in the response facilitates their simple filtration using an additional low-pass filter at the output. When selecting the time constant of the two-port network and the number of pulses per revolution, the expected range of measured speeds must of course be taken into account.

Simulation results are presented, which indicate that a two-fold reduction of the quad constant resulted in a five-fold reduction of the transducer response time constant. Increasing the number of pulses per revolution while reducing their amplitude results in a reduction of the pulsation level in the output signal. This reduction allows the pulsation to be reduced in proportion to the number of markers. The modeled transducer was characterized by a time constant of 50 ms and a variable response component of 5% of the full scale.

The presented system is simple and cheap. The advantages of the analogue output signal and the lack of the need for digital processing of signals from the encoder can be indicated.

The system allows the speed value to be determined in practically any part of the drive system — primarily by generating pulses using the radiation reflected from the rotating element. This method of generating pulses, which is contactless and does not increase the mass moment of inertia of the drive, is particularly useful in miniature drives because it does not worsen their operating dynamics. This applies, for example, to drive systems with DC micromotors with mass moments of inertia of rotating assemblies up to several tens $\mathrm{g \cdot cm^2}$ and electromechanical time constants of the order of several tens of ms.

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