A NOVEL INTEGRATED ANGULAR ACCELERATION, VELOCITY AND POSITION SENSOR

Oto Kužma — Václav Kalaš *

The paper presents a novel integrated angular acceleration, velocity and position sensor for mechatronic applications. The sensor provides complete state information, *eg* angular position, velocity and acceleration. The principle of angular acceleration sensing is based on transformation of angular acceleration to a relative radial displacement of two discs, which is sensed by optical pickup independently of the rotation speed. The sensor has an unlimited rotation range and its parameters can be modified in a wide range, which is considered to be an advantage.

K e y w o r d s: angular acceleration, rotary accelerometers, incremental encoder, flexible magnetic coupling, segment permanent magnets, mechatronic systems

1 INTRODUCTION

In motion control we often face the problem of drive and a driven equipment parameter variations, additionally, the system is subject to various external disturbances due to interaction with working environment. These parameter variations can be continuous as well as discrete.

Typical representatives of that class of applications are industrial robots, NC machines, machining tools, reeling systems, *etc* . Their control systems need to be designed so that the stability and performance of the system is ensured. Hence, it is usually necessary to use sophisticated adaptive or robust control structures and algorithms providing acceptable system behaviour under given parameter variations. Many of these methods require complete state information to be known [1], [2], [3], *ie* besides angular velocity and position, information about angular acceleration has to be available as well.

Nowadays, angular acceleration is obtained almost exclusively by indirect methods based on observers. Direct angular acceleration sensing is limited due to problems encountered with the transfer of electrical signals from rotating parts and therefore majority of available sensors have a limited rotation range [4], [5], [6], poor quality output signal [7] or complex structure [8]. Since the rotary accelerometer can have many applications in industry, a novel integrated rotary accelerometer was designed and developed at the Department of Automation Control FEI STU, which does not have above-mentioned limitations and provides also angular velocity and position.

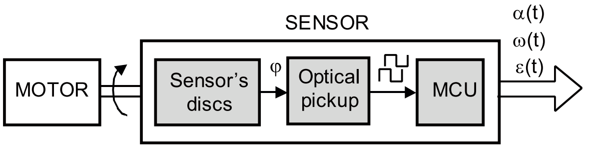

Fig. 1. Sensor's operational principle.

2 OPERATIONAL PRINCIPLE OF SENSOR

The basic operation principle of the sensor is described by the block diagram shown in Fig. 1. The sensor itself consists of three parts: a pair of discs, an optical pickup and microcontroller (MCU). The pair of discs, one of which is connected to the shaft of the motor — solid disc, and the other one can rotate around sensor axis-flexible disc, performs transformation of angular acceleration $\varepsilon(t)$ into a relative radial displacement of the discs φ. The discs are coupled by flexible magnetic coupling created by segment permanent magnets fixed to the discs at their circumferences.

The optical pickup detects the relative displacement d without contact providing signals that are afterwards processed by the microcontroller. To suppress high-frequency components in the output signal, MCU performs digital filtering as well. Angular velocity $\omega(t)$ and angular position $\alpha(t)$ are obtained from the solid disc, which serves as a standard incremental disc used in incremental encoders.

3 SENSOR STRUCTURE

Figures 2 and 3 show the complete sensor structure and single decomposed discs, the numbers denoting sensor components are the same in both pictures. The solid

* Faculty of Electrical Engineering and Information Technology STU, Ilkovičova 3, 812 19 Bratislava, Slovakia

ISSN 1335-3632

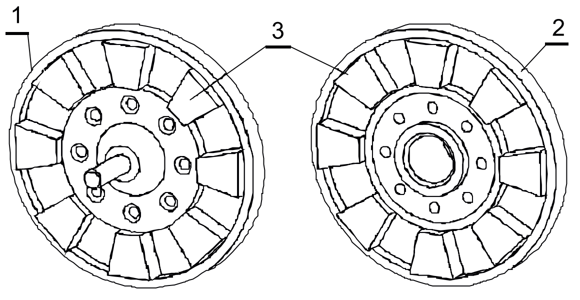

Fig. 2. The solid disc 1 and the flexible disc 2.

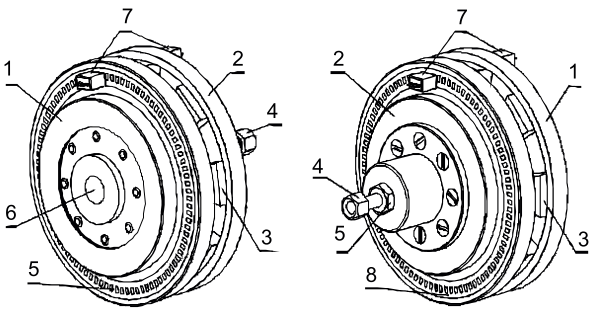

Fig. 3. Sensor structure.

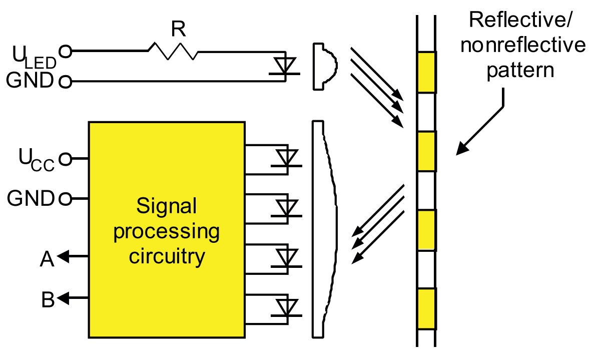

Fig. 4. Block diagram of HP HEDR-8000 optocoupler.

Table 1. Parameters of ferrite permanent magnets.

Material	Durox 330			
Max. energy product	$(BH)_{\max}$	kJ·m^{-3}	Min.	26.4
Remanence	B_r	T	Min.	0.375
Coercivity	H_{cB}	KA·m^{-1}	Min.	175
Temp. coeff. of B_r	$TK\ B_r$	%·K^{-1}		-0.15
Resistivity	ρ	Ω·m		10^3
Curie point	T_c	°C		450
Density	γ	Kg·m^{-3}		4800

disc 1 and the flexible disc 2 are made of nonmagnetic plastic material VESTAMID, which is widely used in reducers and planetary (epicyclic) gears in order to reduce their noise. This material has excellent mechanical and thermal properties, *eg* high strength and dimension stability.

Segment permanent magnets 3 are fixed to the discs by insertion into a groove that compensates centrifugal forces acting on the magnets, and by gluing onto the discs by industrial adhesive PASCOFIX with guaranteed tensile strength 200kg/cm^2. Magnets on the discs face each other with opposite poles so that an attractive magnetic field between the discs is created. Their parameters are in Tab. 1.

The number of magnetic pairs required to obtain a specific gain of the sensor depends on the maximum energy product of the magnets as well as on sensor structural parameters, *eg* moment of inertia of the flexible disc J_2 and width of axial air gap d between the discs. There were used eight pairs of magnets.

To obtain a linear input-output characteristic of the sensor, the torsional torque M_φ between the discs due to acceleration in the system has to be proportional to the relative angular displacement φ of the discs. This can be achieved only if the magnets have the shape of circular segments. However, this is only a necessary but not a sufficient condition and thus linearity is not fully guaranteed since the besides homogeneous magnetic field between the opposite magnetic poles a leakage magnetic field is present as well giving rise to cross-coupling effects.

The flexible disc rolls on two precise ball bearings and the width of air gap between the discs d which defines the sensor gain and damping properties can be modified by screw 4 and nut 5 (Fig. 3). Number 6 denotes a point where the sensor is firmly connected to the motor shaft.

Relative angular displacement φ is sensed by two optocouplers HP HEDR-8100 which use reflective technology to sense reflective/nonreflective patterns, the same on both discs. As seen in Fig. 4, each optocoupler consists of an LED light source and a set of uniquely configured photodiodes that allow to detect the direction of rotation. Signal processing circuitry improves the quality of signals obtained from photodiodes, providing two square wave outputs with an electrical phase shift of 90° e that are interfaced to an 8-bit microcontroller. The maximum encoder's count frequency for pattern resolution 2.95 lines/mm is 15 kHz.

If acceleration is applied to the system, the pulse train at the output of the optocoupler scanning the solid disc reflective/nonreflective pattern dominates the pulse train obtained from the flexible disc optocoupler and the phase shift is proportional to angular acceleration.

The phase shift is converted into a digital form by 8-bit microcontroller MOTOROLA M68HC11. It includes independent input-capture functions based on a free-running 16-bit counter that allow to count the pulses and

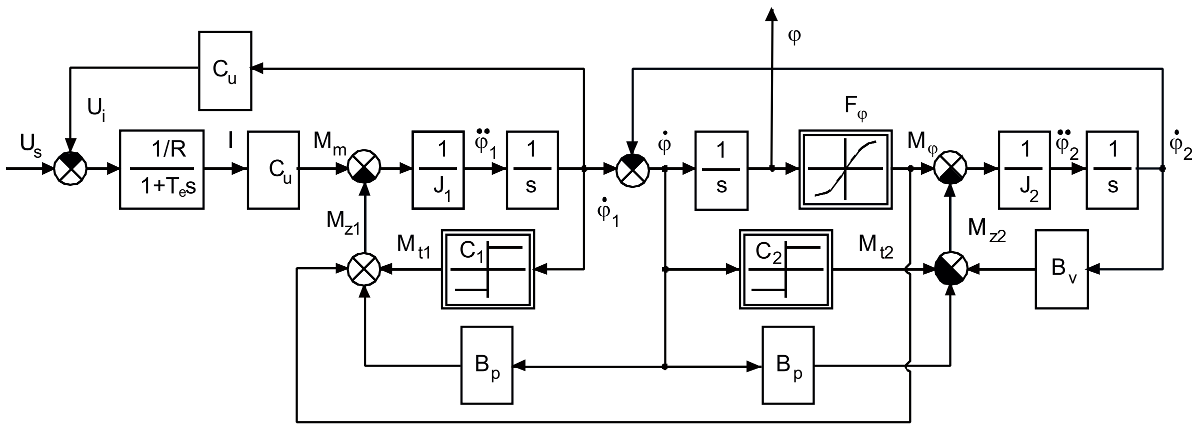

Fig. 5. Block scheme of the sensor connected to DC motor.

detect the rising and falling edges of the signal. MCU calculates also the angular position and velocity from the number of pulses and pulse frequency, respectively, obtained from the solid disc optocoupler and sends the complete state information to the superior system.

4 MATHEMATICAL MODEL OF THE SENSOR

The solid and the flexible discs of the sensor, together with the flexible magnetic coupling, form a flexible mechanical system, which is a special case of a spring-mass system. Since the system is rotary, the masses of the discs are represented by moments of inertia and the input to the system is a torsional torque instead of a force. During the experiments the sensor was connected to the shaft of DC disk motor with no additional load. Thus, the moment of inertia of the solid part J_1 includes the moment of inertia of the solid disc and the rotor as well, the moment of inertia of the flexible disc is J_2. In the following, we will consider Coulomb friction in the motor as well as air resistance acting against the motion of the flexible disc. With respect to the maximal angular velocity, the relation between air resistance and angular velocity is proportional, characterised by friction coefficient B_v. Relative motion of sensor discs is influenced by friction in ball bearings of the flexible disc, which acts against the motion. This friction introduces a small dead zone to sensor input-output characteristic, which can reduce sensor accuracy. In the model, we considered Coulomb friction given by value C_2.

A block scheme of the sensor connected to DC motor, which was obtained from mathematical description of the system based on moment equations, is shown in Fig. 5. In the figure, C_u is the back-emf/torque constant, R — armature resistance, T_e — electromagnetic time constant, $\ddot{\varphi}_1$ is angular acceleration of the motor and relative angular displacement of the discs φ is the output. Block F_1 describes the relation between the torsional torque M_φ and the relative mutual displacement of the discs φ which is in fact the stiffness of the magnetic coupling. This relation is nonlinear [2], however, the part of it corresponding to the small relative displacement φ is linear with gain K_p. Another parameter of the flexible magnetic coupling is damping expressed by the damping coefficient B_p. Voltage signal U_s applied to the motor armature is an input of the system, however, the input for the sensor is dynamical torque $M_{dyn} = M_m - M_{z1}$ which forces the motor to accelerate.

5 ANALYSIS OF SENSOR DYNAMICS

To examine sensor dynamics, first the dynamic model has to be derived. In the following we will consider a linearised model of the sensor. Sensor's input-output transfer function, derived from the block scheme in Fig. 5 is

$$\varphi = \frac{J_2\ddot{\varphi}_1 + B_v\dot{\varphi}_1 + M_{t2}}{J_2 s^2 + (B_p + B_v)s + K_p}\,, \tag{1}$$

$$s^2 + \frac{B_p + B_v}{J_2}s + \frac{K_p}{J_2} = 0\,, \tag{2}$$

and from characteristic equation (2), for sensor eigenfrequency ω_0 and damping factor b it holds

$$\omega_0 = \sqrt{\frac{K_p}{J_2}}\,; \quad b = \frac{B_p + B_v}{2J_2\omega_0}\,. \tag{3}$$

In steady state, the relation between the relative displacement φ and angular acceleration $\dot{\varphi}_1$, obtained from (1), can be expressed by expression

$$\varphi = \frac{J_2}{K_p}\ddot{\varphi}_1 + \frac{B_v}{K_p}\dot{\varphi}_1 + \frac{M_{t2}}{K_p}\,, \tag{4}$$

and finally for the sensed angular acceleration we have

$$\ddot{\varphi}_1 = \frac{K_p}{J_2}\varphi - \frac{B_v}{J_2}\dot{\varphi}_1 - \frac{M_{t2}}{J_2}\,. \tag{5}$$

Expression (5) is a mathematical formulae for the calculation of the angular acceleration in a quasi-steady

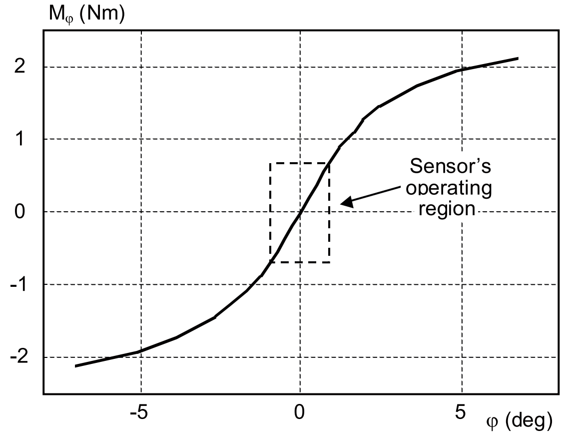

Fig. 6. Sensor's input-output characteristics.

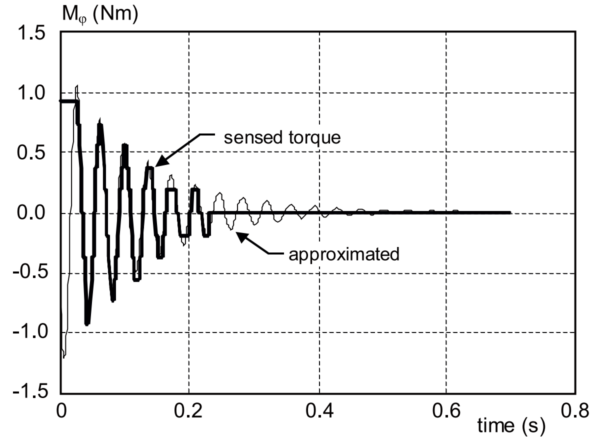

Fig. 7. Sensor's step response to a step change of torque M_φ.

state, taking into consideration also disturbances. Cross-coupling effects in the whole system sensor-motor (as seen in Fig. 5, torsional torque M_φ acts as a disturbance to the motor) can be examined from the transfer function relating velocity of the motor $\dot{\varphi}_1$ to the motor torque M_m (6), in which the influence of air resistance on the flexible disc was neglected, *ie* $B_v = 0$.

$$\begin{aligned}\dot{\varphi}_1 = \big\{(J_2 s^2 + B_p s + K_p)M_m - (J_2 s^2 + B_p s + K_p)M_{t1} \\ - (B_p s + K_p)M_{t2}\big\} / \big\{[J_1 J_2 s^2 + (J_1 + J_2)B_p s \\ + (J_1 + J_2)K_p]s\big\}. \quad (6)\end{aligned}$$

Astatism in the denominator of the transfer function (6) tells about the integral character of the considered system segment. When a constant torque M_m is applied, after transient components have ceased, the motor constantly accelerates. The rate of acceleration is given by expression

$$\ddot{\varphi}_1 = \frac{M_m - M_{t1} - M_{t2}}{J_1 + J_2} = \frac{\frac{M_m - M_{t1} - M_{t2}}{J_1}}{1 + \frac{J_2}{J_1}}. \quad (7)$$

Hence, to minimize sensor impact on motor performance, it is essential to minimize the moments of inertia of the solid and flexible discs, or to keep the flexible disc moment of inertia much smaller than the complete reduced moment of inertia of the motor, *ie* to minimize the ratio J_2/J_1 in denominator of expression (7). In transient state, the angular velocity signal contains a sinusoidal transient component with frequency ω_0^* and damping factor b^* given in (8).

$$\omega_0^* = \sqrt{K_p\Big(\frac{1}{J_1} + \frac{1}{J_2}\Big)}; \quad b^* = \frac{B_P}{2\omega_0}\Big(\frac{1}{J_1} + \frac{1}{J_2}\Big). \quad (8)$$

Thus, to obtain a complete linearized mathematical model of the sensor, it is necessary to identify gain K_p and damping coefficient B_p of flexible magnetic coupling as well as moments of inertia J_1, J_2 and Coulomb friction C_2.

To ensure a good dynamical accuracy of accelerometer, the amplitude of the output signal transient components has to be small and has to attenuate quickly. The damping of the presented accelerometer is influenced by the following factors:

- Damping properties of permanent magnets — B_p
- The width of air gap between the solid and the flexible disc — d
- Electrical properties of nonmagnetic material the discs are made of — B_D
- Coulomb friction acting in ball bearings of the flexible disc — C_2, change of this friction as well as mutual relative velocity of the discs
- Friction between the flexible discs and the working environment the disc is in (air, vacuum, liquid) — B_v

The damping of the accelerometer can be set in the following ways:

- Selection of proper nonmagnetic material for the body of the discs, *eg* copper, which has good damping properties
- To obtain reasonable damping of accelerometer, it is possible to apply thin copper sheet on the body of the discs made of VESTAMID
- Duralumin and bronze would be also proper materials
- It is also possible to apply short copper thread around segment permanent magnets

6 PARAMETERS IDENTIFICATION AND CHARACTERISTICS OF ACCELEROMETER

As already mentioned above, the relation between the torsional torque M_φ and angular displacement of the discs φ is not linear. To obtain complete linearity, the magnet area uncovered due to acceleration in the system has to be proportional to the angular displacement of the discs φ, moreover, we need a pure homogeneous magnetic field between the opposite magnetic poles. This is satisfied only if the magnets have the shape of a circular segment, but in case that large acceleration is applied to the system, the mutual angular displacement of the discs is large and thus the leakage magnetic field between the discs is more significant.

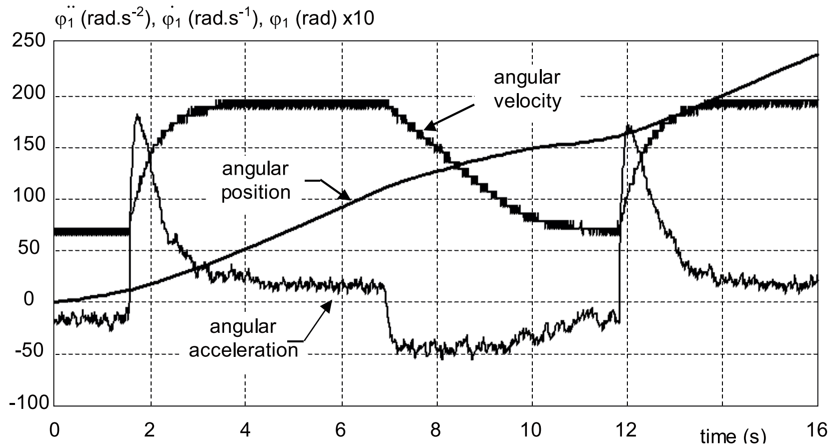

Fig. 8. State signals obtained from sensor for armature voltage step change from 11 V to 25 V.

Finding mathematical formulae relating the torsional torque to the angular displacement is a very complex problem from the mathematical as well as physical point of view. The assumption that for a small angular displacement the input-output characteristic is linear was verified experimentally after completion of sensor assembly, while the assembly and design was based on measurements of the torsional torque between the two permanent magnets [2]. The obtained input-output characteristic is shown in Fig. 6. Measurements were made for a width of air gap $d \doteq 0.33$ mm and as seen in Fig. 6, the linear region corresponds to angular displacement approximately $\varphi = \pm 1.5°$. For this region the relation between the torsional torque and angular displacement is given by gain $K_p = 43.63\,\mathrm{Nm{\cdot}rad}^{-1}$. Sensor's operating region was set to angular displacement $\varphi = \pm 1°$.

The damping coefficient of the sensor and the moment of inertia of the flexible disc J_2 can be determined from the step response of the sensor shown in Fig. 7 which was obtained for a step change of torque M_φ while the solid disc was fixed

$$p(t) = Ke^{-\frac{b}{T}t}\sin(\omega_0 t + \nu)\,. \tag{9}$$

From an approximation of the torque response in Fig. 7 by function (9) we obtained the damping factor $b = 0.048$ and sensor eigenfrequency $\omega_0 = 170\,\mathrm{rads}^{-1}$. The moment of inertia of the flexible disc J_2 and the sum of damping coefficients $(B_p + B_v)$ are expressed on basis of equation (3) as

$$J_2 = \frac{K_p}{\omega_0^2} \doteq 1.51 \times 10^{-3}\,\mathrm{kgm}^2\,, \tag{10}$$

$$B_p + B_v = 2J_2 b\omega_0 \doteq 4.2\,\mathrm{kgm}^2\mathrm{s}^{-1}\,. \tag{11}$$

7 EXPERIMENTAL RESULTS

Testing of sensor prototype was performed in connection with DC motor PARVEX 300 W, 70 V, 6 A, which was equipped with an incremental encoder with a resolution 1000 counts per turn. The encoder was used as a source of reference angular position, velocity and calculated acceleration signals for comparison with signals obtained from the accelerometer. During the experiment, step voltage changes from 11V to 25V and vice versa were applied to motor armature. State signals obtained from the accelerometer are shown in Fig. 8.

In the above experiment, a first-order low-pass filter with a time constant $T_f = 0.08$ s was used with the sensor to cut off the disc's eigenvibration and sensor rotation ripple from the sensed acceleration signal. In quasi-steady state, when the speed of the motor is constant, the angular acceleration riches a non-zero value due to friction in ball bearings of the flexible disc. The friction torque, provided that we assume only Coulomb friction, is given by equations (1) and (5) and its value was identified experimentally, *ie* $C_2 = 22.5 \times 10^{-3}$ Nm. The friction torque can be suppressed by additional improvements made to sensor structure or by implementation of software compensation.

Sensor's ripple originates from mechanical inaccuracies of the reflective/nonreflective pattern and sensor misalignment with the motor shaft. Reflective/nonreflective patterns are not mounted concentrically with the axis of rotation as well. Centres of reflective/nonreflective patterns on the discs are displaced from the axis of rotation causing that the count frequency varies over one revolution and the output signal contains a quasi sine FM component. The expression for the count frequency is

$$f = \frac{\omega N}{2\pi}\Big(1 + 2\frac{\Delta r}{r}\sin\Theta\Big)\,, \tag{12}$$

where $r-$ pattern radius
$f-$ count frequency
$\omega-$ angular velocity of shaft
$N-$ number of counts per turn
$\Theta-$ shaft angle; $\Theta = \omega t$
$\Delta r-$ distance between the center of the disc pattern and the center of rotation.

Removal of sine FM component can be accomplished by precise sensor manufacturing and assembly or by summing the outputs of two sensor located 180° apart on the disc. The second possibility requires two additional optocouplers.

Angular velocity signal (in Fig. 8) contains a quantization noise, which is typical for angular velocity signals digitally obtained from incremental encoders, and it originates from an asynchronous arrival of the sensed pulses and pulses from the measuring pulse generator (included in MCU) to microcontroller. Thus, if the speed of the motor is constant, the number of pulses per unit time obtained in two different sampling instances can differ by one pulse causing a discrete change of the output angular velocity signal. There are several methods used for calculation of the angular velocity [10]. Selection of a method which suits the best for a given application depends on the range of speed to measure, maximum absolute error, measuring time, *etc* . In our accelerometer M-method has been used, which calculates the frequency of pulses obtained from the solid disc over a constant sample period T_s.

Assume N is the number of counts per turn, then the output pulse frequency at the motor speed $\omega(t)$ is

$$f(t) = \frac{N}{2\pi}\omega(t) \tag{13}$$

The number of pulses registered by the pulse counter over measuring time T_c is M, *ie*

$$M = T_c f = T_c \frac{N\omega(t)}{2\pi}, \tag{14}$$

Note that M is an integer number. Thus, with respect to expressions (13) and (14), for the angular velocity $\omega(t)$ and absolute $\Delta_\omega(t)$ and relative $\xi_\omega(t)$ measuring error, respectively it holds

$$\omega(t) = \frac{2\pi}{NT_c}M \tag{15}$$

$$\begin{aligned}\Delta_\omega(t) &= \Big|\frac{\partial\omega(t)}{\partial M}\Big|\Delta M + \Big|\frac{\partial\omega(t)}{\partial T_c}\Big|\Delta T_c \\ &= \frac{2\pi}{NT_c}\Delta M + \frac{2\pi M}{NT_c^2}\Delta T_c\end{aligned} \tag{16}$$

$$\xi_\omega(t) = \frac{\Delta_\omega(t)}{\omega(t)} = \frac{\Delta M}{M} + \frac{\Delta T_c}{T_c} \doteq \frac{1}{M}. \tag{17}$$

Term $\Delta T_c/T_c$ states for the error due to unequal length of the measuring period T_c. This error is sufficiently small in comparison with term $\Delta M/M$ to be neglected. As already mentioned, due to an asynchronous arrival of the sensed pulses and pulses from the measuring period pulse generator, a loss of one pulse can occur, thus $\Delta M = 1$. From expression (16) it is apparent that if the measuring period pulse generator error is neglected, the absolute error $\Delta_\omega(t)$ is constant during measurement and it can be reduced by increasing the counts per turn and measuring period T_c, respectively. The relative error given by expression (17) changes during measurement, it decreases with increasing velocity and vice versa.

For the number of counts per turn $N = 90$ of our sensor and measuring period $T_c = 10$ ms, the absolute error calculated from expression (16) is $\Delta_\omega = 6.98\,\mathrm{rad\cdot s^{-1}}$. The value of quantization noise included in the angular velocity signal shown in Fig. 8 is equal to the absolute error $\Delta_\omega(t)$. The number of counts per turn applied to our sensor $N = 90$ was chosen with respect to construction capabilities of our workshop, however, nowadays it is possible to achieve even several hundreds counts per turn by laser technology used in compact discs bringing excellent resolution.

8 APPLICATIONS OF ROTARY ACCELEROMETERS

As mentioned in the introduction, rotary accelerometers can have many industrial applications, bringing new quality and making possible to solve many problems encountered with the whole class of mechatronic systems *eg* :

- Rotary accelerometers allow exact identification of quasi-steady as well as dynamical torque characteristics of asynchronous drives and characteristics of electromagnetic amortisseurs used in synchronous drives, which can not be obtained in another way especially in the case of high rated output motors. By this approach it is possible to identify even asynchronous and synchronous saddles in torque characteristics.
- Rotary accelerometers allow to identify mechanical frictions present in production machines as well as load on these machines due to technology as a function of velocity. This identification is based on computation of the difference between quasi-steady torques measured while disconnected from a driven machine and the torques obtained after a motor has been connected to a driven machine.
- Rotary accelerometers with a high gain (*eg* optoelectonical sensor based on Sagnac effect) allow to suppress hysteresis and backlash of gears used in motion control systems, which is important especially for ensuring stability of these systems.
- High quality rotary accelerometers enable to realize velocity and position mechatronic systems with highly suppressed torque and velocity ripple at low rotation

speed, which is important in robotics as well as other mechatronic systems

- Rotary accelerometers make possible to apply a special acceleration control loop with an additional controller to mechatronic systems used in transportation to ensure a proper acceleration and deceleration, in every kind of situation in order to protect mechanical parts and transported objects as well.
- Rotary accelerometers allow to increase robustness of mechatronic systems in the case of large parameter changes (*eg* moment of inertia) and load changes without any priori information. This can be achieved by a special acceleration control loop applied as a superior control loop to current control loop and subordinated to velocity control loop [11].
- Application of rotary accelerometers allows to apply original complete invariancy approach bringing excellent robustness against very fast parameter (moment of inertia, mass of the system) and load changes. This is achieved by a single invariancy controller, which processes information about actual torque and acceleration of the system [12].

9 CONCLUSION

In the paper, a novel integrated angular acceleration, velocity and position sensor for mechatronic applications was presented, which provides angular acceleration, velocity and position. This sensor has the capability to sense the angular acceleration independently of rotation speed and has an unlimited rotation range. The sensor structure is simple and sensor parameters can be modified in a wide range according to application needs.

In this paper we did not analyze repeatability of the sensor signal and some other features which need to be analyze to produce a reliable product. An aim was to approve the basic idea the sensor is based on and to identify potential drawbacks, which was found to be a rolling friction in ball bearings. However, experimental results obtained from the first prototype are promising and we hope the sensor can find its way into engineering practice. To improve sensor performance the following structural improvements can be made:

- Application of a single ball bearing or a structure without any ball bearings is also possible in the case of well balanced sensor discs to reduce friction
- Using permanent magnets made of a material with higher energy product $(BH)_{\max}$
- Application of two additional optocouplers located 180° apart on the disc to cancel errors due to imperfections of the discs and patterns
- Proper filtration of the output signal
- Precise and accurate manufacturing and assembly.

References

[1] BUTLER, H.: Model Reference Adaptive Control — PhD thesis, Technische Universiteit Delft, (1990).

[2] KUŽMA, O.: Robust Robot Servosystem Synthesis, Written work for rigorous examination, Bratislava, (1998), (in Slovak).

[3] ZBORAY, L.—UROVSK, F.: State Control of Electric Drives (Stavové riadenie elektrických pohonov), Vienala (1995), (in Slovak).

[4] Endevco Corporation, Piezoresistive Angular Accelerometers, Product Information Catalogue, (1999).

[5] Schaevitz Sensors, Inclinometers and Accelerometers, Product Catalogue, (1999).

[6] Columbia Research Laboratories, Inc., Force Balance Angular Accelerometer, (1999).

[7] Hübner Electromaschinen AG, Sinus-Tachos with Rotary Acceleration Sensor, Product Catalogue,(1999).

[8] GODLER, I.—AKAHANE, A.—OHNISHI, K.—YAMASHITA, T.: A Novel Rotary Acceleration Sensor, IEEE Control Systems, Vol. 1, (1995), pp. 56–60.

[9] Motorola M68HC11, Reference Manual (1990).

[10] Numeric Sevosystems with Vector Control of AM (Číslicové servosystémy s vektorove riadenmi AM), Partial report to contract No. 511/86 – F451 Utilization of Microprocessors in Control of Power Semiconductor Structures (Využitie mikroprocesorovej techniky v riadení výkonových polovodičových štruktúr) (1986), (in Slovak).

[11] KALAŠ, V.—KUŽMA, O.: Robust Cascade Structures of Mechatronic Systems with Derivative Feedbacks, Trends in Control and Applications, VEDA, (1998).

[12] KALAŠ, V.—MOLNÁR, M.: Parametrically Invariant Servosystems of Robots, IFAC Workshop on New Trends in Design of Control Systems, (1994), pp. 61–67.

Received 4 July 2000

Oto Kužma (Ing) was born in Michalovce in 1973. He graduated in Automation from the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Bratislava, in 1996. His research interests include motion control systems, robust systems and design of angular acceleration sensor.

Václav Kalaš (Prof, Ing, DrSc), graduated from the Faculty of Electrical Engineering of the Slovak University of Technology (SVŠT), Bratislava in 1953. He received the CSc degree in technical cybernetics in 1961, became Associate Professor and received the DrSc degree, in 1963 and 1978, respectively. Currently, he is an Emeritus Full Professor. His primary areas of research are motion control systems with emphasis on mechatronics and robotics. In recent years his research interests were in analysis and design of robust systems with nonstationary, in a wide range varying parameters.