18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 177–186
Paper **#88**

EXPERIMENTAL DEVICE FOR TESTING OF SERVOMECHANISMS OF THE PASSIVE OPTOELECTRONIC RANGEFINDER

V. Čech[1], M. Červenka[2], P. Snopek[3], I. Trávníček[4], V. Václavík[5]

Abstract: *It is necessary to use quite a big gear ratio (from 150 to 300) to ensure an accurate control of the angular motions of passive optoelectronic rangefinder (POERF).Used zero-backlash gearings together with the features of rolling-contact bearings generate relatively high nonlinearities which make the achievement of demanded control accuracy of POERF complicated or even totally precluded. Experimental (Test) device for the described drives was constructed in OPROX company. The device was set into function by the composite authors of this article and at the moment, relevant measurements are being made. The aim is to use the testing measurements made on the device in order to design and verify a method and SW for initial and continuous identifications of the parameters of POERF nonlinear model of servo-drive. In this article we will provide basic information on mechanical design of the experimental device construction, control and power parts of servo-drive and on communication protocol including the measurement protocol (output data).*

Keywords: ***Experimental (Test) device, servo-drive, nonlinear system, passive optoelectronic rangefinder (POERF), measurement.***

1. Introduction

During the work on project KT-TA3/103 between 2007 and 2009 we discovered that zero-backlash servo-drives suitable for POERF are very nonlinear and it is impossible to achieve the demanded control quality when control algorithms based on linear theory of automatic control are used (Composite authors (2009)).

At that time, preliminary theoretic analyses were made (Čech, V. & Jevický, J. (2008a), Čech, V. & Jevický, J. (2008b), Čech, V. & Jevický, J. (2009)), and they verified the results acquired in experiments with servo-drives of POERF. Nevertheless, it was obvious that it is necessary to accomplish systematic experiments in order to form the basis for design of nonlinear model of servo-drive that must be implemented into servo-drive controllers so as to achieve the demanded quality of control. At the same time it was apparent that in order to accomplish these operations it will be necessary to construct a specialized experimental (test) device. In addition, it is essential to state that results of measurements mentioned in literature search are inadequate for our purposes.

The experimental (test) device (Fig. 1, 2, 3) was designed by composite authors of this article according to the conceptual design elaborated by V. Čech. The device was constructed and activated in OPROX company in cooperation with other sub-suppliers in 2011. Consequently, exploratory measurements have been made since August 2011 and they are about to be finished now. Mechanical structure was designed by M. Červenka. Power and control electronic units were designed and realized by P. Snopek and V. Václavík. Control and communication SW was realized by I. Trávníček. The measurements are made by I. Trávníček under the supervision of V. Čech.

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[1] Doc. Ing. Vladimír Čech, CSc., Oprox Inc., Brno, Czech Republic, and University of Trencin, Fakulty of Special Technologies, Slovak Republic, e-mail: cech-vladimir@volny.cz

[2] Ing. Martin Červenka, Ph.D., Oprox Inc., Brno, Renneská 413/35, 639 00 Brno, Czech Republic, e-mail: martin.cervenka @oprox.cz

[3] Ing. Petr Snopek, Oprox Inc., Brno, Renneská 413/35, 639 00 Brno, Czech Republic, e-mail: petr.snopek@oprox.cz

[4] Bc. Ivo Trávníček, Oprox Inc., Brno, Renneská 413/35, 639 00 Brno, Czech Republic, and Brno Technical University, Fakulty of Mechanical Engineering, e-mail: i.travnicek@seznam.cz

[5] Ing. Vlastimil Václavík, Oprox Inc., Brno, Renneská 413/35, 639 00 Brno, CR, e-mail: vlastimil.vaclavik@oprox.cz

The aim of this article is to acquaint the specialists with the experimental device construction. In final part, examples of measurement results are stated to prove that zero-backlash drive with a set structure is really nonlinear.

2. Design of the experimental device

2.1. Design of the mechanical structure

Experimental device consists of (Fig. 1) the device 1, control computer 2 with particular SW and of power supply 3.

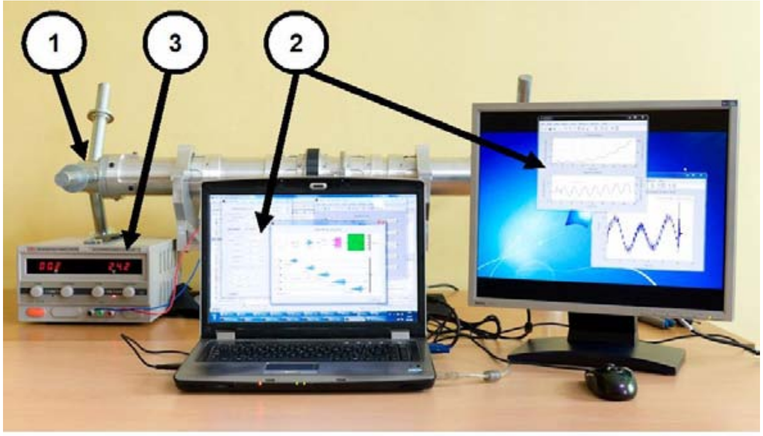


Fig. 1 General view of the Experimental device I.

In order to describe the full construction of the device we will use Fig. 2, 3, 4. In these pictures, there are single items/parts marked by identical arrowheads. The weight of the device is c. 32 kg and with side shanks for placement of weights it is c. 42 kg.

Output shaft (controlled object) 1 is placed with the use of rolling-contact bearings in the frame 2 of the device. The frame of the device 2 is pivoted on a base plate 3 with the use of a shaft 4. A control bar 12 is used to turn the frame 2 manually towards the base plate 3.

Manual turning will be used in the future to accomplish special experiments. For basic experiments that are being currently accomplished, the frame 2 is rigidly fixed to the base plate 3 by the use of stopping mechanism with a fixation screw 10.

On both sides of the output shaft 1 there are three side shanks where discs of different weights 11 can be placed and thus it is possible to change the moment of inertia of the output shaft (controlled system) in relatively high limits (bounds). The moment of inertia of the output shaft without the weights and side shanks (Fig. 2) is 0,014125 kgm^2. Maximal moment of inertia (6pcs of discs ea. 5 kg) is 1,205460 kgm^2.

Lightweight rolling-contact bearings 61818-2RS with inside diameter 90 mm by company SKF are used for placing the output shaft 1 into the frame 2.

Angular displacement of the output shaft 1 towards the frame 2 is measured by means of optic incremental sensor “SIGNUM RESM angle encoder” (arrowhead 8) by company RENISHAW plc, UK (www.renishaw.com) with outside diameter of the incremental ring 115 mm. On the surface of the incremental ring there are 18 000 line counts which correspond to basic resolution 0,35 mrad = 72 arc seconds. Overall resolution is amplified by the use of digital interpolation and the digital resolution can be up to 4000 higher (interpolation factor = 4, 20, ..., 4000). For example if the interpolation factor is 20 then the digital resolution equals 2,75 arc seconds = 0,013 mrad. In the following text we will use abbreviation RESM to refer to the sensor.

The respective servo-drive consists of (Fig. 2, 4) mechanical gearings, DC motor 5 with accessories, control and power unit 7 and power supplies 9.

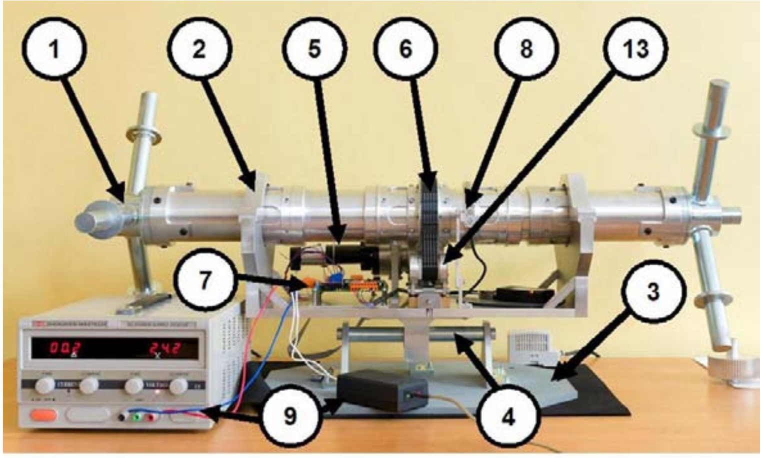


Fig. 2 General view of the Experimental device II.

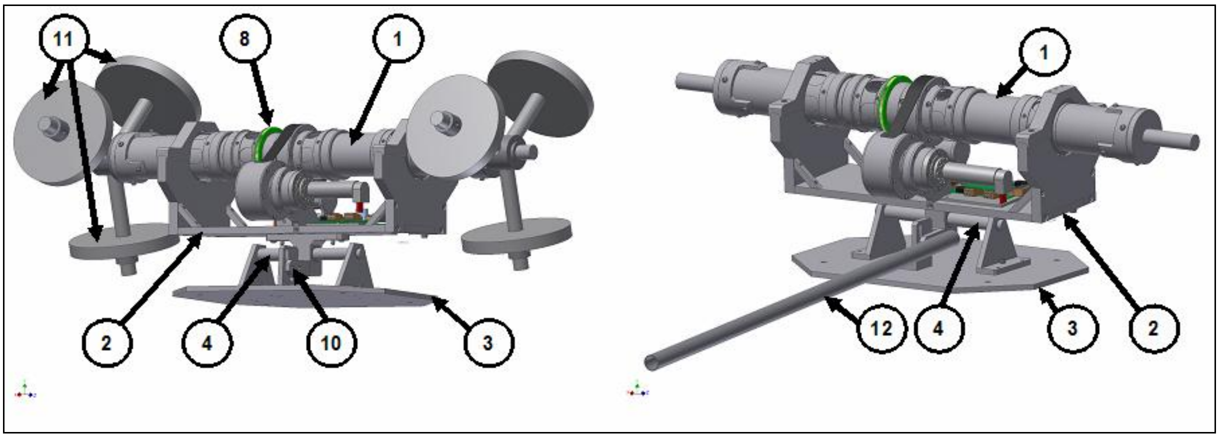


Fig. 3 Assembly of mechanical parts of the Experimental device

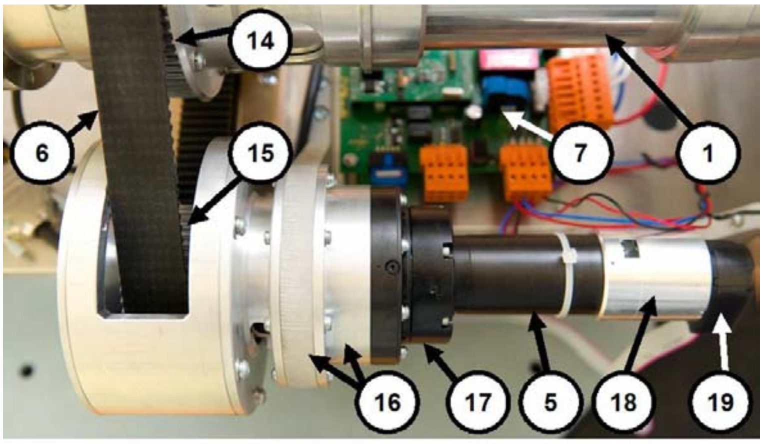


Fig. 4 Assembly of the servo-drive

Mechanical gearings comprise a harmonic drive gearing 17 and a belt drive 6.

Harmonic drive gearing (arrowhead 17) is type CPU-14A-100-M-06.XX-SP with gear ratio i_1 = 100 by company Harmonic Drive AG (www.harmonicdrive.de). Moment of inertia reflected to the gear input is $33 \cdot 10^{-7}$ kgm^2. It is filled with special grease for ambient temperature range from -30 to +50°C. The shaft of the DC motor (diameter 6 mm) is fastened to a hub of input shaft of the gearing by means of grub screws.

The belt drive is set from parts produced by company Gates Corporation, USA (www.gates.com). The drive is based on an indented belt PowerGrip® GT3 625 5MGT 25 (teeth pitch 5 mm, number of teeth 125, pitch length 625 mm, width of the belt 25 mm).

The belt 6 transmits motion from a driving indented pulley 15 to a driven indented pulley 14, which is fixed to the output shaft 1. The driven indented pulley 14 has 78 teeth. The driving indented pulley 15 is interchangeable. We have driving pulleys with 26, or 39 or 52 teeth at disposal so the gear ratio of the belt drive can be i_2 = 1,5 or 2,0 or 3,0. As a result we can make experiments with overall gear ratios $i_C = i_1 \cdot i_2$ = 150 or 200 or 300.

Tightening indented pulley 13 (22 teeth) placed on a slide carriage is used for tightening of the indented belt 6. Horizontal shift of the carriage is done with the use of an adjusting screw.

The driving pulley together with harmonic drive gearing and DC motor are fastened to the frame 3 by means of a console 16.

DC motor RE 35 (Graphite Brushes, 90 W) order number 273 759 is turned out by company Maxon motor (Switzerland), www.maxomotor.com. The DC motor 5 is fastened to a radial face of the harmonic drive gearing 17 with the use of a union flange.

The DC motor has the following basic parameters: number of pole pairs 1, number of commutator segments 13, nominal voltage 48 V, nominal current 0,915 A, nominal speed 2970 rpm, nominal torque 0,105 Nm, no-load speed 3810 rpm, starting current 4,16 A, stall torque 0,493 Nm, terminal resistance 11,5 Ω, terminal inductance 3,16 mH, rotor inertia $65{,}5 \cdot 10^{-7}$ kgm^2.

Accessories of the DC motor 5 mounted on its shaft: Brake AB 28 (24 V) order number 228 387 (arrowhead 18) and Encoder HEDL 5540 (5 V, 500 CPT, 3 channels) order number 110 512 (arrowhead 19). The whole set has order number 368 267. Resolution of encoder HEDL is 0,72° = 2592 arc seconds = 12,56 mrad. In the following text we will use abbreviation HEDL to refer to the sensor.

2.2. Design of control and power electronics

Control and power electronics unit 7 (Fig. 2, 4) is placed on the frame 3. Its photograph is in the picture Fig. 5.

Block diagram can be seen in the picture Fig. 6.

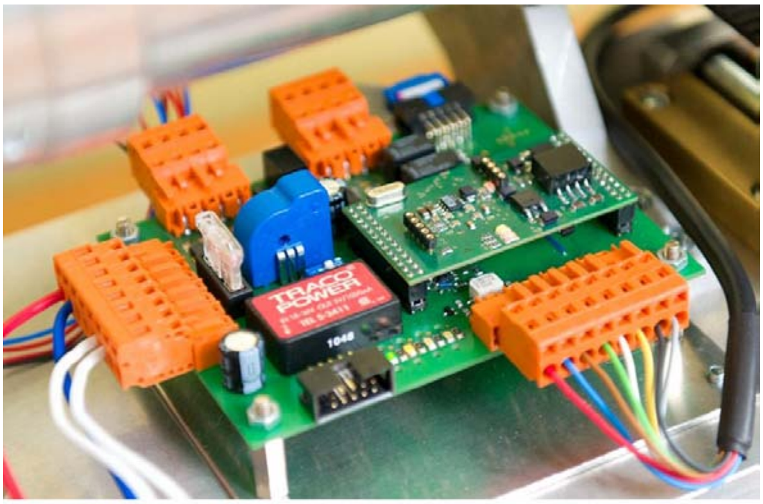


Fig.5 Assembly of power and control units

Servo-amplifier unit represents a basic element for proportional angular control of the servo-amplifier. The unit fulfils the requirements for highly precise settings of the required angular displacement whereas demanding power requirements of regulation are also met. In order to achieve these goals, modern methods for distributed measurement and control are applied. The unit has a maximum output power approx. 220 W at 24 V of continuous output power.

In order to fulfil the requirements for regulation the following characteristic components were used for assembling the servo-amplifier:

- hybrid controllers integrating standard peripheral circuits and powerful processing core usually used by digital signal processors DSP in one case
- highly integrated power stages with modern switching elements for fully digital power control
- modern communication standards
- sophisticated topology of multi-level feedback control

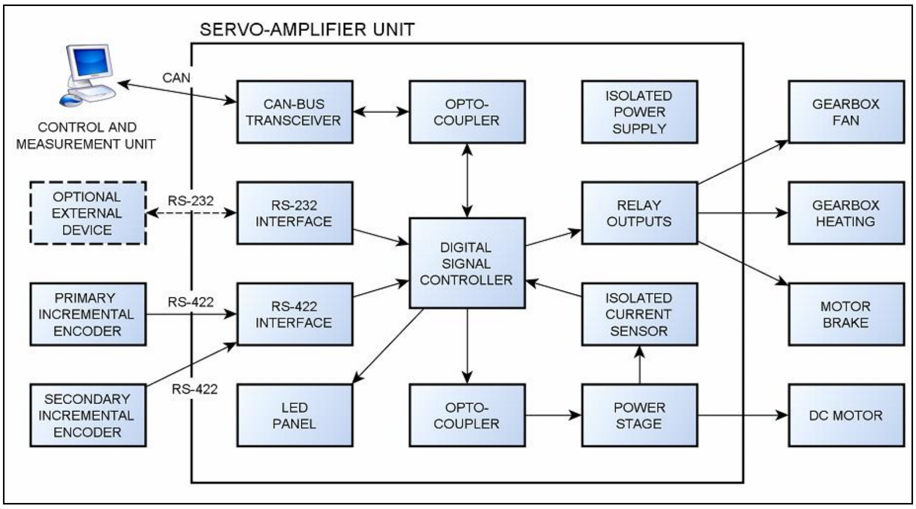


Fig. 6 Block diagram of power and control units

Description of block diagram (Fig. 6):

-*control and measurement unit* - control and measurement unit is based on PC compatible computer with Microsoft Windows operation system. PC computer is equipped with application SW, which sends commands via application interface and communication interface and receives status messages via CAN bus to which the control unit of the servo-amplifier is connected.

-*CAN bus transceiver and optocoupler* - galvanic isolated connection to CAN bus,

-*optional external device* - optional bi-directional communication line for additional devices,

-*RS-232 interface* - converts signal levels between optional external devices and digital signal controller

-*primary incremental encoder (HEDL)* - primary incremental encoder measures shaft turning angle

-*secondary incremental encoder (RESM)* - secondary incremental encoder measures turning angle of output shaft (controlled object) of the servomechanism

-*RS-422 interface* - converts signal levels between angle sensors and quadrature encoders of the digital signal controller

-*digital signal controller* - digital signal controller is equipped with DSP core, powerful timers for real time control, A/D convertors (12 bit), multi-channel quadrature input, CAN communication interface and PWM outputs (16 bit).

-*LED panel* - user interface for operational status of the servo-amplifier indication

-*isolated power supply* - power source for sensors, control electronics and isolated parts of output circuits

-*relay outputs* - high current outputs for general purpose

-*isolated current sensor* - Hall sensor for bipolar measuring of instantaneous current value in DC motor winding

-*power stage and optocoupler* - intelligent galvanic isolated power stage for proportional control of DC motor

-*gearbox fan and gearbox heating* - fan and heating elements for temperature stabilisation of the gear

-*motor brake* - permanent magnet single-face brake

-*DC motor* – DC motor with gearing and output shaft (controlled object)

2.3. Control and communication software

In the picture Fig. 7 there is a basic layout of the measuring system. DC motor is controlled by means of the servo-amplifier. Control commands for the servo-amplifier are sent through the use of CAN bus.

Sensors, that are connected to the same CAN bus, monitor the experimental device status.

In this developmental stage of the experimental device, usual PC (Fig.1, arrowhead 2) connected with the measuring system through the CAN bus is used for its controlling and monitoring the measured physical quantities.

Access of the user application to the CAN bus is provided by communication library (Fig. 7) connected with the communication circuit controllers.

The picture Fig. 8 shows the users interface Generator 1.3 that enables setting of measuring parameters. Generated measurement can be sent by means of pressing “Send to Stend (17)” and it starts moving according to the required signal. The measured results can be then monitored on PC and at the same time they are stored on a hard disk.

At current developmental stage the measurement is made only in an open loop, i.e. the control signal is not dependent on measured values from the sensors. It is possible to invoke a dialogue (Fig. 9) with an open regulation loop scheme of the system with the DC motor by pressing “Loop Settings (14)” – Fig. 8. The control loop (Fig. 9) starts with “Command signal” which represents position reference trajectory.

The DC motor functions as an integration part. The position reference signal needs to be differentiated with respect to time (Fig. 9) as it is necessary to get an output position response again in the open control loop. Servo-amplifier, DC motor and position sensor change the signal magnitude and therefore the signal has to be boosted by correction factor *Kp* (1), that provides units transition. After the boost of the signal by the correction factor *Kp,* we get voltage *u* in volts [V], that will be transmitted to motor clamps.

Application adjusts the voltage *u* to a form which is received by the servo-amplifier. Servo-amplifier needs the voltage to be divided into PWM duty cycle and direction DIR, and then it is transmitted to the DC motor (Fig. 9).

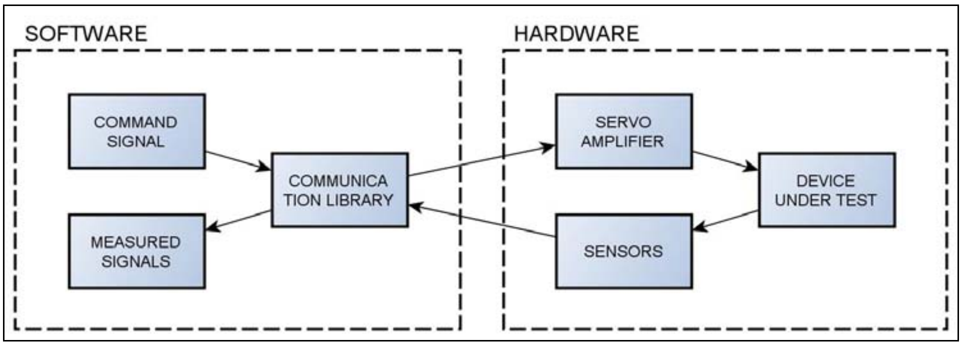
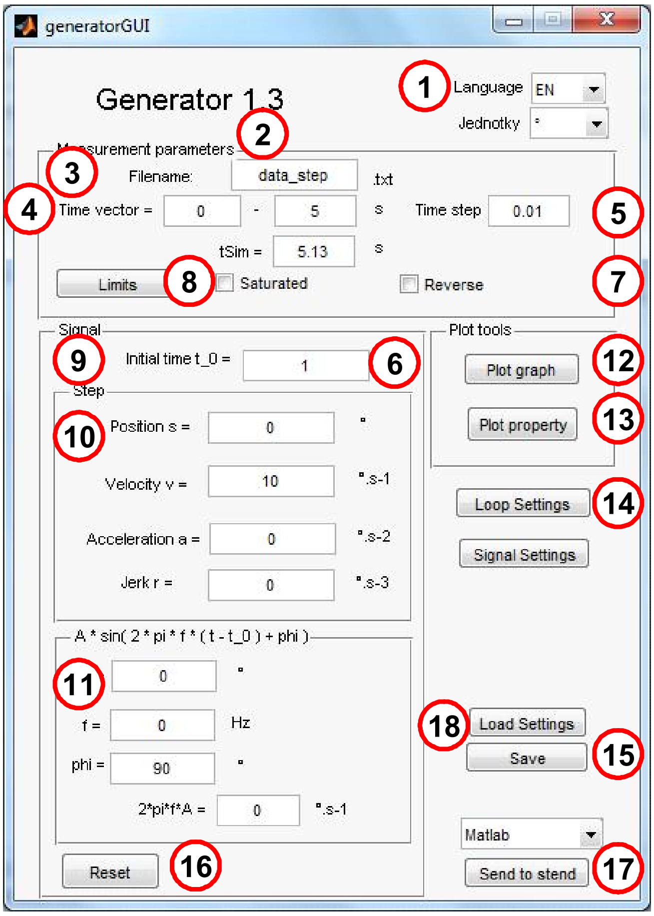


Fig. 7 Communication scheme



Generator 1.3

Language EN

Jednotky °

Filename: data_step .txt

Time vector = 0 - 5 s

Time step 0.01

tSim = 5.13 s

☐ Saturated

☐ Reverse

Initial time t_0 = 1

Position s = 0 °

Velocity v = 10 °.s-1

Acceleration a = 0 °.s-2

Jerk r = 0 °.s-3

0 °

f = 0 Hz

phi = 90 °

2*pi*f*A = 0 °.s-1

Matlab

Fig. 8 Graphic interface – signal generator for the experimental device

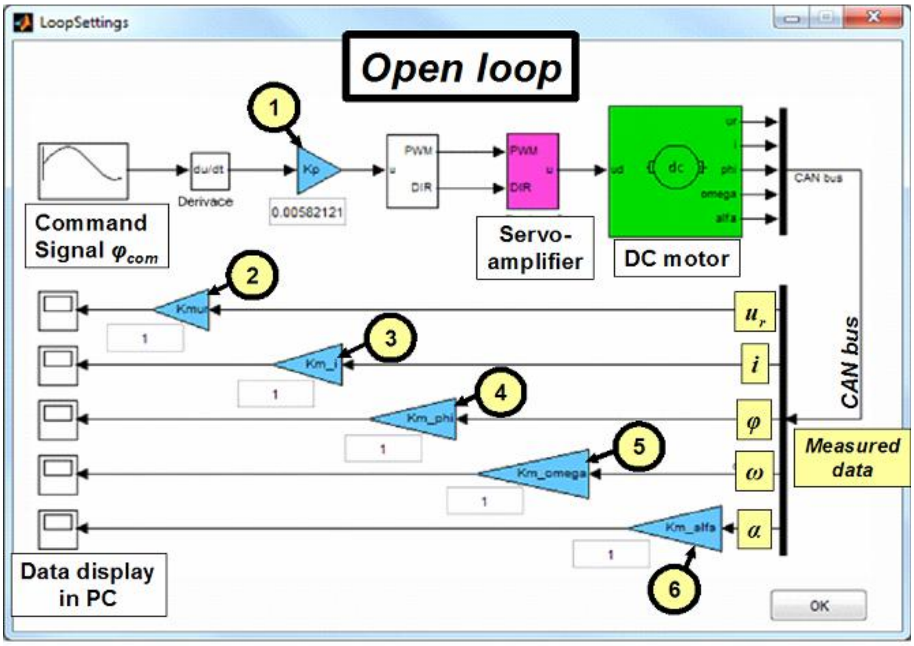


Fig. 9 Open regulation loop

Statuses are measured by means of DC motor and servo - amplifier sensors and those are then transmitted back into the PC by CAN bus. In order to get the measured quantities in SI units, the form in Fig. 9 is supplemented by another editing fields where it is possible to set correction coefficients for voltage (2), current (3), turning angle of the rotor (4), angular velocity of the rotor (5) and angular acceleration of the rotor (6) of DC motor.

At present, the program Generator 1.3 can be used to develop only few basic command (referential) signal processes such as step in a position, step in speed, step in acceleration, and step in a jerk and harmonic signal. In part "Signal" (9) see Fig. 8 there are fields for command (referential) signal adjustment for DC motor control. Command (reference) signal shall be calculated as follows:

$$\varphi_{com} = \varphi_1(t) + \varphi_2(t) , \tag{1}$$

where

$$\varphi_1(t) = \sum_{j=0}^{3} H(t-t_0)\cdot\varphi_C^{(j)}\cdot\frac{(t-t_0)^j}{j!} , \tag{2}$$

where

$H(t)$	is Heaviside step function (unit step function)
$t \in \langle t_{00}, t_K \rangle$	is continuous time (arrowhead (4)) with sampling period T (arrowhead (5)) [s]
t_0	is a moment from which the command signal is nonzero (arrowhead (6)) [s]
$\varphi_C^{(j)}$	is the size of the step of j^{th} derivation (j = 0, 1, 2, 3) – part „Signal“ - arrowhead (10)

$$\varphi_2(t) = H(t)\cdot A\cdot \sin(2\pi\cdot f\cdot(t-t_0)+\varphi_0) , \tag{3}$$

where

CW/CCW – direction of motor rotation ("Reverse" - arrowhead (7))

f is frequency of harmonic command signal [Hz] (arrowhead (11))

A is amplitude of command signal [rad] (arrowhead (11))

φ_0 is initial stage of command signal [rad] (arrowhead (11))

Command signal – reference voltage (arrowhead (2)) can also be limited from bottom and top of its levels and its integration component can be saturated (arrowhead (8)).

Generated command signal can be displayed (arrowheads (12, 13)), set to zero (arrowhead (16)), and saved (arrowhead (15)) under the selected file name (arrowhead (3)).

"Send to Stend" – arrowhead (17) can initiate the simulation in connection with recording of measured data into the database.

3. Examples of measurement outputs

After the command signal parameters are defined, the measurement is made and measured values are sent back to PC. Results of each measurement are saved as text files that are labelled by key name and time when the measurement was made. Such file with results can be processed by e.g. MS Excell or Matlab.

Example of measurement outputs processing in programme Matlab is in Fig.10, where results of frequency analysis of measured signals are listed. Constant step in speed was set for the measurement i.e. the output shaft (controlled object) should have rotated (after the transient response) with constant speed. However, the speed of output shaft rotation actually changes due to nonlinear behaviour of the

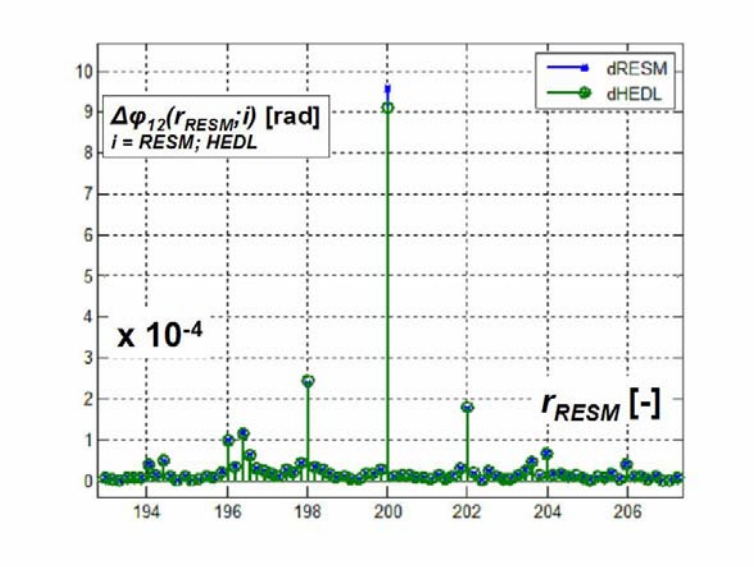


Fig. 10 The spectrum of positional inclinations depending on the position of the output shaft

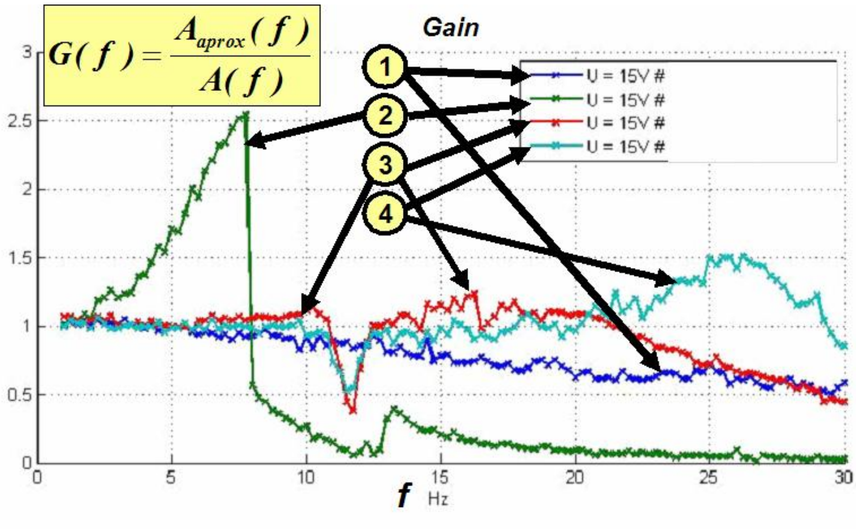


Fig. 11 Gain of the system at different tensions of the belt gear

system. This speed shift is not random but has a periodical pattern in dependence on absolute turning of the output shaft (sensor RESM). Fig. 10 shows, on a relative frequency r = 200 [-], a phenomenon which corresponds to a transfer of disturbed torque from DC motor rotating shaft to output shaft. Other significant harmonic items are at frequencies 198, 202, 196, 204 etc. These are effects of nonlinear behaviour of the system.

In Fig. 11 there are results of analysis for successive measurement which detects harmonic transfer function of the system and the effect of belt tension on system response. Gain of the system consists of point estimates of amplitude gain. Each curve in the graph connects point estimates of measurements with the same parameters, only the frequency f of harmonic command signal is changing. The system was excited by a concrete frequency for each point estimate and braking and damping down of the system preceded each new measurement.

First measurement was made without a belt (1), i.e. only gain to output shaft of the gearing was measured. In accordance with the graph in Fig. 11 we can assume that the system behaves as an inertial item.

While making the second measurement (2) the belt was added however it was not tense which means that the system works with a backlash. From the graph it is obvious that the process differs significantly and a large drop of frequency about 8 Hz demonstrates nonlinear behaviour caused by the backlash. The experimental device is designed as a zero-backlash gearing so if the belt is tense enough, the nonlinearity of backlash type is not demonstrated. When measuring with slightly tense belt (3) and very tense belt (4) only decrease in gain around the frequency 12 Hz is reflected. It was found out that this decrease is caused by anti-resonance of output shaft 1 and the frame 2 against the base plate 3. When the frame structure with a base plate 3 were reinforced (stiffness reinforcement) this phenomenon in measured excitation range was not demonstrated. The effect of belt tense can be seen in Fig. 11 with excitation range about 26 Hz, where the increase of resonance arises (see measurement with very tense belt (4)).

4. Conclusions

We are currently working on improvements of the experimental device. We will report about their realisation and acquired results at some of the following conferences.

In the following period we will focus our effort on development of methodology for measurements and on design of software for automatic evaluation of measurements.

The design of nonlinear model of the servo-drive will be in progress concurrently with the evaluation of sufficiently extensive sets of measurements.

Acknowledgement

This work has originated under the support of financial means from the industrial research project of the Ministry of Industry and Trade of the Czech Republic – project code FR – TI 1/195: "Research and development of technologies for intelligent optical tracking systems".

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