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DEVICES USED FOR STUDYING PRECISION DRIVES

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Abstract:
Division of Design of Precision Instruments considers mechatronic drives and precision drives of low power, one of the main fields of its scientific interests. These drives are dealt with in a complex way, and the works carried out concern their designing and principles of operation of the whole drives and their functional units. Therefore, the works include theoretical studies, designing, manufacturing and experimental studies. We consider the experimental studies very crucial since they make it possible to verify the accepted theoretical models of drives and units. We will focus mainly on ways of and devices for measuring the angular and linear position (for determining the kinematic accuracy) and the real loads. We will also present our abilities and experiences concerning applying load, having constant value or desirable variations, to the drives.

Key words: *precision drives, testing stands, measurement of displacement, loading in test stands, CCD camera, PSD, optoelecronic,*

1. Introduction

Drives for precision and mechatronic devices, we deal with in the *Division of Design of Precision Devices (DDPD)*, are characterised, among other things, by the following features: small dimensions, high accuracy of operating, simple way of their controlling. Usually, the load and velocities of the output member are small, so there do not arise significant problems connected with the strength of materials of the structural members of the drive.

There must be applied small motors in these drives. The main aim of this is their miniaturisation or minimisation of the electric power being consumed (it is particularly important in the case of battery supply). While applying small motor, there is no excessive power and torque. In order to achieve a drive effective enough, in spite of the above, the following must be striven for: minimisation of its resistance to motion and maximisation of its efficiency, minimisation of the reduced moment of inertia of its mobile members. Besides, an instantaneous increasing of the power of the motor is achieved be means of supplying it with an increased voltage. However, it creates a danger of thermal overload of the motor. Analyses concerning determination of permissible parameters of motor supply, in the case of certain operating conditions of the drive, belongs also to the field of our interest [1].

While designing, the required design features of the drives are being formed with a full awareness. It is easy to prove that values of these features are only evaluated at this stage;

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the real values can be obtained exclusively by means of measurements performed on manufactured models of the drives.

We have decided that in the nearest future we will continue the work on drives. Taking the above into consideration, we have recognised that it is purposeful to pursue an improvement of the methodology which makes it possible to build drives adapted to specific requirements concerning the following: operating conditions (load, velocity, range of displacements), accuracy of operation, resistance to motion and their variations, way of controlling. We believe that simulation of the behaviour of a drive under various operating conditions is a very effective tool aiding the process of designing drives. It should be noted that simulation ensures a useful information only in the case when there exist verified theoretical models of the drive and there is knowledge about the real coefficients, which are required to adjust the model to a certain case.

2. Experimental studies

In order to create theoretical models of drives useful for the simulation studies, and then verify their correctness, it was necessary to build special measuring stations making it possible to verify these models in experimental way. We consider the experimental studies very significant, for they allow us also to obtain real operating characteristics of drives and their units, as well as acquire information on values of the quantities, which are hard to be evaluated in theoretical way (coefficients of friction, kinematic errors, resistance to motion, etc.).

Taking into consideration the working conditions in *DDPD*, we believe that it is advantageous to ensure a possibility of a simple configuring of test stations for studying drives and their functional units, aimed for adjusting these stations to specific research needs. Below, there will be presented selected measuring paths that we use for studying drives. It can be easily indicated that for studying drives, it is required to ensure accurate measurements of displacements (linear and angular) and measurements of loads. The first makes it possible to evaluate the kinematic accuracy of a drive, and the second to evaluate resistance to motion, efficiency, or friction coefficients. For determining the real characteristics of a drive, it is necessary to ensure measurements of displacements and loads at the same time.

3. Systems for non-contact measurements of linear and angular displacements

Among other things, the following techniques of non-contact measurements in *DDPD* are used for this purpose:

- detection of variations of optical coupling in an open optoelectronic connection;
- non-contact measurements with application of *PSD* transducers;
- analysis of *CCD* camera images.

3.1. *OPM* technique – detection of variations of the flux received by the photodetector

The first systems mentioned above are applied both for measuring angular and linear displacements.

Structure of the measuring circuit, where optoelectronic connection built of *LED* and *p-i-n* photodiode is applied, is presented in Fig. 1.

Building measuring *OPM* type systems, enabling measurements of relative angular displacement of whirling members, was presented in a detailed way in work [2]. These systems are particularly useful for studies of kinematic accuracy of clutches and miniature gears since they make it possible to carry out experimental analyses of variations of instantaneous positions, under the real operating conditions of the studied unit. Such measurement can be performed while the rotational speed reaches the value up to *5000 rpm*. Resolution of the measurement of variations of the instantaneous position is limited only by the sampling rate of the system recording the analogue voltage signal form the angle transducer.

Fig. 1. Processing of the signal in the circuit measuring changes of coupling in an open optoelectronic connection

DS – diaphragms system, *ET* – electric transducer (open optoelectronic connection), *PU* – unit processing the photodetector current into the output signal, *x* – linear displacement of the mark diaphragm system , α - twist angle of the discs diaphragm system, *A* – resultant area transmitting the beam of infrared radiation, i_F – current flowing in the *p-i-n* photodiode

3.2. *PSD* technique

One also obtained promising results building sensors of linear and angular displacements with application of the *PSD* (*Position Sensitive Detector*) detectors. One used one- and two-point illuminators, where fibre optics were seated directly in lenses of the emission diodes. They collaborated with one- and two-dimensional *PSD* detectors. Position of the light spot illuminating the active region of the *PSD* is determined on the basis of calculated values of currents flowing in particular electrodes. This enables to build systems of sensors measuring linear displacements in one direction or in a plane [3].

The simplest configuration of an angle sensor, as shown in Fig. 2, consists of linear *PSD* detector collaborating with an illuminator, whose angular motion can be traced. The illuminator is built of emission photodiode *1* and fibre optics *2*, which are seated in a rotational member *3*. The light spot illuminates the active region of the *PSD* detector *4*. Systematic (tangential) error, resulted by the accepted schematic of the sensor, as well as errors of nonlinearity (determined at an earlier stage) can be taken into account, while determining a characteristic of positioning error of such a sensor. In configuration of a sensor with the measuring range of ± *4°,* the measurement error was lower than *3′*.

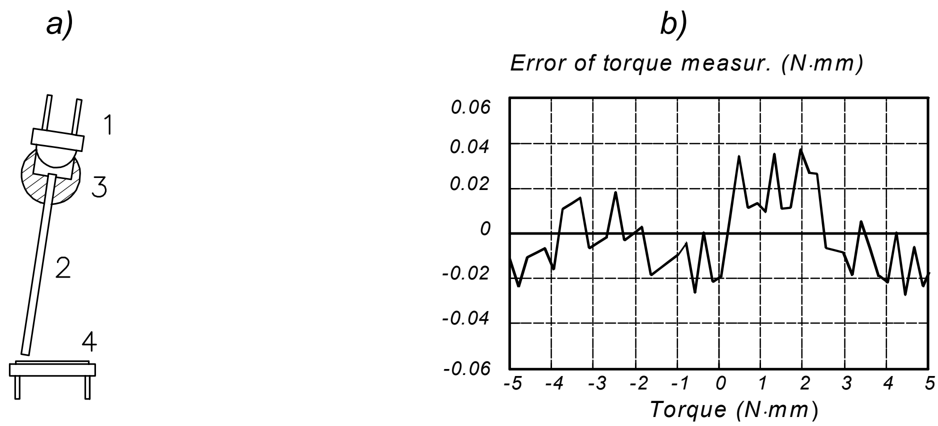

Fig. 2. Angle sensor with *PSD* detector

a) schematic of the sensor, b) measurement error of the torque meter
1 - emission diode, *2* - fibre optics, *3* - rotational member, *4* - one-dimensional *PSD* detector

3.3. Studies of linear and angular displacements with application of *CCD* camera

In *DDPD* one undertook work on application of *CCD* camera for studying precision electromechanical drives, as far as measurements of the parameters of motion are concerned. This particularly concerns non-contact measurements of linear and angular displacements of members of such drives. There were applied digital cameras, colour *camera S-Video NV-DS77EG (Panasonic)* and black-and-white camera *K17-Elemis*, computer card for image digitalisation *PCI Zoltrix*, software for digital image analysis *„MicroScan*", *and „DV STUDIO"* for loading freeze frames images. This set enables recording, processing and analysing of images obtained in the video channel of the *CCIR* television system.

The *NV-DS77EG* camera is equipped with *1/3" CCD* image converter, zoom lens *4,7-47 mm* with automatic diaphragm control. It operates under *Digital Compone*nt recording system *(CCIR* television system: *625 pixels*, *50 images*, *PAL system*).

Image acquisition card and the software enables loading a colour image into the computer memory and then displaying it. Resolution of loading is of *768x576 po*ints. It accepts signals from composite and s-video cameras as well as video recorders. The *Microscan* program uses the hardware resources of the card for freezing the mobile image from the camera, and then garbing it, what enables its further processing. The program contains the following functions: edition, filtration of colour and grey scale image, changes of contrast, saturation, brightness, saving, loading and printing the image. Image analysis contains, among other things, functions of marking and counting of objects, calculation of their area, length, diameter, determining centre of area, brightness profile along a marked line, measurements of a length of segments and angles between segments, edition of displayed and printed measurement results, and saving series of measurements as files. A module of arithmetic functions enables performing 14 arithmetical and logical operations on the images, what enables their comparison and determination of differences – this is particularly useful for tracing "dynamics" of the objects.

The best way of performing measurements of linear and angular displacements of *3D* elements is to locate the optical axis of the camera orthogonally to the plane, which contains the motion path (the measurement plane). As the result, measurements are reduced to algorithms for measuring *2D* elements. The first step is to chose or place markers on the mobile object, most preferably of regular shapes, contrasting with the background or even shining. Then, the measuring circuit should be calibrated; i.e. units of length (or angle in case of certain measurement configurations) should be assigned to units of the display (pixels). It is achieved in the most simple way, by placing a standard in the measurement plane, manual or automatic identification of markers on the standard, determining the displayed distance between them and automatic calculation into the length of the standard.

Measurement of defined objects with markers is performed in the following steps

- recording the image in the initial position of the object (marker);
- recording the image in the final position of the object (marker);
- software filtration and identification of the markers detected manually or automatically;
- automatic determination of the co-ordinations of centres of the markers (and other planimetrical parameters of the objects) and saving the data as a text file;
- calculating the distance between the centres (displacement of the object).

During recording the successive images, the time is recorded also. Therefore, while knowing the value of displacement between successive images, it is possible to determine an average velocity of the studied object.

In the case of the introduced measuring circuit with the *NV-DS77EG* camera, while the lens set to *30 mm*, maximal length of the segment contained within the visual field of the camera is of about *26 m*m (along the longer side). At this time, one pixel on the display corresponds to a segment of *25,7 μm*, provided the resolution is of *1024x768*. During the calibration process of the measuring circuit, it was stated that inaccuracy of identification of the location of the object centre does not exceed the value of *0,1* of a pixel. This means that the measuring error of a segment is lower than *0,2* of a pixel, what in the considered case corresponds to about *5 μm*, while the measurement relative error within the entire range is of about *0,02%.* Of course, in the case of measuring bigger displacements, the focal length of the lens must be longer, so that the value of the absolute error increases, while the relative error does not change.

While measurements of smaller displacements are necessary, one can put a macro-attachment on the lens and then the imaging scale can be of *1:1*, with respect to the *CCD* matrix. This enables measuring displacements with accuracy of about *1 μm*. Further increasing of the accuracy (but also decreasing of the measurement range) requires bigger enlargements in the optical system, what can be realised by means of application a microscope system coupled with the camera.

Measurements of angular displacements can be realised in two options:

- measurements of angles in a plane orthogonal to the optical axis of the camera,
- measurements of angles in three-dimensional space.

As far as the first option is concerned, there can be distinguished two cases: angle measurements between elements of one image and measurements of angular displacements recorded in successive images. In both cases, one should identified appropriate elements and determine their positions, as in the case of linear displacements. It is possible to perform a software angle measurement, as an automatically determined angle between segments of chosen lines. In the second option, after recording successive images, identification of defined areas (e.g. markers on rotating elements) and determining their co-ordinates, one should calculate changes of angular positions on the basis of geometry of the system. Of course, one can calibrate the system before, applying known angular displacements, what allows for the verification of the accuracy of the obtained results to be performed.

In the case of spatial angular displacements there are possible two different systems of identification of angular position changes. There is shown in Fig. 3 a schematic of a system for measuring angles, tested in *DDPD*.

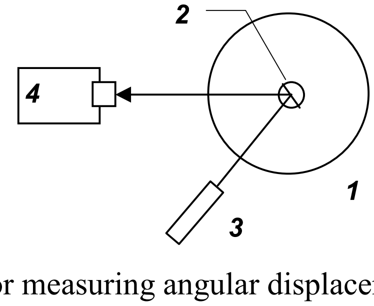

Fig. 3. Schematic of a system for measuring angular displacements

1 – angle transducer *IDW2*; *2* - deflector fixed to the transducer shaft, *3* – fibre optics illuminator, *4* - *CCD* camera

A very significant feature of a camera with lens is the fact that it records not only the position of the light beam emitted by the light source, incident on the lens, but also location of the light source (and the whole image as well). So, during rotating the mirror, the camera records motion of the source image, not the motion of the reflected beam. Therefore, in the case of measuring angular displacements, one can use an arbitrary fragment of the image. However, application of a point source significantly simplifies identification of an object, for it is easy to filtrate the entire background, as having darker brightness.

Geometry of the angle measuring, as in the test station presented above, is shown in Fig. 4 in a schematic way.

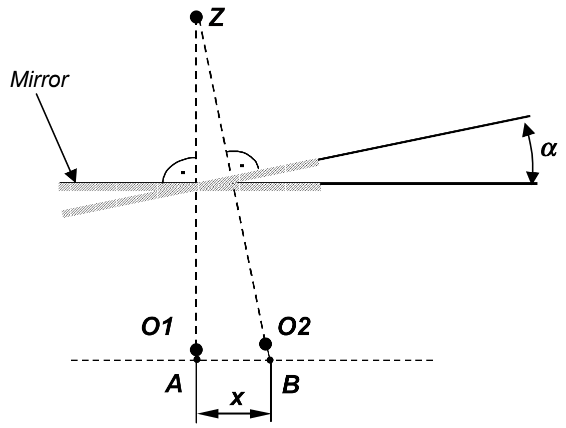

Fig. 4. Measurement of rotation angle of the system with deflector

Z – light source (front of the illuminator fibre optics); *O1, O2* – images of the source before and after rotation of the mirror; *A, B* – projections of the source images onto a plane; *X* – distance between the image projections, α – rotation angle of the mirror

Image of an object in the plane mirror is always formed on a normal, crossing the object (it is a virtual image). This situation is presented in Fig. 4. It can be observed also, that change of angular position of the mirror causes the same change of angular position of the image observed in the mirror. Projecting the images along normal directions with respect to the mirror, onto one plane will not change their angular positions. Then, it will be possible to formulate a dependency between the distance of the projections x and the rotation angle of the mirror α. This dependency has the following form:

$$x = \mathrm{tg}\,\alpha \cdot \overline{ZA}\,.$$

For small values of the angle α, it can be accepted that $tg(\alpha) = \alpha$. Then α can be calculated as below:

$$\alpha = x / \overline{ZA}\,.$$

Because the segment *ZA* has a constant value, the equation of the circuit processing is

$$\alpha = Kx\,.$$

The constant *K* in the above formula is determined by means of calibrating the circuit, i.e. measuring a known angle. So, in the presented variant of a three-dimensional measurement of angular displacement, one should calibrate the measuring system at first. After applying a value of α (measured by the angle transducer *IDW2* with accuracy of *1'*) and then performing software calculation of the *x* value in the images, the processing constant of the measuring circuit can be determined.

4. Systems of precise application of loads in rotational motion

In order to apply a passive braking torque, it is advantageous ***to apply electromagnetic powder brakes*** equipped with a system for measuring the reactive torque of the stator (casing of the brake). Examples of measurement configurations, in which they were applied, are presented in Fig. 5 (Fig. 5a presents coupling of the brake with a torsional torque meter based on strain gauges; Fig. 5b presents a set of the brake and a dynamometric torque meter).

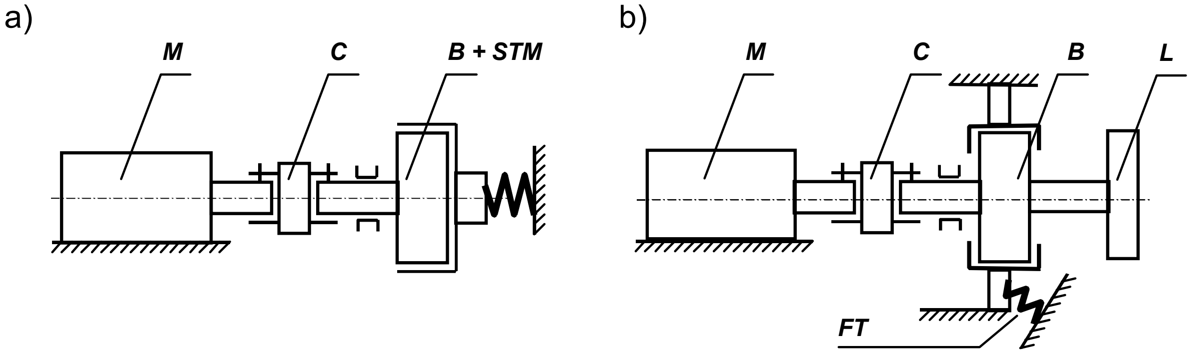

Fig. 5. Braking in testing of drive systems

C – coupling, *STM* - stationary torque meter, *FT* – force transducer of dynamometric torque meter, *B* - brake, *L* – load, *M* – drive unit/micromotor

In powder brakes the braking torque is produced by the friction between molecules of a ferromagnetic powder, placed in a space separating the rotor and the stator electromagnet. Friction couple is dependent on magnetisation rate of the powder, which is proportional to the current supplying the stator winding.

The significant advantages of such brakes are the following:

– durability (negligibly small wear of the stator and rotor surfaces),
– possibility of matching such operating conditions, when there is practically no dependence between the braking torque and the rotational speed of the rotor,
– simplicity of achieving automated control because of the existing dependence of the developed torque on the excitation current.

In the systems for applying load, built in *DDPD*, there were applied brakes *hc 2.7* type, manufactured in Poland, having the following catalogue parameters: range of *0.5 N·m* for the excitation current of *0.8 A* and the rotational speed no higher than *3000 rpm*.

In order to ensure monitoring course and values of the braking moment in the test stations, the brake stator is fixed to a stationary torque meter *SPM* type, based on strain gauges. Its measuring range is of *0.5 N·m*. There is also applied a dynamometric torque meter, based on strain gauges or piezoelectric transducer, measuring force acting on a defined arm [4]. Measurement of the braking torque is performed by determining the reactive torque of the brake stator.

There are applied specialised circuits for supplying the brake. Their current output signal is proportional to the control voltage being applied. Range of variation of the control signal is from *0* up to *5 V* and is adjusted to the standard of outputs in typical computer control/measuring cards. These systems can operate in one of the two following modes:

– proportional controlling; when the brake current is a linear function of the control voltage,
– stabilised controlling; when a constant level of the braking torque is kept – the system operates in negative feedback, where the signal form the integrated system of torque measurement is used.

The presented systems for applying a braking torque are used:
– during determining load characteristics of *DC* micromotors,
– in studies of dynamics of stepper motors (during determining frequency characteristics),
– during analysing thermal behaviour of the above motors,
– during determining the instantaneous efficiency of transmission units (clutches and gears),
– in studies of kinematic accuracy of driving systems operating under certain load conditions,
– in the tribological studies (e.g. of bearing pair).

Control procedures used in our test stations enable applying the following courses of input functions of the braking torque: stepwise (including a sequence of step functions), variable in linear way, variable in harmonic way (sinusoidal, sawtooth) and constant.

5. Conclusions

Precision machines, when subject to research work tests, are specifically noted for the requirement of special designs of rigs and measuring transducers as well as application of new and unique test methods. Also an essential problem while preparing the mathematical model of the drive is to determine properties of transmission assemblies (precision gears and couplings) analytically and experimentally - so that to express them by two basic functions: instantaneous transmission ratio and instantaneous efficiency, and additionally - torsional rigidity and damping coefficient. In number of our works it was found necessary to include results of experimental test into formal descriptions of transmission assemblies.

We will focus in presebted paper mainly on ways of and devices for measuring the kinematic accuracy and the real loads. This paper corresponds with the next one, proposed by the same authors, in which there will be presented exemplary results of experimental studies, possible to be obtained thanks to application of the devices discussed here.

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