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PROBLEMS OF DESIGN AND APPLICATION OF ROTARY TORQUE METERS FOR MEASUREMENT OF A SMALL TORQUE

MACIEJ BODNICKI

Institute of Micromechanics and Photonics, Warsaw University of Technology
e-mail: m.bodnicki@mech.pw.edu.pl

Torque measurements in precise equipment reveal a specific nature, which makes it very difficult or impossible to use many typical methods and measuring devices. Successful implementation of new torque meters prototypes and construction of new OPM/Z series of types allowed for new interesting experiments. New optoelectronic rotary torque meters, characterized by a minimal moment of inertia of the rotating subassembly, made it possible to take measurements of the torque both on the rotating and fixed shafts. Computer-aided experimental stands enable registration of a torque signal as well as automatic corrections of the measurement way. Formulation of a mathematical model of torque meters combined with numerical simulation allows for optimization of the torque measuring path e.g. by the selection of constructional features of individual elements of the stand.

Key words: rotary torque meters, mechatronic drives, mechatronic equipment

1. Introduction – torque measurement in the field of mechatronic drives

There are some specific features, which should be considered when investigating the power transmission systems of precise equipment and micromotors:

- Rapid changes of the quantities characterising their functioning, appearing due to small values of electrical and electromechanical time-constants of the motor operators

- Small values of thermal time-constants, which requires application of the measuring methods that eliminate the influence of temperature on the results obtained
- Small dimensions of small-power motors as well as other elements, causing technical problems when selecting and installing the measuring transducers
- Small moments of inertia of the rotating units, often involving interaction between the examined object and mechanical units of measuring system
- Small values of many parameters determined directly, which limits or even prevents from the use of measuring transducers that are typical of medium and big power systems diagnostics.

One of the basic quantities in power transmission systems is a torque. Generally, torque measurements can be divided into the following two categories:

- Continuous or discrete measurements aimed at enabling the operation control
- Measurements aimed at finding features of the system, taken under laboratory or production conditions.

The torque measurement in power transmission systems and their subassemblies used in precise technology (range up to 2 Nm) is usually a stage of research or diagnostic procedures. There are also the cases when the magnitude of torque currently determined is used in automatic regulation of power transmission system operation.

There are the following three kinds of methods for torque measurement in a precise equipment (Jaszczuk et al., 1991):

- Indirect methods
- Methods using measurement of the angular acceleration
- Direct methods (using torque meters).

The *indirect methods* are used mainly for determination of the torque generated by small-power motors, knowing a priori a formal specification of power changes accompanying the work of electric machine and using data and measurement results of magnetic induction.

The method using the *measurement of angular acceleration* makes it possible to determine a dynamic torque. It can be used for measurement of dynamic torque of the small-power motor when the working mode of power transmission system changes (start-up, acceleration, braking). A special case of using this method is determination of load characteristics of a small-power motor with an additional element attached to the rotor, the moment of inertia of which is known.

The *torque meters* can be divided into the three groups: swing torque meters, dynamometers, torsion meters.

The *swing torque meters* operate in the same way as a physical pendulum. The angular displacement of the pendulum can be converted into an electrical quantity by means of another device, e.g. angular transformer or synchro-control transformer. Such devices are usually used for measuring the reaction torque of the stator of a small-power motor or brake.

The operation of *dynamometric transducers* is based on direct measurement of a reaction of a force on with a fixed lenght. The force is measured using strain gauge, inductive or piezoelectric devices. During examination of the power transmission system the torque meters of this type are usually used for measuring the stator reaction in a small-power motor or brake. In practice, these specialised devices are mostly designed for special diagnostic stands.

The *torsion meters* operate basing on elastic deformation of the *mechanical transducer* (MT) (the so-called torsional element) when subject to a torque. Considering the fact that the angular torsional element can change its position with relative to the fixed parts of the power transmission system, we can distinguish:

- Torque meters with fixed torsional elements – the so-called *stationary torque meters* – used mostly for measuring the stator reaction in electromechanical subassemblies
- Torque meters with rotating torsional elements – the so-called *rotary torque meters* (RTM).

2. Classification of the rotary torque meters

During investigations the rotary torque meters are situated between parts of the tested drives (e.g., micromotor and load). The RTM shaft rotates at the same angular velocity as rotating elements of the tested drive. There are two main elements of measuring paths of the RTM: mechanical and electric transducers.

A classification of RTM is proposed in Fig.1 (location of main elements) and Fig.2 (kinds of measuring paths).

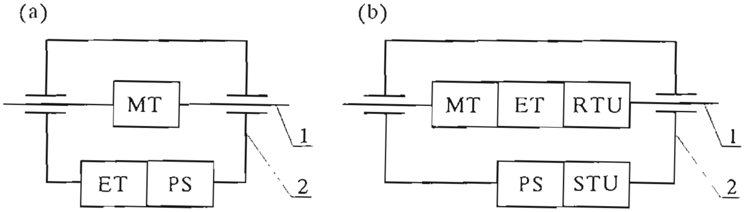

Fig. 1. Two types of RTMs: (a) signal generated in a stationary part of the RTM, (b) signal generated in a rotating part of the RTM; 1 – rotating part of the RTM, 2 – stationary part of the RTM, MT – mechanical transducer, ET – electrical transducer, PS – processing system, RTU – rotating element of signal transmission unit, STU – stationary module of signal transmission unit

The most popular types of electrical transducers used in the RTMs are inductive, strain gauges, optoelectronic and magnetostrictive ones.

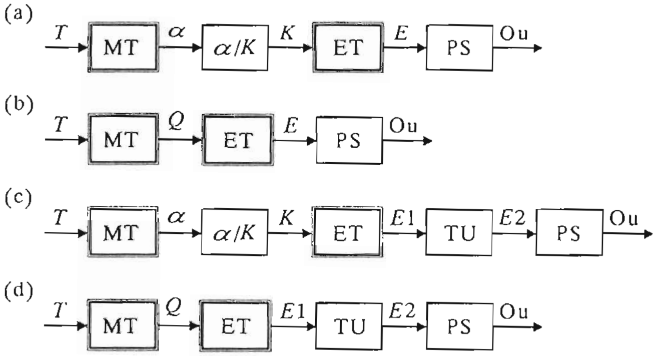

Fig. 2. Measuring paths of RTMs; T – torque, α – angle of the MT twist, K – physical quantity depending on the angle of twist, Q – torque dependent physical quantity transmitted through the MT (e.g. linear displacement); $E, E1, E2$ – electrical quantities, Ou – output signal

The following measuring paths are presented in Fig.2:

(a) processing of the angle of mechanical transducer (angle of MT twist) – signal generated in a stationary part of the RTM

(b) processing of other torque dependent physical quantity transmitted through the MT (but not the angle of twist) – signal generated in a stationary part of the RTM

(c) processing of the angle of MT twist – signal generated on the RTM shaft

(d) processing of other torque dependent physical quantity transmitted through the MT – signal generated on the RTM shaft.

3. Some special design problems

3.1. Mechanical transducer (torsion element)

Mechanical transducer (MT) is a properly formed piece of rotating unit of the RTM. Commonly used shapes of the converter are shown in Fig.3. The "drilled" cruciform version (system of flat springs) is employed, however, in stationary torque meters (Wierciak, 1991). Dimensions and constructional materials of the converter determine the RTM torsional stiffness, and – for a specified sensitivity of converter – the measuring system range. Usually, optimisation of a mechanical converter consists in both: finding the proper sort of material and geometrical shape, assuring the adequate RTM torsional rigidity, at the assumed dimensions. The influence of loads other than the torsional one (e.g. bending torque) should be also eliminated. Adequate torque meter design provides proper RTM overload capacity (the ability of carrying loads exceeding the measurement range), fatigue strength and linearity of torque convertion. The formulas used in calculation in the design process of typical mechanical transducers of RTM are presented in Table 1. Calculation of the material strain is necessary in the case of employing popular strain gauge techniques.

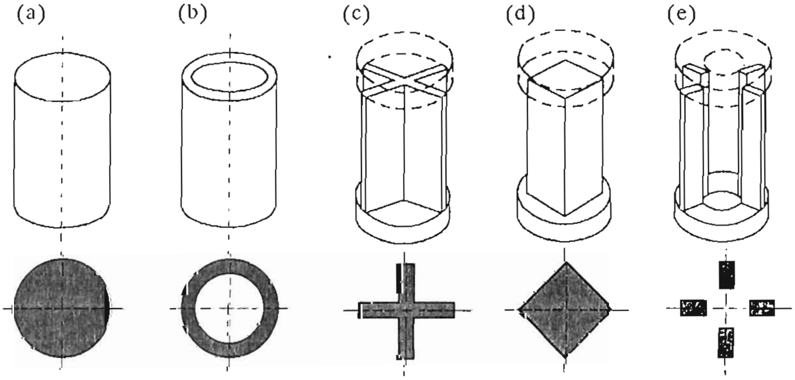

Fig. 3. Mechanical transducers; segments of shafts with different cross-sections; (a) – circle, (b) – ring, (c) – cruciform, (d) – quadratic, (e) - "drilled" cruciform (system of flat springs)

Table 1. Formulas used in calculation in the design process of typical mechanical transducers of RTM (Brzoska, 1979)

	Circle	Ring	Square	Cross
Stress τ_{max}	$\frac{16M}{\pi D^3}$	$\frac{16MD}{\pi(D^4-d^4)}$	$\frac{M}{0.208b^3}$	$\frac{3M}{(2s-h)h^2}$
Angle of twist φ	$\frac{32Ml}{\pi GD^4}$	$\frac{32Ml}{\pi G(D^4-d^4)}$	$\frac{Ml}{0.141Gb^4}$	$\frac{3Ml}{G(2s-h)h^3}$
Strain ε	$\sigma/E \qquad (\sigma = \tau_{max})$			
where: l – MT length, G – shear modulus, D – diameter of the outside circle, d – diameter of the inside circle, b – square side, h – width of the cross arm, s – diameter of the circle circumscribed on the cross, M – torque, E – Young modulus				

3.2. RTM put into the transmission system under test

Torque measurement with use of RTM consists in repeated interference in structure of examined system. Using RTM, means an additional rotating element of the system, characterised always with specific parameters: mass moment of inertia, torsional stiffness, motion resistance in gas, and sometimes with: bearings friction, resistance of signal transfer systems.

According to the dynamics laws of mechanical systems, parameters of the added element i.e., the rotating part of the RTM, will affect the examined transmission system.

The RTM measurement signal always results from conversion of the physical value corresponding to the mechanical converter rigidity. Deformation of mechanical converter depends on the measured instantaneous magnitude of torque, and may be also affected by the d'Alambert torque (during accelerated motion), torsional oscillations and additional resistance to motion.

3.3. Bearing of the shaft of RTM

Elimination of the systematic component resulting from the motion resistance of the roller bearing is particularly important in measurements of torque up to several or a few dozen N mm.

Removing bearings (and elimination of such a component) is seldom used in practice. The lack of roller bearings can make it difficult to solve the problem of signal transmission between stationary and rotating units in typical contact systems or those supplied with transformers. In the case of torque meters with the signal transmitted by the fixed part, we can also expect some additional interference resulting from the shaft and electrical transducer element misalignment.

The corrections can be introduced using one of the following methods:

- Assuming the constant resistance to motion, which corresponds to the friction of rest in bearings
- Including the estimated constant resistance to motion in bearings, which corresponds to the assumed rotational speed of the shaft unit in the accepted measurement model
- Updating instantaneous resistance to motion of the shaft according to the accepted model (including instantaneous values of rotational speed).

The third method can ensure best results, provided that the model of resistance to motion in bearings is proper and the rotational speed can be measured.

4. New proposition of rotary torque meters – the OPM series of types

The rotary torque meters of small measuring ranges (up to 2 Nm) are produced by only few famous manufacturers of the research equipment. When analysing the literature about laboratory stations, one cannot escape the impression that the users are satisfied by the very possibility of using torque meters for measurements. Often, even when planning dynamic measurements, selection of the meter for determination of a torque up to 2 Nm seems to have depended only on the measuring range of the device.

Application of the optoelectronic technique gives the possibility of generating an output signal directly in the stationary part. Three series of types of torque meters have been developed in the Institute of Micromechanics and Photonics of Warsaw University of Technology (IMP WUT). The idea of measuring system used in the OPM called type meters is presented in Fig.4 and processing in open optoelectronic pair in Fig.5. New features providing system novelty and originality are the shape of beam of light or infrared radiation coming through discs with scale marks and propositions of specific construction schemes. The OPM idea provides the ability to measure the torque with rotating or immovable shaft. The measurement signal is generated in a stationary part of the RTM (Bodnicki et al. – patents 1 and 5).

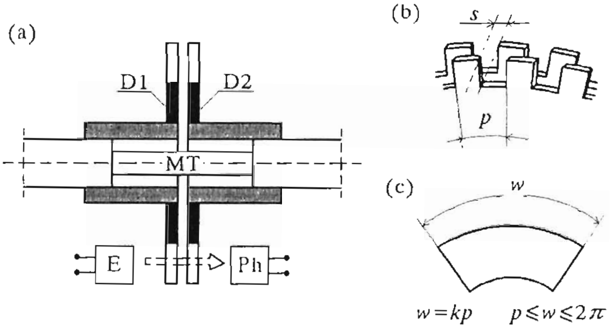

Fig. 4. General idea of the new measuring system; (a) scheme of the system, (b) plan of some part of the system, (c) characteristic bound of the beam; $D1, D2$ – glass discs being mutually twisted, p – angular pitch of one sector (with transparent and non-transparent parts) of the disc (recommended ratio = 0.5), s – resultant width of the clearance within one pitch, E – light or infrared radiation emitter, Ph – receiver of light or infrared radiation, w – angular width of window bounding the beam, k – number of sectors (markers on the disks)

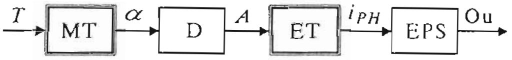

Fig. 5. Practical realisation of the measurement – data processing in the OPM type Rotary Torque Meters; T – measured torque, MT – mechanical transducer, α – angle of the MT twist, D – two discs and stationary diaphragm with special angular windows, A – resultant transparent area, ET – electrical transducer (open optoelectronic connection), i_{PH} – resultant current of p-i-n photodiodes, EPS – electronic processing system, U_{OPM} – output voltage

New designs have been also worked out, taking into consideration signal gain and noise reduction in optoelectronic devices, which could be useful for practical realisation of the RTM method (Bodnicki et al. – patents 2,3,4), presented in detail by (Bodnicki and Sakowicz, 1990).

In the new RTM series of types specific for actual mechatronic systems, the joining element has appeared: mechanics, optics and electronics.

In practise the two design concepts have been used – see Fig.6 and Fig.7.

The following performance features of the advanced type – called OPM/Z (practical realisation the idea presented in Fig.7; scheme – see Fig.8) – should be noted:

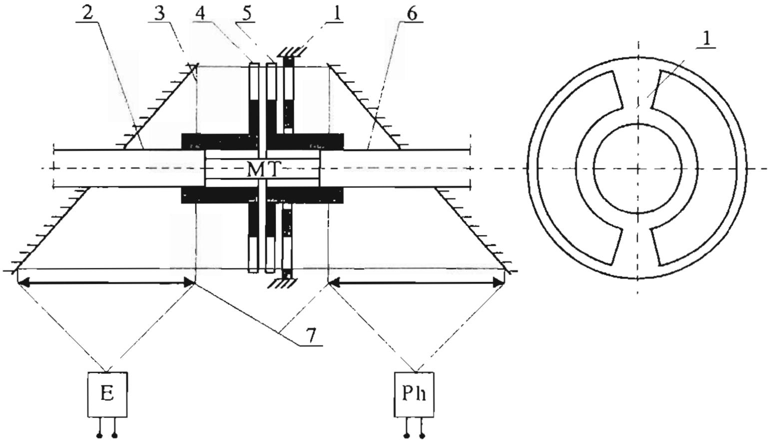

Fig. 6. Practical realisation of the measurement concept – the system with one emitter-receiver pair (schemes of mechanical and optical parts); E – emitter (infrared LED), Ph – receiver (p-i-n photodiode), MT – mechanical transducer (cross section type), 1 – stationary diaphragm with two angular windows, 2 – shaft of the torque meter, 3 and 6 – mirrors, 4 and 5 – glass discs with markers (transparent and non-transparent – made using the chromium technique), 7 – lens systems

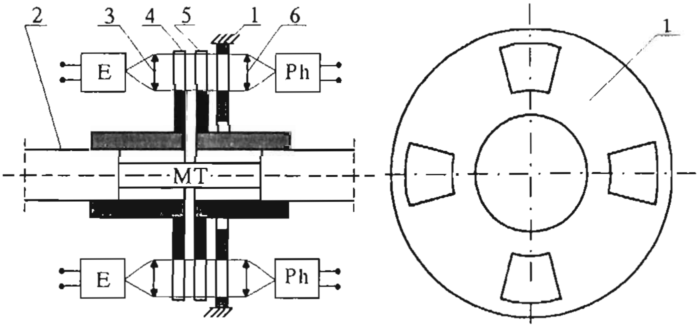

Fig. 7. Practical realisation of the measurement concept – four emitter-receiver pairs (schemes of mechanical and optical parts); E – four emitters (infrared LED), Ph – four receivers (p-i-n photodiodes), MT – mechanical transducer (cross-section type), 1 – stationary diaphragm with four angular windows, 2 – shaft of the torque meter, 3 and 6 – lens systems, 4 and 5 – glass discs with markers (transparent and nontransparent)

- Output signal is generated in the stationary part of RTM in four opto-electronic pairs
- Neither the angular position nor the angular velocity of shaft affect the output
- Measurements can be taken also when the shaft is stopped
- Output signal (voltage within the range $-5\mathrm{V} \div 5\mathrm{V}$) can be easily recorded
- Measurement range can be selected (range of the series of types is $0.05\mathrm{Nm} \div 2.0\mathrm{Nm}$)
- Very small moment of inertia of rotating parts $12.0\,\mathrm{g\,cm}^2$
- In the series of types the internal measuring path has been used; the path is provided with the original transducer, which does not influence the moment of inertia of the rotating unit and allows for a continuous measurement of speed.

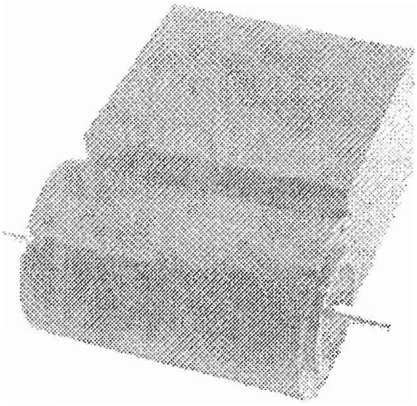

Fig. 8. View of the OPM/Z type Rotary Torque Meter

5. Modelling of the mechanical part of RTM and the considered drive system

5.1. Model with lumped parameters

For modelling of dynamics of the mechanical transducer used in the examined power transmission system structure, the Hamilton principle is used (principle of least action). The mechanical structure of the examined object is presented as a chain system made of elements of lumped parameters – non-deformable elements (bodies) with of specific moments of inertia and massless elastic elements. Angular positions of the respective non-deformable elements are the generalised coordinates. The general structure of such a model is presented in Fig.9.

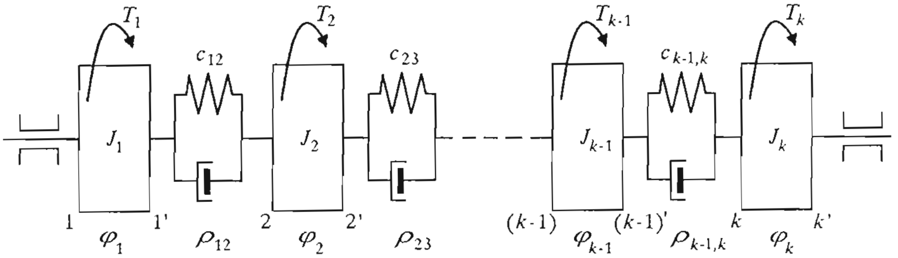

Fig. 9. General structure of the model of mechanical structure (cf Kruszewski and Wittbrodt, 1992; Szklarski and Jaracz, 1986); k – number of the degree of freedom, φ_i – angular position of the non-deformable element (sections i and i') generalised co-ordinate), T_i – torque, J_i – moment of inertia of the non-deformable element, $\rho_{i-1,i}$ – coefficient of viscous damping, $c_{i-1,i}$ – torsional stiffness of the deformable element

The model can be described by the set of equations

$$
\begin{aligned}
&J_1\ddot{\varphi}_1 = M_1 - c_{12}(\varphi_1 - \varphi_2) - \rho_{12}(\dot{\varphi}_1 - \dot{\varphi}_2)\\
&J_2\ddot{\varphi}_2 = M_2 + c_{12}(\varphi_1 - \varphi_2) - c_{23}(\varphi_2 - \varphi_3) + \rho_{12}(\dot{\varphi}_1 - \dot{\varphi}_2) - \rho_{23}(\dot{\varphi}_2 - \dot{\varphi}_3)\\
&\vdots\\
&J_{i-1}\ddot{\varphi}_{i-1} = M_{i-1} + c_{i-2,i-1}(\varphi_{i-2} - \varphi_{i-1}) - c_{i-1,i}(\varphi_{i-1} - \varphi_i) +\\
&\qquad +\rho_{i-2,i-1}(\dot{\varphi}_{i-2} - \dot{\varphi}_{i-1}) - \rho_{i-1,i}(\dot{\varphi}_{i-1} - \dot{\varphi}_i)\\
&J_i\ddot{\varphi}_i = M_i + c_{i-1,i}(\varphi_{i-1} - \varphi_i) - c_{i,i+1}(\varphi_i - \varphi_{i+1}) +\\
&\qquad +\rho_{i-1,i}(\dot{\varphi}_{i-1} - \dot{\varphi}_i) - \rho_{i,i+1}(\dot{\varphi}_i - \dot{\varphi}_{i+1})\\
&J_{i+1}\ddot{\varphi}_{i+1} = M_{i+1} + c_{i,i+1}(\varphi_i - \varphi_{i+1}) - c_{i+1,i+2}(\varphi_{i+1} - \varphi_{i+2}) +\\
&\qquad +\rho_{i,i+1}(\dot{\varphi}_i - \dot{\varphi}_{i+1}) - \rho_{i+1,i+2}(\dot{\varphi}_{i+1} - \dot{\varphi}_{i+2})\\
&\vdots\\
&J_k\ddot{\varphi}_k = M_k + c_{k-1,k}(\varphi_{k-1} - \varphi_k) - \rho_{k-1,k}(\dot{\varphi}_{k-1} - \dot{\varphi}_k)
\end{aligned}
\tag{5.1}
$$

5.2. Identification of the model

During the research, it has been confirmed, that simulation of mechanical structure of the RTM, where the only deformed element is torsional stiffness of the MT, is correct (see Fig.10).

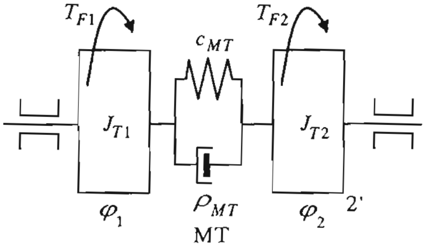

Fig. 10. Model of the mechanical structure of the RTM

The experiments have been made, consisting in application of an input torque, while one end of the shaft was immovable. The experiments have been made with different values of additional mass moments of inertia. Signal oscillations have been measured using measurement card, PC and digital oscilloscope. Basing on the measured response, the period of system free damped vibration and damping coefficient has been determined. The measured period has been compared with the ond calculated, from an analytic (precise) differential equation, which represents the mechanical model of the system. Therefore, the period of vibrations T_{osc}, has been calculated from the equation

$$T_{osc} = \frac{2\pi}{\sqrt{c_{MT}/(J_{T2} + J_{add})}} \tag{5.2}$$

The vibration have been neglected – and after damping coefficient had already been established, it has been checked, that this simplification for $\rho_{MT} \approx 10^{-4}\,\mathrm{N\,m\,s/rad}$, has influenced the calculated value of period only with about $10^{-8}\%$. Fig.11 shows an example of the registered response.

The values of torsional stiffness of mechanical transducers, have been experimentally determined during the static calibration process – via analysis of calibration variability of OPM/Z meter with an immovable shaft.

The values of vibration periods measured experimentally and analytically differ from each other no more than 3%. The reasons for divergence could be:

- Deviation of experimental determination of torsional stiffness, according to analysis of RTM calibration signal

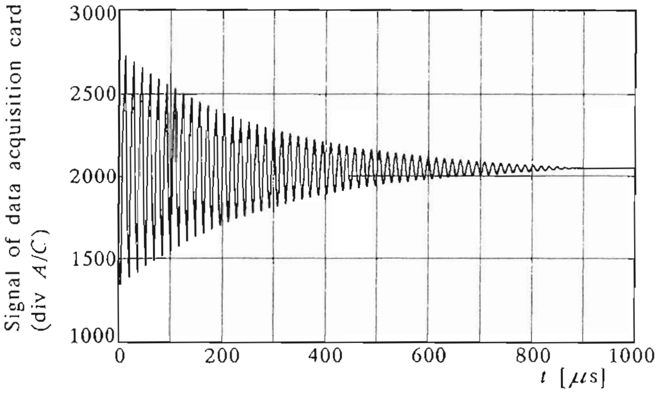

Fig. 11. Example of system response to the torque input; $c_{MT} = 4.3\,\mathrm{N\,m/rad}$, $J_{T2} + J_{add} = 275 \cdot 10^{-7}\,\mathrm{kg\,m^2}$

- Neglecting of friction in the shaft bearing
- Deviation caused by constructional friction in an elastic clamp, fixing one end of the shaft; this deviation, according to data from the literatura (Pisarenko, 1976), would make the vibration period longer than that calculated, what was confirmed by experiments.

The torsional damping of RTM mechanical transducers has also been experimentally determined. It was assumed, that damping is the result of internal fraction. The model has been simplified assuming linearity of the characteristic curve of elasticity, without temperature and damping non-linear influence. In the literature one can find in an approximate description of damping effects, application of the viscosity damping – where the characteristic curve is a linear curve of displacement derivative and time.

The coefficient ρ_{MT} was calculated from the equation

$$\rho_{MT} = \frac{2}{nT}(J_{T2} + J_{add}) \ln \frac{A_i}{A_{i+n}} \tag{5.3}$$

where

n – number of periods, after which, the vibration amplitude drop has been measured

A_i – first vibration amplitude taken into calculations

A_{i+n} – vibration amplitude after n periods (in experiments $n = 10$), where the final average value is $\rho_{MT} = 10^{-4}\,\mathrm{N\,m\,s/rad}$.

6. Modelling of signal processing in the OPM type torque meters

For simulation experiments, the measuring path model shown in Fig.12 is useful. This model has been developed on the basis of both theoretical analysis and the experiments conducted with the use of the constructed torque meters and a special experimental stand (Bodnicki, 1997).

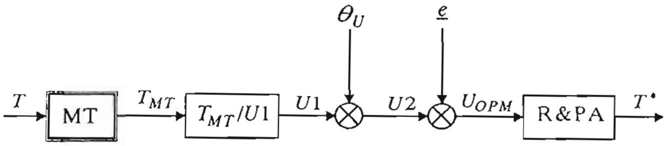

Fig. 12. Specific features of the measurement path model of the OPM type torque meter; T – measured torque, T_{MT} – torque transmitted by the mechanical transducer, $T_{MT}/U1$ – voltage signal generation (with certain frequency limitations), $U1$ – voltage signal with no disturbance included, $U2$ – voltage signal including the influence of the shaft angular position, U_{OPM} – output voltage, T^* – registered torque values, θ_U – voltage signal component occurring at the shaft angular position change, $\underline{e}$ – random disturbance added to the voltage signal level, R&PA – model of the registrating device (e.g. sampling, storing and analogue/digital converter) and processing algorithm

In the simulation model, the following disturbances were included twice:

- Determined disturbances – connected with angular position of the torque meter shaft – identified on the basis of spectral analysis of the signals registered on the experimental stand (with regard to the nature of typical applications, a random distribution of initial angular positions of the shaft assembly for a single experiment is assumed)
- Random disturbances, determined on the basis of a series of static calibrations.

The indices of the measurement path model were determined with the use of a specially designed modular experimental system, and a laboratory version of the torque meter. The following features were determined:

- Static curve and relation between the measurement range and MT torsional stiffness – on the basis of static calibrations at immobilised shaft assembly
- Conversion accuracy ($\underline{e}$ disturbance nature) – basing on the analysis of a series of static calibrations

- θ_U disturbance nature – basing on a spectral analysis of signals registered during the shaft assembly turn
- Damping ratio in the MT.

The obtained results helped to formulate general conclusions. A normal distribution of the random variable $\underline{e}$ has been assumed. Three dominating harmonics have been indicated in the additive θ_U disturbance, and a uniform distribution of its initial phase has been assumed in the range $< 0, 2\pi >$, as well as the relations between the MT torsional stiffness and amplitudes of $\underline{e}$ disturbance harmonics as well as the θ_U distribution variance.

7. Simulations

7.1. General characteristics

The problem of designing the torque measurement system with the use of RTM can be treated as a question of defining and solving the problem of torque meter choice for the examined power transmission system.

It is worth mentioning that in static measurements this problem can be solved acting on recommendations concerning general rules of choice of the device with a well-known error characteristics within the measuring range. If the stabilised torque is measured – when the movable unit of the torque meter is rotating – making corrections can eliminate the additional resistance motion in bearings.

The examined types of the transmission systems, used in precise engineering, belong to so called "low rigid transmissions", i.e., responding to changes (oscillation) of load torque of micromotor with the rotational speed change.

In most examined cases, the changes of load torque are characterised with a large speed of signal growth. In some cases, there are even striking changes, with time constant of the order of milliseconds, they appear e.g. in transmission systems during electromechanical clutch switching, in running of powder brakes in stands used for diagnostics of micromotors, during transmission systems starting, and when resistance appears during technological device operation.

Choosing the value of braking torque, it has been matched to the kind of tested transmission systems – in this case, specific working points of micromotor have been taken into consideration.

The load torque reduced to the micromotor shaft is similar to a nominal torque, in correctly designed systems. A larger load torque may appear during micromotor testing on the stand for mechanical characteristics determination.

Note, that dynamic properties of the apparatus used, may be also important for RTM user, not interested in torque measurement for the transmission system, in transient states, but after they disappear. It may be, for example the designer of experimental stand for load characteristics measurement by means of the point method, who tries to preserve static measurements. In such a case, which goes beyond the range of this publication, the basic criteria of RTM selection may be minimum time for the torque signal to become steady, after load change, and further – the information about torque deviation measurement, specified by the manufacturer or obtained from specific unit testing.

7.2. Simulation results

In the study (Bodnicki, 1997), an analysis has been carried out of the influence of selected constructional features of the RTM – moment of inertia of the rotating unit and MT torsional stiffness – on the results obtained. The research method included analysis of the histories of signals registered after applying a standard load signal (braking torque jump) to the power transmission system, at various combinations of moments of inertia of: micromotor, torque meter, and load, and at various torsional stiffness values. The torque signal – registered by a rotary torque meter – was compared with the reference signal. The torque registered in the power transmission system without the torque meter served as the reference signal. In the dynamic measurement analysis, the assessment criteria established with the use of different measures of dynamic error were applied: integral error, maximum error, or relative duration of non-stationary state. The experiments were made with the use of AMIL simulation software (developed by Stabrowski (1991)). There were also used the program MATLAB/SIMULINK (Bodnicki and Patoka, 1998).

Fig.13 shows the values of relative deviations of transient states time, with various combinations of moments of inertia of driven system, micromotor and RTM.

Examples of the RTM signals, determined using PC simulation with the described mathematical model, are shown in the following figures (see Fig.14).

The experiments have demonstrated:

a) For a drive, with the moment of inertia of micromotor rotor J_s the order of magnitude of which is bigger than the reduced mass load moment of inertia J_{load}, the measurement system with RTM does not represent the torque of micromotor shaft, but it represents oscillations of load torque. This configuration may be recommended for monitoring of brakes used in experimental stands.

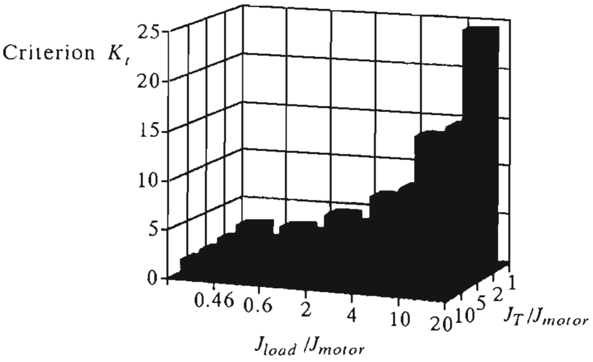

Fig. 13. Values of criterion of relative deviations of transient states time in dvices under test for various combinations of mass moment of reduced load (J_{load}), micromotors (J_{motor}) and RTM (J_T), respectively

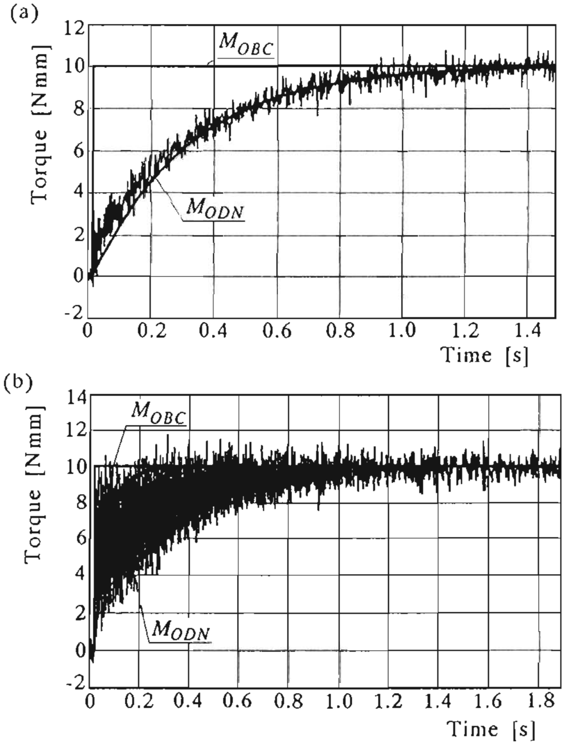

Fig. 14. Sample signal in comparison to the reference M_{odn} and load M_{obc} torques; (a) – $J_{motor} = 0.1 J_{load} = 5 \cdot 10^{-6}\,\mathrm{kg\,m^2}$, $J_{RTM} = J_{motor} = (2.5 + 2.5) \cdot 10^{-6}\,\mathrm{kg\,m^2}$; range: 60 N mm with $c_M = 11.5\,\mathrm{N\,m/rad}$; (b) – $J_{motor} = J_{load} = 10^{-6}\,\mathrm{kg\,m^2}$, $J_{RTM} = 10 J_{motor} = (2.5 + 2.5) \cdot 10^{-5}\,\mathrm{kg\,m^2}$ range: 60 N mm with $c_M = 11.5\,\mathrm{N\,m/rad}$

b) Measurement system, in that the shaft moment of inertia in RTM is comparable to the moment of inertia of the micromotor rotor, allows for reference signal.

c) Moment of inertia of RTM rotating unit, confirms the measurement quality. It proces the RTM design performed in view of that should be first oriented to minimise this parameter.

The torsional stiffness of MT increases, leading to higher vibration frequency during load changes in the allowing for easy elimination of oscillations through RTM signal filtering. However, it makes to instrument indications uncertain.

8. Applications of the OPM/Z type torque meters

The research conducted in the institute with the help of new torque meters included:

- Measurement of the torque when determining the mechanical characteristics of micromotors in a kinematic way (see Fig.15 – equipment and Fig.16 – sample results of the test)
- Measurement of the torque when determining the mechanical characteristics of DC micromotors by applying the braking torque (pointwise or continuously)
- Measurement of the torque when determining the start-stop and synchronic characteristics of the stepper motors as well as of power transmission systems including these motors
- Measurements of the instantaneous torque in elements of power transmission systems of precise equipment, e.g. during the research into resistance to motion and efficiency of fine mesh toothed gears.

An interesting problem, which can be solved with the help of new torque meters, is connected with the determination of instantaneous torque of fine mesh toothed gears. The block diagram of a laboratory stand is presented in Fig.17 (Mrugalski et al., 1993).

The measurements included the estimation of variability of instantaneous torque on the driving pinion (at a steady load of the driven wheel). This is important in examination of counting gears of clock mechanisms. A special feature of using a rotary torque meter in this problem is using of a correction

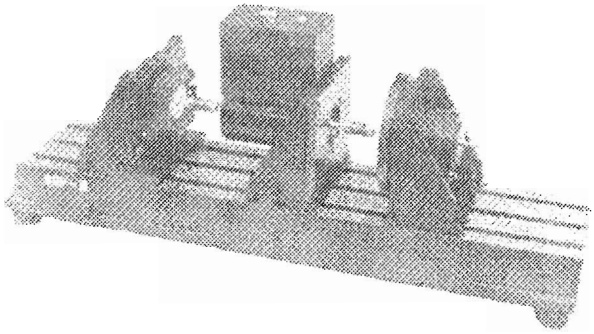

Fig. 15. Test stand for determination of the micromotors characteristics in the kinematic way (for links: micromotor under test, torque meter, inertial load)

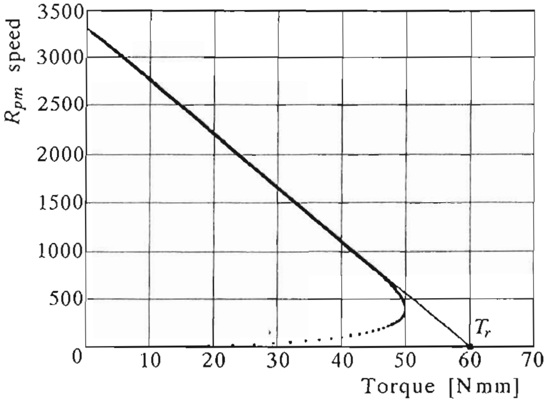

Fig. 16. Mechanical characteristic (speed-torque line) of the DC micromotor – registration with the use of RTM

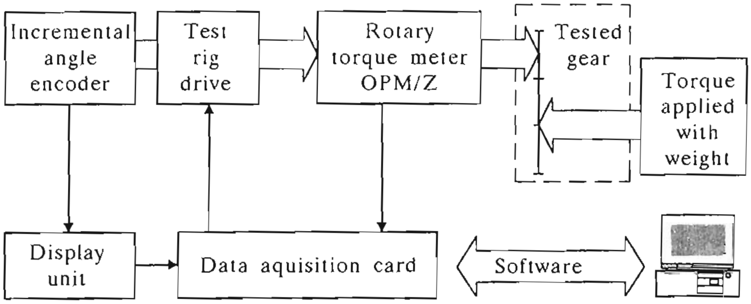

Fig. 17. Block diagram of the computer-aided experimental stand for investigations of fine mesh toothed gears

procedure the data acquisition system, for elimination of the defined variable component of the output signal associated with the angular position of the torque meter shaft. The calibration procedures include determination of the "angle chart", i.e., table of the identified variable component of the torque meter signal versus angular position of the RTM shaft. This is possible due to the use of a high-resolution angle converter.

The control procedures at the stand included:

- Control of the examined gear motion according to a given algorithm, performed by mean of sending appropriate clock and direction pulses to the commutator of the driving stepper motor
- Logging of digital signals from the angle converter for selected angular positions of the driving wheel (pinion) of the examined gear
- Logging of analogue torque meter signal values corresponding to angular positions of the driving wheel
- Automatic correction using the "angle chart" values
- Charting and visualising the measurement results, storing the data files.

The performed experiments presented above completed the theoretical analyses suggesting the use of properly modified involute meshing with raised teeth and heavily undercut pinion teeth in counting gears. These studies prove advantages of the new meshing.

9. Conclusions

In the course of research conducted in the IMP WUT the necessity for measuring the torque up to 2 Nm in different parts of power transmission systems and their subassemblies stimulated the process of developing and improving the construction of original torque meters. The successful activation of prototypes of new torque meters and creation of new OPM/Z devices made it possible to carry out new interesting experiments. New optoelectronic torque meters, charac- terised by a minimal moment of inertia of the revolving subassembly, make it possible to measure the torque both on rotating and fixed shaft. Computer-aided experimental stands enable registration of the torque signal during quite number of experiments.

The results of both experimental investigations and simulations acknowledge the conception – assumed during the design process – of the system mass moment of inertia minimalization. The assumed range of torsional stiffness PM, allows for achieving measurement ranges to 2 Nm, provided that a good processing precision is maintained. Maximum torsional angle value MT, processed by the electric transducer of the OPM/Z meter, comes from using a system of disks with 100 scale marks. The measurement rule applied (torsional angle of MT processing using two discs and diaphragm) involves a quite clear relation between the torsional stiffness and measurement range. During experimental investigations the angle range of measurements has been determined. Note, that even small overflow, will make the results untrue, although it is not dangerous mechanically for the system.

Application of simulation methods makes it possible to carry out a thorough analysis of the measured systems, including torque measurement systems. The development of verified simulation models of new rotary torque meters allows us to customize our hardware offer to specific needs of clients. Further works are aimed at using the results of simulation research in a comparative analysis of various torque measuring methods in mechatronic devices. Systematisation of the assessment criteria will allow us to use the adopted research method to analyse the influence of torque measurement position on the load curves of electric small-power motors.

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Problematyka konstrukcji i stosowania momentomierzy obrotowych do pomiaru małych momentów

Streszczenie

Istnieje wyraźna specyfika pomiarów momentu obrotowego w urządzeniach precyzyjnych napędzanych mikrosilnikami, utrudniająca, lub uniemożliwiająca wykorzystywanie wielu typowych metod i urządzeń pomiarowych. Opracowanie nowej koncepcji momentomierzy (nazwanych ogólnie typem OPM) i wykonanie kolejnych egzemplarzy w ramach 3 typo-szeregów stworzyło warunki do przeprowadzenia wielu badań doświadczalnych. Nowe optoelektroniczne momentomierze obrotowe o zakresach do 2 Nm wyróżniają się znikomym momentem bezwładności podzespołu wirującego oraz umożliwiają pomiar momentu zarówno na wałku wirującym, jak i unieruchomionym. Opracowane skomputeryzowane stanowiska badawcze pozwoliły na dogodną rejestrację sygnału momentu, często z automatycznymi korektami zwiększającymi dokładność pomiaru. Opracowanie modelu matematycznego momentomierzy typu OPM i wykorzystywanie badań symulacyjnych umożliwiło w praktyce optymalizowanie toru pomiaru momentu poprzez dobór cech konstrukcyjnych części mechanicznej mierników.

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