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AN AUTOMATIC SYSTEM FOR MEASURING OF PROPERTIES OF PRECISION GEARBOXES

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Abstract: This paper deals in its first part especial requirements which must be fulfilled by gearboxes being used in applications demanding very high accuracy: uniformity of motion, exactly described hysteresis loop, limited vibrations and good efficiency. In the second part the basic conception of a realised experimental stand is described. The stand allows to perform all measurements, data acquisition and evaluation mentioned later. The control of all components of the measuring stand and the necessary data processing and final presentation of results is performed by a PC.

Keywords: gearbox, uniformity of motion, measuring stand

1 INTRODUCTION

The gearboxes are components of mechanical systems having no ideal properties. Their behaviour is appointed as by the physical parameters of the construction materials being used so as by the processing of these materials, by the imperfections of the design and production work and, last but not least, by the external influences as like is the transferred power, temperature etc. The behaviour of the gearboxes must be exactly recognised by measurements.

The measuring of precision gearboxes being appointed for use in high-quality servomechanisms must fulfill some especial requirements: The transmission ratio of the gearbox can no more be treated like a constant value. It changes during each revolution of input and output shaft [and also the intermediate shaft, if present]. These changes rise due to production imperfections of all components of the gearbox, e. g. of cogwheels, their unique teeth, shafts and other parts of the gearbox under test.

Due to this fact the transmission ratio of the gearbox may be interpreted like a constant number only in the sense of its mean value. All deviations mentioned above commonly cause the error(s) of transmission ratio - and this error must be measured.

The error of the transmission ratio changes in the dependence on the operation conditions of the gearbox, e. g. on the torque being transmitted by the gearbox, but also on the velocities of rotation of its shafts, on temperature etc. and on the momentary position of all its moving components.

There may be said, generally, that all quantities affecting the working point affect also the error of the transmission ratio.

Therefore we can distinguish:

a] the immediate transmission error, which may change in each moment and only under especial conditions may be repeated at least after a high number rotations of the related shaft.

b] the static transmission error which may be described like a group of statistical parameters of a set of immediate values of transmission error [a] , availed during a predestined time interval of free run of the gearbox.

c] the dynamic transmission error, which may be availed like the static one [b], but under a defined type of load.

These requirements results into the conception of a measuring stand for measuring of precise gearboxes.

2. MEASUREMENT

The basic measurements should describe the relations between:

a) the temporary positions of the output and input shaft of a gearbox. The relation between these positions will be appointed at the free (no loaded) run of the gearbox, when the imperfections of the gearing itself appears,

b) the temporary positions of the output and input shaft of a loaded gearbox. This relation will depend on the transferred power and on the output torque namely. This torque will cause as the twisting of the shafts of the gearbox so as the deformations of all its construction parts (the deflections of the teeth of the gearwheels, the deformations of the box). These deformations will cause further the differences between the theoretical and real position of the output shaft of the gearbox, which depends on the transferred torque in form of a hysteresis loop.

The lost motion has relatively small influence on the shape of this hysteresis loop at precise gearboxes, but at the usual gearboxes it plays a dominant role.

Generally the same is valid for the couplings, which have to transfer the torque between two shafts with pass by axis (the coupling may be considered as a gearbox with a transmission factor i = 1). The measurements mentioned above may be performed statically, but different additional effects, e.g. the torsion oscillations may affect the results remarkably. For this reason the relations between the positions of the input and output shafts must be measured also dynamically, at different values of the speed of rotation (angular speed), at different values of torque being transferred and at different types of load (Newton's friction, viscous friction, additional moment of inertia and at presence of damping elements).

3. THE CHARACTERISTICS OF GEARBOXES

The properties of each gearbox may be described by the aid of many characteristics. The continuous development of gearboxes requires creating of a database containing data describing all recent types. This database must allow exact evaluation of the influence of all changes which appeared as at gearboxes produced hitherto so as of new types of gearboxes. To keep the amount of the database as small as possible there will be useful to store some important parameters only (or groups of them). The following choice of characterizations and parameters seems to be useful.

3.1 The efficiency

In the simplest case there is usual to show the efficiency as one parameter being valid for one operation point of the gearbox described, e.g. for nominal rotational speed and nominal torque. More general the efficiency will be described as a (multidimensional) function depending on the speed of rotation, torque, temperature etc. and will be depicted by a group of characterizations (curves). The efficiency must be measured on a running gearbox.

3.2 The uniformity of motion

The uniformity of rotation of the output shaft of a gearbox under the condition of absolute uniformity of the rotation of the input shaft is a next very important parameter describing the gearbox measured. Seeing the impossibility of the absolute uniform running of the input shaft, the uniformity of the rotation of the output shaft must be derived from the relation of the instantaneous positions of both (input and output) shafts. In the ideal case the eq. (1) should be valid:

$$\varphi_2 = p_{id} \cdot \varphi_1 \qquad (1)$$

where $\varphi_2(t)$ and $\varphi_1(t)$ are the instantaneous positions of the shafts and p_{id} is the ideal transmission factor of the gearbox appointed by the number of teeth of gearwheels in the gearbox (in the case of couplings and for the test rod see Fig.2c, $p_{id} = 1$). Due to the imperfections of the production the real transmission factor p fluctuates periodically. This period is appointed by the angle Φ_1 (for shaft 1 or Φ_2 for shaft 2) which must run off between the position where a certain pair of teethes (one tooth of wheel 1 and one tooth of wheel 2) has met and meets again.

In the simplest case the angles Φ_1 and Φ_1 are defined by the product $N_1 . N_2$ of numbers of teeth N_1 and N_2 of wheels 1 and 2. Then (if the greatest common divider $D(N_1 ; N_2)=1$)

$$\Phi_1 = 2\pi N_1 \text{ and } \Phi_2 = 2\pi N_2 \qquad (2)$$

The non-uniformity $v_2(\varphi_1)$ of motion of the output shaft is usually expressed as a function of the position φ_1 of the input shaft, see eq. (3):

$$v_2(\varphi_1) = \varphi_2 - p_{id}\varphi_1 = \varphi_2 - p_{id}(\varphi_1 - 2\pi k\phi_1) \text{ ,k=0,1,2.} \qquad (3)$$

3.3 The hysteresis loop

On the hysteresis loop, see Fig.1, there is possible to find out these important parameters: the stiffness, the lost motion and the hysteresis torque.

Instead of the original hysteresis curve there is useful to introduce the average curve M_c. It may be achieved by averaging in the direction of the axis φ or of the axis M or in the so called 'time - axis'. It does mean that averaging follows over the points having the same indexes. This mode gives best results.

The hysteresis curve shown on Fig. 1 belongs to such situation where the gearbox is heavily overloaded. In practical use of the gearbox this situation must not appear.

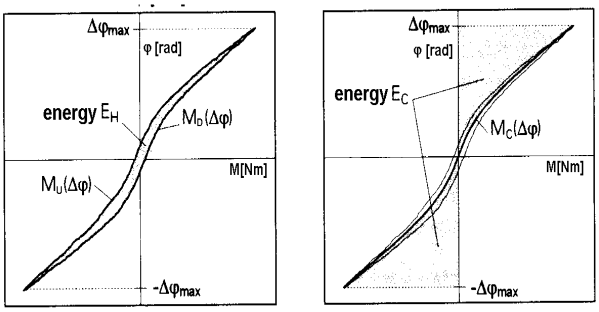


Fig.1 The dynamic efficiency

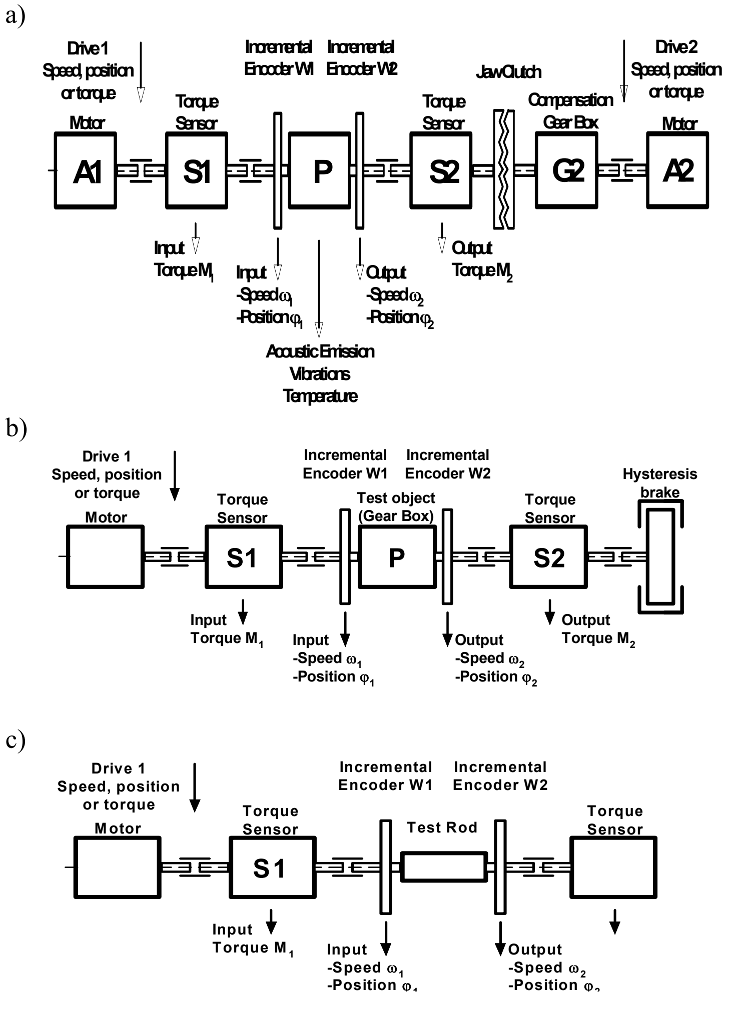


Fig.2 Basic block diagram of measuring stand

3.4 The measuring of vibrations

The measuring of the vibrations supplements properly the measuring of non-uniformity of run of the gearbox. While the measuring of the non-uniformity of run shows the imperfections (non-exactness e.g.) of the manufacturing affecting the static operational properties of the gearbox, the measuring of vibrations shows the imperfections affecting its dynamic behaviour.

3.5 Auxiliary measurements

Into this group belong measurements having a supporting character. The most important of them is the measuring of temperature, noise and acoustic emission. The temperature is nearly connected with the efficiency of the gearbox and with the friction. The vibration and acoustic emission carries the diagnostic information about the conditions of bearings and about the wearing out of surfaces of teeth.

4 . REALIZATION OF THE STAND

The stand allows to perform all measurements mentioned in the previous chapter. It was designed for gearboxes of transmission factor from i = 1:30 to 1:150 and for transmitted power from 0,2 to 6 kW, with input rotational speed max. 3000 rpm.

The first possible realization of the stand is shown in Fig. 2a. The stand is realized with two motors, the first of them (A1) drives the input shaft of the measured gearbox (P) via a torque sensor (S1); the angle sensor (encoder W1) is connected directly with the input shaft of the gearbox (P). The second motor (A2) brakes the output shaft of the gearbox (equipped by a second angle sensor - encoder W2) usually via a torque sensor (S2), a jaw clutch and usually a compensation gearbox (G2). The compensation gearbox has approximately an opposite transmission ratio (1/i) as the measured one.

The jaw clutch allows to disconnect the second drive (A2) and measure the gearbox (P) at free run - if we can neglect (or subtract, if known) the breaking torque being introduced by the second angle sensor (W2).

This arrangement has two advantages: 1) Both drives A1 and A2 can be identical. 2) There is possible to measure the efficiency of gearbox P in both directions - it is important because these two efficiencies need not be identical. And this measurement can be performed also if one of these efficiencies is so small that the gearbox P is in the given direction selflocking.

The second frequently used arrangement of the measuring stand is shown on Fig. 2b. The stand has one drive only - the input one (A1) - and the gearbox measured is loaded on its output by a hysteresis brake. The setting of the breaking torque of the hysteresis brake may be realised either by the direct setting of the magnetisation current - and the output torque sensor (S2) may be used for visual checking of the braking torque only or eventually be omited - or the breaking torque may be created by a control loop where the sensor (S2) plays the role of the measuring element.

The advantage of the arrangement with the hysteresis brake consists primarily in the simplicity of the system and secondly in smaler moment of inertia being connected with the output shaft of the measured gearbox in comparison with the arrangement mentioned above.

Fig. 2c shows the main method of testing of the measuring system. Instead of the measured gearbox (or coupling) is used a test rod. This rod should have its elasticity and moment of inertia as small as possible. By the aid of static measurement there may be checked the elasticity remaining between both encoders (W1 and W2). By dynamic measurement there will be checked the basic error which will be introduced due to the imperfections of fitting of encoders into the measurement of non-uniformity of motion and in the measurement of lost motion if it will be calculated from the courses of non-uniformities.

4.1 The control part

At the stand being equipped by two drives the first one represents either the (theoretic) mechanical source of position or the angular speed for the input shaft of the measured gearbox. The second one plays the role of the load being represented in both these cases by a theoretical source of mechanical torque.

In both drives there were used three-phase synchronous motors with an electronic position/frequency control system. These drives were controlled from a superior computer (Pentium III). The measuring stand must be considered as a mechanical circuit. Its scheme, where also unwanted component (like moments of inertia, elasticities of components etc.) are present is shown in Fig. 3.

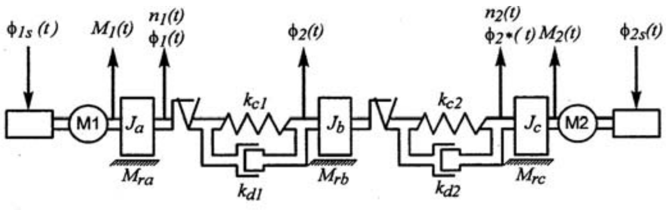


Fig.3 Scheme of linear representation of the stand

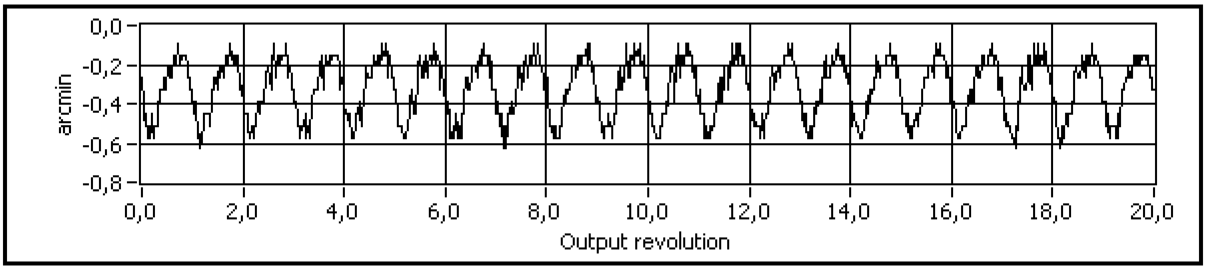
4.2 The measuring part

The sensors installed on the measuring stand must allow as the measuring of position of the input shaft and its rotational speed so as the measuring of both of these quantities on the output shaft. For measuring of position of the shafts there were used various types of Heidenhain encoders - from 100.000 strokes per turn (2.500 optically, x10 electronically, x4 logically) to 720.000 strokes per turn (18.000 optically, x10 electronically, x4 logically) on the input shaft and from 360.000 to 1,440.000 strokes (36.000 optically, x10 electronically, x4 logically) on the output shaft - at this arrangement one stroke represents 0,9"..

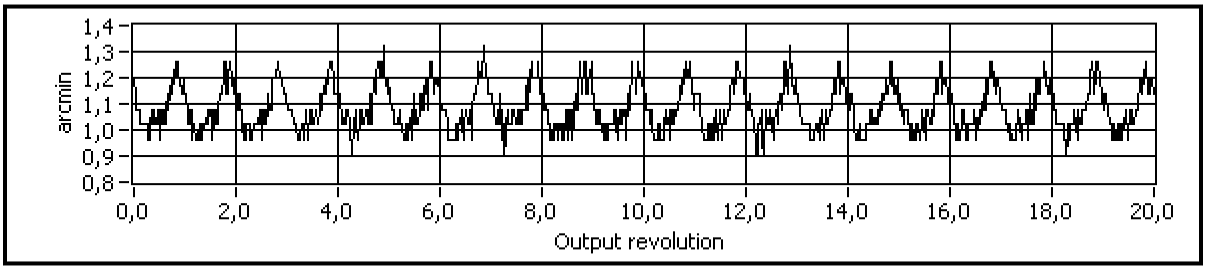
The torque has been measured by Hottinger-Baldwin T30FN transducers (with the ranges from 10 Nm on the input shaft till 2 kNm on the output shaft - between both gearboxes), both in 0,1 % class.

Then follow the measuring of temperature, vibrations and acoustic emission (1 channel each). These sensors need not to fulfil any especial requirements and therefore usually available modules are applied.

a) Uniformity Left



b) Uniformity Right



c) Lost Motion

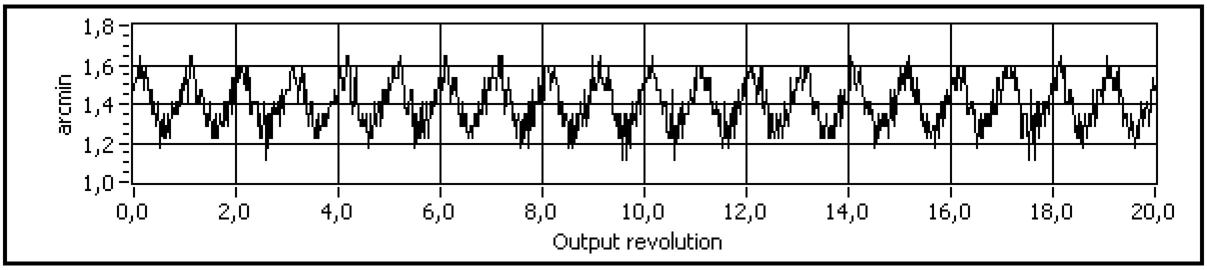


Fig. 4 Measurement with a test rod of non-uniformity of motion

5. CONCLUSIONS

The measurings of non-uniformity of motion shown in Fig. 4 a, b have been done by the aid of a test rod. They showed that the peak-to-peak value of non-uniformity of motion equals to 0,4 arcmin (=24" or approx. 26 strokes) in both directions of rotation. The measuring was very short, 20 turns only at speed 1 turn/s. The sample rate was approx. 400 samples/s or 8192 samples per 20 turns. Moreover, the repeatibility was tested and the results showed that it is very good, when the measuring is repeated in the same section of a turn. For this reason the improvement of the non-uniformity of motion may be expected after careful adjustment of mechanical parts. These and following tests have proven that the arrangement of the stand is fully convenient for its practical use – measurement of gearboxes with lost motion of 1-2 arcmin.

The test measurings have shown also the limit of possible rotational speed of encoders (W1 and W2) – 2 turn/s or 120 rpm without any lost on quality of measurement. Moreover the elasticity of the fittings of the test rod has been found as 7 Nm/arcmin, with this quantity there may be calculated when the test rod (or a measured gearbox) will be loaded by a known torque.

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