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wave drive,
accuracy of positioning

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INVESTIGATION OF OPERATIONAL PROPERTIES OF WAVE TRANSMISSION

This article describes the structure and operation of the Harmonic Drive wave transmission. The most important operational properties and advantages of such transmissions have been formulated here. The paper presents the results of experiments performed on the transmission, particularly ones pertaining to angular sensitivity, invariability of transmission ratio and precision of positioning. The presented results are connected with the influence of various methods of drive motor operation and diverse motor speeds on the operational properties of the transmission.

1. INTRODUCTION

There are many structural solutions of rotary motion transmissions that can be classified as special. They are constructed for a strictly defined purpose, e.g. to acquire very high gear ratios while taking up very little space or volume. In many cases there are classified as mechatronic components [1]. As an example, the wave transmission developed by Harmonic Drive will now be described [2]. Its structural design and operating diagram are shown in Fig. 1.

The most significant component of such a transmission is a gear in the form of a flexible, cog wheel and an elliptical shaft, on which that wheel is set in bearings. Additionally, the flexible cog wheel co-operates (meshes) with an internal cog wheel, which is another part of the machine. The rotating elliptical drive shaft makes the cog wheel deform so that it remains in continuous meshing engagement with the internal cog wheel, which is a shaft being driven. The difference in the number of cogs amounts to 2 (Z_2 - Z_1 = 2).

The producer offers a single transmission with the gear ratio from 1:50 to 1:320, which allows for transfer of driving torque from 0.5 to 5000 Nm and even more. At the same time, the dimension of such a transmission (the largest diameter) falls within 80 to 200 mm. No other known mechanical transmission can offer such advantageous parameters [3].

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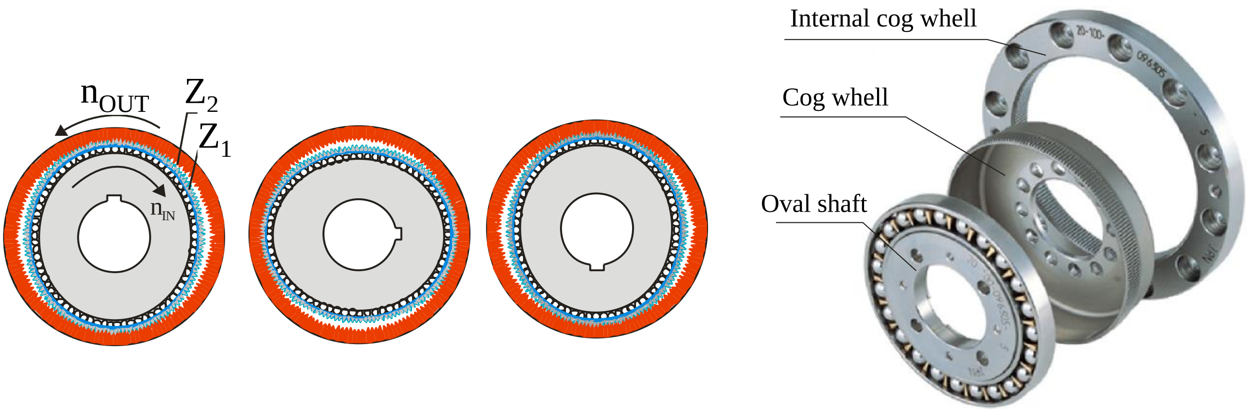

Fig. 1. Structural design of the wave transmission of Harmonic Drive type [2]

What is significant here is that the flexible cog wheel pressing down against the internal cog wheel results in acquiring play-free drive transmission. Another immensely important property of such a transmission is that it is several cogs that engage in meshing, which substantially influences the effort degree of each cog. As a result, the transmission can be loaded with high torques and show strong durability at the same time.

2. HFUC-8-100 WAVE TRANSMISSION

The object of the study was a wave transmission by Harmonic Drive [4], one of the few world producers of wave gears: HFUC-8-100, which ranks among the smallest. Those transmissions operate on the basis of an original patent. Structural solutions, mechanical sizes, mechanical gear ratios and transmitted torques offered make it possible to select an adequate transmission for virtually any device or machine. The HFUC symbol represents one of the structural types, shown in Fig. 2a.

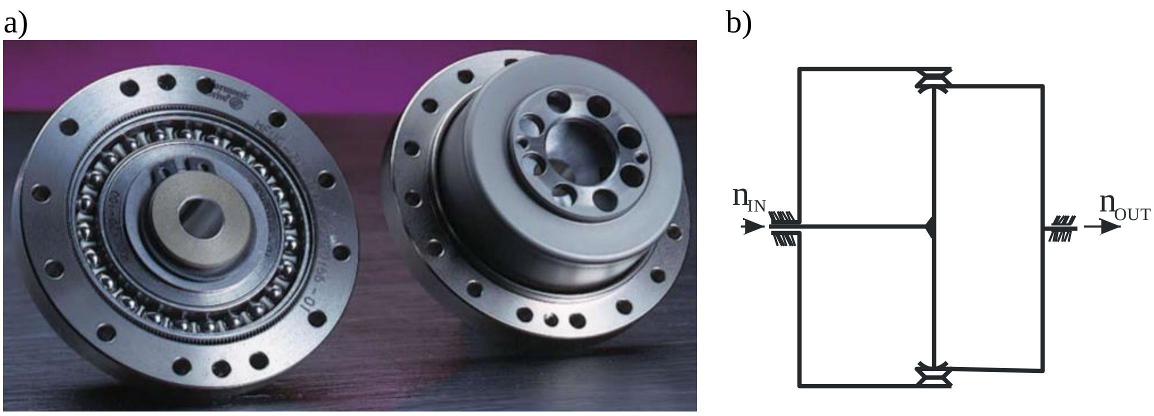

Fig. 2. Transmission of HFUC type (a) and a kinematic diagram (b)

The basic components of the HFUC transmission are the following:
- shaft with elliptical cam, serving as the entry to the transmission (drive shaft) in most cases,
- internal cog wheel, most often serving as the bed of the transmission (during transmission operation it is immobilized; however, it can be used as another entry in a summing transmission).
- yoke, in the form of a deformable cog wheel engaging with the internal cog wheel. In many applications of such transmissions, the yoke is the output component, i.e. the driven shaft (it is admissible to reverse its function, i.e. use it as the drive shaft, but then the kinematic transmission ratio of the mechanism changes dramatically).

The kinematic properties of such wave transmissions are well shown in Fig. 2b, which illustrates the diagram of an epicycle transmission. In such a transmission, the transmission ratio, understood as the ratio of input to output velocity, may be illustrated as follows:

$$i = \frac{n_{OUT}}{n_{IN}} = -\frac{1}{z_1} \tag{1}$$

where: n_{IN} - velocity of the input shaft, a cam shaft in this case,
n_{OUT} - velocity of the output shaft, a yoke with flexible cog wheel in this case,
i - transmission ratio of the epicycle transmission.

If, as is the case with Harmonic Drive transmissions, the number of cogs in the internal cog wheel (Z_1) is different from such number in the cog wheel (Z_2) by 2 and if $Z_1 = 100$ (this applies to the HFUC-8-100 transmission), the transmission ratio equals 1:100.

If the roles of the input and output shafts were exchanged in the same transmission, i.e. the drive were applied to the yoke and the shaft with elliptical cam was the output, the transmission ratio would be 100, i.e. the output velocity would be 100 times higher than the velocity of the input shaft.

The diagram in Fig. 2b also indicates that putting the immobilized internal cog wheel into motion allows for introducing another drive operating independently of the first one, thus creating a summing transmission. The transmission in question can transmit torque of 2.4 Nm on a long-lasting basis (the rated torque value at rated velocity of 2000 RPM) and it can be overloaded to 4.8 Nm for a short period of time. Those are very high torque values if the weight of the entire transmission is assumed to be 26 grams. The maximum rotational velocity at the input to the transmission reaches, depending on its lubrication (oil or grease) 14000 RPM, which gives 140 RPM at the output. Solid moment of inertia equals 0.003 $kgcm^2$. The example technical data shows that such transmissions are mostly fit for slow-velocity mechanisms, e.g. the mechanism of an indexing table, indexing head, rotary working head, etc.

A significant operational property of the wave transmission is high angular (torsional) rigidity, which makes it useful for precise angular positioning. In the case of the studied transmission, the rigidity index is about 1.0 x 10^3 Nm/rad, which means that for the rated load of 2.4 Nm the angle of rotation at the output shaft will not exceed 8.25'.

The producer also guarantees great precision of positioning - below 2', with the repeatability not worse than +/- 0.1' and hysteresis below 2'. The present study aimed to verify some operational parameters of the HFUC-8-100 transmission.

Unfortunately, the many advantages of wave transmissions are accompanied by some disadvantages (apart from high price). The minimization of those disadvantages depends greatly on the designer of the kinematic, drive chain. An important structure- and assembly-related requirement is to prevent any transverse loads acting mostly on the yoke of the mechanism, but also on the shaft with elliptical cam. The occurrence of such loads will result in abnormal operation of the transmission and first and foremost very quick wear and tear of the component parts. This means that the input shaft with elliptical cam must be independently set in bearings and perfectly coaxial with the internal cog wheel. Independent setting in bearings will prevent transverse loads on the flexible cog wheel from occurring. In turn, the yoke, as the driven shaft (the output part in the transmission), should not be coupled with the driven device in any way limiting the operational freedom of that device. Therefore, the output shaft (yoke) is prepared for engagement with for instance the Oldham coupling, which allows for transmitting driving torque only (Oldham couplings cannot transmit any transverse load, but it allows for co-operation with non-coaxial shafts). However, please note that if the shafts are not coaxial, friction loads will occur that will be the sources of transverse loads and, consequently, of hysteresis.

Furthermore, it has to be noted that relief from transverse loads very much depends on geometric precision, especially on the coaxiality of bearing seating on the side of the drive shaft, driven shaft and the internal cog wheel. Hence, the requirements related to the precision of design and assemblies of the structural form are very high.

3. TESTING STAND

As already said, the study aimed to verify some operational properties of the HFUC-8-100 wave transmission, particularly the value of elementary angle of rotation (kinematic sensitivity), invariability of transmission ratio and precision of positioning. To this end, a testing stand was established, shown in Fig. 3.

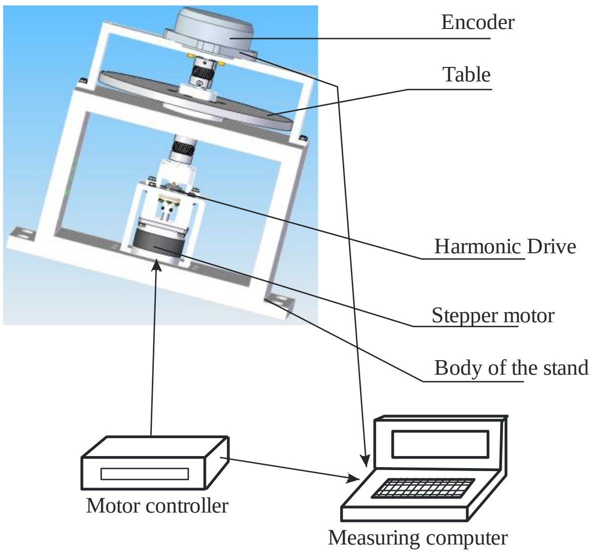

Fig. 3. Diagram of testing stand with HFUC-8 transmission

The stand includes:

1. body where the entire kinematic chain of the indexing table drive is installed, i.e. a FL57ST41-1564A stepper motor, HFUC-8-100 wave transmission and indexing table,
2. rotary-pulse transmitter (encoder), ROD 207, developed by Heidenhein,
3. control system of an SSK-B01 stepper motor, containing an AVR Atmega8 microcontroller and an MZ-02 supply system,
4. measuring computer with an A/C USB 6211 card and software compiled in the LabView environment.

The employed stepper motor allows for 200 steps per one shaft revolution. Thus, a single step equals 1.8°, which means that the smallest set angle of table rotation is 1.08'. Since it can be controlled on a half-step basis, a single step of the motor amounts to 0.9° and the smallest set angle of table rotation is 32.4".

The used rotational and impulse convertor generates 18000 impulses per shaft revolution, but an internal interpolator allows for a 5-time increase in the number of measuring impulses, i.e. up to 90000 impulses per revolution. Considering that each impulse allows for using the leading and trailing edge, the overall number of impulses that can be employed to measure the angle of rotation equals 360000, which means that the minimal angle of rotation can be measured at the level of 3.6". As the smallest angle of rotation to be achieved at the test stand is 1/40000 of the round angle, i.e. 32.4", measuring the angle of rotation with the sensitivity of 3.6" is precise enough.

The rotary table, its solid moment of inertia strictly speaking, is of significance as well. It equals 87.5 $kgcm^2$ and after reduction to the motor shaft - 0.00875 $kgcm^2$. On comparing it with the moment of inertia of the wave transmission, i.e. 0.003 $kgcm^2$, it can be stated that the total, reduced moment of inertia at the motor shaft is 0.011875 $kgcm^2$. As the moment of inertia of the motor itself amounts to 0.057 $kgcm^2$, it may be assumed that the rotary table along with the wave transmission does not overload the motor inertia-wise.

4. EXPERIMENT RESULTS

Three experiments were performed as regards the following:

- kinematic sensitivity, understood as the number of set motor steps after which the rotary-pulse transmitter generates at least one measuring impulse,
- invariability of transmission ratio, understood as a relation of transmission ration to the set angular position of the table,
- precision of angular positioning of the table.

The said experiments were carried out in the set range of rotational velocity and acceleration (applies to accelerating and braking by means of the so-called ramp). The investigation of the kinematic sensitivity was to verify the possibility to control the angle of table rotation with a precision not worse than 2' (acc. to the producer of the transmission). It included setting one step at the motor input and repeating it in both directions at least 10 times.

Theoretically, a single motor step may be associated with the angle of table rotation equal to 0.54'. Fig. 4 shows the results of this investigation [5].

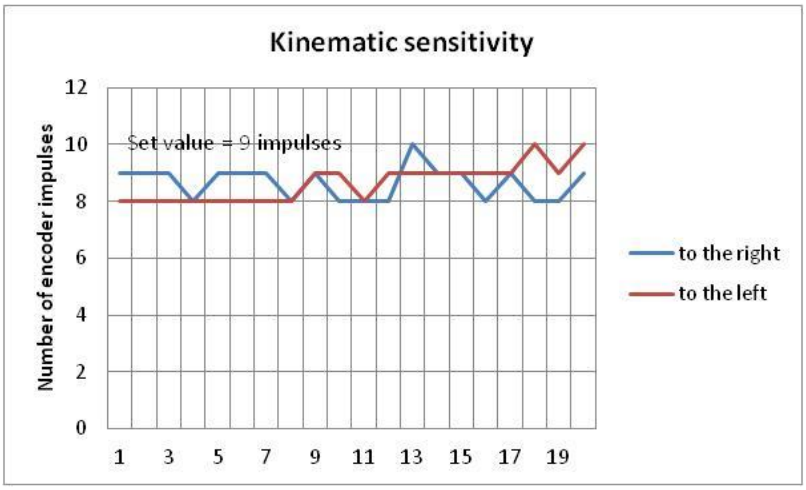

Fig. 4. Investigation results of kinematic sensitivity of wave transmission [5]

It illustrates the readings of the encoder (rotary-pulse transmitter) after setting twenty steps (in both directions) in the incremental system. A single set motor step theoretically means that the table will rotate by 1/40,000 of the round angle, which corresponds to 9 encoder impulses (in the Figure labeled as "set value=9 impulses"). Fig. 4 explicitly shows that the elementary angle of table rotation does not differ from the set value by more than 1 encoder impulse, i.e. 0.001° (3.6"). This means that a single motor step results in the table rotating by 0.54' +/- 3.6". Setting an angle of rotation that corresponds to a single motor step, it may be assumed that it will not be lost.

The above investigation covered the case with a single elementary shift. Such case are rare in practice. Generally, the set value of shift is higher. To assess the precision of transmission operation in motion, investigation on the relation of angular path of the table to the set path at the input of the motor have been done. The investigation was static, i.e. by summing the angle of table rotation each time after a shift by one step was set. The experiment also aimed at evaluation of the transmission ratio of the transmission.

Fig. 5 shows the results of this investigation in the form of a relation of angle of rotation at the input and output of the transmission (to be precise, it is a relation of the set angle of motor rotation to the measured angle of table rotation). Fig. 5 indicates that the direction of movement influences the relation between the rotary motion of the table and the motor. This is so as there occurs a hysteresis loop of about 0.006°, i.e. about 0.36' (the producer guarantees hysteresis will not exceed 2'). In Fig. 5 there are also regression lines, which help evaluate the actual transmission ratio. It amounts to about 1:104.2: it is higher than the value provided by the producer (1:100).

For the purposes of assessing the influence of velocity of rotary motion and the so-called ramp (it is a method of implementing acceleration or deceleration, based on linear regression of the signal of set motor; it is defined as the number of input impulses in the motor due to which the motor accelerates to the set velocity; the higher the number of ramp impulses, the lower the motor acceleration) the repeatability of achieving the set table position (in this case for one and five set motor revolutions) for two values of rotational velocity (54 and 111 RPM) and two ramp values (0 and 200 impulses). Fig. 6 shows the results of this investigation.

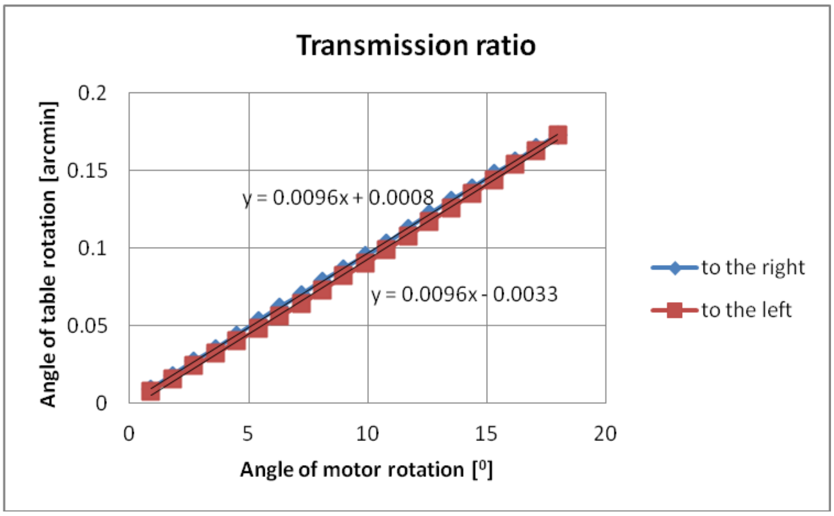

Fig. 5. Angle of the table rotation in relation to set angle of motor rotation for n=0 RPM [5]

a) b)

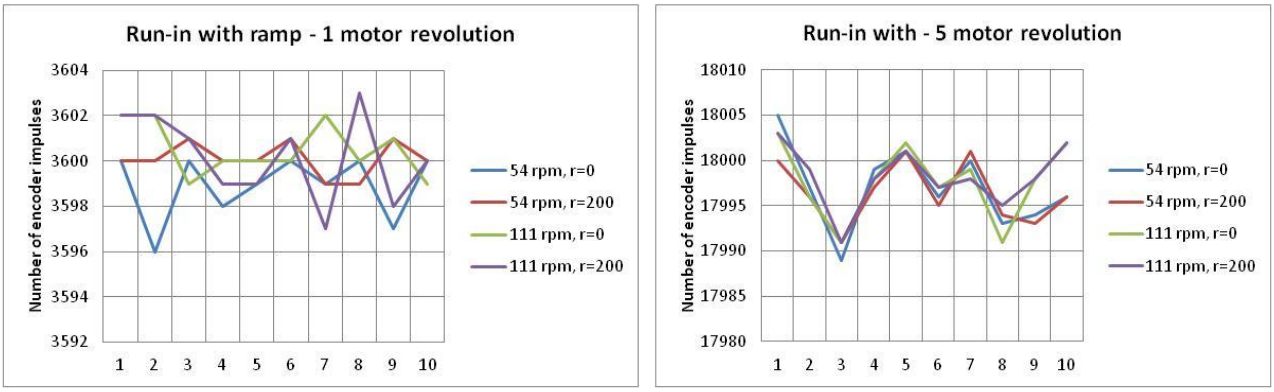

Fig. 6. Dependence of the angle of table rotation on the set angle of motor rotation: set angle of motor rotation: a) 1 revolution; b) 5 revolutions, for two velocity values: 54 and 111 RPM and two ramp values: 0 and 200 impulses, for 10 repetitions [5]

Fig. 6 shows the acquired angle of table rotation (as the number of impulses measured by the encoder) for two rotational velocities: 54 and 111 RPM and two ramp values: 0 and 200 impulses, for the set angular motor path: 1 revolution and 5 revolutions, for 10 repetitions. Theoretically, the number of encoder impulses is as follows: 3600 impulses for 1 motor revolution and 18000 impulses for 5 revolutions.

The conclusions are not explicit because if they are related to Fig. 5b, a view may be formulated that the rotational velocity and ramp do not have a significant influence on the repeatability of achieving the set table position. The set table position (18000 impulses) is reached with deviation to 10 impulses, i.e. 36", so it is an excellent result. If, however, conclusions are to be drawn from Fig. 6a, a view may be formed that an increase in ramp value (decrease of acceleration) facilitates higher repeatability of reaching the set position and the deviation does not exceed 4 impulses, i.e. 14.4". Moreover, the transmission ratio determined on the basis of those investigations is within 1:100 +/- 0.1, i.e. it does not differ considerably from the ratio guaranteed by the producer.

The conclusions drawn from the investigations so far were based on the steady state, i.e. after the transient state (run-in) is finished. In order to assess the mechanism quality properly it is necessary to take into consideration its operation in that latter state as well. It is shown in Fig. 7, which illustrates several courses in the transient state (run-in) in the form of a time course of angle of table rotation measured by the encoder.

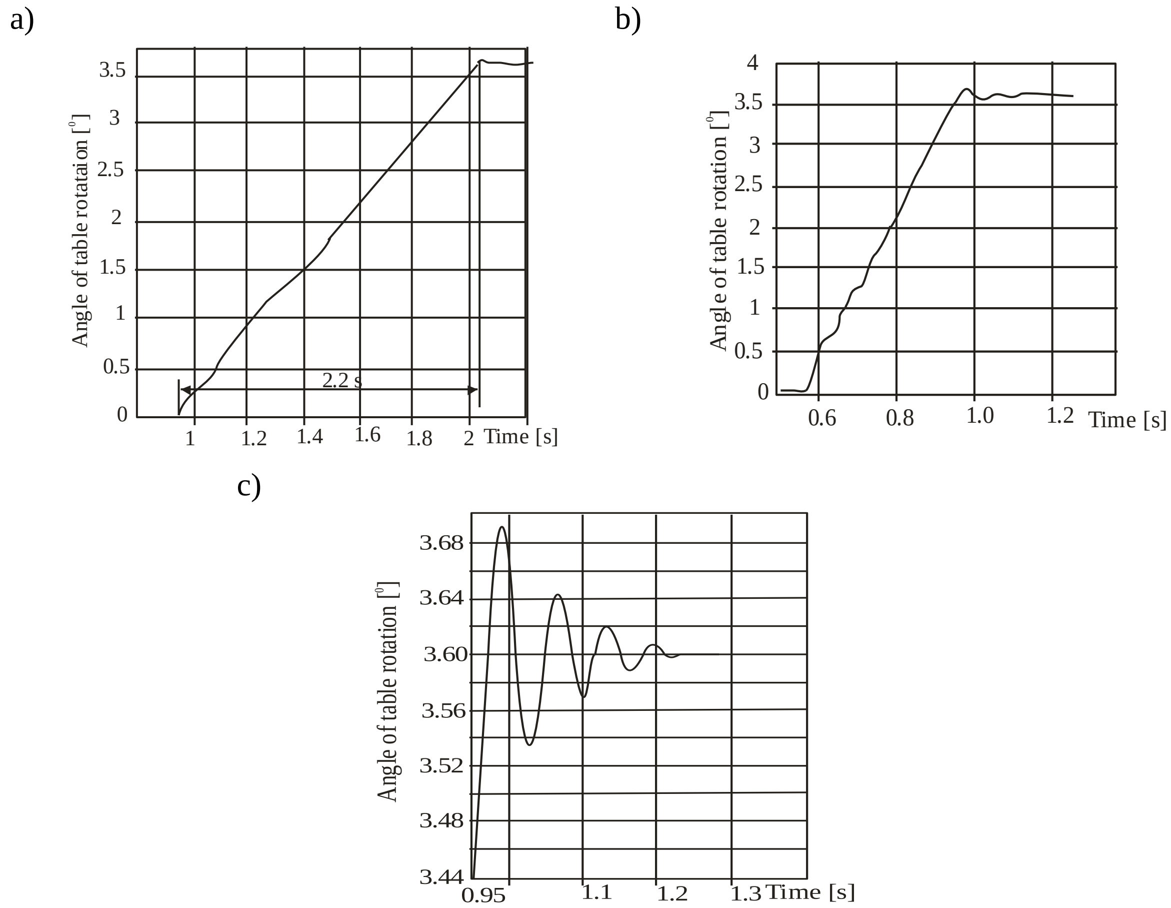

Fig. 7. Time courses of the angle of table rotation: a) 54 RPM; b) 111 RPM; c) in the final phase of table rotation [5]

As the velocity increases, oscillations in rotary motion of the table and time required to achieve the steady state increase as well. This is best illustrated in Fig. 7c, which shows the behavior of the table in the final phase of its motion. The oscillations have the frequency of about 13 Hz, overshoot constitutes merely 3% of the steady state.

Fig. 8 will now be employed to assess the influence of the ramp on the time course of angle of table rotation. It shows two courses: without the ramp and with the ramp of 200 impulses. The difference in time courses is substantial. Use of the ramp causes much lower overshoots, but the period of reaching the steady state is prolonged.

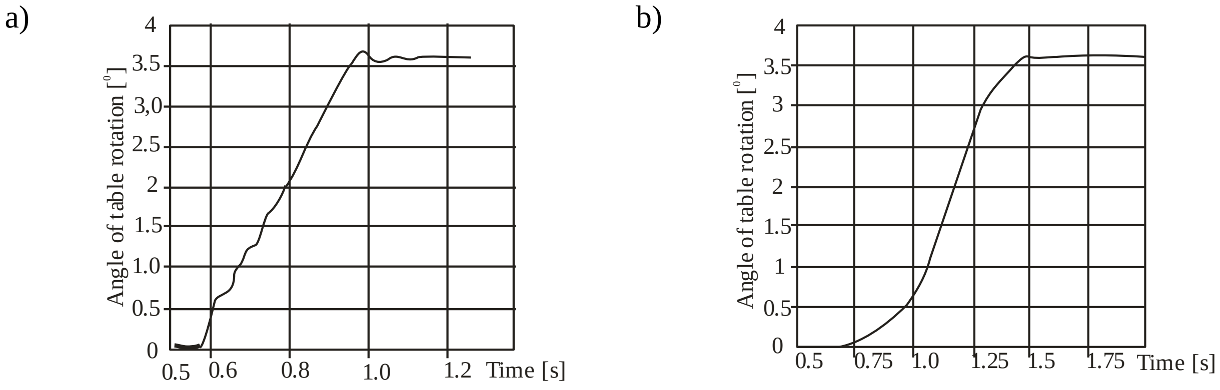

Fig. 8. Time courses of the angle of table rotation: a) without ramp; b) with ramp of 200 impulses [5]

In summing up this part of the study it has to be noted that transient states are strongly dependent on dynamic parameters of the motor itself. The role of the transmission is slight and comes down to influencing solid moment of inertia and potentially reducing the friction caused by resistances.

The precision of positioning is the best indicator of mechanism quality as the methods used for its assessment are regularized and standardized. This allows for objectivity in the process of evaluation. The studies on the precision of positioning were carried out in compliance with the ISO 30-2:1997 standard [6]. The investigation on the wave transmission were performed in the scope of one full revolution of the motor shaft, which corresponds to 1/100 of the round angle of table rotation. Fig. 9a shows example results of measurements of table positioning in relation to the set angle of motor rotation.

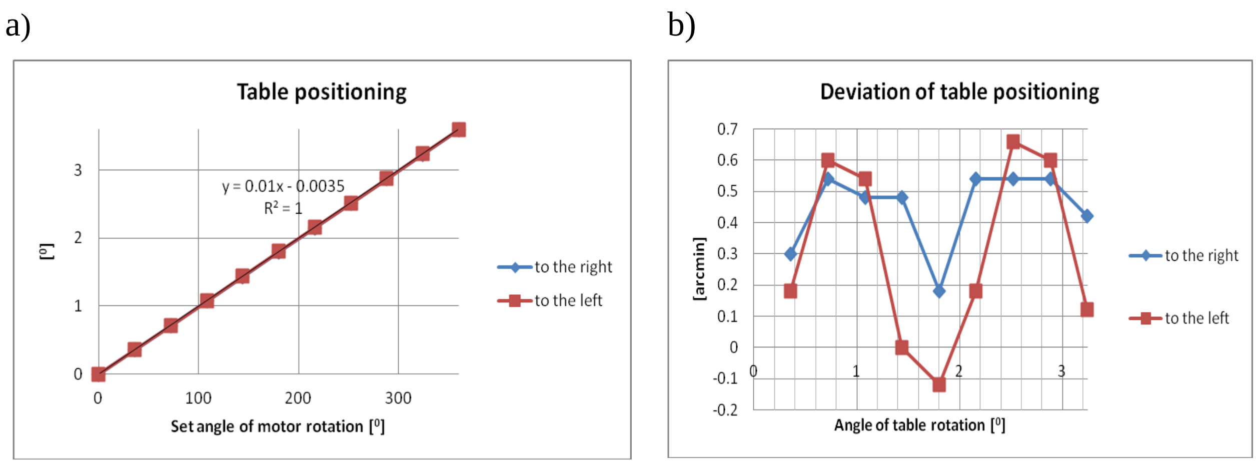

Fig. 9. Example results of investigation on the precision of table positioning (a) and deviations from the theoretical value (b) [5]

Between the set angle of table rotation and the positioning of the table there is a linear relation with the angular coefficient of 0.01, equal to the inverse of the transmission ratio. The correlation coefficient is 1. In Fig. 9b there are positioning deviations from the theoretical (set) value. The greatest deviation does not exceed 0.6', i.e. it is much lower than guaranteed by the producer of the transmission (2').

On the other hand, Fig. 10a shows the values of unidirectional repeatability of positioning and Fig. 10b values of that repeatability being bidirectional.

a) b)

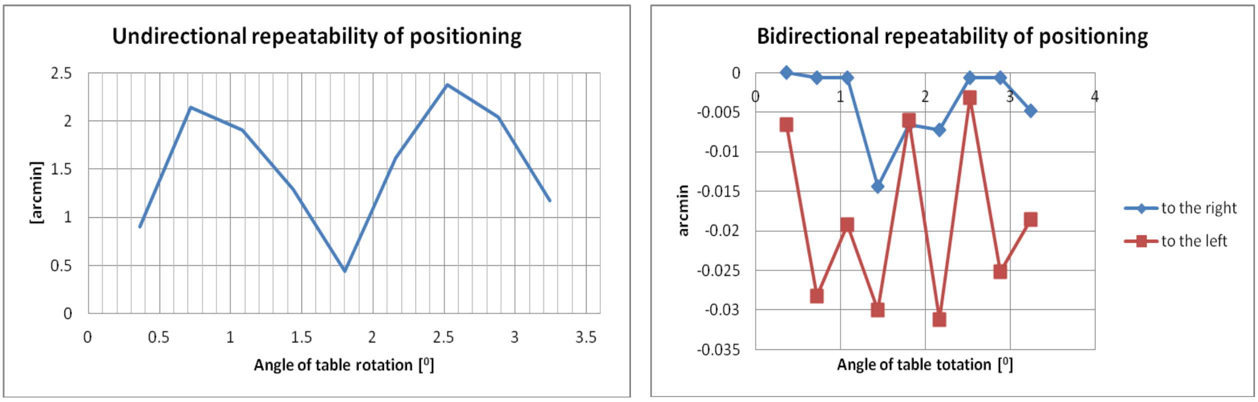

Fig. 10. Values of positioning repeatability: a) unidirectional repeatability; b) bidirectional repeatability [5]

The positioning repeatability is not worse than 0.03' (unidirectional) and 0.01' (bidirectional). What it means is that it is better than what the producer has guaranteed (+/-0.1'). Therefore, the investigated mechanism allows for positioning with the step of 0.009° (0.54'), deviation not exceeding 0.6', unidirectional repeatability not worse than 0.03' and bidirectional repeatability not worse than 0.01'.

5. CONCLUSIONS

The object of the study was a precise wave transmission of HFUC-8-100 class, as a mechanism for precise angular positioning of - for instance - rotary tables. The study aimed to assess the quality of such a transmission, i.e. to identify the smallest possible angle of rotation, known as kinematic sensitivity, actual transmission ratio and precision of positioning. The investigation of the transmission was performed in a system with a stepper motor of 400 steps per revolution. It was determined that it was possible to set the smallest angle of rotation at the level of 0.54' with deviation not exceeding 0.6'.

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