EXPERIMENTAL TESTS TO ASSESS THE DYNAMIC CHARACTERISTICS OF WORM GEARBOXES

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The article deals with the issue of experimental assessment of the dynamics of worm gears. The design of the methodology and the material and technical assurance of experimental tests to determine the impact of the use of various structural modifications on the dynamics of the worm gear are described. In the pilot part of the experiment, a gearbox was tested with an original design solution of bearing the worm wheel shaft in special damping inserts. The goal is to find ways to reduce the dynamic load of the most stressed components of the worm gear and increase their service life.

KEYWORDS

experimental tests, worm gears, dynamics, measurement methodology, vibrodiagnostics

1 INTRODUCTION

Scientific research on Department of Technical Systems Design and Monitoring of Faculty of Manufacturing Technologies of the Technical University of Kosice with the seat in Presov is oriented to determine the influence of dynamic load on the service life of different types of gears. According to [Pavlenko 2021], the dynamic behavior of the transmission mechanism is determined by a number of factors [Mascenik 2019 and 2022]. For the internal factors, there are the basic parameters of the gear transmission, various design solutions, material, gear manufacturing technology, gear manufacturing accuracy, gear assembly accuracy, gear backlash, etc. For the external factors, the function of the gearbox is fundamentally affected by the operating conditions [Pavlenko 2006].

The goal of worm gear research is to find ways to reduce the dynamic load of the most stressed components, or of the design joints of the worm gear, with the aim of increasing their service life. One of the proposed solutions was a design modification of the worm wheel shaft bearing using special damping inserts. The aim of the experiment described below is to determine the effect of using the proposed damping inserts on the dynamics of the worm gear. As part of the preparation of the experiment, the following basic tasks were set:

- Selection of a suitable experimental object.
- Proposal of a methodology for measuring and assessing the dynamic behavior of gearboxes of different designs under the same operating conditions.
- Material and technical assurance of the experiment.

2 METODOLOGY

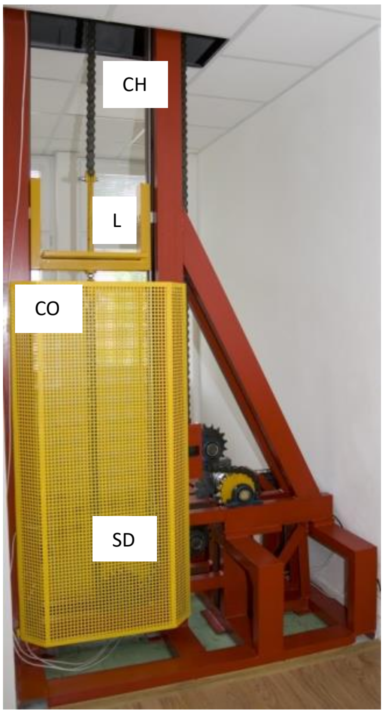
The overall plan and implementation of experimental measurements were elaborated with regard to the possibilities of material and technical assurance of measurements, the availability of the necessary equipment and the possibility of carrying out individual measurements in-house in the premises of the laboratories of the Department of Design and Monitoring of Technical Systems.

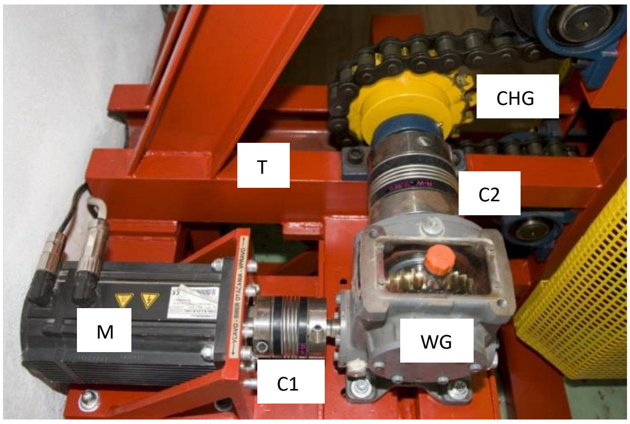
2.1 Test station for dynamic tests of gears

The test station for dynamic tests of gear transmissions (see Fig. 1) enables short-term as well as long-term tests of various types of gear transmissions in conditions close to their real operation. For the experimental tests carried out at this stand, a methodology was developed for assessing the technical condition of transmission mechanisms using several methods of non-destructive, non-dismantling diagnostics [Cacko 2014a,b].

The following parameters can be measured and analyzed:

- durability, reliability, wear (contact wear);
- efficiency, temperature, temperature gradient;
- friction power, friction moment, axial load;
- run-in events, load capacity changes after run-in;
- assessment of individual components: gears, bearings; lubricant, sprocket and chain;
- resonance phenomena and operation at critical speeds.

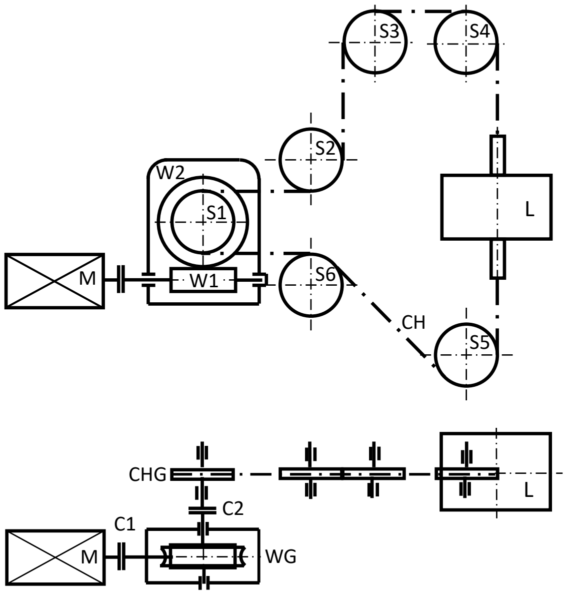




M – electric motor; C1, C2 – couplings; WG – worm gearbox, CHG - chain gear; CH – chain; L – load (weight); CO – cover; SD – spring dampers; T – table

Figure 1. Test station for dynamic tests of gear

The test station simulates a working machine. Fig. 2 shows its principle diagram. A detailed functional description of the test station is given in [Smeringaiova 2015].



M - electric motor; C1, C2 - couplings; WG - worm gearbox; W1- worm shaft; W2 - worm gear; CHG - chain gear; S1 - S5 - sprockets; CH - chain; L - load (weight)

Figure 2. Principle scheme of the test station

With the help of the weight **L** (see Fig. 1 and Fig. 2), the load on the output shaft of the **WG** gearbox is produced from the side of the working machine. The weight moves vertically in both directions (up and down) in a line that is protected by a **CO** cover. **SD** shock absorbers with springs, located in the upper and lower parts of the vertical frame, serve to dampen shocks. The operation of the test station is controlled using a frequency converter according to the selected load program. The number of revolutions and the size of the load can be changed as needed. The continuous mode of operation and reverse operation allow monitoring the course of wear of the functional parts of the gears and assessing their service life in an accelerated mode.

2.2 Description of an experimental worm gearbox

A standard manufactured worm reducer Z80-J-010-P (ZŤS Sabinov, a.s.) was used as the object of the experiment.

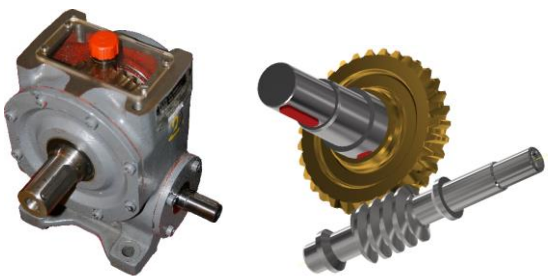


Figure 3. Worm reducer Z80-J-010-P and 3D model of a worm gear

Table 1. Technical parameters of the worm gearbox Z80-J-010-P

Gear ratio i_{ZP} / i_{ZPsk} [-]	31.5 / 31
Max. input power P_1 [kW]	1.69
Max. input speed n_1 [min^{-1}]	1400
Max. torque [N.m]	265

For the needs of the experiment, the following structural modifications were made to the gearbox:

- **Opening the upper part of the gearbox housing** – Fig. 3.

The gearbox was originally closed. The hole created after milling the upper part of the gearbox housing allows access to the teeth of the worm wheel at any time during the experiment. To determine the wear of the functional parts of the tooth flanks, it is also possible to use simple diagnostic methods, such as continuous measurement of the thickness of the worm wheel teeth or visual assessment of the functional surface of the tooth flank. It is not necessary to disassemble the gearbox during the experiment. During the test operation, the opening is closed with transparent Lexan.

- **Replacement of bearings and fitting of the worm wheel shaft, respectively bearings in damping inserts.**

To improve the dynamic characteristics of the worm gear, the use of special damping inserts was proposed. After placing the outer rings of the worm gear shaft bearings in the damping inserts, better damping properties should be achieved at the place of storage. This assumption needs to be verified by the experimental tests described below.

In order to place the shock absorbers, it was necessary to create a space in the gearbox housing. The original intention – increasing the diameter of the hole for the outer ring of the bearing was rejected based on the production drawing of the gearbox housing. The thickness of the walls in the place where the bearings are stored is 5 mm. The assumed sufficient thickness of the damping rings is 4 to 5 mm. Removing the material would significantly weaken the gearbox housing wall in the exposed location.

Figure 4. Damping inserts made of NYLON PA12 material installed in a worm gearbox

The following solution was accepted and implemented [Hrabcak 2021]. The helical gearbox was dismounted. The original 7209AA single-row angular contact ball bearings have been replaced with 6009-2RSR bearings. The diameter D of the outer ring of the new bearing is smaller by 10 mm. By replacing the bearings, a space was created in the gearbox housing for the placement of the damping insert.

The shape and dimensions of the damping ring (damping insert) were designed in such a way that it correctly defined the exact position of the worm wheel shaft according to the worm shaft. Creality model CR-10S.Damping rings will be produced by additive 3D printing technology on the device Creality model CR-10S. The advantage of this technology is the possibility of producing parts from different materials and also making part walls with different internal filling structures [Coranic 2021]. As part of the experiment, the damping effects of damping rings made of different materials and with different internal structures will be tested.

A prototype of the damping insert to verify the dimensional accuracy of the initial design and overall compatibility with the bearing and the location of the bearing in the flange was printed from PLA material. After tuning the correct shape and dimensions, prototypes of damping rings were made for the first, verification series of experimental tests. The material Nylon PA12 from Fiberlogy was chosen for the production of damping inserts. It is a technical material with high resistance to high temperatures and chemical compounds. It is extremely resistant to abrasion, almost unbreakable and very flexible. The "cube" pattern was chosen as the filling pattern. The advantage of producing a damping insert with a filling pattern is the saving of material and the lower weight of the part. The advantage is also the shorter time needed to produce the part compared to printing a wall without an internal pattern. The main argument for choosing a wall with an internal pattern was the assumption that a damping insert with a structured wall would have better damping properties than a damping insert with a wall made of solid material.

In Fig. 4 is a damping insert pressed on the outer ring of the bearing. The second damping insert is already installed in the gearbox flange.

2.3 Description of measurement

In the pilot part of the experiment, experimental tests of the worm gearbox in the original, standard version were carried out. Subsequently, the disassembly and assembly of the gearbox was carried out. The worm wheel shaft was placed in replaced bearings, and damping inserts were used in the place of storage. Experimental tests were again carried out on the structurally modified worm reducer. In both cases, the same operating conditions were set for the test operation of the worm gear reducer. The operating conditions of working modes 1 to 4 are listed in Tab. 2. Mogul CLP 220 transmission oil was used for lubrication. It is a commonly available gear oil recommended by the manufacturer for the given type of worm reducers.

Table 2. The operating conditions of working modes 1 to 4

Mode	Input Speed n [min^{-1}]	Load [-]	Total Weight m [kg]	Measure-ment Time t [s]
Mode 1	600	0	26*	64
Mode 2	600	3	97.5	64
Mode 3	1080	0	26*	64
Mode 4	1080	3	97.5	64

*weight of the weight holder

The basic methods of vibrodiagnostics were used to determine the dynamic characteristics. Under the term vibration, or by mechanical vibration, we mean detectable and measurable vibration of machine surfaces, construction nodes, machine bases, etc. The importance of measuring the mechanical vibration of machine parts lies in its high information content. Mechanical vibration is an indicator of the machine's condition, it warns about the dynamic stress of the machine, its base and surroundings and provides the basis for machine diagnostics [Murcinkova 2016, 2020 and 2021, Klimenda 2019, Olejarova 2021, Vasina 2019].

In each mode, three measurements of low-frequency vibrations were carried out at three selected measurement points for both alternatives of the worm gearbox design (standard, design modification) - see Fig. 5. The measuring point **1H** was chosen on the flange in the direction of the worm wheel shaft axis. The measuring point **2H** was chosen on the flange in the direction of the screw shaft axis. At the measuring point **3V**, the vibration speed was measured vertically in a direction perpendicular to the axis of both shafts. Low-frequency vibrations were sensed on the surface of the gearbox housing. Before the measurement, reflective stickers were placed on the individual measurement points. The result was a better reflection of the laser beam and an amplification of the received signal. During the measurement, the temperature on the surface of the gearbox housing was also monitored.

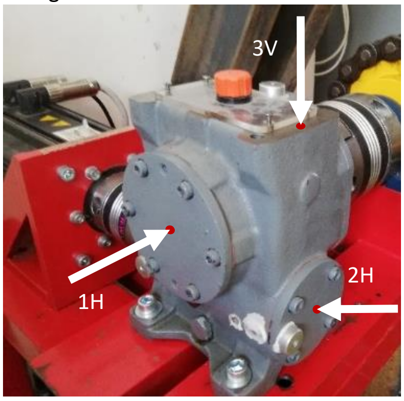


Figure 5. Measurement points

Used measurement technique:

- laser vibration sensor Polytec PDV-100 placed on a separate tripod (see Fig. 6),
- convertor Polytec VIB-E-220,
- software program for processing measured data VibSoft-20.

Figure 6. PVD-100 Portable Digital Vibrometer

Polytec's Portable Digital Vibrometer PDV (frequency range from 0.5 Hz to 22 kHz, velocity ranging from 0.05 µm/s to 0.5 m/s, best resolution 0.02 µm/s) was used for non-contact measurement of surface vibrational velocities. The PDV is a compact, portable laser vibrometer with state-of-the-art design of optics and signal processing [Polytec 2022a]. The obtained data were transferred via the Polytec VIB-E-220 converter to the computer and processed using the VibSoft-20 software program. VibSoft provides both data acquisition and profound analysis of vibration measurement results [Polytec 2022b]. It has two input channels (measurement and reference) and enables data analysis in the time and frequency domain.

For both alternatives of the tested gearbox (standard, structural modification), low-frequency vibrations were recorded during the test operation in all working modes in the time interval t = 64s.

Fig. 7 shows the interface of the Polytec VibSoft-20 software. An example of displaying data measured and processed during one measurement is presented. The upper graph shows the time recording course of the amplitude of the vibration speed. In the middle part there is an octave analysis in a logarithmic scale, which shows the energy of vibrations in a given frequency band. The bottom part shows the result of the FFT analysis of the recorded low-frequency vibrations. Compared to octave analysis, the Fourier transform provides a better peak resolution.

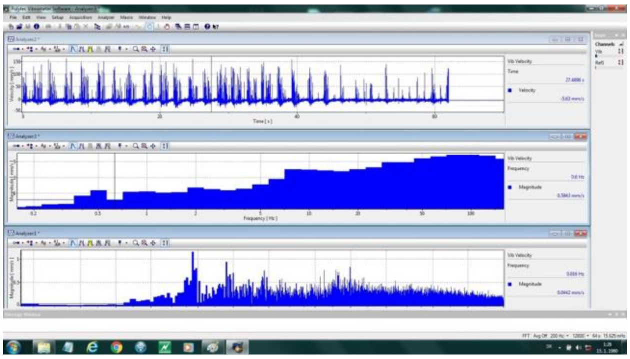


Figure 7. Polytec VibSoft-20 software interface

The measured values of the vibration rates were also evaluated in terms of the standard [STN ISO 10816-3 2022]. The standard sets safety limits for the overall level of mechanical vibrations VELOCITY (mm/s, RMS) in the 10-1000 Hz band as follows: Alarm 1 – warning – 2,8 mm/s and Alarm 2 – danger – 4,5 mm/s.

3 RESULTS AND DISCUSSION

The data measured during the verification series of measurements were processed and analyzed. In Fig. 8 and Fig. 9 are examples of measured and processed data. Fig. 8 shows a graphical record of the time course of the vibration velocity measured at points 1H and 2H during the test operation of the worm gearbox in Mode 1. The vibration values measured at point 1H increased slightly for the modified gearbox (from – 20 mm/s to + 10 mm/s) compared to the values measured for the standard gearbox (from – 15 mm/s to + 8 mm/s). From a comparison of the vibration velocity curves measured axially with the axis of the worm shaft at point 2H, we see that in the case of the modified gearbox, the mechanical vibrations have stabilized and reach significantly lower values (from - 15 mm/s to + 8 mm/s) than in the case of the standard gearbox (from - 30 mm/s to + 39 mm/s).

In Fig. 8 is a comparison of the results of the octave analysis of mechanical vibrations at point 2H. The magnitude in octave analysis reaches a peak vibration energy of 1.6 mm/s at a frequency of 0.4 Hz. In the frequency range of 0.5 to 40 Hz, it varies in values up to 1 mm/s. At 50 Hz up to 135 Hz, its value increases again just below the limit of 1.5 mm/s. The vibration energy of the worm gearbox with adjustment using Nylon PA12 damping inserts in the 0.4 Hz range drops significantly to 0.1 mm/s. Higher values (max. 1.2 mm/s) were recorded at a frequency from 50 Hz to 100 Hz.

From the above results, it is possible to preliminarily conclude:

- After the structural modification (bearing of the worm wheel shaft in the damping inserts), there is a change in the dynamic characteristics of the gearbox measured at all measurement points.
- Confirmation of theoretical outputs published in [Pavlenko 2006], according to which the reduced torsional stiffness of the worm wheel shaft from the side of the driven machine is usually one order of magnitude smaller than the average reduced stiffness of the gearing, respectively torsional stiffness of the worm from the side of the drive motor.
- Confirmation of the damping effect of damping inserts on transmission dynamics. After placing the worm wheel shaft in the damping inserts, there was a decrease in the values of mechanical vibrations in the direction axial to the axis of the worm. This indicates e. g. reducing the stiffness of the worm wheel shaft supports and subsequently reducing the stiffness of the worm shaft.
- From the time courses of low-frequency vibrations, it is obvious that high values are reached above the level of recommended limits for safe operation. The tested gearbox was already operated in another experiment. The wear of the functional flanks of the worm gear teeth, which occurred during the test operation, had an impact on the significant deterioration of the dynamic characteristics of the worm gear.

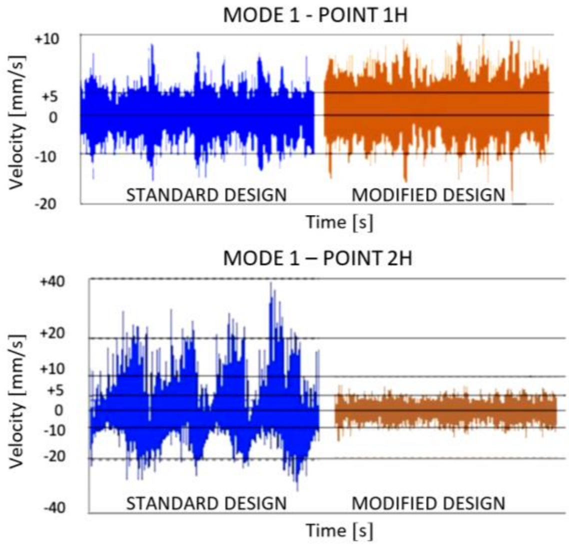


Figure 8. Sample vibration velocity time history

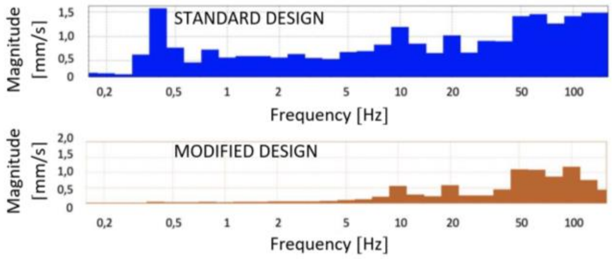


Figure 9. Octave Analysis in MODE 1 - POINT 2H

To increase the objectivity of the results of further planned experimental tests, it will be necessary:

- Use a different gearbox, which is preferably running in, or with minimal tooth wear.
- Use another type of replacement bearing suitable for worm gears.
- To ensure higher accuracy of repeated assembly of the gearbox.
- Add diagnostic methods for continuous assessment of the technical condition of the worm gear and bearings:
    - measuring the wear of the worm gear teeth,
    - measurement of vibration acceleration.
- Extend the intervals of operation and at the same time the interval of online recording of vibrations in individual work modes.
- Prepare at least 10 alternative versions of damping inserts.

4 CONCLUSIONS

The presented article deals with the problem of the service life of worm gears. In order to achieve a reduction of the dynamic load and at the same time increase the life of the worm gear, an original design solution for the bearing of the worm wheel shaft was proposed. We assume that by using damping inserts it is possible to eliminate the adverse effects of dynamic load, especially in the mode of start-up and run-down of the transmission, its reversal. Such a working mode is characteristic especially for lifting devices, cranes and elevators.

In order to determine the influence of the use of the proposed damping inserts on the dynamics of the worm gear, a plan of experimental tests was developed. The article describes the measurement methodology and requirements for the material and technical support of the experiment. Partial results of a verification series of experimental tests are indicated. All measured results will still be subjected to a thorough comprehensive analysis. Based on the first results of the experiment, measures were proposed to achieve higher objectivity of the results of further experimental tests of structurally modified worm gears. It is planned to manufacture, use and test the damping effects of at least 10 alternatives of damping inserts made of different materials and with different types of wall filling.

By confirming a significant increase in the life of the worm gear, it would be a relatively economical, innovative design solution that could be interesting for manufacturers of worm gears.

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