Study vibration of worm gear boxes

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Abstract. The article describes the method of experimental analysis of transmission mechanisms. The test station enables to test different types of gears and to simulate their different operating conditions close to reality. The tests may be short-term and long-term. The course and results of the test operation of the screw reducer are described. Measured and evaluated were low-frequency and high-frequency vibration, temperature and wear functional parts of the teeth.

1. Introduction
Worm gear drives are characterized by a simple design, which allows the realization of a high gear ratio within one stage. Worm gearbox reducers are one of the basic nodes of machine drives and have a wide range of applications in various areas of industrial practice. Their technical level and load carrying capacity substantially determines the technical, economic and operational characteristics of the machines of which they are a part. Therefore, the issues of securing and constantly increasing the service life of worm gearbox reducers are still relevant.

The modern dynamics of machines as the dynamics of mechanical systems requires a dual approach. On the one hand, there is detailed research of individual parts of the system and on the other hand, comprehensive analytical research of the entire system. [1] The dynamic behavior of the transmission mechanism is determined by a number of factors, which corresponds to a wide range of areas of gear research. [1-10, 14-17, 21] Among the internal factors, these are the basic parameters of the gear transmission, the design solution, material characteristics, the technology of gear production, degree of the gear accuracy, the clearance in the gear, deviations of individual dimensions, suitable lubricants, etc. From external factors, the operating conditions have a major influence on the function of the gearbox: external load and its changes causing transient states, intensity of working regime, working environment.

Numerous theoretical and experimental studies have been dedicated to gear lubrication, especially on lubrication modelling and composition of lubricants. Improvements on lubrication methods and conditions can reduce friction, suppress wear and scuffing, and increase gear flank capacity and fatigue life. [2] According [3] the most effective method of testing a gear oil is in a real gearbox, especially in terms of contact pressure and temperature. This is the only way to verify that a gear oil provides low friction and high efficiency, low operating temperatures to improve oil service life, and low wear and delayed fatigue of materials.

Research focused on the materials of the functional parts of worm gears is important. There are various raw materials that are commonly used in gear construction, and each one has a sweet spot where its mechanical properties stand out as the superior choice. The main categories of materials are copper alloys, iron alloys, aluminum alloys, and thermoplastics. Dengel [4] states that "Unobtainium" is an
ideal material for all types of transmissions, but it has not yet been developed. Typically, a worm gear drive consists of a case-hardened worm paired with a bronze worm wheel, as shown in Figure 1. The use of expensive and deficient materials for worm gearbox wheels (preferably based on copper and tin) and low efficiency due to large friction losses in the gearing is a major disadvantage of worm gears. The use of cast iron wheels [5] or steel wheels [6] is an existing part of current research. The higher strength of iron compared to bronze leads to further increase in the permissible load and thus to higher tooth forces within the worm toothing. By now, the use of plastic gears in applications that require low loads and precision motion transmission is established. Thermoplastics are the best choice for gears where weight is the most important criteria. The possibilities of using plastic gears even at higher loads are being investigated. For an instance Albiero and Mazzarella [7] point out that the polyamide-based polymer loaded with glass fibers can be used for the metal replacement of gears used in applications with high power.

One of the decisive factors in terms of gear dynamics is the production accuracy of all functional elements (gears, shafts, bearings, gearbox housing), their deformation due to operating load, as well as the actual deformation of gears, deformation of teeth depending on gear ratio, the wear, working environment, operation, assembly accuracy, etc. As a result of the mentioned phenomena, the gear ratio becomes a variable depending on the angle of rotation. [1] The above-mentioned production deviations become a source of kinematic and dynamic inaccuracy of the gear, which is manifested by the occurrence of undesired vibrations and noise, when the angular frequency corresponding to the rotational frequency of the respective shaft is superimposed by periodic changes of instantaneous gear engagement caused by the described phenomena.

New calculation methods and extensive software support for gear design and simulation also have a significant impact on improving the dynamic properties of gears. [8, 9] The development of new production machines makes it possible to use new production technologies and the associated better technological parameters (eg roughness Ra) and structural modifications of functional parts of gear wheels [10].

There has also been a significant shift in the area of monitoring and diagnostics of gears. [11 - 15] Vibration diagnostics belongs to modern methods of non-destructive technical diagnostics, by means of which it is possible to determine the current technical state of various production machines and equipment directly in the process of operation. The use of methods of vibration diagnostics is the basis of experimental tests of dynamic properties of gears. The task of technical diagnostics of transmission mechanisms is to provide information on the technical condition of gearboxes, on the basis of which it is possible to:

- In the case of gearbox manufacturers to optimize their production technology, design concept and to verify the data on performance parameters and the selection of recommended oils, respectively method of gearbox lubrication.
- In the process of operation, it is possible to identify damage to machine parts, resp. to ensure strategic planning and management of maintenance of machines and equipment and thus prevent the occurrence of an emergency condition of machinery.

2. Methodology
Determining the effect of dynamic loading on the service life of helical gears is one of the areas of research at the Department of Technical Systems Design and Monitoring, Faculty of Manufacturing Technologies, Technical University in Košice. As part of the solution of this project, a test station was built to perform comparative tests of gears. The test station at Figure 3 allows the simulation of real operating conditions of the gearbox, resp. operating conditions of the entire drive station and the working machine. It is possible to perform both short-term and long-term load tests of gearboxes in order to improve their parameters and increase their service life. A methodology for experimental assessment of the technical condition of gear mechanisms using several methods of non-destructive diagnostics was developed.
The proposed methodology for assessing the technical condition of gears was verified by a series of experimental measurements. The course and results are described in detail in [16, 17, 18]. Two standard worm gearbox reducers shown in Figure 2, of the same type and parameters were modified for the needs of the experiment. The purpose of these tests was also to verify if the test station functionally meets the specified requirements.

An accuracy check was performed on both reducers before the test run. In addition to complex measurements of gear accuracy according to STN 01 4689, DIN 3962 a DIN 3974-2, the results of which are given in [18], for worm gearbox wheel and the gear, the dimensional accuracy, character of the surface and the geometric tolerances of all functional surfaces were checked as prescribed in the production drawings. An accuracy check was also performed on the gearbox housing and on the worm gearbox wheel shaft. The hardness of the surface layers was also measured and evaluated on the functional parts of the gear unit. The technical condition of the worm gearbox reducers was monitored in two different operating modes during the experimental operation. The measurements were performed in an accelerated loading process. Dynamic variables (temperature, vibration, ultrasound) were monitored at selected measuring points of

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**Figure 1.** Worm gears.  
**Figure 2.** Worm reducer Z80-J-010-P.  
**Figure 3.** Test station for dynamic tests of gear. 1 – electromotor, 2 and 4 – clutch, 3 – helical, 5 - chain gear, 6 – chain, 9 – spring dampers, 3 - helical gearbox, 7 – weight, 8 – cover, 9 – spring dampers, 10 – table.
the gearbox (see Figure 4 and Table 1). At measuring points 1H, 2H a 4V the individual quantities were measured in the Online mode. From measuring points 2H a 2A dynamic data (vibration and ultrasound) were collected on foot in Off line mode.

Figure 4. Location the sensors on the surface of the worm gearboxes. [17]

| Measuring point | Measured parameter | Device          |
|-----------------|--------------------|-----------------|
| 1H              | Vibrations         | NI PXI          |
| 1H              | Temperature        | Oktalon 2K      |
| 2H              | Temperature        | Oktalon 2K      |
| 4V              | Vibrations         | NI PXI          |

2.1. Used measuring instruments
- Sensors: accelerometers PCB IMI of type 607A11 with integrated cable (sensitivity 100 mV/g, frequency range up to 10 kHz), accelerometers SKF SEE.
- NI PXI: data acquisition was performed by NI PXI measurement system (measurement card type PXI 4472B, 8-channel simultaneous acquisition, 24-bit A/D converter, sampling frequency up to 102kHz, dynamic range 110 dB). Data were analysed using Lab View Professional Development System, including the Sound and Vibration Toolset and Order Analysis Toolset.
- Oktalon 2K: double-channel online system Oktalon 2K, based on the LWMONI2 module, through which the power supply of sensors and the evaluation of vibrations were realized. Application programmed in the system Promotic for the realization of data acquisition.
- Microlog GX a CMVA 55: dataloger and frequency analyser from SKF company.

2.2. Used methods of technical diagnostics
Gear functional surfaces attrition was evaluated on the basis of these measurements:
- gearbox temperature measurement and determination of the temperature gradient,
- low frequency vibrations versus time (DTMF - measuring the speed of vibration),
- high frequency vibrations (MFA (Acceleration) - measuring the acceleration of vibration),
- low frequency and high frequency vibrations, depending on temperature of the gearbox
- determine the free frequencies of mechanical system,
- ultrasonic emission See - measured offline by Microlog CMVA 55,
- high frequency vibrations - measured offline by Microlog CMVA 55 (ENV1,2,3,4 (Enveloping) - measuring the envelope of the acceleration of vibration)
• continuous measurement of the oil temperature,
• tribotechnical diagnostics of oil,
• continuous measurement of the tooth thickness,
• visual assessment of the gear functional surfaces.

2.3. Application of test station and proposed methodology of experiments
The test station can be adapted for different types of gears. When realising the experiment, it is also possible to use only selected diagnostic methods and measurement techniques. The planned experiments are designed primarily for testing these parameters of gears, respectively parts of the driveline station:
• durability, reliability, wear (change of geometry - abrasion of contacts);
• efficiency, temperature, temperature gradient, thermal expansion, friction performance, friction moment, axial load;
• running actions, intensity and duration of running, change of load carrying capacity after running, the impact of abrasion on the contact surfaces, effect on grease, effect on durability;
• assessment of individual components, mainly gearing, bearings, grease, chain wheel and chain.

3. Result of the experiment

3.1. Accuracy measurement
All functional parts of the worm reducers have met all the prescribed accuracy requirements. A detailed description of accuracy control is in [18].

3.2. Measurement of mechanical vibrations
Low frequency vibrations and high frequency vibrations were measured in the tested gearboxes. Due to resonance phenomena, the low-frequency vibrations were not stable on the monitored mechanical system of bodies (test station). In Figure 5 is shown a graphical record of the measured values of mechanical vibrations for measuring points 1H and 4V in both operating modes. In the case of operation in Operating Mode 1, the measured vibration values exceed the limits for the total level of mechanical vibrations of velocity, (mm / s, rms), in the band of 10-1000 Hz recommended by the standard STN ISO 10816-3 [19]. The measured facility does not meet the required criteria in this respect.

![Figure 5. Low-frequency vibration for measuring points 1H and 4V.](image-url)

High-frequency vibrations are suitable for assessing the engagement of the gear teeths and also for assessing the operating state and mode of operation of the rolling bearings. The temperature is measured together with the vibration measurement for correct detection of gear wear. The relationship between temperature and transmission vibration provides valuable information about the condition of the gearbox. In the case of helical gearboxes, the gears often overheat rapidly, so an important part of the
tests was the continuous monitoring of the increase in oil temperature, resp. increase in gear box temperature.

3.3. Gearbox housing temperature measurement and temperature gradient determination
A comparison of graphical temperature curves and low-frequency vibrations (Figure 6) shows that in the case of Operating Mode 1, mechanical vibrations are stabilized after the temperature is stabilized. During operation in Operating mode 2, the mechanical vibrations of the monitored mechanical system remain stable despite the changing temperature. Measurements of high-frequency vibrations showed that as the temperature of the gearbox gradually increased during operation in the setted mode, the overall level of high-frequency vibrations also increased, up to a steady state. The waveforms of the measured values in Figure 7 shows their interrelationship, with temperature and total high frequency vibrations being related to load (5 or 2 weights).

![Figure 6](image1)

(a) Operating mode 1.

(b) Operating mode 2.

**Figure 6.** A comparison graph of the temperature and the low-frequency vibrations.

![Figure 7](image2)

(a) Operating mode 1.

(b) Operating mode 2.

**Figure 7.** A comparison graph of the temperature and the high-frequency vibrations.

3.4. Ultrasonic emission measurement
The technical condition of a mechanical system is generally determined by the amplitude of the ultrasonic emission and its position on the time axis. In Figure 8 is a record of the amplitude obtained by measuring at point 2H. In Figure 8(a) the dependence of the amplitude magnitude on time is recorded during the lifting of the weight. In this interval, the ultrasonic emission is excited, the amplitude gradually increases and the condition of the mechanical system deteriorates (lower load-bearing capacity of the oil filter - greater seizure of the contact surfaces). In Figure 8(b) is a record of the amplitude during the lowering of the weight. The recorded signal is attenuated, the amplitude is gradually reduced and the state of the mechanical system is improved.
3.5. Determination of oil lifecycle

In the footprint image (Figure 9) particles of Cu and Sn alloys (bronze radiant particles) are clearly visible in both assessed oil samples. The worm gearbox has a bronze worm gearbox wheel. The presence of Cu and Sn alloy particles therefore confirms the significant wear of the contact surfaces of the tooth flanks of the worm gearbox wheel.

3.6. Wear assessment based on tooth thickness measurement

Tooth thickness was measured sequentially on all wheel teeths before the start of experimental operation and at the end of Operating Modes 1 and 2. The comparability of the measured values was ensured by the clamping jig of the meter to precisely define its position during the measurement (see Figure 10) and by the program which control the operation of the gearbox so that it is possible to turn the worm gearbox wheel by one turn by the clearance.
The kinematic inaccuracy of the worm gearbox wheel was also taken into account in the final evaluation of the measurement results [18]. Despite the lower measurement accuracy (0.2 mm), different values of the thickness of the wheel teeth were recorded, which indicate a significant wear of the tooth flanks at the points of contact with the worm shaft.

3.7. Visual wear assessment

The appearance of the teeth side at the end of the first phase of laboratory tests is shown in Figure 11(a). Attrition of the tooth flanks is unequal and it has not the same character. Figure 11(b) shows the tooth side state in the course of upward lift of the weight with visible signs of attrition surface elements and pitting. Figure 11(c) shows the changed status of the other tooth side surface, when sinking the weight.

![Figure 11](image)

Figure 11. The worm gear tooth sides surface a) of unused gearbox, b) of the first phase of the experiment [18].

4. Discussion

During the test operation of the worm reducers, all the above mentioned methods were applied to determine their technical condition. By checking the accuracy of the gear functional parts design and the kinematic accuracy of worm gear before the start of the test operation, determined accuracy class of the design was confirmed and guaranteed by the manufacturer.

In connection with wear at the contact points of the tooth flanks, the same wear patterns were determined by all diagnostic methods used (measurement of ultrasonic emission, low-frequency and high-frequency vibrations, temperature measurement of the gearbox housing, measurement of tooth thickness and oil analysis). Based on this fact, the proposed methodology of dynamic tests was evaluated as suitable for testing gears. When testing different types of gearboxes, it is possible to apply all or only some selected measurement methods. For an objective assessment of the technical condition of the worm reducer gearing, it is necessary to state that during the six hours of operation there was considerable wear of the worm wheel in the contact surfaces with the worm. There was a significant deterioration in the engagement conditions on the gears due to significant resonance events. The recommended limits according to ISO 10816-3 [19] were exceeded mainly for the vertical beam and the horizontal frame under the sprocket with the subsequent transmission of these vibrations to the gearbox. The operating conditions during start-up and run-down of the engine (gearbox) were also unfavorable, especially at higher loads, where vibrations were again transmitted to the gearbox. Under these circumstances, it was not possible to make an objective assessment of the technical condition of the tested reducer.

Based on the results of the technical condition of screw reducers monitoring, a modification of the basic supporting structure of the test station was designed and implemented. The aim was to increase the rigidity and shift the natural frequencies of the frame beyond the operating frequencies of the tested gearboxes. Fulfillment of this condition necessary to achieve objective results of the planned experiments was verified by the impact test described in the impact test in [20].
The results of experimental tests of the above-mentioned screw reducers, which were carried out after the design modification of the test station, are described in [21]. The mounting of the worm shaft in the gearbox housing has been modified to achieve the best possible damping properties. Using additive technology, damping inserts were made. They were inserted between the outer rings of the bearings and the gearbox housing (see Figure 12). Materials Nylon PA12 and Filaflex were used for the production of the rings. Compared to the unmodified gearbox a reduction in vibration was observed during the test run. The measured values of vibration velocities varied depending on the measuring point, operating parameters and the material of the damping rings.

Figure 12. Filaflex damping inserts fitted in a worm gearbox. [21]

5. Conclusion
The article describes the design of the methodology of accelerated dynamic tests of gears and the creation of material conditions for their implementation. The result of dynamic tests should be information on the behavior of gearboxes in different operating conditions. In the accelerated test process, it is possible to obtain information on the achieved performance parameters and load capacity of the reducers (especially in extreme transient modes), transmission efficiency and the like. From the test results it is possible to obtain a lot of information about the influence of technological parameters of production, used lubricant and various design modifications on the dynamics of drives and to optimize their influence on the dynamic load of gears. Further research will therefore be focused primarily on the study of the dependence of the dynamic properties of the worm, but also other types of gears on the lubricant used and various design modifications.

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