Design and implementation of a diagnostic system for measuring high-precision reducers

M Kočiško¹, M Pollák¹, A Vodilka¹, D Paulišín²

¹Technical University of Košice, Faculty of Manufacturing Technologies with a seat in Prešov, Bayerova 1, 080 01 Prešov, Slovak Republic
²Spinea technologies Ltd., Volgogradská 13, 080 01 Prešov, Slovak Republic

e-mail: marek.kocisko@tuke.sk

Abstract: At present, the industry is in a phase where there is an effort to maximize the automation of production processes. In many places, human power is being replaced by automated machines and industrial robots. Automation makes it possible to increase work efficiency, significantly reduce production costs and also increase the quality of the final product. A precondition for increasing the quality of production is to achieve high accuracy of specialized machines and industrial robots, resp. the accuracy of positioning of individual parts. Due to the drive system and the achieved speed, the gear unit includes a gearbox. Reducers used in robotic joints are the most complex subsystems of robots. For very precise applications, the designers will reach for the so-called backlash-free reducers for their characteristic properties (minimum values of backlash in teeth, angular transmission errors, hysteresis and others). Despite many positive properties, high-precision reducers also show their characteristic nonlinearities, which influence the behavior of the whole system and it is so important to know their behavior. Given these facts, this article deals with the design and implementation of mechatronic diagnostic equipment for the identification of nonlinearities, static and dynamic parameters, vibrodiagnostic measurements and measurements of the efficiency of bearing reducers.

1. Introduction
The current industry requirements for driving units place increased demands on the transmission of force effects with higher kinematic accuracy, as well as on the precise setting of the position of these effects. This results in deployment of high-precision cycloidal and harmonic propulsion systems.

The main part of these systems is a reducer the main function of which is to transform power quantities. It is designed to reduce the speed of the driving machine to the input speed of the driven machine at constant transmission (Figure 1).

These high-precision transmission mechanisms allow the use of reducers in robotics and automation, machine tools, measuring devices, navigation systems, in the aerospace industry, in the military and medical field, in woodworking, in the printing industry, in textile and glass processing machinery, in filling machines, etc. [2].
Technological complexity is the hallmark of reducers production with high demands on accuracy and constitutes a niche engineering production, as its outputs must meet the strictest international criteria for production accuracy, assembly, measurement of selected parameters (accuracy characteristics), durability and reliability tests. The production of individual components consists of roughing (blasting) operations, heat treatment, final (grinding) operations and the assembly itself, and last but not least, measurement of functional dimensions and kinematic quantities. From the point of view of final (finishing) operations, rounding the external and internal dimensions necessitates the application of the most recent grinding technologies. The manufacturing accuracy of the internal and external dimensions of the components is measured in microns. In most cases, single-purpose devices are applied, considering the design and technological requirements placed on the component, as well as on the superiority of assembly [4].

High-precision reducers are based on several mechanical transmission principles [1]:

- Planetary mechanism - reducers with involute gearing (Nabtesco).
- Cycloid mechanism - reducers with trochoidal gearing (Sumitomo, Spinea – Figure 2).
- Harmonic mechanism - reducers with involute gearing (Harmonic Drive – Figure 3).

Despite many positive features, the reducer also exhibits its characteristic nonlinearities (e.g., nonlinear mechanical characteristics such as lost motion, angular transmission error, interference with higher harmonics, influence of interpolation distortion), which need to be further investigated and analyzed, as they often have a significant impact on the behavior of the system as a whole. Compensation for these nonlinearities subsequently beckons the possible use of any linear regulator. The use of a suitable mechatronic diagnostic system is necessary for correct identification of and subsequent compensation for these nonlinearities. [8]
2. Design of a mechatronic diagnostic system for measuring high-precision reducers

To create a general idea of the process of analysis of the mechatronic diagnostic system of the object (high-precision reducers) examined, it is necessary to create the model defined by the object, as well as models of diagnostic mechanisms. A mechatronic diagnostic system can generally be characterized as a mechatronic system interconnected through functional elements that respond independently to a set of input signals. The functional elements and the links between these elements form a set represented by a diagram of the diagnosed object.

The aim of the solution is to achieve a functionally and structurally integrable diagnostic process of the mechatronic system. Such representation of the system consists of a set of elements and steps corresponding to the research and development purpose and diagnostic tasks of the object under examination [6].

We will use the model to study the relational structure and behavior of the mechatronic system via a controlled system of monitoring and diagnosing the investigated object. The methods, procedures and means of choice focus on monitoring and troubleshooting the technical condition of the examined object. The result is a diagnosis that makes it possible to make recommendations for production, operation, maintenance. Such clarification of the nature of elements affecting reliability can be further used in changing operating conditions, as well as in design and technological innovation [9-11].

![Figure 4. Mechatronic diagnostic system design](image-url)

Parameters of a specific technical design and implementation of a modular diagnostic device, in which the system of measuring devices and components necessary for analysis and evaluation will be integrated, need to be defined as follows (Figure 4):
• diagnosed object - type, size,
• monitored quantity - parameter, range (measured technical parameters) [5].

The investigated object to be diagnosed is a reducer or a rotary actuator and the rolling bearings. Harmonic Drive, Nabtesco, Sumitomo and Spinea are among the world's leading manufacturers of high-precision reducers used in robotics and equipment requiring high-precision rotary motion. The products made by the respective manufacturers differ both in principle and in the company itself. [10]

The mechatronic diagnostic system proposed will make it possible to conduct the following measurements and tests:
• measuring the LR effectiveness,
• measuring the LR starting moments,
• measuring the LR feedback moments,
• measuring LR vibrations and temperature at defined work cycles,
• start-up tests,
• LR durability tests.

3. Design of diagnostic equipment
A diagnostic measuring device MDS for particular types of measurements allows for the measuring to be done in several configurations. According to the load type, it can be divided into two groups, namely:
• loading with mechanical weights on the arm,
• loading with a stress servomotor or a powder dynamometer.

Prior to starting the designing process, it is necessary to establish secondary operational requirements related to placement, use and, last but not least, legislative requirements. Therefore, the mechatronic diagnostic system must allow [7]:
• to have its base part of the frame anchored to concrete floor,
• for insulation of mechanical vibrations produced by equipment positioned on the same concrete floor,
• connection to an existing earthing system,
• metal components be surface treated,
• modular connection and dismantling of individual nodes and subgroups,
• easy assembly and dismantling,
• the space for rotational movement of loads be secured with a mechanical barrier,
• the area be secured against entry of unauthorized persons (e.g., with a mechanical barrier - this is not a part of the design).

The mechatronic diagnostic system will consist of three basic parts:
• Mechanical structure - frame.
• Control part.
• Measuring part.

The measuring device design consists of a set of interconnected mechanical components. The structure consists of a free-standing frame, a linear system and fastening flanges and shafts.

The final design of the mechatronic diagnostic system for measuring the bearing reducer (Figure 5) consists of a support structure made of a frame (1), a linear guide (2), a bracket (3), (4) and (5), cranks (28) and (29). The structure consists of four nodes: the stress node, the drive node, the sensing node, and the test node. The stress node consists of a flange (6), an intermediate flange (7) and a stress drive (8) and provides for the creation of a load moment. The drive node generates movement according to the parameters required for making the measurements and consists of a flange (22), a drive (23), a separate linear guide (24) and a crank (25).
The sensing node ensures the measurement of torque and angular velocity values and consists of an output torque sensor (10), an input torque sensor (20), a stand (26) and (27). The test node consists of an output flange (14), a bearing reducer (15), an intermediate flange (16), a flange (17), a shaft (18). Linking of individual nodes into the measuring chain is done by means of a coupling (9), a bellows coupling (11), a reducer (12), a quick coupling (13), a bellows coupling (19) and a coupling (21). Measurement control and sensing of the measured quantities is ensured by the input / output device (33).

**Figure 5. Diagnostic system - structural design**

An integral part of this device are backlash-free bellows couplings, which are used, among other things, for their ability of backlash-free synchronous transmission of rotary motion and the ability to compensate for manufacturing inaccuracies.

**Figure 6. Principle connection diagram of diagnostic system**
Hydraulic ETP Express type clamping sleeves are used for a reliable connection of the shaft to the hub. In addition to the transmitted torque, crucial criteria include properties such as reliability of connection, fast clamping, and connection release.

The structural design was followed by design of the mechatronic diagnostic system's control and measuring part. The proposed circuit diagram of the diagnostic system for measuring bearing reducers is shown in Figure 6.

In industrial applications, as well as in our case where we need to regulate speed, the electrical equipment most frequently used for control and regulation of drive mechanisms is a frequency converter. Based on the specified servomotor power series derived from the specified objects of diagnostics, frequency converters to be used for measurement in the mechatronic diagnostic system, were designed (Figure 7).

A type 8661 torque transducer was designed to measure static and dynamic torques clockwise and counterclockwise (Figure 8). It is designed for contactless operation and zero maintenance adapted to production environments. The torque sensor 8661 is a special-purpose device for measuring constant torque during continuous operation and measuring torque, tear-off torque. Built-in USB interface and connection to a laptop with the DigiVision PC program makes instant digital access to torque measurement diagnostic data possible. DigiVision PC allows us to read, visualize and archive the data measured. The 8661-torque sensor enables the system integration into the LabView environment.

For high accuracy of position measurement at the output of the bearing reducer in both directions, a position sensor of REXM 150 type from Renishaw will be used (Figure 9).

![Figure 7. Proposed frequency converter](image1)

![Figure 8. Torque sensor 8661](image2)

![Figure 9. Renishaw position sensor, REXM 150](image3)
The sensor has a pair of reading heads to eliminate errors or deviations caused by inaccuracy in the mounting of the measuring disc. The sensor emits an output analog signal ± 10V and a pair of incremental TTL signals. Suitable for applications that require the highest angular accuracy, the REXM angular position sensor is ideal for metrological purposes of measuring angular accuracy.

4. Conclusion

The present paper deals with the design of a diagnostic system for measuring high-precision reducers and rotary actuators. The rotary actuator is a higher unit that integrates the reduction mechanism, the servomotor, and the position sensor. Prior to the design itself, the main and the specific goals were set, the aim of which was to design a mechatronic diagnostic system for research and development purposes and diagnostic tasks. One of the requirements was to design a modular diagnostic device capable of adapting to defined troubleshooting tasks, changing the measured quantity or the size of the transmission mechanism. At the same time, requirements have been voiced for the system to be designed in a way that, if necessary, it could easily change the measured configuration and, at the same time, allow for integration of other measuring devices and instruments.

Subsequently, an MDS diagnostic system model and configuration of measurements according to the type of load and the quantity measured were designed. Prior to the diagnostic system's actual implementation, a draft design was made in Creo. The design considered dimensional and power parameters of the investigated objects serving as the basis for deriving the conversion of power series of servomotors, converters, sensors, as well as torque transmission components, connection brackets and shafts. Subsequently, a diagram connecting specific hardware with software was elaborated. Data flow control was processed in the programming environment of Labview.

The resulting mechatronic diagnostic system is fully functional and it is used for measuring and diagnosing high-precision bearing reducers (Figure 10).

![Figure 10. A real view of the constructed mechatronic diagnostic system](image)

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