Method and tool for assessing the residual life of the planetary electric actuator of the exoskeleton

A V Egorov¹, V N Belogusev¹, K E Kozlov¹, A V Lysyannikov², Yu F Kaizer²
N N Lysyannikova², V L Tyukanov² and A V Kuznetsov³

¹ Volga State University of Technology, 424000, Yoshkar-Ola, 3, Lenin Square, Russia
² Siberian Federal University, 660041, Krasnoyarsk, 82/6, Svobodny Avenu, Russia
³ Krasnoyarsk State Agrarian University, 660049, Krasnoyarsk, 2 Kirenskogo, Russia

E-mail: kaiser171074@mail.ru

Abstract. This article proposes a method and tool for assessing the quality of assembly and technical condition of the electric drive of the exoskeleton, on the basis of its moment of starting as one of the main indicators of the level of degradation of its components. The existing methods are based on the determination of the moment of starting with the help of additional devices that require the participation of the operator in the measurement process, which increases its time and labor costs and makes it difficult to automate. In contrast to the existing methods and tools, the proposed in this article method and hardware-software complex, allow you to automate the measurement process, do not require expensive equipment and can perform monitoring of the technical condition without dismantling the drive from the exoskeleton. In the experimental part of this article, the proposed method and tool were evaluated on the basis of electric drives with reducers for Electromechanical orthosis of the lower limb exoskeleton. In the course of experimental studies, for the first time, the dependences of the residual life and the efficiency of the electric drive on the moment of moving the input shaft of the gearbox were determined. The results obtained allow us to conditionally determine the level of resource development and the efficiency of the electric drive, based on the measurement of its starting moment, which allows us to carry out maintenance of gearboxes and electric drives according to their actual condition, adjust their maintenance schedule and replacement time, and also increases the reliability of the product in use.

1. Introduction
The exoskeleton allows people with impaired mobility to regain the ability to stand and walk on the ground, performing daily tasks. Compared to traditional physical therapy, auxiliary rehabilitation with an exoskeleton has several advantages, which consist in reducing the working hours of the therapists, allowing the patient to conduct intensive rehabilitation training and providing a quantitative assessment of the level of recovery by measuring strength and movement patterns.

When choosing methods and means of assessing the quality of assembly and the technical condition of electric drives and reduction gear that are part of exoskeletons, special attention is paid to the possibility of determining indicators characterizing the level of degradation processes in their individual elements, which are most due to the frictional moment at the junctions. One of these
indicators is the starting moment off, which in a number of scientific papers is defined as one of the most important indicators of the quality of assembly and manufacturing of reduction gear and electric drives.

At the moment, the determination of the starting moment of the electric drive is carried out both on the input and output links of the reduction gear, however, the most preferred method is to measure the starting moment on the input link, since it has a direct effect on the electric motor. There are two main methods for determining the moment of starting at the entrance link. According to the first method, the measurement of the moment of breaking is reduced to the determination of the force of gravity created by tared loads, which is necessary to overcome the static moment of friction in the nodes of the electric drive. The second method is more accurate and differs from the first one in that the measurement of the force required to overcome the friction forces in the junctions is carried out using a gramometer. The main disadvantages of these methods are the high requirements for accuracy of the experiment and their complexity. The moment of starting at the output link of the reduction gear, in turn, is measured when it is not possible to measure at its input link (when dismounting the reduction gear causes difficulties). For example, in nabelsco reduction gear, the moment of breaking off at the output link is reduced to the moment of breaking off at the input link using a gear ratio. The main disadvantage of this method is the neglect of the efficiency of the reduction gear in the calculations.

According to the first method, the measurement of the moment of starting is reduced to the determination of the gravity force created by the calibrated loads, which is necessary to overcome the static friction moment in the electric drive units. The second method is more accurate and differs from the first in that the measurement of the effort required to overcome the frictional forces at the nodes of the pairing is carried out using gramometer. The main disadvantages of these methods are the high requirements for the accuracy of the experiment and their complexity. The moment of starting at the output link of the reducer, in turn, is measured when it is not possible to measure at its input link (when dismantling the reducer causes difficulties). For example, in nabelsco reduction gear, the moment of starting at the output link is is given to the moment to the moment of starting at the input link by means of a gear ratio. The main disadvantage of this method is the neglect of the efficiency of the reducer in the calculations.

On the basis of the analysis of methods and means of determining the moment of starting reduction gear, we can conclude that the existing methods either have a low accuracy of measurement, or require significant labor and time resources, which is an obstacle for rapid diagnosis of the studied objects during their operation and maintenance. In addition, the improvement of existing methods in terms of automation of the measurement process is a time-consuming task due to the presence of a large number of factors affecting the measurement result.

The purpose of this article is to develop a method, technique and means of measuring the moment of starting the reducer and electric drive for exoskeletons, which are devoid of the shortcomings of existing methods and means of measurement. To assess the applicability of the developed method and software and hardware complex, it is proposed to conduct a study to determine the dependence of the moment of starting from the residual life and the efficiency of the electric drive for the Electromechanical orthosis of the lower limb.

2. Materials and methods

Determination of the values of the moment of starting at the input link of the reduction gear. The essence of the proposed method is shown in the figure 1.

With the help of an electric motor included in the study of the electric drive, the input link of the reduction gear is rotated. Current and voltage sensors register their values when the reducer is rotated by a given angle, $\alpha$, taken as the beginning of the movement of the object of study. The rotation of the electric motor stops when a predetermined angle, $\beta$, taken for the end of the reduction gear. The rotation angle increment is conditionally calculated according to the following equation:
\[ \Delta = \frac{360}{i}, \]  

where \( i \) - the gear ratio.

Then, after stopping the electric motor, with some time delay, the process of measuring the current supply of the electric motor continues, where the initial angle of rotation of the input link of the reducer is equal to the final angle of its rotation in the previous measurement:

\[ i_360 = \Delta, \]  

\[ \alpha = \beta + \frac{360}{i}, \]  

Figure 1. Scheme of implementation of the method of determining the breakaway torque of the actuator: 1 – output gear unit; 2 – reducer; 3 – input gear unit; 4 – absolute encoder; 5 – electric motor.

Measurements of current and voltage on the windings of the drive motor continue until the \( i \) speed of the input link of the reduction gear, which corresponds to one full speed of its output link. In this case, the resulting increment, \( \Delta \), allows to complete the measurement process in the initial phase of the movement of the output link of the reducer.

Thus, during the test of the electric drive according to the proposed method, the reducer and the electric motor operate in the "start-stop" mode, which allows to determine the starting currents at different angles of the output link of the reducer. At the same time, having determined the coefficient establishing the dependence of the moment of starting and the current of starting the electric motor (specified in the passport data of the electric motor or calculated experimentally), it is possible without the use of additional load devices and devices (gramometer, a set of weights, etc.) to determine the moment of starting the object under study, and consequently, the quality of its Assembly during production, and to assess the technical condition during its operation.

The number of current measurements can be determined according to the following equation:

\[ N = i^2. \]  

In turn, it should be borne in mind that the specified rotation angle increment does not fully cover the entire turning range of the reduction gear. Therefore, an additional stage of the developed technique is to measure the change in current on the windings of the motor (or controller) at a constant
voltage and uniform rotation of the electric drive when making i turns of the input gear unit. The speed of rotation of the input link is selected from the calculation of the maximum permissible value of the electric drive start current. Thus, when exceeding this current value above the permissible deviations can be judged on an unacceptable increase in the level of friction in the gearing of the transmission links, and, consequently, the unsatisfactory technical condition of the electric drive.

3. **Construction of the dependence of the residual life of the reducer and the moment of starting the drive motor**

Currently, the life of the electric drive and reducer is determined by their operation at nominal load values until their failure. The time of release of the tested products from the operating state is exceeding the permissible values of the temperature of the frame of the product, the appearance of atypical noises, as well as product failure. However, the operation of such indicators is largely dependent on subjective factors, usually associated with the experience and professionalism of the staff. Therefore, the most preferable in determining the residual life of the electric drive is the use of measuring instruments and methods to minimize the impact of the human factor. The proposed in this article method of measuring the moment of starting the electric drive has the potential to determine its residual life, but for its implementation to solve the problem requires experimentally to obtain a curve of the residual life and the moment of starting (current of starting). Therefore, in the experimental part of this work, studies were conducted to determine the desired dependence.

Similarly, it is possible to build a dependence of the moment of starting the electric drive on its efficiency, determined by a torque sensor mounted on the output link of the gearbox. The results obtained can form the basis of indirect methods for determining the effectiveness of research objects without the use of expensive equipment.

4. **Experimental base**

To assess the proposed method of control of the technical condition of the electric drive, as well as the study of the dependence of the moment of starting from the efficiency and residual life of the electric drive for the Electromechanical orthosis of the lower limb, a hardware software package was developed (figure 2).

![Figure 2. The Structure of the hardware and software complex for control of the moment of starting the electric drive at different angles of rotation of the input link of the gearbox.](image)

With the help of the presented hardware and software complex, the registration of the angles of rotation of the input link of the reducer and the currents (starting currents) when the specified values of the rotation angles are reached. Based on the data measured by the developed complex, the instantaneous and average values of the desired values are calculated.
Absolute magnetic encoder with SSI interface is used to measure angles of rotation of the input link gear unit with sufficient accuracy. Structurally, it is an electronic chip with a small number of auxiliary components and a permanent magnet rotating at a short distance from the chip. The magnet when rotated provides a varying magnetic field that is detected by the Hall sensor. Hall sensor is made by MEMS technology and integrated into the encoder chip. The used as5040 chip encoder is capable of operating in the mode of absolute and full-speed incremental encoder. This allows it to be used on the input link of the gear motor for precise control of the absolute position of the gear shaft. The encoder is equipped with a compact round Board integrated into the gear motor. To communicate with the microcontroller used SSI (Synchronous Serial Interface synchronous – serial interface). Its advantages are its simplicity and high polling rate.

Current and voltage sensors are made in the form of low resistance resistors.

Hardware software complex has one analog measuring channel (low resistance resistors) and one digital measuring channel (encoder). Digital and analog signals from the sensors are received at the input of the registration unit, in which the galvanic isolation of the signals and the filter fall into the measuring microcontroller Atmega 640 with a clock frequency of 16 MHz. The galvanic isolation system consists of two blocks – the power isolation unit and the signal line isolation unit. The digital signal from the microcontroller enters the Flash memory until the end of the measurement. After the measurement is completed, the data from the Flash memory is transferred to the personal computer (PC) and processed by the terminal program installed on the PC hard disk.

In the terminal program on the PC is carried out mathematical processing of the data array, determining the moment of starting for each angle of rotation of the input gear unit, statistical processing of the values, their comparison with the permissible level of values and determination of the residual life of the electric drive. The results are presented graphically. The terminal program has a built-in real-time clock that allows you to save the time and date of the control parameters. The complex is made in a shielded aluminum housing.

The tested electric drive is rotated by means electromotor's of an EC flat manufactured by Maxon Motors. These motors are characterized by high efficiency and compact flat design.

The reducer for Electromechanical orthosis of the lower limb is manufactured in the laboratory «Mechatronic systems» of the Volga state technological University in the framework of the project «Creation of high-tech production of multifunctional robotic exoskeleton for medical purposes».

To build the dependence of the average starting torque on the torque of the tested electric drive, a torque sensor M40-100 manufactured by LLC Tilcom, Minsk, was used. Sensors of this type are designed for measuring torque in a wide range of nominal values from 0.1 N*m to 100 N*m. Located on the rotor of a microprocessor-based electronic module converts signals from the strain gages into a digital code that is transferred from the rotor to the stator by the proximity telemetry communication channel. The main advantage of the M40 torque sensors is the ability to measure both static and dynamic, rapidly changing torque of positive and negative polarity.

To build the dependence of the average starting moment on the number of hours of operating time of the electric drive under rated load, measurements of its starting moment were made according to the developed method and technique using the control and measuring equipment described above. The measurement step was equal to 100 hours of operating time of the object of study. The moment of failure of the electric drive was considered the moment of its failure or a significant increase in the noise level emitted by its coupling nodes.

5. Results and discussion

To conduct a study to determine the dependence of the moment of starting from the residual life of the electric drive and its efficiency, 8 electric drives with reducers for Electromechanical orthosis of the lower limb were tested, which were operated at rated load. Measurements of the moment of starting with the help of the developed method, technique and hardware-software complex, as well as the efficiency with the help of a torque sensor M40-100 were carried out every 100 hours of operation of the electric drive under nominal operating conditions. The moment the output of the drive down was
chosen as the time of occurrence of the elevated temperature of the housing cover of the gearbox exceeding 60 degrees Celsius, with nominal values equal to 40 degrees Celsius.

Figure 3 shows a graph of the average value of the change in the moment of starting the electric drive, depending on the number of hours of its operating time for eight reduction gear.

According to the above dependence in the period of the first 100 hours of operation of the electric drive under study, the moment of starting slightly decreased. This may be due to the time required to burn in the friction units of the electric drive and reduce the viscosity of the lubricant. A slight increase in the average value of the moment of starting is observed when reaching 50% of the claimed lifetime of the electric drive. In the development of 80% of its life the moment of starting begins to increase significantly, which indicates the presence of an increased level of friction in the nodes of the object under study. Thus, on the basis of the results obtained, it can be concluded that with the help of the obtained graph, it is possible to indirectly determine the values of the moment of starting, at which further operation of the electric drive can lead to a sudden failure of it. In our case, the permissible values of the moment of starting were taken, exceeding the nominal ones by 5 times.

Figure 4 shows the dependence of the moment of starting the electric drive on its efficiency.

The presented dependence can be used to assess the effectiveness of the object under study according to the obtained values of the moment of starting. As can be seen from the graph, the obtained dependence has the reverse character, which is a confirmation of the reliability of the data obtained. As the friction level in the interfaces of the electric drive elements increases, the efficiency decreases, and the force required to overcome the increased resistance level in the nodes increases,
which leads to an increase in the resulting moment of starting.

Thus, according to the obtained results of experimental studies, it is possible to judge the applicability of the developed method to assess the technical condition of the electric drive of the Electromechanical orthosis of the lower limb, both at the stage of its production and operation.

As express tests of the electric drive it is offered to carry out its testing at uniform rotation of an input shaft of a reducer at low frequencies of its rotation. At the same time, given the permissible level of the moment of starting, it is possible to control the technical condition of the object of study, without resorting to complex, labor - and financial-cost methods and means of control.

6. Conclusion
The hardware-software complex offered in this research allows to carry out control of a technical condition of the electric drive in the automatic mode with low level of influence of a human factor and with smaller time and labor costs, in comparison with existing methods of control. The use of an encoder with a high accuracy of measuring the angle of position of the input shaft of the reducer built into the electric drive system can potentially allow rapid testing of the object under study without the use of additional equipment.

In the course of experimental studies, the dependences of the residual life and the efficiency of the electric drive on the moment of starting the input shaft of the reducer were determined for the first time. The obtained results allow to determine the level of resource development and efficiency of the electric drive, based on the indications of measuring its moment of starting, which allows to carry out maintenance of gearboxes and electric drives according to their real state, to adjust the schedule of their maintenance and replacement time, and also increases the reliability of the operated product.

This method can be widely used in manufacturers and enterprises operating exoskeletons, as it reduces the time and financial costs of testing and quality control of their Assembly and technical condition due to the versatility of the method and weight and size indicators of the developed hardware and software complex, as well as the lack of need for calibration of measuring bodies.

At the level of the technical control Department of the manufacturer, having determined the tolerance for changing the moment of starting the electric drive and the reducer of a certain model, as well as equipping the studied object with a hardware and software complex, it is possible to promptly respond to the deterioration of their energy performance, which allows to improve the quality of their Assembly, ensure high efficiency of the equipment produced, as well as to carry out their timely maintenance and repair.

In further studies, it is expected to improve the developed method and hardware-software complex for the possibility of assessing the technical condition of the electric drive and reducer without dismantling them from the Electromechanical orthosis of the lower limb, which will allow self-diagnosis of the technical condition, residual life and efficiency of the electric drive by means of the control bodies of the exoskeleton during its input control and operation.

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