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DEVISING A TECHNIQUE FOR MEASURING TORQUE OF ELECTRIC MOTORS USING MACHINE VISION

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The object of research is the technique for measuring torques of electric motors. The main problem to be solved is the need to expand the range of informative parameters used in transmission torque converters of electric motors. This need arises from the design complications of placing the measuring devices directly on the motor shaft.

As part of the study, a system was designed for determining the torques of electric motors, which combines the procedure for assessing the load on the shaft and software tools for visually determining the quantitative characteristics of such a load using machine vision.

In order to acquire visual characteristics of the twisting of the shaft, a special coupling with an insert containing a liquid was designed. This coupling is able to change its shape in proportion to the load on electric motor shaft. The proposed visual control system, based on video information processing techniques, makes it possible to analyze changes in the shape of the coupling caused by the action of the torque.

Features of the application of the proposed measurement technique are that there is no need to place electronic components of the measuring transducer directly on the shaft. Due to the specified features, the proposed procedure provides a solution to the problems of torque measurement in aggressive environments, which is of crucial importance for the efficiency of some specific production processes.

Analysis of the visual characteristics of torque showed that the proposed approach could be applied in measuring transducers. At the same time, the results of testing the procedure confirmed that it requires the use of high-precision video recording equipment. This paves the way for the design of new, more modern, and reliable measurement systems that could be used in a wide range of industrial solutions

Keywords: machine vision, rotational torque, measurement technique, electric motor parameters, dynamometric coupling

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1. Introduction

Problems related to measuring the torques of electric motors are associated with many factors, including the negative impact of vibration, non-linearity of the measuring channels, the influence of white noise, etc. This especially applies to certain conditions of operation of electric motors, for example, electric motors of floating vehicles, aircraft electric motors, electric motors of drilling rigs, pumping equipment and other types of electric machines, the operation of which is associated with a number of destabilizing factors. Such working conditions require the search for new measurement methods that can function effectively taking into account the specified destabilizing factors. However, some measurement methods are difficult to apply due to certain limitations. In particular, the strain gauge method, although widely used in many areas of technology, has limitations related to the need for adhesive mounting of sensors on shafts, which is time-consuming and requires compliance with complex technological processes.

At the same time, the use of torsiometer inserts, which are elements of the shaft and transmit torque, has proven successful in many industries since this measuring technology has many advantages. In particular, it does not include rotating electronic components, which makes the sensors extremely reliable, provides high protection against overloads and guarantees long-term stability. However, such sensors are also based on the aforementioned technologies of primary processing of mechanical quantity and have a number of problems associated with their application. In addition, it is not always possible to provide power to the sensor, which is located on the shaft, due to the special operating conditions of the electric drive. For example, under conditions of critical temperatures, humidity, pressure, radiation, etc. Therefore, there is a question of defining both new informative parameters and new methods of converting the measured quantity.

For the above-mentioned conditions, methods of optical analysis of mechanical quantities can be applied. Additional informative parameters can be pressure and distance. However, for their application, it is necessary to conduct a number of studies related to the assessment of the possibilities of using such methods and parameters. Therefore, research aimed at devising new ways of recognizing changes in mechanical quantities is relevant. This is related not only to the needs of remote measurements in complex languages but also to the need to make the measurement process cheaper in this way. At the same time, this technique could be more universal compared to traditional methods since machine vision can be integrated into measuring systems of various types.

2. Literature review and problem statement

Most torque measurement methods are based on the impulse characteristics of two sensors. For example, in work [1], the results of research on rotary systems are given, in which the majority of electric machines, which are designed to work under predicted linear modes, are considered. At the same time, the relevance of measurements of non-linear rotating systems, where there is significant uncertainty, is emphasized. Under such conditions, impulse moment measurement methods are the most popular, as their accuracy and ease of implementation is a determining factor in instrumentation. But when using impulse methods, issues related to the choice of primary measuring transducers, the speed and accuracy of which directly affect the measurement result, remain unresolved. In addition, there is a need for signal processing, which imposes special requirements on secondary converters.

The vast majority of devices use photometric methods for measuring torques. However, this technique requires the installation of the sensor directly near the shaft, which complicates the measurement due to vibrations and the influence of additional destabilizing factors.

Non-contact measurement means can be an option to overcome the relevant difficulties. This is the approach used in work [2], in which moment measurement consists of using pulse counters on a shaft with a special dynamometric insert, on both sides of which there are elements for fixing a certain angle of rotation. The resulting angle can be converted to a torque using a predetermined torsional stiffness of such a dynamometric insert. The effectiveness of this method was confirmed by an experiment, the results of which revealed a high degree of correlation between the measurement of the moment and the modeling of the elasticity of the shaft. This measurement technique is used for measuring moments of large mechanical drives [3], which confirms its effectiveness.

In detail, the principle of action of pulsed methods of measuring fundamental moments in photometry is presented in [4]. But the application technique of this method includes, unlike standard semiconductor sensors for obtaining a pulse [2], optical probes. These probes respond to a change in the color of special labels that are placed on the shaft. Accordingly, the angle of rotation of the shaft determines the phase shift between the pulses generated by the probes. The removal of relevant characteristics in this way approximates the use of machine vision during measurement, as it occurs by identifying the gradient of the color image, which is placed on the drive shaft.

Taking into account the fact that the application of this method is simple to implement, paper [4] does not provide experimental data regarding limitations on the speed of rotation of the shaft. So, research was not conducted at a speed exceeding 2000 rpm, but only for speeds of 1600, 1700, 1800, and 1900 rpm.

Understanding such parameters is important at high rotation frequency, where the need for high-speed measuring devices increases. This is due to the determination of the limit speeds at which the sensors can work without significant errors. All this gives reason to claim that the accuracy of the measurement depends on the speed of the optical probe and signal processing methods. Thus, solving the problem of accuracy when using such methods should be related to taking into account the sensitivity function and the speed of the sensors of the primary signal conversion. At the same time, the practical implementation of impulse moment measurement methods requires additional filtering from additional noise caused by external destabilizing factors.

However, research in the direction of improving their choice is constantly being conducted. Thus, work [5] shows the development of a non-contact sensor for measuring shaft micro torque based on optical coherence displacement measurement (OCDM), which has advantages in accuracy compared to the previous one due to an increase in the sampling frequency of the received signal and the speed of measurement sensors. The sensor proposed in [5] includes a simple mechanical test measurement system, namely: a calibration device to establish the measurement baseline and a polyetheretherketone (PEEK) shaft to increase the resolution of the system to 0.003 Nm.

The measurement results showed a non-linearity error of 0.0484 %, a maximum repeatability error of 0.2771 %, and a maximum hysteresis error of 0.2252 %. The high accuracy of such a system is also explained by the fact that the use of physical mapping of the torque makes it possible to increase the detail of the measurement. But the issue of using this method of measurement under certain conditions, in particular under conditions of vibrations, elevated temperatures, and non-linearity of the measuring channel, remains unresolved.

Adaptation to such conditions makes the device based on OCDM quite expensive. Therefore, special attention is paid to measuring the moments of electric motors under conditions of pulsations, elevated temperatures, etc., which are harmful to industrial equipment.

In order to minimize such destabilizing factors, special algorithms for their smooth elimination are used. As it is, for example, implemented in work [6] for solving the problem of torque ripples in permanent magnet synchronous motors (PMSM). An interesting solution here is the proposed technique of active control over current waveforms to enable smooth torque generation and reduce the impact of torque ripples directly in the motor itself, where the function of changes in such vibrations is known. But, taking into account the variety of loads on the shaft, such studies need to take into account additional influencing factors. Therefore, they must be solved depending on the nature of vibrations, shaft rotation speed, and loads.

There are other methods based on the recognition of visual features of shaft rotation. Among them are measurement methods that are based on the use of photo sensors that receive a pulse characteristic of rotation using special slots in discs placed on the shaft, which are fixed by logical semiconductor photocells. An example can be the implementation given in works [7, 8], in which the pulse method of moment measurement is presented. Its practical implementation is based on measuring the time between pulses. The generation of such pulses is carried out by sensors that record the rotational movement of the shaft. Time processing is carried out by microcontroller timers, which change their state by receiving an impulse from sensors. In this way, the accuracy of the measurement depends on the clock frequency of the microcontroller, which also depends on the number of pulses received as a result of one revolution of the shaft. Therefore, in this case, it is necessary to obtain a balance between the power of the microcontroller and the frequency characteristics of the pulse generator. A similar technique of moment measurement using photo sensors was also used in work [9].

However, such methods cannot be termed those that use computer vision. These are rather stroboscopic methods, where the primary converter can be replaced, for example, by inductive sensors, as was implemented in [10]. An example can also be the solution proposed in work [11], in which permanent magnets are used instead of generating pulsations of the light flux of the slots on the discs, which are placed on the shaft. The primary transducers in this case are sensors that use the Doppler effect. In this way, it is possible to measure the moment without the need to use complex technology.

The advantages of such methods are ease of use and high speed. A disadvantage to be considered is the impossibility of obtaining moment indicators at high speeds, which is connected with the calculations of the time Δt between the phases of individual pulses.

In numerous studies tackling the measurement of torques of electric motors, the importance of analyzing the properties of dynamometric elements is often underestimated. These elements, used to determine the angle of twist of the shaft, should demonstrate a linear dependence on the applied moment. However, research interest is often focused on the use of standard, already calibrated dynamometric modules with predefined elasticity characteristics. This trend may be due to the convenience of using ready-made solutions that do not require additional calculations of properties for standard applications. However, in situations where electric motors are integrated into non-typical systems, standard methods of calculating the properties of dynamometric elements become insufficient. This indicates the importance of an in-depth study of the properties of dynamometric elements, which will make it possible to adapt measurement methods to the specifics of non-typical applications. Although there are works that consider these properties in detail, the general picture indicates the need for a more in-depth and systematic approach to the study of dynamometric elements. Such an in-depth study will not only expand the understanding of the fundamental aspects of their work but also contribute to the development of new, more accurate, and application-specific measurement methods. An example is a patent for a utility model [12], which includes an elastic element located between the motor shaft and an additional disc housing. This element acts as a connection, allowing the torque to be measured. The useful model takes into account the calculation of the dynamometric properties of the elastic element, which allows obtaining a linear relationship between the twist angle and the rotational load on the shaft.

The results of the research on the dependence of moment on the magnetic flux presented in [13] take into account the resistance of the magnetic elements, the effect of eddy currents and the load on the shaft. This made it possible to build an accurate mathematical model of the rotational parameters of the electric motor. However, it can only be used for high-torque Permanent Magnet Torque Motor (PMTM) electric motors.

However, the application of these principles on the basis of modern computer technology requires the development of new ways of their integration and implementation.

Non-contact moment sensors based on optical methods are described in [14], in particular, moment measurement methods using laser speckle effect, Doppler effect, and a number of other optical methods were evaluated. However, the cited study could be supplemented by analyzing the capabilities of non-contact torque sensors with other measurement and control systems. This can include aspects such as interoperability with data acquisition software, ways to integrate with equipment from different manufacturers, and adaptation to different industrial communication protocols.

Determination of the torque directly on the shaft in this way should include calculations of the elasticity of the dynamometric elements. So, to eliminate the non-linearity of the measuring channel, due to insufficiently defined elastic properties of the dynamometric element, there must be a correction table based on expressions that take such non-linearity into account. Therefore, there are models that can be used to calculate the elasticity of dynamometric elements. An example can be methods of calculating dynamometric springs of measuring devices, some of which are reported in [15, 16].

Thus, despite a significant number of publications, there is an unsolved problem of integration of devices based on the above-mentioned principles into modern measuring systems. It is related to the specific features of the application of transmission devices that are placed on the shaft, where specific methods of powering the measuring elements are used, specific methods of signal transmission, as well as measuring equipment resistant to vibrations and the influence of centrifugal forces.

This especially applies to cases where it is important to minimize the influence of destabilizing factors on the measured systems.

Under such conditions, measuring transducers require more complex techniques for converting mechanical quantities, and the need for universal, inexpensive and at the same time accurate devices is growing in the direction of non-contact moment measurement. Therefore, non-contact measuring techniques can be adaptable to different conditions of use, universal for different types of electric motors, and integrated into other measuring systems.

Considering machine vision technologies for these tasks, it can be noted that they have a wide range of applications. They can be integrated into complex solutions for the implementation of monitoring, diagnostic, and optimization functions of electric drives and various rotary systems.

Most methods of visual control over moving objects are implemented using special matrix detectors. One of the examples is the study described in [17], in which an attempt was made to determine the angular velocity of wind turbine blades using image processing methods. In order to more clearly record the movement, special signal marks were installed on the turbine blade. Algorithms have been developed to accurately detect the position of such marks and track blades in successive frames of the video stream. For this, algorithms such as FAST, SIFT, SURF, BF, FLANN, AE, and SVM were used. This made it possible to estimate the angular speed of the blades with an accuracy of 95.36 % over the entire measurement range. Note that the average error of standard angular velocity sensors is 0.5–3 %. Therefore, the use of this technique is not enough to implement optimal control of the turbine, for example, under conditions of high wind speed. They are trying to solve such problems by parallel application of machine vision methods and other methods of measurement conversion, adapting recognition algorithms to specific narrow tasks. An example can be the implementation presented in [18], in which special algorithms are used to detect icing on the wing of an aircraft, which spreads quite dynamically and can be the cause of an accident. And although this technique works flawlessly under ideal conditions, relying solely on machine vision in this case is dangerous. This is explained by the presence of a significant number of destabilizing factors, which include the variability of lighting, the quality of video recording, and other factors that affect the reception of a clear image. Therefore, in those areas where there must be perfect fault-free measurement devices, the methods of recognizing the dynamics of movement using machine vision must use backup measurement systems.

In safer areas of application, machine vision is quite actively used as the main informative parameter. For example, in [19], an automatic control system is proposed, which uses algorithms to detect plant growth based on data on changes in the shape and color of the object. Such a system determines the change in the number of pixels of a certain color, which allows simple calculations. The absence of complex calculations is explained by the use of separate filters and detectors, which can be used to highlight the contours of the measurement object and its color scheme on the image. At the same time, the use of this technique for more complex objects, or in the absence of stationary lighting, requires separate trained models.

Thus, tools for measuring rotational parameters based on machine vision technologies require advanced data processing techniques where high computing speed is crucial to ensure the accuracy of the indicators. This is especially relevant in cases where the accuracy of measurements of angular displacements during torsional loads on the shaft is required. Therefore, the need is to devise solutions that are able to fully reflect such displacements.

The above procedures considered in studies [18, 19] do not always meet the needs of modern measurement systems due to limitations in image processing speed and the influence of certain destabilizing factors. This requires additional integration processes aimed at using machine vision together with modern methods of measuring rotational parameters. This especially applies to those conditions where typical measuring devices based on strain-gauge or inductive transducers cannot be fully applied due to the negative impact of an aggressive environment on the operation of the device components located on the shaft.

Therefore, there is a need to design universal tools for measuring torques based on non-contact determination of angular loads on the shaft, while ensuring proper accuracy and speed.

3. The aim and objectives of the study

The purpose of our research is to devise a technique for measuring torques of electric motors based on the application of machine vision and a special dynamometric coupling that changes its shape depending on the torsional load on the shaft.

This will make it possible to carry out non-contact measurements under aggressive conditions, where the electronic measuring elements placed on the shaft cannot fully function.

To achieve the goal, the following tasks were set:

– to design a special transmission dynamometric coupling that will allow visualizing the angular deformations of the shaft;

– to carry out a computer simulation of the operation of a direct current electric motor, taking into account the transient characteristics of the dynamometric coupling, which will be mounted in the electric motor shaft;

– to acquire visual characteristics of the torque from the dynamometric coupling.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is the technique for measuring torques of electric motors by recognizing the indicators of changes in torsional loads on the shaft, which are displayed by a specially designed dynamometric coupling.

The hypothesis of the study assumes that there are criteria for visual diagnostics of the torque, which allow monitoring changes in the angle of deformation of the shaft during its loading. These changes can be transmitted hydraulically. To this end, a special mechanism can be used, which visualizes the pressure generated in the liquid under the action of the load on the shaft. Such a mechanism can be constructed on the basis of a specially designed dynamometric coupling.

Therefore, it is assumed that acquiring the visual characteristics of torsional loads on the shaft can be carried out using machine vision by recognizing the translational movements of the signal elements of the dynamometric coupling proportional to the rotational moment. The design feature of the dynamometric coupling can provide that the translational movement of its signal elements is proportional to the pressure created as a result of the torsional load on the shaft. This suggests that the proposed technique allows applying a new informative parameter in the process of measuring torques, which is based on the visual characteristics of the torsional element placed on the shaft.

4. 2. Requirements for designing a dynamometric coupling

A number of important technical and functional parameters must be taken into account for the effective design of a dynamometric coupling. A dynamometric coupling must be a tool capable of providing accurate torque measurement within the rated load range. It should be characterized by stability and reproducibility of indicators, which guarantees the reliability of measurements during long-term use. The structure of the coupling must be able to withstand regular loads and mechanical influences. It must be compatible with different types of shafts and machines so that it can be easily integrated into other industrial systems.

The materials from which the coupling is made must be resistant to corrosion and wear, which ensures long-term operation under various conditions.

Integration of the coupling with control and data analysis systems should be provided to automate the processes of monitoring the rotational parameters of the electric motor.

4. 3. Requirements for measurement transformation modeling and determining transformation methods

In order to study the properties of the pulse conversion method of the deformation angle of the dynamometric element placed on the shaft (Fig. 1, element 4) into the output unified signal, the time interval Δt was determined between the pulses received from sensors 5–7 according to Fig. 1. In turn, Δt depends on the moment M applied to the shaft and on the elasticity coefficient of the dynamometric element K_1.

The time interval Δt can be defined by the following expression:

$$\Delta t = \frac{dl}{V_{rpm}}, \quad (1)$$

where dl is the torsion angle of the elastic element; $V_{rpm} = (2\cdot\pi\cdot R_D)/T = \omega\cdot R_D$; R_D – radius of circle, discs; T is the rotation period of the engine shaft; ω is the angular velocity.

Twisting can be represented as the product between the torque and the coefficient depending on the properties of the elastic element $dl=M\cdot K_1$, where K_1 is the coefficient depending on the properties of the elastic element.

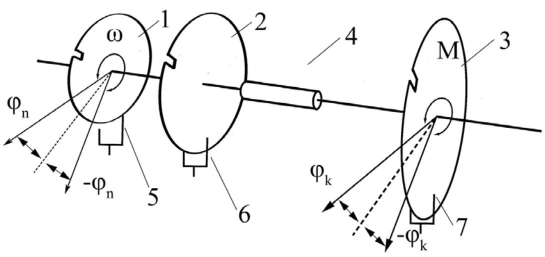


Fig. 1. Principle of measurement of torque, rotational velocity, and acceleration using impulse methods [12]

Expressing the value of the measured torque from this expression, the torque is obtained:

$$M = \frac{dl}{K_1} = \frac{\Delta t\cdot V_{rpm}}{K_1} = \frac{\Delta t\cdot 2\cdot\pi\cdot R_D}{K_1\cdot T} = \frac{\Delta t}{T}\cdot K_2, \quad (2)$$

where $K_2 = \frac{2\cdot\pi\cdot R_D}{K_1}$ – proportionality factor; $K_1 = \frac{\Delta t\cdot V_{rpm}}{M}$.

Thus, this technique involves determining the torque by measuring the time interval Δt and the rotation period of the shaft T (Fig. 2). At the same time, the constant K_2 is determined in advance during the calibration process using accurate means of measuring the torque.

This technique can also be implemented using separate probes by recognizing the color change of individual sections of the shaft (Fig. 3).

The corresponding concept can also be implemented using magnets instead of slots on the disks of disks 1–3 (Fig. 1), and instead of photo sensors 5–7, motion sensors based on the Doppler effect.

It is also important to take into account K_2, which is determined in advance during calibration using accurate torque measuring devices.

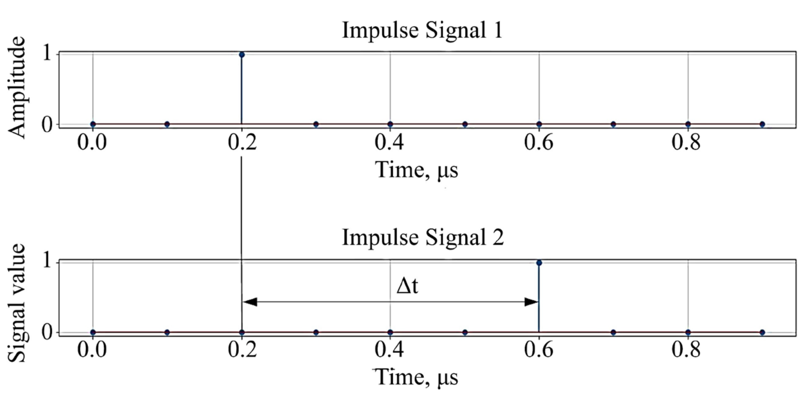


Fig. 2. Torque measurement by impulse method. *Note: based on* [11, 12]

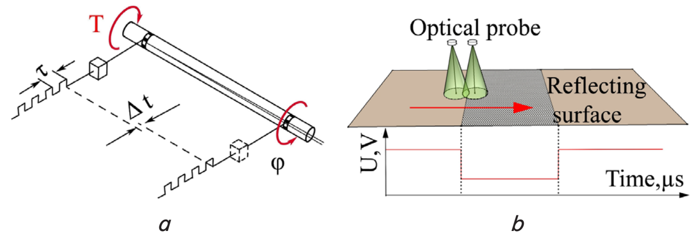


Fig. 3. Torque measurement using the optical method: *a* – placement of sensors; *b* – principle of measurement. *Note: based on* [4]

Due to the lack of a torque standard, it is planned to create a conditional graduation, where dl is determined depending on the elasticity K_1, as shown in Fig. 4.

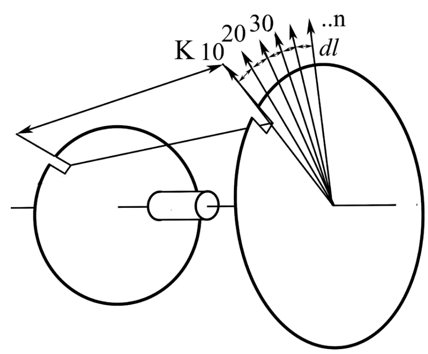


Fig. 4. dl – twist angle of elastic element at K_1 = 10, 20,..., n

It is essential to assess the dependence of Δt on such parameters as the diameter of the spring wire d, its length l, and the angle of twist μ, which are key to understanding the interaction between these quantities.

Thus, there is a need to determine Δt, provided that K_1 depends on the diameter of the spring wire d, the length of the spring l, twisted by an angle μ.

To check the dependence, known rules for calculating dynamometric springs of the helical type were used, where the torque acting on the cross section of the spring is expressed by special equations [15, 16]. So, having the main parameters of the spring twist, it is possible to model the dependence of the electric motor moment on these parameters. To do this, it is necessary to obtain the characteristic of the shear modulus of the spring material G by expressing it from the following expressions.

The angle of twist of two sections of the spring relative to each other is represented by the following expression:

$$d_\mu = \frac{d_a d_\varphi}{\cos a}, \quad (3)$$

where d_a is an infinitesimally small value by which the angle of inclination of the helical line of the spring changes; d_φ is the length of cross-section diameters perpendicular to the axis of the spring, the angle between which is minimal; α is the angle of inclination of the helical line of the spring.

Taking into account the length of the spring, the moment of inertia of its cross-section, as well as the overall deflection, the twist angle is determined as follows:

$$d\mu = \frac{dMdL}{GJ_0} = \frac{dPR\cos\alpha dL}{GJ_0}, \tag{4}$$

$$J_0 = \frac{\pi d^4}{32}, \tag{5}$$

$$dL = \frac{Rd_\varphi}{\cos a}, \tag{6}$$

where L is the total length of the spring; dL is the length of the part of the spring between two sections; R is the radius of the spring turns; J_0 is the moment of inertia of the cross-section of the spring relative to the center of this cross-section; dP is the force acting at the moment of twisting the spring; d is the diameter of the wire from which the spring is wound; G – shear modulus of the spring material; dM is the twisting moment acting on the cross section of the spring $dM=dPR\cos a$.

To determine the shear modulus of the spring material G, the overall change in the deflection of the entire spring when the load changes is considered:

$$dh_c = dP\frac{32R^3}{G\pi d^4}\int_0^{\varphi_C} \cos\alpha \cdot d\varphi, \tag{7}$$

where dh_c is the total change in deflection of the entire spring when the load changes; φ_C is the full angle of twisting of the spring.

To determine G, both sides of the equation were multiplied by $G\pi d^4$ to move G from the denominator to the numerator on the right-hand side of the equation:

$$G\pi d^4 dh_c = dP \cdot 32R^3 \int_0^{\varphi_C} \cos\alpha \cdot d\varphi. \tag{8}$$

Divide both sides of the equation by dh_c (assuming $dh_c \neq 0$ to isolate G:

$$G\pi d^4 = \frac{dP \cdot 32R^3 \int_0^{\varphi_C} \cos\alpha \cdot d\varphi}{dh_c}. \tag{9}$$

Divide both sides of the equation by πd^4 to get G separately:

$$G = \frac{dP \cdot 32R^3 \int_0^{\varphi_C} \cos\alpha \cdot d\varphi}{\pi d^4 dh_c}. \tag{10}$$

For a more detailed study of the process of measuring the torque conversion of an electric motor, it is necessary to integrate the properties of the dynamometric spring into a separate model. Given that K_1 from expression (2) is a coefficient that depends on the properties of the elastic element, for its study, the calculation of dynamometric elastic elements was carried out.

Assuming that K_1 in expression (2) is a function of G, J_0, R, dM and α, defined in (4), (5), (6), (10), an attempt was made to investigate its properties.

So, given that dM (the moment acting on the cross-section of the spring) is the main factor that determines K_1 and depends on R and a, then K_1 is expressed as a function of these parameters:

$$K_1 = f(G, J_0, R, \alpha) = \frac{1}{GJ_0} \cdot g(R \cdot \alpha), \tag{11}$$

where $g(R, a)$ is a function describing the influence of the spring radius R and the angle α on K_1. This function can be determined experimentally. To carry out such experiments, measuring chains of a dynamic system are used [20]. Paper [20] reports an iterative model for measuring the torque of an electric motor taking into account vibration and rotation speed, based on which, having the data of the acceleration moment of the electric motor, it is possible to study the behavior of other components of the system. Applying this example to model the transient characteristics of the moment during acceleration of the electric motor from (2) Δt was expressed:

$$\Delta t = \frac{M \cdot K_1 \cdot T}{2\pi \cdot R_D}. \tag{12}$$

This made it possible to check the relationship between the simulated value of the moment and its individual characteristics, which should be linearly dependent on each other.

Having a model of torque measurement by the impulse method, a study of the system's behavior was carried out using the machine vision method, comparing the main characteristics of the measurement.

Considering that the system for measuring the torque requires the integration of mechanical, optical, and software components, a system of dynamic chains was built based on [20] but taking into account the function of converting the torque into the shaft deformation angle (Fig. 5). The role of the converter in this case is played by the dynamometric coupling proposed in the work.

Thus, a functional scheme for modeling the measurement process was constructed. This scheme should ensure the fixation of visual information about the angular deformation of the shaft. It should also take into account the time for processing the video information to determine the twist angle. The scheme must take into account shaft speed, feedback, and vibration. The vibration should be given by an aperiodic function of the second order. Also, resistance moments, starting moment and total moment should be taken into account.

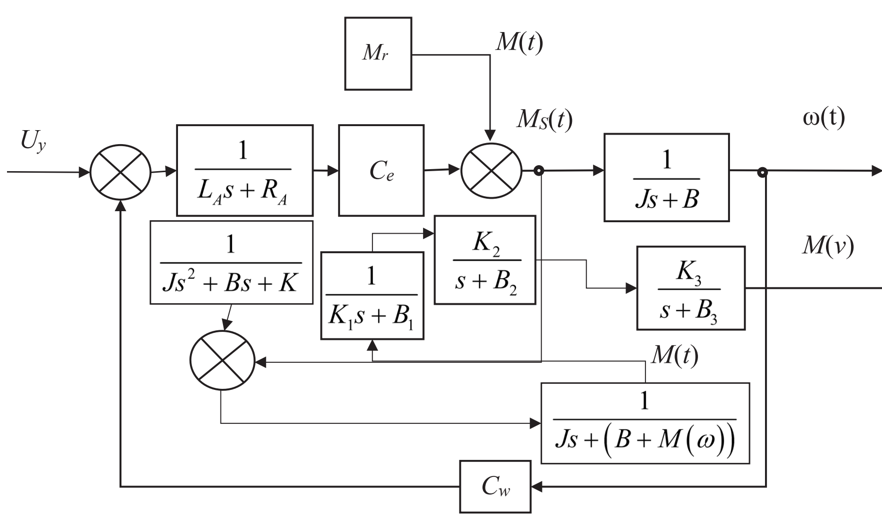


Fig. 5. Block diagram of the process of measuring the torque of a DC electric motor

The functional scheme, built on the basis of dynamic chains, takes into account the key functions that are necessary for modeling the measurement process, thus ensuring its effectiveness. So, the functional scheme consists of the following transfer functions:

– the function of recording visual information about the angular deformation of the shaft, which includes the analysis of video information to accurately determine the twist angle; the function of changing the speed of rotation of the shaft, provided with effective feedback;

– the function of the influence of vibration on the torque, which is modeled using a second-order aperiodic function;

– resistance moment function; function of starting moment; the total moment function.

Each of these functions plays an important role in ensuring the accuracy and efficiency of the process of measuring angular deformations and moments on the shaft. Voltage is the input parameter for controlling the electric motor. The output parameter is the video signal and its processing algorithm regarding the angular displacement of the dynamometric coupling.

In Fig. 5, M_r, M_s, M are the resistance moment, driving moment, and total moment applied to the rotor shaft. B is the coefficient of friction affecting the movement of the shaft. C_e is the force moment coefficient, which determines the influence of external forces. C_w is the speed coefficient associated with the movement of the shaft. U_y is the voltage in the system. I_A is the current in the armature circuit of the motor, which is important for its operation. R_A is the resistance of the armature circuit, which affects the operation of the motor. J is the moment of inertia of the rotor, which is important for its rotation. K_1 is the degree of elasticity in the dynamometric element (torsion shaft), determines the ratio of the angle of deformation of the shaft to the applied torque. K_2 is the conversion factor of the optical signal, showing how the system converts the angular deformation of the shaft into a video signal. K_3 is the efficiency factor of the signal processing algorithm for determining the twist angle. B_1 – damping in the shaft, affects the dynamics of angular deformation, B_2 – damping of the optical system when converting physical parameters into a video signal. B_3 is a time delay associated with the video processing algorithm.

The proposed functional scheme includes a modification of the well-known model of acceleration of the electric motor taking into account additional functions of data processing. Testing such a scheme will make it possible to determine the differences between the indicators of the standard operating mode of the electric motor and the indicators obtained as a result of their measurement based on machine vision.

Signal data processing during measurement involves a sequence of steps to account for all factors affecting the conversion. Therefore, it is important to determine individual deviations from signal linearity and other errors.

A known technique for determining such deviations is expanding the function of the output signal $y(t, a)$ into a Taylor series by the parameter a, which characterizes the amount by which the device deviates from its rated value [21, 22]:

$$y(t,\alpha)=y_0(t)+\left.\frac{\partial \dot{y}(t,\alpha)}{\partial\alpha}\right|_{\alpha=0}\alpha+\left.\frac{\partial^2 y(t,\alpha)}{\partial\alpha}\right|_{\alpha=0}\frac{\alpha^2}{2}. \tag{13}$$

The coefficient at the first power a is called the sensitivity function, which can be denoted by $z(i)$:

$$z(t)=\left.\frac{\partial \dot{y}(t,\alpha)}{\partial\alpha}\right|_{\alpha=0}. \tag{14}$$

With small deviations of the parameters from their rated values, when solving practical problems, it is enough to consider the first two terms of the series (8). However, in certain scenarios there is a need to consider higher-order sensitivity functions, such as the second:

$$z^2(t)=\left.\frac{\partial^2 y(t,\alpha)}{\partial\alpha^2}\right|_{\alpha=0}. \tag{15}$$

To determine the sensitivity functions of the system, it is not necessary to find the response of the system $y(t, \alpha)$, and then differentiate it by the parameter α. The sensitivity functions can be directly determined through the sensitivity equation. In the case of linear systems, the Laplace transform is used. So, let $\Phi(s, \alpha)$ be the transfer function of the system, where α deviates from the rated value of the parameters. Then the Laplace transform of the output signal of the system is written as:

$$Y(s,\alpha)=\Phi(s,\alpha)X(s), \tag{16}$$

where $X(s)$ is the Laplace transform of the input signal.

The output signal of the system is defined as follows:

$$y(t,\alpha)=L^{-1}\left\{\Phi(s,\alpha)X(s)\right\}. \tag{17}$$

After differentiating expressions (14) and (15) and equating a to zero, the values of the corresponding sensitivity functions are obtained:

$$\left.\begin{aligned} z(t)&=L^{-1}\left\{\left.\frac{\partial\Phi(s,\alpha)}{\partial\alpha}\right|_{\alpha=0}X(s)\right\};\\ z^2(t)&=L^{-1}\left\{\left.\frac{\partial^2\Phi(s,\alpha)}{\partial\alpha^2}\right|_{\alpha=0}X(s)\right\}.\end{aligned}\right\} \tag{18}$$

To determine a sensitivity function, e.g., of the first order, for an aperiodic link whose time constant can deviate from its nominal value, the following transfer function is given:

$$\Phi(s,\alpha)=\frac{1}{(T+\alpha)s+1}. \tag{19}$$

If the input signal is a unit step function, then the input signal can be expressed as follows:

$$x(p)=\frac{1}{s}. \tag{20}$$

The output signal at the nominal value of the time constant will be as follows:

$$y_0(t)=1-e^{-\frac{t}{T}}. \tag{21}$$

In this case, the sensitivity function defined by formula (18) can be represented as follows:

$$z(t)=$$
$$=L^{-1}\left[\left.\frac{\partial}{\partial\alpha}\frac{1}{(T+\alpha)s+1}\right|_{\alpha=0}\frac{1}{s}\right]=L^{-1}\left[-\frac{1}{(Ts+1)^2}\right]=-\frac{t}{T}e^{-\frac{t}{T}}. \tag{22}$$

In turn, the output signal of the system with an error caused by a change in the time constant can be written as:

$$y(t,\alpha)=y_0(t)+z(t)=1-\left(1+\frac{t}{T}\alpha\right)e^{-\frac{t}{T}}. \tag{23}$$

Given that models of the behavior of an electric motor during its operation have been studied in sufficient detail, such as [20], it is possible to take such deviations into account when modeling measurements based on machine vision. To this end, it is necessary to determine the deviation taking into account the delay of the optical system, which is associated with the object recognition error, as well as the deviation associated with the non-linearity error and the deviation associated with instrumental and other errors.

An important factor for this measurement system is its sensitivity since the response of optical systems has a significant impact on the overall measurement system. Therefore, there is a need to investigate the sensibility of such a system. To this end, you can use the well-known Laplace transform method for the sensitivity function [23, 24].

Schematically, the structural diagram of sensitivity measurement can be represented as follows (Fig. 6).

In this case, attention should be paid to the condition when the amplification factor of one of the system components differs by the value α from its rated value A_0.

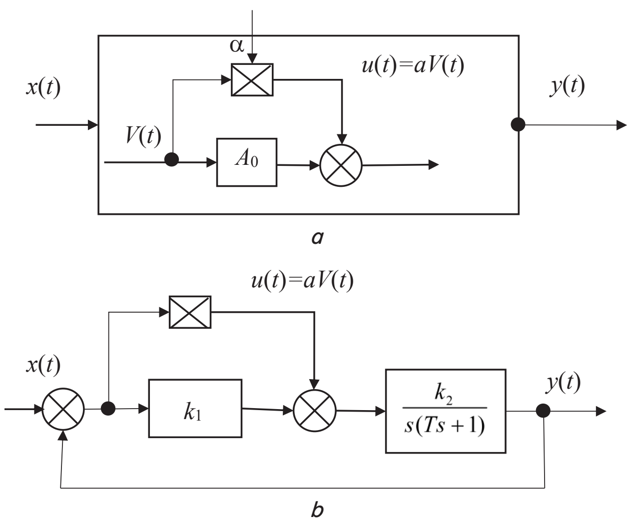


Fig. 6. Structural diagram of the measuring sensitivity of the system: *a* — general diagram; *b* — a second-order sensitivity scheme with a random amplification factor

In general, an element with a specified gain can be placed in any part of the system. Thus, Fig. 6, *a* shows the entire system, where $x(t)$ and $y(t)$ are the input and output signals, respectively. Inside this rectangle, shown in Fig. 6, *a*, the equivalent circuit of an element with a variable amplification factor is reproduced, for which the following two equations can be formulated:

$$\left.\begin{aligned} Y(s,\alpha) &= \Phi_{x\varphi}(s)X(s)+\alpha\Phi_{xu}(s)V(s,\alpha); \\ V(s,\alpha) &= \Phi_{\upsilon\varphi}(s)X(s)+\alpha\Phi_{\upsilon u}(s)V(s,\alpha), \end{aligned}\right\} \quad (24)$$

where $V(s, a)$ is the signal transformation function at the input of the measuring device with variable gain; Φ_{ij} are transfer functions connecting various points of the system with the rated values of the parameters. The following expression is derived from equations (19):

$$Y(s,\alpha)=\Phi_{x\varphi}(s)X(s)+\frac{\alpha\Phi_{xu}(s)\Phi_{\upsilon\varphi}(s)X(s)}{1-\alpha\Phi_{\upsilon u}(s)}. \quad (25)$$

Differentiating this expression by α and equating a to zero yield:

$$z(s)=\left.\frac{\partial Y(\alpha,s)}{\partial\alpha}\right|_{\alpha=0}=\left.\frac{\left(\Phi_{xu}(s)\Phi_{\upsilon\varphi}(s)X(s)\right)}{\left[1-\alpha\Phi_{\upsilon u}(s)\right]^2}\right|_{\alpha}= =\Phi_{\upsilon\varphi}(s)\Phi_{xu}(s)X(s), \quad (26)$$

$$z^2(s)=\left.\frac{dY(\alpha,s)}{d\alpha}\right|_{\alpha=0}=\left.\frac{2\Phi_{\upsilon\varphi}(s)\Phi_{xu}(s)\Phi_{\upsilon u}(s)X(s)}{\left[1-\alpha\Phi_{\upsilon u}(s)\right]^3}\right|_{\alpha}= =2\Phi_{\upsilon\varphi}(s)\Phi_{xu}(s)\Phi_{\upsilon u}(s)X(s). \quad (27)$$

The Laplace transform for the output signal using sensitivity functions can be represented as follows:

$$Y(s,\alpha)=Y_0(s)+Z(s)\alpha+Z^{(2)}(s)\frac{\alpha^2}{2}+... \quad (28)$$

Considering the application of the described procedure on the example of a second-order system, it should be noted that the amplification factor of the output signal can vary. The structural diagram of this system is shown in Fig. 6, *b*.

In the considered case, the transfer functions $\Phi_{ij}(p)$ are defined as follows:

$$\Phi_{x\varphi}=\frac{\dfrac{k_1k_2}{s(Ts+1)}}{1+\dfrac{k_1k_2}{s(Ts+1)}}=\frac{k_1k_2}{Ts^2+s-k_1k_2}, \quad (29)$$

$$\Phi_{\upsilon\varphi}=1-\Phi_{x\varphi}=\frac{Ts^2+s}{Ts^2+s+k_1k_2}, \quad (30)$$

$$\Phi_{xu}=\frac{\dfrac{k_2}{s(Ts+1)}}{1+\dfrac{k_1k_2}{s(Ts+1)}}=\frac{k_2}{Ts^2+s-k_1k_2}. \quad (31)$$

In this case, the Laplace transform of the first-order sensitivity function will be as follows:

$$Z(p)=\frac{k_2\left(Ts^2+1\right)}{\left(Ts^2+s+k_1k_2\right)^2}X(s). \quad (32)$$

For a system whose input signal is a unit step function, the expression is as follows:

$$Z(s)=\frac{k_2(Ts+1)}{\left(Ts^2+s+k_1k_2\right)^2}. \quad (33)$$

As a result, the sensitivity function can be determined using the inverse Laplace transform.

In the case of a variable-parameter system, the output signal can be approximated by a first-order sensitivity function:

$$y(t)=y_0(t)+az(t). \quad (34)$$

If α is a random variable with variance σ_a^2, then the variance of the dynamic error component caused by a parameter change can be represented as follows:

$$\sigma_x^2(t)=\sigma_a^2\left[z(t)\right]^2. \quad (35)$$

However, the sensitivity theory provides only an approximate solution, which is acceptable provided that the variances of the variable parameters are small enough.

In practice, quite often structural diagrams with transfer functions of individual elements are used to study the properties of sensitivity functions, without applying the differentiation of the general initial parameters of the system.

This approach makes it possible to more intuitively understand and analyze complex systems, focusing on the interaction between their components, and not on the mathematical description of the entire system as a whole.

To determine the sensitivity of the measurement system based on machine vision, it is necessary to take into account the sensitivity of not only the measuring dynamometric element but also the sensitivity of the entire measuring channel, including the means of photo and video recording of shaft mixing.

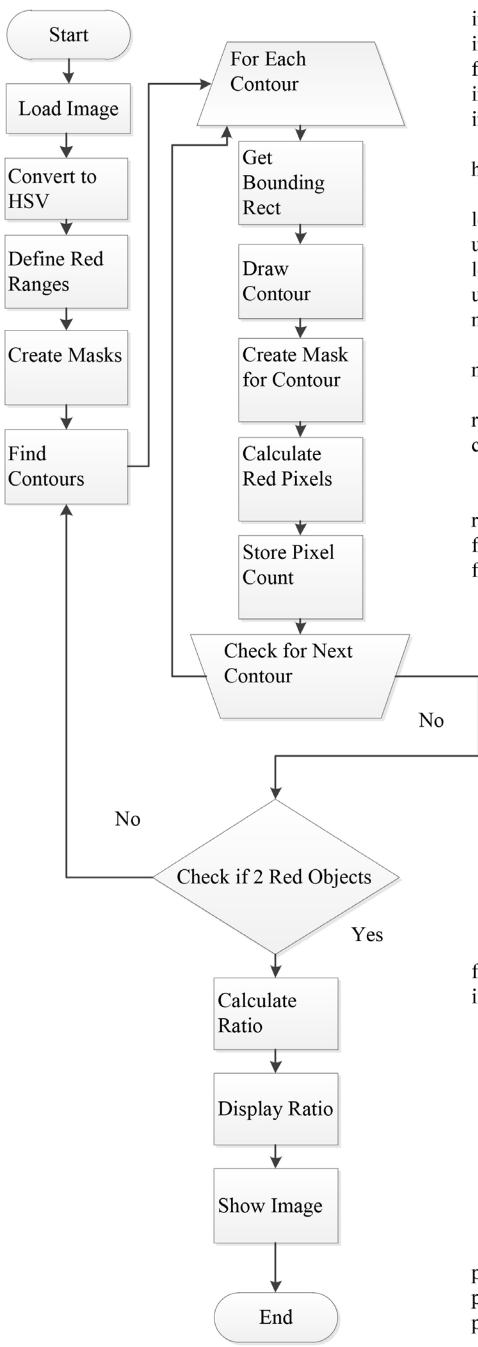
4. 3. Acquiring visual characteristics of the torque from the dynamometric coupling

Critical is the ability to accurately size the signal marks on the coupling, one of which has a static size while the other changes size depending on the applied torque. This procedure includes an algorithm for edge detection, image segmentation, and object tracking. Therefore, the software must be integrated with other measurement systems on the motor shaft to enable data consistency and accuracy.

One of the important features of the software is the ability to compensate for potential measurement errors and noise that may occur due to vibrations, lighting, and other external influences.

Therefore, taking into account the needs of software integration, it was decided to apply the common Python programming language and the OpenCV software library to obtain graphic objects.

To detect red objects that form signal labels using this programming language, software was developed, the algorithm of which and the source code are shown in Fig. 7.




```
import cv2
import numpy as np
from matplotlib import pyplot as plt
image_path = r'C:\PROJECT\im.jpg'
image = cv2.imread(image_path,
   cv2.IMREAD_COLOR)
hsv_image = cv2.cvtColor(image,
   cv2.COLOR_BGR2HSV)
lower_red = np.array([0, 150, 100])
upper_red = np.array([10, 255, 255])
lower_red2 = np.array([170, 150, 100])
upper_red2 = np.array([180, 255, 255])
mask1 = cv2.inRange(hsv_image, lower_red,
    upper_red)
mask2 = cv2.inRange(hsv_image, lower_red2,
    upper_red2)
red_mask = cv2.bitwise_or(mask1, mask2)
contours,_=cv2.findContours(red_mask,
   cv2.RETR_EXTERNAL,
      cv2.CHAIN_APPROX_SIMPLE)[-2:]
red_object_pixel_counts = {}
font_scale = 2.9
for i, contour in enumerate(contours):
   x, y, w, h = cv2.boundingRect(contour)
   cv2.drawContours(image, [contour], -1,
      (0, 255, 0), 2)
   mask = np.zeros(image.shape[:2],
      dtype=np.uint8)
   cv2.drawContours(mask, [contour], -1,
      255, thickness=cv2.FILLED)
   red_count = np.sum(mask == 255)
   red_object_pixel_counts[f'red_object_{i+1}'
      ] = red_count
   text_position = (x + w + 10, y + h // 22)
   cv2.putText(image,f'{red_count}', text_position,
      cv2.FONT_HERSHEY_SIMPLEX, 2, (0, 0, 0), 4)
   cv2.putText(image,f'{red_count}',text_position,
      cv2.FONT_HERSHEY_SIMPLEX, 2, (0, 0, 0), 2)
font_scale = 2.0
if len(red_object_pixel_counts) >= 2:
   sorted_counts = sorted(
      red_object_pixel_counts.values(),
       reverse=True)
   ratio = (sorted_counts[1] / sorted_counts[0]) * 100 \
   if sorted_counts[1] > 0 else 0
   cv2.putText(image, "Ratio:", (10, 50),
      cv2.FONT_HERSHEY_SIMPLEX, 2, (0, 0, 0), 2)
   ratio_text = f"{ratio:.2f}%"
   cv2.putText(image, ratio_text, (5, 110),
      cv2.FONT_HERSHEY_SIMPLEX, 2, (0, 0, 0), 2)
plt.imshow(cv2.cvtColor(image, cv2.COLOR_BGR2RGB))
plt.axis('off')
plt.show()
```

Fig. 7. Algorithm and program code for highlighting the signal labels of the dynamometric coupling in the image

The proposed software solution makes it possible to calculate the number of pixels of red objects in the image and determine the ratio of the signal label to the reference one, displaying them on the image, which demonstrates the possibility of measuring the torque in this way.

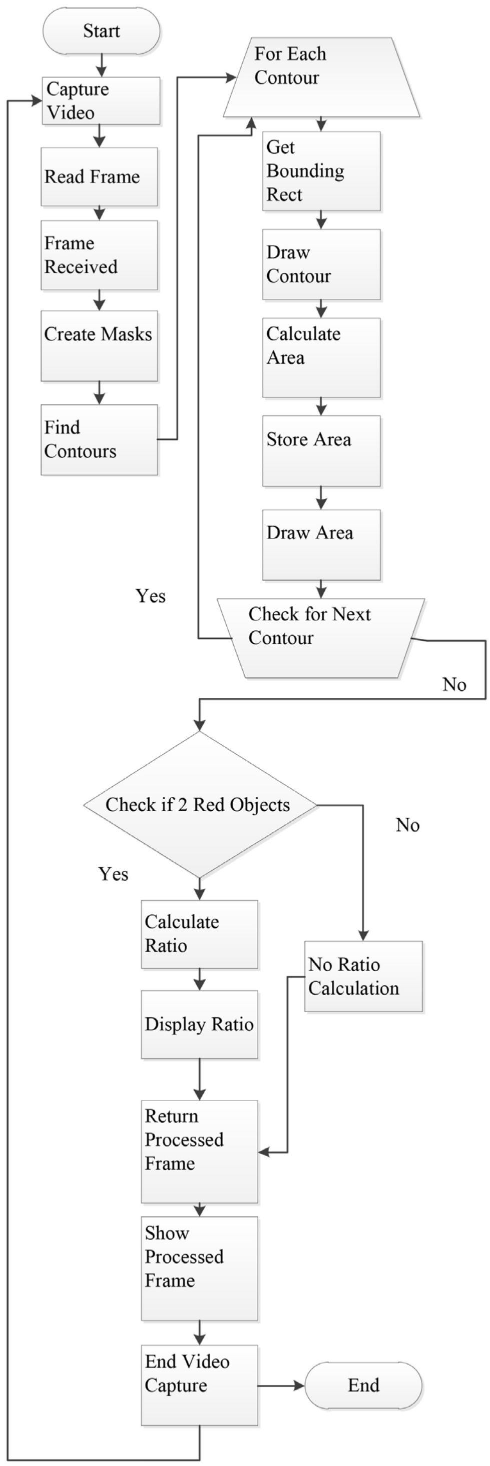
A similar technique, but with the use of a video camera under online data processing mode, is implemented in the following way (Fig. 8).

Their difference is that the second technique includes cyclic processing already under the video stream mode.

5. Results of investigating the technique for measuring the torques of electric motors based on machine vision

5. 1. Design of a transmission dynamometric coupling for measuring angular deformations of the electric motor shaft

The structure and principle of operation of the proposed transmission dynamometric coupling is shown in Fig. 9.




```
import cv2
import numpy as np
def process_frame(frame):
    hsv_frame = cv2.cvtColor(frame,
        cv2.COLOR_BGR2HSV)
    lower_red = np.array([0, 150, 100])
    upper_red = np.array([10, 255, 255])
    lower_red2 = np.array([170, 150, 100])
    upper_red2 = np.array([180, 255, 255])
    mask1 = cv2.inRange(hsv_frame, lower_red,
        upper_red)
    mask2 = cv2.inRange(hsv_frame, lower_red2,
        upper_red2)
    red_mask = cv2.bitwise_or(mask1, mask2)
    # Знаходження контурів
    contours,_=cv2.findContours(red_mask,
        cv2.RETR_EXTERNAL,
        cv2.CHAIN_APPROX_SIMPLE)[-2:]
    min_contour_area = 100
    contour_areas = []
    font_scale = 2.0
    for contour in contours:
        if cv2.contourArea(contour) > min_contour_area:
            x, y, w, h = cv2.boundingRect(contour)
            cv2.drawContours(frame, [contour], -1,
                (0, 255, 0), 2)
            contour_area = cv2.contourArea(contour)
            contour_areas.append(contour_area)
            text_position = (x + w + 10, y + h // 2)
            cv2.putText(frame,f'{contour_area}',text_position,
                cv2.FONT_HERSHEY_SIMPLEX, font_scale,
                (0, 0, 0), 2)
    if len(contour_areas) >= 2:
        sorted_areas = sorted(contour_areas, reverse=True)
        ratio = (sorted_areas[1] / sorted_areas[0]) * 100
        ratio_text = f"Ratio: {ratio:.2f}%"
        cv2.putText(frame,ratio_text,(10,50),
            cv2.FONT_HERSHEY_SIMPLEX, font_scale,
            (0, 0, 0), 2)
    return frame
cap = cv2.VideoCapture(0)
while True:
    ret, frame = cap.read()
    if not ret:
        break
    processed_frame = process_frame(frame)
    cv2.imshow("Processed Frame", processed_frame)
    if cv2.waitKey(1) & 0xFF == ord('q'):
        break
cap.release()
cv2.destroyAllWindows()
```

Fig. 8. Algorithm and program code for highlighting the signal labels of the dynamometric coupling on video

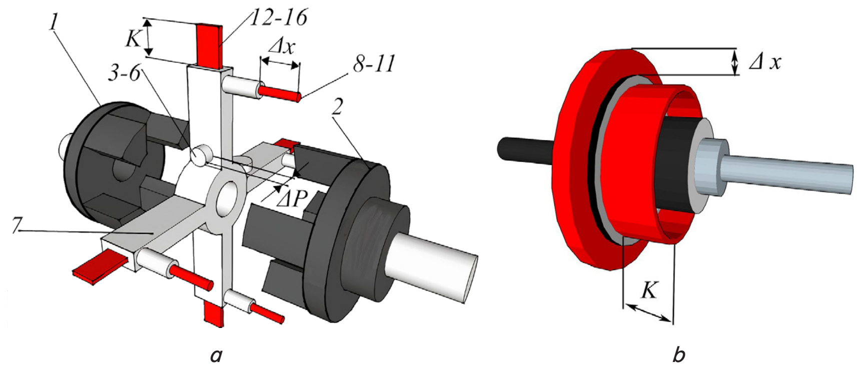


Fig. 9. The structure and principle of operation of the dynamometric coupling: *a* — characteristics of the elements; *b* — view during shaft rotation

The coupling consists of two semi-couplings 1, 2, which are rigidly connected to the shaft. They press under the action of the torque of the shaft on pistons 3–6, which are displaced by the amount ΔP and are hermetically mounted in the cross-shaped body 7, which is filled with liquid. Under the action of the pressure of pistons 3–6, the liquid pushes out signal pistons 8–11 by the amount Δx, which are also hermetically built into housing 7. Thus, under the action of the pressure, signal pistons 8–11 perform a linear movement parallel to the axis of the electric motor shaft, which makes it possible, during its rotation, to derive the value of Δx in pixels.

In this way, the approximate dependence $M=k\times\Delta x$ was built, where k is the proportionality constant, since it is assumed that there is a linear relationship between the moment and the movement of signal pistons 8–11.

Piston displacement Δx can be measured in pixels using a machine vision system, and if one pixel is equivalent to a distance d, then $\Delta x=d\times p$, where p is the pixel dimension of the signal piston image. This technique can be invariant to the photofixation distance, if d is determined taking into account reference marks 12–16, the length of which will be unchanged, $K=\Delta x_{max}$. This feature makes it possible to perform a comparative analysis of two objects in the image in pixels, devising a distance-invariant moment determination method.

Thus, the movement of signal pistons 8–11 is an indicator proportional to the torque. To measure the length of the signal pistons and compare them with the reference segment K, the OpenCV software library was used, which allows the analysis of the image acquired from the camera directed at the coupling.

5. 2. Computer simulation of an electric motor with a dynamometric coupling and its characteristics

In order to test and optimize the proposed torque measurement system, mathematical modeling of the process of converting torque into pressure acting on the translational movement of signal pistons 8–11 of the dynamometric coupling was carried out (Fig. 9). This made it possible to determine the linearity of the conversion process and identify possible sources of errors. The results of such modeling will help in the further improvement of the design of the dynamometric coupling and the optimization of data processing algorithms obtained by video recording of the position of the signal pistons.

An important factor when using machine vision in the process of measurement transformation is the deviation of the received signal from its expected value, which is caused by a number of system delays, errors, and measurement speed. Therefore, when using impulse methods, the transient characteristic of the signal depending on the deviation should be taken into account. In order to study such a deviation by modeling the delay of the output signal depending on the response of the system to the input pulse, the method of Laplace transformations was used. To a large extent, this transitional process concerns measurements based on photometric sensors (Fig. 1, 3).

Thus, after simulating the output signal of the system with the error caused by the change of the time constant, according to expression (23), the transient characteristic of the change of the output signal depending on the parameters a=0.1, 0.2, 0.3....1 at the input of the measuring converter was obtained (Fig. 10).

As a result, it can be seen that when the deviation increases, it is quite difficult to avoid measurement errors in the process of normalizing the output signal.

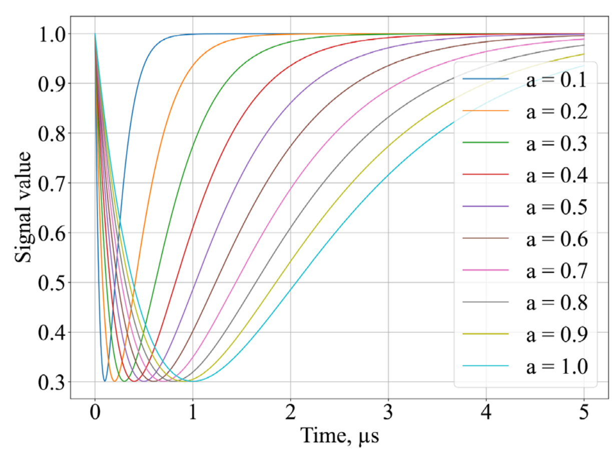


Fig. 10. Output signal taking into account the error caused by the change in the time constant, when a=0.1, 0.2, 0.3...1

The derived transient characteristics depending on the time constant for each individual deviation indicator a according to expression (23) indicate that the use of the pulse method for measuring torques makes sense when there is a slight deviation of the signal in the range of a~0.1–0.3. This indicates high requirements for photo sensors used in devices for measuring torques (Fig. 1, 3).

In this case, it is necessary to reduce the time of the transition process, which is recorded by optical measuring sensors. This is important because the deflection process depends on the conversion time and the linearity of the measurement system.

If we take into account the conversion process by the impulse method, which is used in [4], then it is necessary to evaluate the dependence of the time characteristics of the output signal on the elasticity of the dynamometric element. To do this, Δt (12) was derived for different values of elasticity K_1 of the dynamometric spring. As a result, a linear dependence was established for individual parameters of elasticity K_1 of the dynamometric element (Fig. 11).

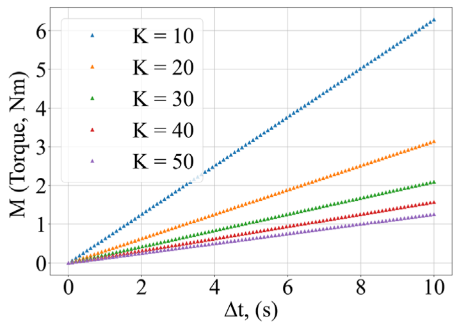


Fig. 11. Dependence of torque on Δt at $K_1 = 10, 20 \ldots n$

In this way, having a reference torque, it is possible to calibrate the measuring device or make additional calculations of its properties.

The study of measurement transients involves the analysis of various components; to this end, it is possible to use already existing data sets that can be simulated or those obtained experimentally.

The well-known iterative models for reproducing the rotational parameters of electric motors, taking into account vibration and rotation speed, can be used to conduct a study of additional functional chains. For example, the model in [20] can be used to study the behavior of an impulse torque converter. Thus, having built expression (11) and substituting it in (12), it is possible to take into account the main elastic properties of the parameter K_1, which is a function of many elastic characteristics of dynamometric springs.

Having the electric motor acceleration model [20] and applying it to expression (12), the dependence of Δt on torque was derived (Fig. 12).

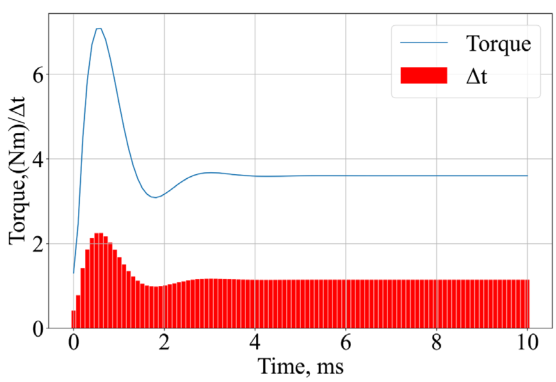


Fig. 12. Characteristics of torque indicators and time intervals derived using the pulse measurement method

At the same time, the parameters on which K_1 depends can only be taken into account experimentally, which creates certain difficulties that are associated with the determination of the transient characteristics of the elasticity of dynamometric elements. In addition, it is necessary to take into account the temperature factor, which affects the linearity of the transformation.

This also applies to other measurement techniques, but the use of pulse methods always requires additional computing power and signal filtering.

Strain gauge sensors are used to partially solve this problem. In these sensors, the angle of rotation of the shaft affects the change in the resistance of the sensitive element. This makes it possible to get the output signal by voltage. However, there are problems with fastening these elements. This leads to an increase in operational checks and specific conditions of use of devices. Therefore, the solution to this problem requires other ways of converting the shaft twist angle.

Taking into account the main dynamic properties of the torque measurement system, which uses machine vision (Fig. 5), an analysis of the transient characteristics of the output signal during the simulation of the acceleration moment of the electric motor was carried out. Fig. 13 shows a comparison of measurement results using exemplary parameters of the acceleration moment of the electric motor [20] and additional transfer functions that describe the dynamics of changes in elasticity in the dynamometric element (torsion shaft), the dynamics of changes in the position of signal pistons 8–11 of the dynamometric coupling (Fig. 9), speed video signal processing to determine the twist angle by means of machine vision.

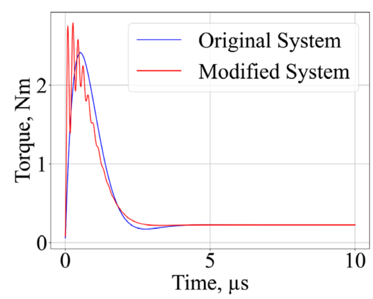


Fig. 13. Transient characteristics of the electric motor torque taking into account additional transfer functions

The resulting transient characteristic indicates a significant delay time of the signal and the unevenness of its stabilization, which is associated with its rapid increase during startup and stabilization in the stable mode of operation.

The solution to such a problem can be to reduce the reaction time of the system, which can be adjusted in the software code that was used for simulation (Fig. 8).

Fig. 14 shows a reduction in the reaction time of the circuits of this system, which describe the torque conversion functions using a dynamometric coupling and the video stream processing time by 10 %, 20 %, 30 %.

Thus, due to changes in the response of video signal processing and image analysis, it was possible to reduce discrepancies. It can be seen that the discrepancies between the simulated torque data obtained during acceleration of the electric motor according to the model in [20] and the data obtained as a result of modeling the complete measurement system based on machine vision (Fig. 5) are decreasing.

Therefore, in the course of the simulation, the discrepancy between the output signals obtained using the traditional method and the technique using machine vision was reduced. This was achieved by reducing the reaction time of the measurement function itself, which uses machine vision.

Thus, the optimization of this function increased the accuracy of determining the torque during the acceleration period of the electric motor (Fig. 14).

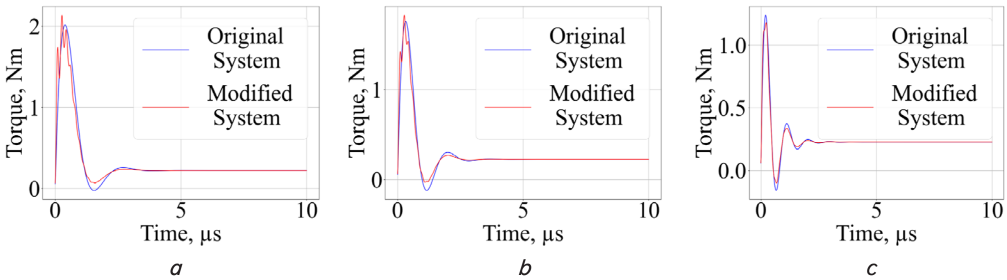


Fig. 14. Transient characteristic of the electric motor torque taking into account the reduction of the reaction time of additional transfer functions by 10 %, 20 %, 30 %: *a, b, c* – reaction levels of the measuring system circuits, respectively, reduction of the reaction time

In turn, reducing the reaction time of the system in a practical sense for the proposed technique means the use of high-speed video cameras and powerful computing devices. Therefore, the accuracy and speed of devices built on the basis of such approaches will depend on these parameters.

5. 3. Testing of the means for acquiring visual characteristics of the torque from the dynamometric coupling

As a result of our high-quality visualization of the results of the recognition of the rotational moment, an analysis of the operation of the dynamometric coupling was carried out. An analysis of the accuracy of the tool for processing the visual characteristics of the dynamometric coupling was performed. Such a tool includes the developed software code (Fig. 7, 8), an oldie Raspberry Pi 3 computer, and an IMX708 video camera. As a result, the visual changes of signal labels 8–11 of the dynamometric coupling (Fig. 9) were determined, and a high-quality visualization of such changes was obtained.

This made it possible to identify and quantify the level of deformation of the shaft (Fig. 15). In accordance with the algorithm for obtaining a high-quality visualization of the movement of signal labels (Fig. 7), two areas of red color are highlighted. After that, the pixels in each area are counted. At the final stage, the ratio of the number of red pixels in the area of moving signal labels 8–11 and reference labels 12–16 is determined (Fig. 9).

The study of the signal transformation characteristics during measurement using the video stream analysis algorithm (Fig. 8) made it possible to obtain the results shown in Fig. 16 and given in Table 1.

From Fig. 16, one can see that the torque characteristics derived in this way of measurement show a significant deviation from the average value, especially at the time of acceleration. This is due to the fact that the measurement procedure was implemented on the basis of an IMX708 video camera, which has a low resolution, and a low-power computing device Raspberry Pi 3. In addition, the influence of additional destabilizing factors, such as vibration and nonlinearity of the measurement channel, should be taken into account. Therefore, under better conditions of the experiment, the result could be much more accurate.

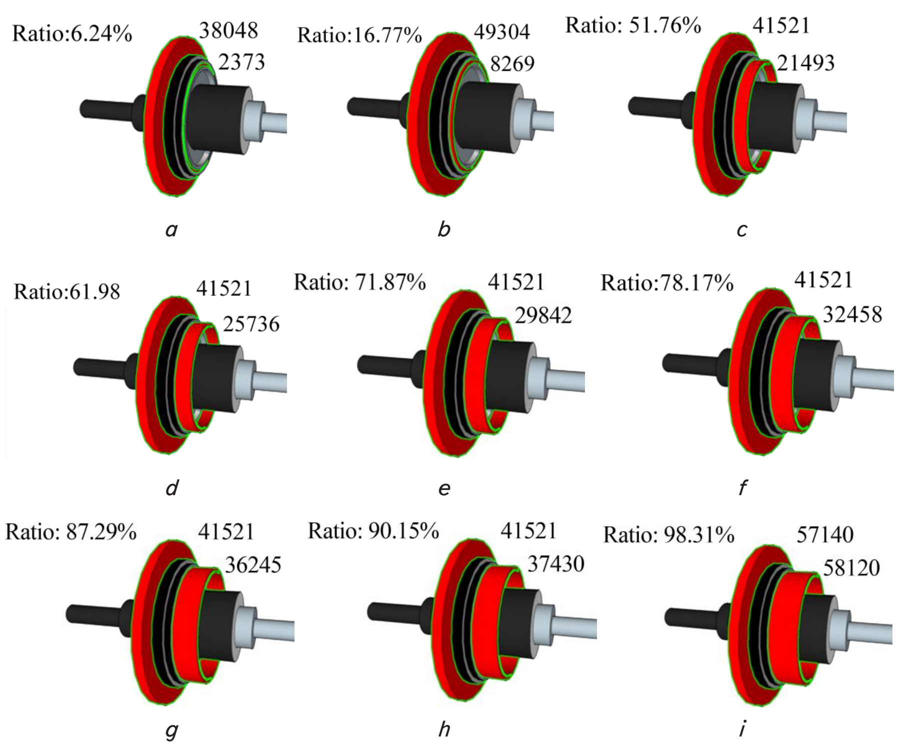


Fig. 15. Determining the change in the signal element by the method of object recognition by color shows discrepancies between the reference label and the variable depending on the applied moment: *a* – 6.2 %; *b* – 17.8 %; *c* – 51.8 %; *d* – 62 %; *e* – 71.9 %; *f* – 78.2 %; *g* – 87.3 %; *h* – 90.1 %; *i* – 98.3 %

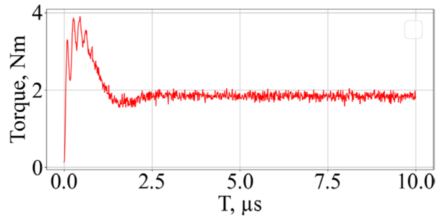


Fig. 16. The result of measuring the torque based on machine vision using a video stream

Table 1

Results of statistical observation of the results of torque measurements using machine vision employing a video stream

Indicator	Formula	Result, (Nm)	Designation
Mean value	$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i$	1.8	x_i – individual measurement values; N – total number of measurements; $\bar{x}$ – average value of measurements
Variance	$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$	0.03	
Standard deviation	$\sigma = \sqrt{\sigma^2}$	0.17	
Coefficient of variance (CV)	$CV = \frac{\sigma}{\bar{x}}$	0.09	
Mean absolute error MAE	$MAE = \frac{1}{N}\sum_{i=1}^{N}\lvert x_i - \bar{x}\rvert$	0.14	
Mean relative error MRE	$MRE = \frac{1}{N}\sum_{i=1}^{N}\left\lvert\frac{x_i - \bar{x}}{\bar{x}}\right\rvert$	7 %	

At the same time, the technique for determining the torsional loads on the shaft using machine vision and a special dynamometric coupling made it possible to determine the characteristics of the load intensity in a non-contact manner. And the use of the developed software code (Fig. 8) made it possible to conduct a comparative analysis of pixels on the signal and reference marks of the dynamometric coupling (Fig. 9).

6. Discussion of results of torque measurement using machine vision methods

Our results reported in this study can be explained by investigating the procedure for measuring the torques of electric motors based on a new informative parameter that uses the visual characteristics of the torsional load and determines them by machine vision methods.

Thus, owing to the features of the proposed dynamometric coupling (Fig. 9), the measurement can be carried out directly on the electric motor shaft without the use of electronic measuring transducers. Their function can be performed by a computing device with the necessary technical characteristics that can process the stream of video information. In comparison with tensometric or inductive moment converters, where the signal processing and its transmission is carried out directly on the shaft, this technique makes it possible to avoid the negative impact of an aggressive environment, elevated temperatures, radioactive radiation, etc.

In contrast to [12], in which the moment is measured by the pulse technique, the use of a dynamometric coupling as a converter of the angle of rotation of the shaft into a torque makes it possible to avoid the limitations of the sampling frequency of measurements, which are caused by the needs for the speed of signal processing tools. This becomes possible owing to the use of a new way of implementing the measurement transformation. So, the pressure that occurs in the dynamometric coupling during the occurrence of a rotational load is proportional to the moment. Accordingly, the pressure moves signal pistons 8–11, shown in Fig. 9, the movement of which is determined by means of machine vision. This, in turn, makes the proposed measurement technique independent of the shaft rotation speed since frequency characteristics are not used in the measurement process. Alternative existing solutions [4], in which the recognition of the signal marking of the shaft in the places of measurement of torsional loads, although they carry out a non-contact measurement technique, are based on frequency conversions, which requires high-precision probing sensors. Studies of the transient characteristics of the received pulse signal in this way have shown that the use of the pulse method for moment measurement is expedient within the limits of sensor deviation of ~10–30 %. The increase of such a deviation makes it much more difficult to recognize the pulse itself (Fig. 10).

The proposed dynamometric coupling could be used in torque measurement systems for visual control of shaft loads. The model of such a coupling is universal for use in many machine vision systems, which is explained by the structure of its signal elements, which change their shape under the action of the shaft twisting moment, allowing the use of such systems even under aggressive conditions where traditional methods are ineffective. However, the use of such a coupling has disadvantages, in particular, sensitivity to external conditions, especially to lighting and optical interference. Accuracy depends on the quality of manufacturing of signal elements and the quality of optical and computing equipment.

Despite this, the proposed dynamometric coupling could be used for non-contact measurements in cases where other torque converters may not work (open space, elevated ambient temperature, radioactive radiation, etc.).

The results of our study of the transient characteristics of torques of the electric motor showed the possibility of determining the response of the system to the input pulse. The simulation was carried out in order to determine the necessary characteristics of sensors used in frequency converters of moments.

Thus, the simulation of the response of the measuring system according to expression (23), based on the determination of the transient characteristics of the output signal depending on the errors caused by changes in the time constant for different values of deviation (0.1....1), demonstrated the following result.

The impulse method of measuring torques, which demonstrates high efficiency at deviations in the range of 10–30 %, faces certain difficulties when the response to the signal becomes unclear. This, in turn, requires the use of highly sensitive photosensors to enable the accuracy of measurements.

The linear relationship between Δt and K_1 elasticity values, which was found in the study using expression (12), indicates that the sensitivity of the pulse method could be adapted and optimized by adjusting the mechanical parameters of the dynamometric element (Fig. 11). This opens up opportunities for precise calibration of measuring systems depending on the specific needs of the application. The established linear dependence emphasizes the effectiveness of the impulse method, especially in applications where high sensitivity to minimal changes in torque is important. This can be especially valuable in cases where small vibrations or load changes need to be monitored.

Our results of simulating the process of measuring the torque of electric motor during acceleration using a well-known simulation model [20] were applied to test expression (12). This showed the correspondence of the obtained curve in comparison with the simulated one (Fig. 12), which indicates the effectiveness of model (12).

Analysis of the transient characteristics of the output signal of the torque measurement system using machine vision has shown the importance of dynamic properties when modeling the acceleration moment of an electric motor. The study included a comparison of standard acceleration torque parameters with data obtained using additional transfer functions. These functions take into account the dynamics of changes in the elasticity of the dynamometric coupling, the change in the position of its signal labels (Fig. 9), and the speed of video signal processing. The results shown in Fig. 13 demonstrate a significant delay time of the signal and the unevenness of its stabilization, especially under the mode of starting the electric motor. This is due to the significant inertia of the measurement conversion process, as video signal processing requires significant computing power. The solution to the problem was a reduction in the reaction time of individual chains of this system, which describe the torque conversion functions using a dynamometric coupling and the video stream processing time by 10 %, 20 %, 30 %.

As a result of reducing the reaction time to the input signal by 30 %, the deviation of the exemplary transient process [20] for the acceleration moment and the transient process obtained using the proposed functional model (Fig. 5) was minimal (Fig. 14, *c*). This made it possible to reduce the discrepancy between the measurement results between traditional methods and techniques using machine vision. Therefore, there is a need to use high-speed video cameras and powerful computing devices.

At the same time, this approach also has disadvantages since this system does not take into account the element of non-linearity of the measuring channel and instrumental errors of the dynamometric coupling itself.

This is confirmed by the results of testing the means of obtaining visual characteristics of the torque from the dynamometric coupling. They were carried out under the image recognition mode of the signal labels of the dynamometer coupling using the code developed in the Python programming language (Fig. 7). As well as under the video stream analysis mode (Fig. 8). In both cases, according to the algorithm for obtaining a high-quality visualization of the movement of signal labels (Fig. 7, 8), the selection of two red areas is achieved. After that, the pixels in each area are counted. At the final stage, the ratio of the number of red pixels in the area of moving signal labels 8–11 and reference labels 12–16 is determined (Fig. 9). The results of testing based on image processing (Fig. 7), shown in Fig. 15, demonstrate the possibility of carrying out such measurements and have an approbation nature.

The results of measuring the torque during acceleration of the electric motor, obtained under the video stream processing mode (Fig. 8), shown in Fig. 16, have a statistical interpretation. This interpretation is the subject of the discussion of the effectiveness of this technique, summarized in Table 1.

The Raspberry Pi 3 computing platform and the IMX708 video camera were used to conduct the experiment using this technique.

Thus, as a result of the analysis of our data, it is possible to identify several key aspects that help understand the behavior of the torque under the conditions of our experiment. In particular, the average value of the torque, which is 1.8 Nm, attracts attention. This indicates that, on average, the system generates a sufficiently strong torque. The variance of 0.03 Nm and the standard deviation of 0.17 Nm indicate a certain spread of torque values from the mean. Although the scatter is moderate, it indicates the existence of some fluctuations in the torque, which can be caused by external factors such as vibrations. Such a scatter of data is due to the peculiarities of the processing of the video stream and instrumental errors. However, the coefficient of variation of 0.09 indicates that the scatter of the data is relatively small compared to the average value, which demonstrates a fairly high stability of the torque under the considered conditions. This is a very important indicator for systems that require predictability.

The average absolute error of 0.14 Nm indicates that the average absolute deviation of the measurements from the mean value is significant. The mean relative error (MRE) is 7 %, which in general indicates a stable operation of the system, but which is not without accuracy deficiencies. The low accuracy of the measurements is due to the use of the IMX708 video camera with limited resolution and the weak computing device Raspberry Pi 3. The influence of vibrations and nonlinearities of the measurement channel also introduces some destabilization. Therefore, accuracy may improve under more optimal experimental conditions.

Since this technique is based on visual characteristics, it can be sensitive to lighting conditions and the quality of optical equipment. Inhomogeneous or insufficient lighting can affect the accuracy of measurements. However, despite the detected errors caused by the limitations of video equipment, the procedure for using machine vision to measure torques opens new prospects for estimating shaft loads.

To improve this technique of measurement, optimization of image processing algorithms and video capture tools is necessary. This would significantly improve the accuracy and reliability of such a technique, making it an important tool in industrial applications and scientific research.

7. Conclusions

1. A special transmission dynamometric coupling has been designed to combine mechanical measuring elements and machine vision tools. It has both advantages and disadvantages. Among the advantages, we can note an innovative approach to torque measurement, which includes the use of visual analysis to track mechanical deformations. This enables non-contact measurements and reduces the impact of external destabilizing factors on the measurement process.

Testing of this coupling made it possible to detect visual changes in the signal moving element and quantify the level of shaft deformation. The results of the statistical analysis of our research indicate that during the experiment the average torque was 1.8 Nm with a variance of 0.03 Nm and a standard deviation of 0.17 Nm, indicating the stability of the system. The coefficient of variation of 0.09 demonstrated high homogeneity of the results. In turn, the absolute and relative errors of 0.14 Nm and 7 %, respectively, indicate the need to improve the accuracy of this measurement technique, since modern tools for diagnosing torques located on the shaft have a ten times smaller error. However, the potential for improved accuracy in the experiment was limited by the low resolution of the video camera and the low power computing device.

Nevertheless, our results show that the integration of machine vision into the measurement process opens up new prospects for improving the accuracy and reliability of measurements in the future.

2. As a result of modeling the rotational parameters of a direct current electric motor, a system of dynamic chains has been built, which includes the functions of visual fixation and analysis of shaft deformation. Testing of the model made it possible to establish that the sensitivity of the measurements depends not only on the speed of rotation of the shaft and the characteristics of signal processing but also on the characteristics of the sensor, which can increase the cost of the equipment and the time of signal processing.

The study of transformations of torques made it possible to build a simulation model of the dependence between the elasticity of the dynamometric element and the characteristics of the output signal of the measuring transducer. We also obtained the transient characteristics of the output signal taking into account the deviation from the rated value and integrated the considered models into already existing simulation systems. This made it possible to evaluate the linearity of the measuring channel and to determine ways of further diagnosing measuring systems of this type.

When comparing the transient characteristics of the output sample signal during the simulation of the acceleration moment of the electric motor and the signal with the addition of additional circuits describing the dynamic characteristics of the measurement process using machine vision, signal discrepancies were found. Reducing the reaction time of circuits simulating the time characteristics of image processing processes of the proposed functional model by 30 % made it possible to eliminate discrepancies between simulated data and actual results. The practical implementation of such a reduction requires more expensive and fast-acting equipment.

3. To acquire the visual characteristics of the torque from the dynamometric coupling, a program code used for processing graphic information is proposed. Its implementation involves two modes: static, for image processing, and online, for video stream processing. Obtaining the visual characteristics of the rotational moment was carried out online and demonstrates the successful approbation of the software code, which was implemented on the basis of a single-chamber computer Raspberry Pi 3, which has the ability to work with a video camera IMX708.

Their use made it possible to recognize the position of special marks of the dynamometric coupling, the translational movement of which is proportional to the torque. The process of converting such translational movement into an output unified signal confirms the possibility of introducing a new informative parameter based on the visual characteristics of the torsional element placed on the shaft.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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