Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 3373197, 9 pages
https://doi.org/10.1155/2021/3373197

Research Article

Technical and Economic Description of the Research on a Measuring Device for Continuous Measurement of the Diameter and Vibration of the Workpiece during the Machining Process

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Received 12 August 2021; Accepted 30 October 2021; Published 20 November 2021

Academic Editor: Georgios I. Giannopoulos

This article is devoted to the economic and technical aspects of the research on continuous noncontact measurement of the workpiece diameter during the manufacturing operation using a suitably selected and designed sensor. In order to achieve this main goal, it was necessary to meet these partial goals. We develop and describe a method of accurate continuous technical measurement of the workpiece diameter during the machining process. We propose a principle of continuous technical measurement of workpiece diameter, design a scanning method based on this principle, and verify the developed equipment on a specific case of technical measurement. At the same time, the development includes the expansion of the use for continuous noncontact measurement of workpiece vibrations. Based on test measurements, an optical sensor was selected, the analysis of which is presented in a part of the article. The introduction of this article provides a simple view of the need for continuous measurement of the workpiece diameter. The second chapter presents the current state of the problem. The third chapter is devoted to the theoretical analysis and description of practical implementations of the solution. The conclusion, as it could be expected, includes evaluation of the results.

1. Introduction

Continuous measurements of the workpiece diameter are based mainly on the principle of the contact motion of a measuring system component by which the workpiece surface position is transmitted. This method is relatively accurate; however, it has some pitfalls such as wear of the contact zone (measurement inaccuracy is increased), need of moving the contact arm forward and backward when changing the workpiece, mechanical transfer of vibrations from the workpiece to the measuring system (causing the measurement inaccuracy and mechanical damage to the measuring system), and need of cleaning the splinters off the contact zone [1–4].

During specific measurement of the workpiece diameter, this method is not fully used when compared to its overall possibilities and the necessity of using highly sensitive measuring system. This measurement with a mechanical arm finds its use mainly in the field of 3D measurement of complicated component shapes or in case of technical diagnostics used to search and determine the defective parts of a machine or other mechanical system that contains rotating or sliding components. In such case, the contact measuring system serves to detect the axis deviation, wobbling, offset, etc. This system is described in more details in publications [5–8].

To achieve specific continuous measurement of the workpiece diameter, we can focus on those quantities that are influenced to the greatest extent by the changing of the workpiece diameter. When selecting these quantities, the emphasis was also put on other indicators influencing the result of the measurement such as difficult construction of mechanical and electronic device necessary to provide the sensing, simplicity of the sensing principle, energy and economic efficiency of the sensing process, and sensing precision and sensitivity [9–12].

After taking into consideration all the aspects and facts, we opted for direct continuous measurement of the workpiece diameter. The measurement of this quantity was chosen because it fulfilled the foregoing requirements when compared to other possible quantities [13–18].

The following chapters of this paper deal with the measurement of the workpiece size change which then influences another parameter being the height of the circular segment X in the cross-section of the workpiece (Figure 1). By measuring the size of this parameter, we can find out the exact workpiece diameter. It also has several other advantages. Beside the continuous measurement of the workpiece diameter, we will focus on the processing of the measured quantity, its evaluation, and the application of its results. When the respective tests were carried out, the optical sensor proved successful for the following reasons [19–21]: sufficient sensitivity (suitable for measuring the change of the workpiece size), relatively simple and affordable installation and dismantle of the sensor into the holder and the machine tool, the simple construction of the sensing unit as such , which corresponds to its price, cost and time, efficient service, high durability and constancy of the parameters under recommended operation, negligible effect of the surroundings on the functionality, and precision of the measurement [22–29].

As an example, worldwide research results in this direction may include research work dealing with modeling of boring mandrel working process with vibration damper, research results presented in the work diagnostics of electrical drives and logical-linguistic model of diagnostics of electric drives with sensors support, and research results in design of the construction and research of vibrations and heat transfer of mine workings. On the issue of damping external loads of mine racks, geometrical method for increasing precision of machine building parts and case study of performance analysis and development of robotized screwing application with integrated vision sensing system for automotive industry are used [30–35].

2. Description of the Device for Measuring the Diameter and Vibrations of the Workpiece

Based on the well-known excellent qualities of optical sensors proven by measurements, the continuous measurement of the workpiece diameter and vibrations was elaborated. The principle of the instrument is described in Figure 1. It is composed of a transmitter transmitting the infrared light, a receiver with a photosensitive element, and a holder and a bracket with a tool bit stabilized with screws. The adjustable arm is mounted to the bracket and stabilized with a screw. The adjustable holder is stabilized with a screw and placed on the other side of the bracket under a given angle, depending on the horizontal plane passing through the workpiece axis with the radius R_1 or the radius R_2 at the measuring place. The measurement is carried out with a measuring device that allows us to directly read the value of the workpiece radius.

As shown in Figure 1, the device is composed of the transmitter transmitting the infrared light and the receiver working on the principle of controlling the power of the light beam that impinges on the receiving part composed of a photosensitive element. The transmitter and the receiver are placed opposite to each other on an adjustable metal holder under a given angle, depending on the horizontal plane passing through the workpiece axis. The tool bit is tightly stabilized to the bracket with two screws, on which the adjustable arm is mounted and stabilized as necessary with a screw. On the other side of the adjustable arm is the adjustable holder with sensors, which is stabilized with a screw. A light beam is transmitted towards the light receiver under a given angle depending on the horizontal plane passing through the workpiece axis with the radius R_1 or the radius R_2. However, during a certain part of the trajectory, the light beam is partially shadowed by the work surface of the workpiece, which will show up as the control of its optical power. The shadowed part X_1 and X_2 of the light beam depends on the momentary size of the workpiece diameter in the place of measurement. For this reason, only a part of the light beam arrives at the receiver. Its size depends on the size of the shading workpiece surface, on the workpiece diameter. Precision and sensitivity of the measurement depend on the selected angle. The angle is given by the equation.

Electric signal from the light receiver is processed by measuring and evaluating using a display device that serves at the same time to control the light beam transmitter. The instrument can be used for the contactless, continuous measurement of the workpiece diameter during the continuous fabrication on the lathe. The sensitivity of the measurement can be adjusted mechanically by changing the size of the angle between the light beam and the horizontal plane passing through the workpiece axis. Precision and sensitivity of the measurement depend on the size of the angle. The infrared LED diode is used as the light source. Receiving part is composed of three infrared phototransistors connected in parallel. Phototransistors are placed close to each other to ensure continuous and smooth lighting. To eliminate the undesirable light beams, aperture is placed in front of phototransistors.

Size of the shaded portion X is calculated as follows. For angle α between light beam and horizontal surface passing through the axis of the workpiece applies a relationship shown in Figure 2.

$$\sin\,\alpha = \frac{a_1}{R_1} = \frac{a_2}{R_2}. \tag{1}$$

The shaded portion of the light beam is determined:

$$\begin{aligned} X_1 &= R_1 - a_1 = R_1 - R_1 \cdot\ \sin\,\alpha, \\ X_2 &= R_2 - a_2 = R_2 - R_2 \cdot\ \sin\,\alpha. \end{aligned} \tag{2}$$

Thus,

$$X = R \cdot (1 - \sin\,\alpha). \tag{3}$$

The percentage obscuration of the beam:

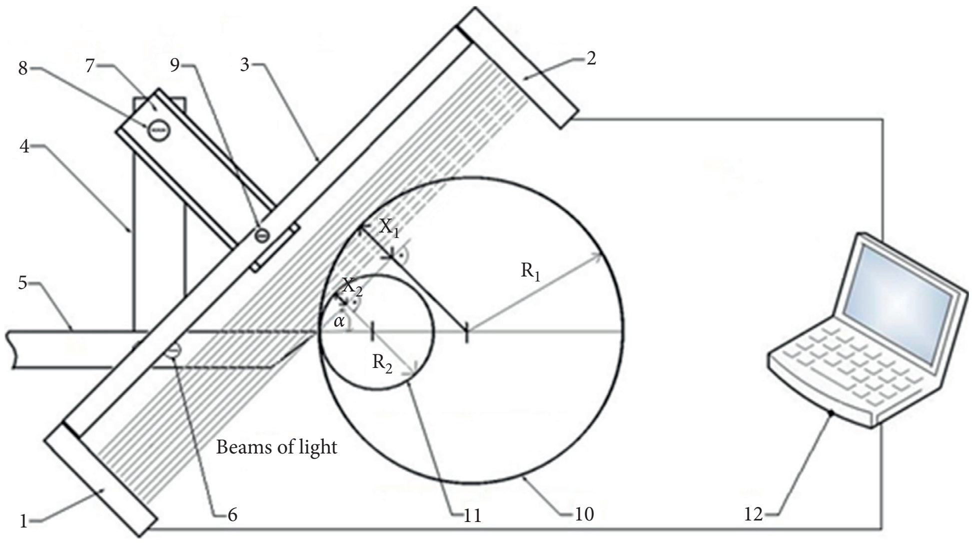

Figure 1: Optical sensor placed on tool holder. Description: transmitter of infrared light (1), receiver of infrared light (2), adjustable holder (3), console (4), turning tool (5), mounting bolt (6), adjustable arm (7), bolt of distance setting (8), bolt of angle setting (9), workpiece with radius R_1 (10), workpiece with radius R_2 (11), measuring, evaluation, and display device (12).

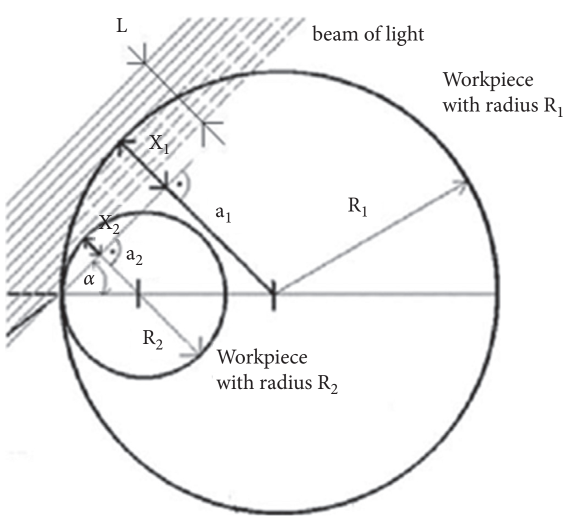

Figure 2: The relationship of parameters in the position of light beam and workpiece.

$$X\,(\%) = \frac{R \cdot (1 - \sin\alpha)}{L} \cdot 100. \quad (4)$$

It follows that the measured radius R is calculated:

$$R = \frac{X}{1 - \sin\alpha}. \quad (5)$$

Another possible way of implementing a sensor is creating a reflexive optical sensor based on the principle of reflecting the light beam off an obstacle. However, the size of the reflected light power would also depend on the workpiece surface roughness and, thus, a defective factor of the measurement would be created. Solving this task was divided into the following phases: design of the sensing part of the device, design of the electric part of the device, function verification of the device, and sensor design.

The design of the sensor placement is based on the assumption that the sensor will be based on the principle of the size change of the light beam power falling on the receiver caused by the change of the workpiece diameter. It is also necessary to take into consideration the fact that the sensing light beam should pass through the area of cutting as close as possible so that it can immediately react on the change of the workpiece size, however, not too close because the rebounding splinters could obstruct the transition of the light beam.

To ensure the exact position of the light beam towards the workpiece, the possibility of precise adjustment must be guaranteed. One of the possible ways of its construction is shown in Figure 3.

The possibility to adjust the position of the sensing beam towards the workpiece is provided with a special sensor holder containing the arm to adjust the sensor in terms of the X-axis and Y-axis and the angle of rotation. The sensor holder is mounted with screws with notched washers to increase the frictional power. After adjusting the suitable position of the light beam, the screws are securely tightened.

2.1. Sensor Placement. When designing the placement of the sensor, various alternatives were taken into consideration. However, these placements had various disadvantages such as the problem of precise adjustment of the light beam transition.

As shown in Figure 1, this position of the placement was chosen because the tool and the light beam are moving at the same value in the same direction and the sensor records the momentary value of the workpiece diameter and vibrations. The impact of the splinter is partially removed by placing the light beam transmitter with rounded upper part in the lower part of the device and, at the same time, by the fact that the receiver and transmitter are distant enough from the zone of cutting.

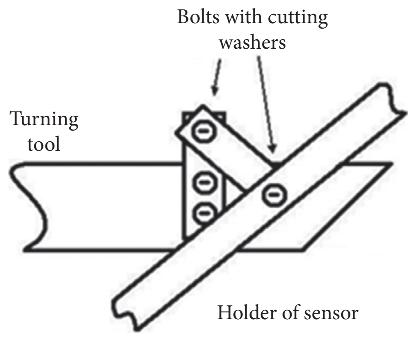

Figure 3: Construction of sensor holder.

A great advantage of the optical sensor among other sensor types is that the shading from external electromagnetic and electrostatic factors is not necessary since the light beam is resistant to them. Another great advantage is that the sensing is not dependent upon the temperature in the zone of cutting because both the light beam receiver and transmitter are distant enough from this zone. Measuring the workpiece diameter with the optical sensor is hardly affected by vibrations of workpiece and tool. Protection against this interference is achieved by a low-pass RC filter, at the output of which the mean value of the measured quantity is achieved. Alternating component caused by these vibrations is filtered out of the direct component by a capacitor. It is then controlled by a full-wave rectifier and its process is smoothed by an output capacitor. In this way the mean value of the measured signal is achieved at the output which represents the value of workpiece vibrations. We can prevent the interruption caused by elastic deformation by placing the sensor in the front part of the holder. The sensing part contains a special infrared filter which transmits only the infrared part of the luminous spectrum. This way the interruption caused by the penetration of undesirable light can be eliminated.

3. Design of the Electric Part of the Device

When changing the workpiece diameter, the light power falling on the receiving part of the sensor is decreased. This change is transformed into the change of the electric voltage which is measured and displayed at the same time by a measuring device.

3.1. Possibilities of the Measuring Device with the Optical Sensor. A measuring device for measuring the workpiece diameter with the optical sensor has the following possibilities in the measurement process: measuring of the workpiece diameter with possible adjustment of the measurement range, possibility of active measurement of workpiece vibrations before the tool starts to cut, so that the working is effective, possibility of connecting the device to the computer and the vibrodiagnostic data processing during the measurement, possibility of device calibration—the device is portable and driven by electricity— and possibility of device calibration.

Description of individual blocks of the measuring instrument. The proposed system contains the following blocks: a block necessary to provide the sensing of the workpiece diameter and a block used to process the sensed quantity and reach the required shape and the signal level to evaluate the diameter and the vibrations of the workpiece.

A block is necessary to provide the sensing of the workpiece radius. From the above-mentioned reasons we decided to measure the workpiece diameter using the contactless optical method continuously during the working without having to remove the workpiece from the spindle. To measure the workpiece radius, a precise and sensitive optical sensor with photosensitive element plugged into the electric bridge was used (Figure 4).

The electric bridge was designed to ensure a balanced position and the ability to convert electric resistance of phototransistors connected in parallel to electric voltage. Values of resistors placed in the bridge had to be selected so that it did not load the circuit and the output voltage could be set to a desired range. The output of the bridge is composed of a voltmeter with the possibility of selecting the measurement range from one to one hundredth of a volt. Block of the photosensitive element model represents three phototransistors connected in parallel. The model is composed of resistors connected in parallel that gradually disconnect from the circuit with a switch. This represents a process during which the receiving part is gradually shaded by a workpiece and the electric resistance of the phototransistors is gradually increased in order from one to three. When these changes are not made in order, a discrete change of the electric resistance will occur as well as a discrete change of the output voltage value. To smooth the process from the interrupting impulses, a filtrating capacitor is connected in parallel to the phototransistors. When changing the voltage values, the capacitor causes a transition process with a delay.

From the results of transition analysis (Figure 5), it can be seen that the connection reaches the satisfactory voltage change when changing the resistance in full extent. When changing the resistance value of the photosensitive element from $R_1 = 1500\Omega/4$ to $R_2 = 1500\Omega/3$ when switches from Step 1 to Step 3 are turned on, electric voltage was changed from 1.4 V to 1.8 V. The difference is 0.4 V. When changing the electric resistance from R_2 to $R_3 = 1500\Omega/2$, the difference in the resistance is 0.7 V. The change of the electric resistance from R_3 to $R_4 = 1500\Omega$ causes a voltage change V_1 of 1.6 V. V_1 is the input voltage and V_2 is the output voltage. The separation of the vibrations from the workpiece diameter is shown in Figure 6. A signal is obtained from the phototransistor. The one-way component of the signal V_2 is used to evaluate the value of the workpiece diameter. The alternating signal component V_1 is used to evaluate the vibration value of the workpiece. It can be seen that the speed of the voltage increase is increasing with gradual shading of the receiving part of the sensor. This condition is very useful because, at the initial level, when the voltage changes are smaller, the voltage range can be reduced, which enables the increase of the sensor sensitivity even in this initial sensing part.

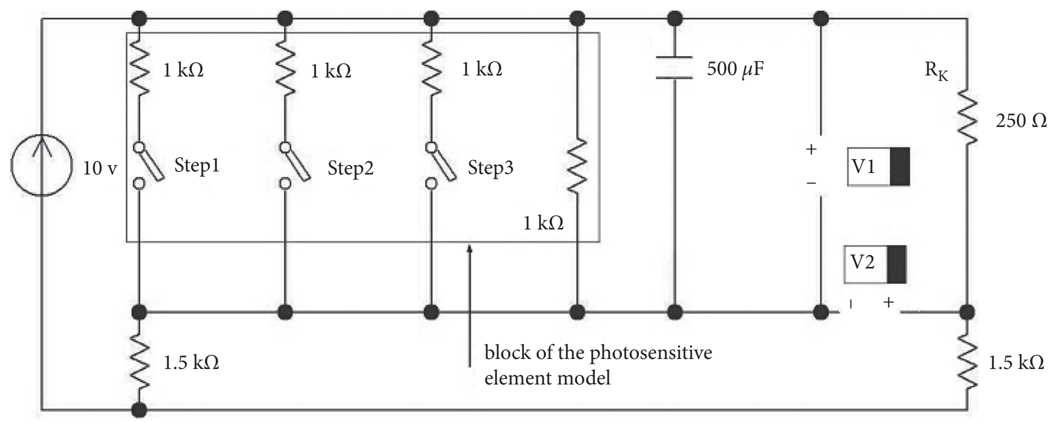

FIGURE 4: Connection of electric bridge with a photosensitive element.

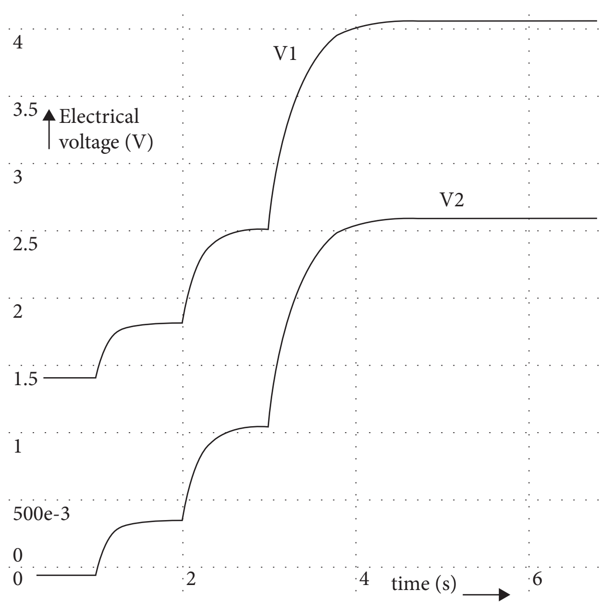

FIGURE 5: The results of transient analysis plugged into an electrical bridge with a photosensitive element.

This ensures sufficient precision of the sensor during the measurement. The device is calibrated to zero by a calibration resistor. Low-pass RC filter that was used to reduce the short-term undesirable signals from the controlling process causes the delay of the quantity transition from one value to another after the initial impulse arrival for the value of time constant $T = R{\bullet}C$, where R stands for the value of the resistance when the electric capacitor C is charging.

3.2. Procedure and Conditions of Practical Measurement. A specially adjusted and attached micrometric screw was used as a model device. With this screw, the precise motion of the observed point can be achieved. The sensor was tightly secured to the table. Micrometric screw mounted perpendicularly to the sensor beam served as a substitute for the workpiece with changing diameter. By means of the a working screw, the movable tip replacing the workpiece is moved towards the beam so that the workpiece is shaded to a certain extent. This point is set as the initial point and the values from the micrometric screw and the voltmeter are subtracted. Then the movable tip creating a shade is moved for the first measured value ΔX and the value from the micrometric screw and the voltmeter is subtracted. Then the movable tip creating a shade is moved away. In the second measurement, it is moved back to the same position as in the previous measurement. The measurement is repeated 10 times with the same position of the movable tip creating a shade. Measurements are provided at 10 different tip positions and the results are evaluated.

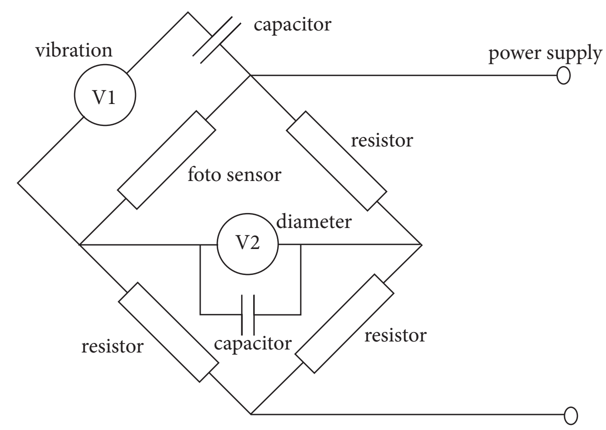

FIGURE 6: Separation of vibrations from the workpiece diameter.

3.3. Determination of the Range of the Measurement Precision and Verification of the Sensor Function. Gradually, the voltage was measured at various positions of the tip creating a shade. Results are recorded in Figure 7. Graphic dependence of particular characteristic values and their mutual comparison is shown on diagrams in Figures 7 and 8.

From the measured values we can see that the dependence of the measuring voltage on the position of the tip creating a shade is at certain intervals almost linear. The result is a graphical plot of the transfer in Figure 8. Also, the course of the split to parts can be linearized and used to measure display element switchable ranges.

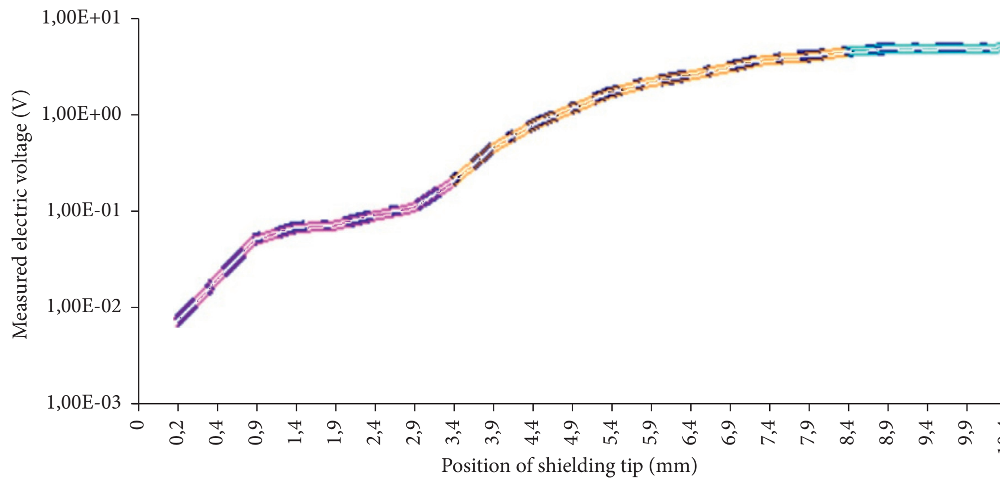

Figure 7: Graphical plot of the arithmetic mean of electric voltage to the position of the shielding tip in a logarithmic scale.

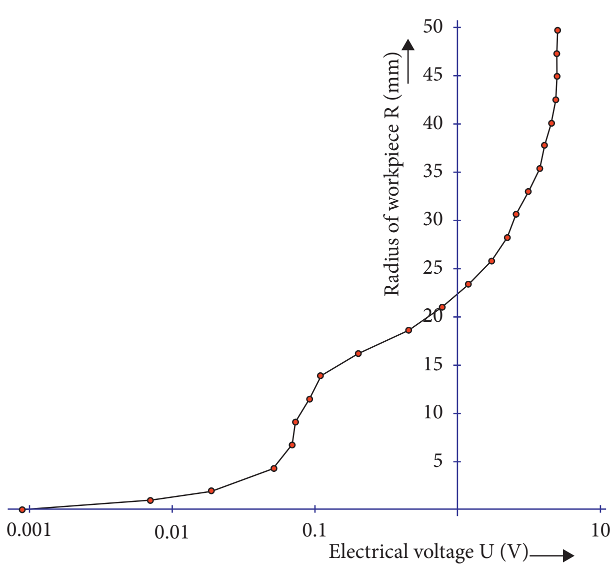

Figure 8: Graphical plot of transfer $R = f(U)$ on a logarithmic scale.

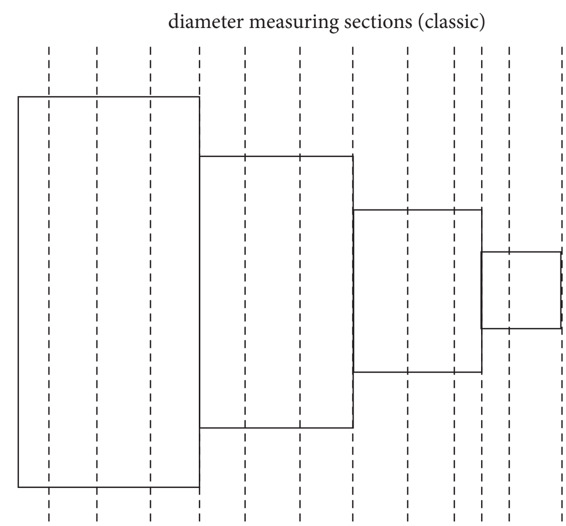

Figure 9: The shape of the test sample.

4. Practical Verification of the Device

In the practical verification of the optical sensor for measuring the diameter and vibration, good results were found. The optical sensor was mounted on a lathe and production was underway. The workpiece (Figure 9) had graduated diameters. The sensor was tested for each diameter. The measurement result was compared with the actual one. The estimated benefit in production is 15%. A practical verification of the functionality of the diameter measuring device was performed. The shape of the test sample (material 100CrMnSi6-4) is shown in Figure 9. Hourly productivity with classically performed average measurements was 11 pieces per hour. The number of measurements per hour was 132. The time required for one classical average measurement was 8 seconds, 17.6 minutes per hour. With automatic diameter measurement, this time is saved. By using the automatic measurement of the diameter, the steps necessary for the measurement in the classical way will be reduced. The time saved means lower production costs and more efficient production.

4.1. Benefits for Practice. Achieving higher efficiency of workpiece diameter control directly during the turning operation saves time required to perform part size control measurements during machining to obtain information on machining accuracy. Avoid production of insufficiently precise workpieces due to unwanted vibrations of the workpiece and tool during turning. Higher efficiency in the machining control process is achieved due to the possibility of applying a feedback mechanism to stop the machine in case of exceeding the vibration limit value or tool wear. There is a reduction in the number of inspectors due to continuous monitoring of the turning process with the possibility of computer data processing, saving time required to perform part size control measurements during machining to detect tool wedge wear. There is higher efficiency of control of machining processes due to the possibility of concentrating data from several machine tools on one computer, higher efficiency in the process of implementing the wear compensation of the cutting tool wedge due to the possibility of applying the automatic correction performed by the auxiliary sliding device controlled by the control element, higher efficiency in the control of the machining process due to the possibility of implementing the control of several machine tools simultaneously using a computer, by the application of appropriate software, and higher efficiency in remote monitoring and control of the machining process due to the possibility of data transmission over the electronic network. There is a possibility of archiving data obtained from the machining process.

4.2. Benefits for Theory. The theoretical description of the following is presented: a mathematical model of an eccentrically rotating workpiece from the point of view of machining; an optical sensor working with a shielding screen, in terms of the principle of functionality and the possibility of application in the field of machining; the practical application of a bipolar transistor operating in the region of the highest current rise; a mathematical model of the process of wear of a cutting tool wedge with an application in the field of simulation; a mathematical model of the cutting tool wear correction process with application in a simulation environment; an example of the application of a probability function $R(t)$ in the machining process, and the practical application of the microcontroller as an A/D converter.

4.3. Benefits for the Pedagogical Process. The benefits of the pedagogical process are demonstrations of technical construction and measurements when taking over the curriculum; implementation of measurements used to develop assignments; implementation of measurements used to prepare the final bachelor's and master's theses; and sample measurements to verify the functionality and principle of the measurement.

5. Conclusion

The use of optical sensing in the field of turning has several advantages, especially due to properties such as contactlessness, resistance to most disturbances, and achieving high accuracy. This work solved the continuous measurement of the workpiece diameter during the machining process. This principle has been practically and theoretically verified and meets all the prerequisites for application in practical operations. An associated application of this sensor has been shown to measure the vibrations of the workpiece before the actual removal of the knife, so that machining is not inefficient. Measuring vibrations before removing the knife will make it possible to determine the correct clamping of the workpiece to the spindle, bending of the workpiece, or an anomaly in the geometry of the workpiece.

When comparing this method with other methods, it is possible to start from different points of view. The accuracy of a method based on vibration sensing depends to a large extent on the accuracy of the setting of the system formed by the tool and the workpiece. The accuracy of the method based on measuring the force acting on the tool, or the temperature near the cutting zone, is influenced mainly by the hardness of the technical material and also by the setting of the system formed by the tool and workpiece or cutting parameters. In the case of measuring the wear of the cutting tool wedge, it is a process with very little dynamics over a relatively wide time interval. For this reason, it is not very important to deal with the comparison of measurement methods in terms of sensing possibilities, with the least possible delay. When verifying the function of the sensor in the machining process for a given type of sensor holder, there were difficulties with the outgoing chip of larger dimensions. Therefore, it is necessary to design a holder of minimum dimensions at the location of the workpiece with the greatest possible distance from the workpiece.

The measuring device is equipped with an A/D converter created from a programmable Arduino microcontroller. The microcontroller is modular, has treated inputs and outputs, and can communicate with other devices of the same but also different type. The A/D converter is connected to the computer via a USB connector, but programming takes place on the computer via a simulated serial interface. A conversion function has been programmed into the microcontroller, which allows direct display of the value of the required quantity and in the required units. The visually displayed value is updated with an adjustable frequency.

The researched device has a wide practical application. Its application is possible in the manufacturing industry as a diagnostic device for modeling the work process of the drill mandrel using a vibration damper and as a device for diagnostics of electric drives and logical-linguistic model of diagnostics of electric drives with the support of sensors. The research was applied in the design and research of vibrations and heat transfer of mining parts, in the damping of external loads of mining racks, in the geometric method to increase the accuracy of machine parts, and in a case study of performance and development of robotic screwdriving with integrated vision sensing system for automotive industry.

Data Availability

No data were used to support this study.

Disclosure

This paper has been elaborated in the framework of the project ITMS no. 26220220063, project VEGA 1/0051/20, project KEGA 004TUKE-4/2020, and project KEGA 038TUKE-4/2021

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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