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Design and Development of a Model for Accuracy Assessment and Measurement Error Quantification of Optical Rotary Encoders Under Vibration

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This study presents the development and implementation of an innovative model designed to evaluate the measurement errors of optical rotary encoders subjected to mechanical vibrations. The methodological framework involves the analysis of factors related to the accuracy and stability of three commercial optical rotary encoders, with the objective of quantifying measurement errors induced by vibrations. To obtain a more profound understanding of the encoders' behaviour under realistic dynamic conditions, the results were processed in MATLAB, enabling an advanced analysis of the system's response to vibration. This approach improves both the accuracy and reliability of the model, allowing for a thorough assessment of encoder performance under varying vibration disturbances. The designed and developed model within this study represents a significant and original contribution to the field of optical rotary encoder performance analysis under dynamic operating conditions, with a particular emphasis on the impact of mechanical vibrations on measurement accuracy and stability.

Keywords: *Resolution, Angular position, Frequency, Amplitude, Test series, Angular Error, Performance.*

1. INTRODUCTION

An optical encoder is a highly precise electromechanical sensor and an important part of modern systems for automation, control, and measurement. Depending on its functional purpose, the type of motion detected, the measurement principle employed, and the configuration of the output signal, an optical encoder is typically categorised as either a rotary or linear type [1,2].

The optical rotary encoder (Fig. 1) is specifically designed to provide accurate determination of angular position, angular velocity, and rotational direction of mechanical components in motion. Due to its capability for real-time data acquisition with high measurement resolution, the encoder is extensively utilised in a wide range of applications, including CNC machines, robotic systems, servo mechanisms, motion control units, and various automated industrial processes [3-5].

The primary function of an optical rotary encoder is to convert rotational mechanical motion into electrical signals suitable for processing by various types of electronic controllers or computer-based systems. These signals facilitate precise monitoring, control, and ana–lysis of rotary motion, thereby enabling a high level of automation and accuracy within technical systems. As a result of their high resolution and measurement stability, optical rotary encoders are commonly considered the standard solution in applications requiring maximum reliability in the detection of positional and speed variations [6,7].

Figure 1. An optical rotary encoder [8]

The fundamental operating principle of the optical rotary encoder is based on the interaction between a light beam and a specially designed rotating disc fea–turing alternating zones with distinct optical charac–teristics, typically transparent and opaque, or reflective and non-reflective surfaces. This disc is mechanically coupled to the rotational axis of the object whose angular displacement is being measured, ensuring that it rotates synchronously with the object. This confi–guration provides continuous, real-time measurement of the angular position [9,10].

The light source, typically a light-emitting diode (LED), emits a monochromatic beam that passes thro–ugh or is reflected from the surface of the rotating disc, depending on the optical configuration of the encoder. As the disc rotates, the beam interacts with the patterned structure of this disc, resulting in periodic modulation of

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the light signal in the form of interruptions or pulses. These modulated light signals are detected by photo–sensitive elements, commonly photodiodes or photo–transistors, positioned opposite the light source (Fig. 2). Each interruption or transmission of the light beam generates a distinct electrical pulse, forming a sequence of pulses with frequency, phase, and order that can be analysed to accurately determine the angular position, rotational direction, and speed of the rotating object [11].

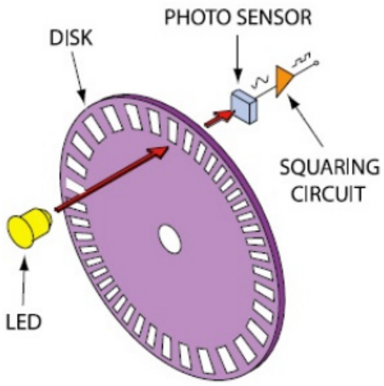

Figure 2. The fundamental operating principle of an optical rotary encoder [12]

One of the key parameters that directly influences the accuracy of angular position measurement of optical rotary encoders is the resolution. Resolution is defined as the number of electrical pulses generated by the encoder during a single full rotation of its disc. For instance, an encoder with a resolution of 100 pulses per revolution (PPR) produces 100 discrete pulses for each complete 360-degree rotation. Consequently, each pulse corresponds to an angular displacement of 3.6° (i.e., 360°/100). In comparison, an encoder with a resolution of 200 PPR generates one pulse for every 1.8° of rotation, while a resolution of 360 PPR enables angular measurements with a precision of 1° per pulse [13].

As the resolution increases, the angular segments become progressively smaller, enabling the measure–ment of each displaced position of the rotating object with enhanced precision and greater information den–sity. A higher resolution not only contributes to improved measurement accuracy but also enhances the stability and responsiveness of the overall motion con–trol system. The higher the resolution, the greater the system's capability to detect minute variations in motion and respond appropriately, which is critical in appli–cations characterised by high dynamic performance requirements [14,15].

1.1 Literature Review on Optical Encoders

The analysis of performance and the estimation of measurement errors in optical encoders constitute a critical aspect of research in dynamic operational environments, where accuracy and precision are paramount. Scientific studies in this domain underscore the importance of examining the various factors that influence measurement accuracy. According to Alejandre and Artés [16], the most significant impacts on the performance of optical encoders stem from structural deformations, temperature fluctuations, and vibrations within the systems in which these devices are integrated.

In the context of structural deformations and tempe–rature fluctuations, Delbressine et al. [17] developed a methodology for measuring and modelling thermally induced deformations that contribute to positioning errors in multi-axis metal cutting machines. This rese–arch proposes a model for reducing encoder measu-rement errors by analysing temperature distribution and applying the principles of rigid body kinematics.

Additionally, Alejandre and Artés [18] conducted a comprehensive investigation into the influence of ther–moelastic deformations, induced by various thermal sources, and ambient temperature fluctuations on the accuracy of optical linear encoders. They developed a real-time compensation model for geometric and ther–mal error in optical linear encoders. Implemented on an FPGA platform, this model demonstrated a remarkable reduction in measurement error by up to 98%. Similarly, Kim et al. [19] explored the impact of thermally induced deformations, primarily resulting from heat generated in linear motor systems, on both the accuracy of encoders and the structural performance of metal-cutting mac–hines. Their study systematically identified the primary sources of thermal errors and the corresponding deformations, including thermal expansion, displace–ment of linear scales, and deformation of machine components.

In the study performed by Ramesh et al. [20], the effects of prolonged and uninterrupted operations of metal cutting machines were examined, with particular emphasis on the implications for machine performance over extended periods. The findings indicated that heat generated during continuous operation leads to thermal expansion of the machine's structural components, the–reby compromising the positioning accuracy of the moving elements. In a related study, Altintas et al. [21] carried out a systematic analysis of CNC metal cutting machines, identifying structural deformations and tem–perature fluctuations as critical factors affecting the accuracy of encoder measurements. Their research identified temperature fluctuations and mechanical deformations as the primary contributors to the degra–dation of positioning accuracy in CNC systems.

Although considerable research has addressed the impact of structural deformations and temperature fluc–tuations, comparatively fewer studies have examined the behaviour and performance of optical encoders under the influence of vibrations. Traditionally, analyses of encoder measurement errors, particularly in relation to the accuracy required for synchronising mechanical motion and ensuring precise positioning, have focused predominantly on the structural aspects of the systems in which encoders are integrated. Such approaches typically investigate constructional deficiencies, mecha–nical design limitations, damping effects, and the implication of mechanical clearance within the consti–tuent components, transmission mechanisms, and other system elements [22-25].

Despite the fact that measurement errors during the operation of optical encoders are most commonly asso–ciated with structural imperfections in the mechanical systems in which they are integrated, relatively few studies have examined the encoder itself as a potential source of error, particularly under dynamic operating conditions. Nevertheless, several research studies indicate that the encoder may indeed contribute to such inaccuracies, thereby opening new fields of research that remain insufficiently investigated.

In this context, the study conducted by Alejandre & Artés [26] is specifically noteworthy. In addition to evaluating the measurement errors of optical linear encoders resulting from deformations and temperature fluctuations, they also examined the impact of vibra–tions on linear encoder performance. Their methodology was orientated toward the identification, classification, and quantitative assessment of vibrations, with the objective of understanding the limitations of these devices across various dynamic technical and industrial environments.

Building upon these earlier findings, Alejandre & Artés [16] later expanded the scope of their research to emphasise the necessity of developing a systematic method for assessing the accuracy and quantifying the measurement error of optical linear encoders subjected to vibrational disturbances. In this subsequent study, they proposed an innovative framework for analysing the dynamic behaviour of optical linear encoders operating under vibration. In contrast to traditional approaches, their methodology introduced the novel concept of "measuring error for a frequency range". This perspective facilitates a more comprehensive assessment, revealing that under real operating con–ditions, it is indeed feasible to quantify the measurement error of optical linear encoders subjected to vibration.

The implementation of this method allowed for the development of a high-resolution behavioural spectrum of the linear encoder, effectively identifying instability zones in the examined frequency range. The method represents a significant advancement in this field by addressing two critical aspects: (1) the magnitude of measurement error at resonance frequencies and (2) the magnitude of measurement error in non-resonant frequency intervals.

Further expanding this line of inquiry, the study by López et al. [27] offers another application-orientated perspective by examining the impact of different moun–ting conditions on the measurement accuracy of optical linear encoders under vibration. In their experimental investigation, three commercial optical linear encoders from different manufacturers were tested in order to obtain general and representative insights. The proposed methodology focused on assessing the reduction in measurement accuracy as a function of vibration influence and mounting conditions. Key experimental parameters, including frequency range, vibration ampli–tude and test duration, were defined to ensure consis–tency and replicability.

The results demonstrated that the dynamic response of optical linear encoders varies considerably depending on the direction of vibrations. Moreover, specific mo–unting positions were found to introduce new resonance modes, which in turn generate substantial measurement errors. The results were visually represented through a series of graphs, illustrating how measurement errors correlate with vibration frequency.

1.2 Review of Literature Limitations as a Basis for the Design and Development of a New Model

Through the review of relevant literature, it is empha–sised that optical encoders are critical components in measurement and control systems, with their accuracy being influenced by various mechanical and thermal factors. While the effects of temperature fluctuations, thermally induced deformations, and structural defici–encies in the integrated systems have been previously investigated, the performance of optical linear encoders under the influence of vibrations has been explored to a significantly lesser extent, particularly in the context of real-world dynamic operating conditions.

Although certain initiatives have focused on deve–loping models for the assessment of optical linear encoder accuracy under dynamic conditions, the available literature indicates that a comprehensive and standardised model encompassing the measurement error of optical rotary encoders has yet to be developed. This gap represents a significant research challenge and opens opportunities for further analysis of optical rotary encoders as a potential source of measurement error in precision automated systems.

To address this gap, an innovative model is designed and developed in this study to evaluate and assess the performance of optical rotary encoders under varying levels and frequencies of vibration. The model enables a systematic investigation of encoder behaviour in realistic operational scenarios and provides critical data for the quantification of their measurement accuracy in dynamic environments. The focus of this study is essential for improving the accuracy and reliability of measurements obtained from optical rotary encoders, as well as for enhancing the dependability of the systems in which they are integrated.

2. DESIGN AND DEVELOPMENT OF THE MODEL

During the design and development process, the model was conceptualised as an integrated system, illustrated in Figure 3.

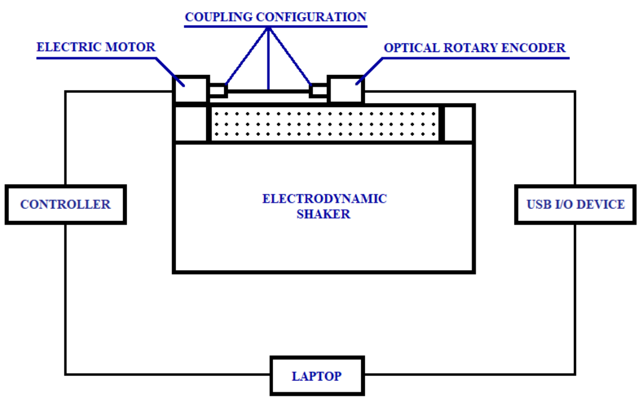

Figure 3. Design of the model

All of its constituent components were detailed and planned, and their integration was systematically orga–nised. Consequently, the model was structured as an integrated system comprising the following compo–nents: an optical rotary encoder, an electrodynamic shaker, an electric motor, a coupling configuration (including one flexible and two rigid couplings), a controller, a laptop computer, and a USB multifunction I/O device.

The commercial optical rotary encoder designated for testing is conceived as a central component within the integrated system. It is planned to be firmly mounted onto the electrodynamic shaker (model L1024M-PA115, manufactured by SENTEK EUROPE S.R.L.), which will generate controlled vibrations to simulate realistic operational conditions. In order to ensure high mechanical stability and measurement precision, a specialised clamping mechanism is to be employed to securely fasten the encoder onto the shaker, thereby reducing relative displacements and ensuring the relevance and reliability of the acquired test data. This approach is essential for eliminating potential measurement errors caused by undesired movements or improper positioning of the device.

The electric motor (ClearPath-SCSK series) is envisioned as the primary source of torque required to induce encoder rotation. This motor will be mechanically connected to the encoder and also rigidly attached to the electrodynamic shaker. Nevertheless, it is intended to be mounted on the shaker's isolated frame, allowing it to operate under static and stable operating conditions. This configuration is crucial for eliminating the influence of vibrations on the motor's performance and for achieving greater efficiency and long-term operational stability.

Torque transmission between the electric motor and the encoder is planned to be achieved through the carefully selected coupling configuration, consisting of one (commercial) flexible coupling and two rigid couplings (manufactured employing 3D printing).

This configuration is designed to enable optimal transmission of torque, with each component contributing distinctly to the dynamic stability of the overall system.

Each coupling has a distinct functional role: the flexible coupling is essential for reducing vibration-induced impacts during torque transmission, while the rigid couplings contribute to mechanical precision and alignment. Overall, this coupling configuration is designed to maintain a direct mechanical connection without significant elastic deformation, a prerequisite for accurate synchronisation between the electric motor and the encoder throughout the testing process. Additionally, it is intended to reduce potential energy losses and enable stable operation of the integrated system under nominal working conditions.

To facilitate the operation of the electric motor, the system design integrates the motor controller (ClearCore CLCR-4-13, manufactured by TEKNIC), which will interface directly with the laptop. Operating as an interconnecting component between the laptop and the electric motor, the controller will receive and process motion commands from the laptop while simultaneously controlling the motor in a manner that ensures stable and reliable operation. This linkage ensures secure and precise transmission of speed and directional commands, thereby contributing to optimal control and synchronisation within the integrated system.

The electric motor will act on the received commands and utilise its built-in encoder to provide real-time feedback on position and speed, enabling the controller to perform continuous regulation and maintain high control accuracy.

Simultaneously, the laptop will be directly linked to the USB multifunction I/O device (model USB-6363, manufactured by NI, EMERSON group), which in turn will be interfaced with the tested encoder. This connection is designed to allow real-time acquisition of the encoder's pulse-based output signal, which will be directed to the digital inputs of the I/O device for further processing and conversion into an appropriate digital format.

The USB multifunction I/O device is intended to function as an interface that bridges the analogue and digital domains within the system. Through its multi–functional capabilities, it will enable high-resolution monitoring of the encoder's dynamic behaviour, particularly the continuous registration of angular displacements under varying vibrational conditions.

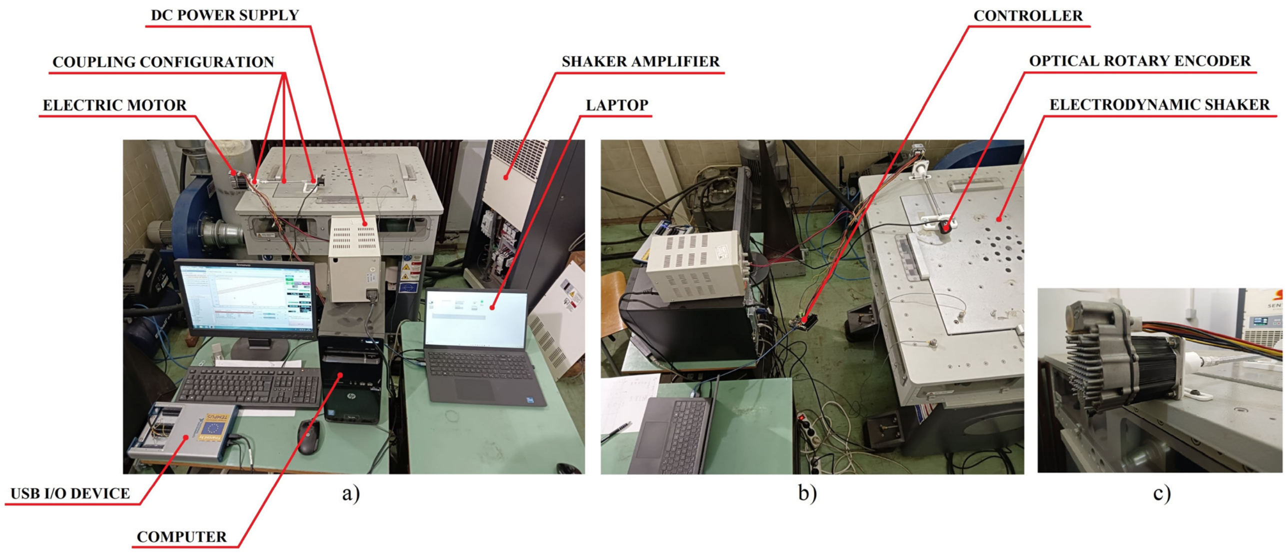

Figure 4. Development of the model

The laptop, acting as the central computational unit, will be responsible for performing data processing, real-time visualisation, and analytical operations. Through the application of specialised software, the acquired data will be filtered, converted into appropriate physical units, and systematically archived for subsequent analysis. The resulting digital archive is considered essential for comparative evaluation, error identification, and verification of the implemented methodology. Its structured organisation and continuous expansion will support thorough post-test analysis and contribute to a more comprehensive assessment of encoder performance under vibrational influence.

In accordance with the model design illustrated in Figure 3, the planned final configuration of this integrated system represents a pivotal point in the development process. Its design ensures that all system components operate in close synchronisation, supporting functional integrity and uninterrupted data flow across the entire testing process. Once implemented, the configuration (Fig. 4) is expected to provide full operability and robustness of the model, thereby enabling a systematic and reliable methodology for testing encoder performance under controlled and repeatable conditions.

2.1 Model Implementation

The model was implemented continuously and without interruption to ensure the integrity and consistency of the obtained results throughout the testing process. Three commercial optical rotary encoders of the same model type were subjected to testing, differing solely in resolution: the first encoder featured 100 PPR, the second 360 PPR, and the third 1000 PPR.

The methodology for defining vibration parameters and selecting the key variables for measuring and analysing their influence on the encoder is connected to the previous research. Notably, the studies conducted by Alejandre & Artés [16] and López et al. [27], referenced in Section 1.1, provide a comparative basis for defining the vibration parameters and selecting the key variables used in the encoder testing process. Accordingly, a separate test sequence was performed for each encoder, resulting in three independent test series.

Table 1. Test parameters

Test No.	Frequency [Hz]	Rotational Speed [RPM]	Amplitude [mm]	Time [s]
1	10	50	0.3	10
2	10	100	0.3	10
3	10	150	0.3	10
4	50	50	0.3	10
5	50	100	0.3	10
6	50	150	0.3	10
7	100	50	0.3	10
8	100	100	0.3	10
9	100	150	0.3	10
10	150	50	0.3	10
11	150	100	0.3	10
12	150	150	0.3	10

Each test series consisted of 12 individual measurements, leading to a total of 36 measurements across all encoders. The specific test parameters for each test series are presented in Table 1. The first column lists the test sequence numbers, while the second column shows the vibration frequency in hertz [Hz]. The third column indicates the rotational speed [RPM] of the electric motor, through which the torque is transmitted to the encoder under test. The amplitude and duration of the vibrations remained constant across all measurements, with their respective values given in the fourth and fifth columns.

During each repetition, the encoder being tested was individually mounted and subsequently removed, ensuring that all three optical rotary encoders were tested under identical conditions. This consistent approach allowed for reliable comparison of performance across different resolutions and ensured both the validity and reproducibility of the test results.

2.2 Phases of Model Implementation

To improve clarity and provide a clear understanding of the implementation process, it is divided into four interdependent and logically connected phases. A detailed explanation of each phase is given below.

First Phase

The initial phase of the model implementation begins with the activation of the electrodynamic shaker, controlled via a computer system operating custom-developed software.

The control process starts with the precise configuration of parameters that define the shaker's operating conditions, including frequency, amplitude, and the duration of each test. Once the parameters are verified, the shaker is activated through a software command and begins generating vibrations according to the predefined settings.

The central panel of the software interface provides real-time graphical representations of the measured signals, offering immediate visual feedback essential for monitoring the dynamic response of the system visible on the computer monitor. This real-time visualisation provides detailed insight into the shaker's operation and enables prompt identification of any deviations from the defined test parameters.

Second Phase

The second phase involves the precise regulation of the electric motor's rotational speed, a critical factor in generating the torque required to drive the optical rotary encoder under test. Speed regulation is achieved through the controller that acts as an interface between the laptop and the electric motor, enabling seamless communication and control.

The controller is programmed using a LabVIEW-based application developed specifically for this purpose and operated from the laptop. This application allows for the definition of rotational speed parameters, expressed in revolutions per minute (RPM), which are tailored to the requirements of each test. Following the confirmation of the specified input values through the software interface, the electric motor is activated, producing the torque necessary for encoder operation.

Third Phase

The third phase centres on the continuous transmission of torque from the electric motor to the optical rotary encoder under test via the coupling configuration. The generated torque is transmitted through the combination of one flexible and two rigid couplings. The flexible coupling compensates for minor misalignments and mitigates irregularities in torque transmission, while the rigid couplings ensure efficient and stable transmission of rotational motion.

This configuration allows for continuous and unin–terrupted torque transmission even as the electro–dynamic shaker remains active, persistently simulating real operating conditions. Consequently, the encoder is subjected to dynamic environments representative of industrial applications, while the electric motor operates under isolated and vibration-free conditions (Fig. 4c). This setup provides a realistic and rigorous test environment for evaluating the encoder's measurement performance under vibrational disturbances.

This phase highlights the core objective of the developed model. The fundamental principle of the model relies on the comparative analysis between the rotational position of the tested encoder and the reference position supplied by the electric motor, which serves as the reference standard.

Specifically, the electric motor is equipped with a built-in high-precision encoder that operates indepen–dently and provides highly accurate reference values. These reference data are used to assess the accuracy of the tested optical rotary encoder. By comparing mea–sured and reference positions, it becomes possible to quantify the measurement error induced by vibrations, allowing for a detailed performance evaluation under dynamic conditions.

The dynamic effects acting on the tested optical rotary encoder during continuous torque transmission lead to angular displacements, which are of critical importance for the measurement process and the evaluation of encoder performance. To enable precise quantification, these errors are precisely determined through comparison with the reference values obtained from the motor's built-in encoder.

Within the measurement process, the angular position of the tested encoder is recorded and compared to the reference angular position of the electric motor, characterised by high consistency and stability. This comparative analysis allows for the detection and characterisation of possible errors in the form of angular displacement, which are caused by the present vib–rations and directly impact the accuracy of the tested encoder's measurements.

Ultimately, this approach enables an objective asse–ssment of the impact of vibrations on the measurement accuracy of the optical rotary encoder under test and enables a deeper understanding of its operational reliability under dynamic conditions.

Fourth Phase

The fourth and final phase of the model implementation involves the transfer of the encoder's output data to the laptop for further processing and analysis. Angular errors, representing the primary measured quantity, are transmitted in real time via the USB multifunction I/O device, which establishes the connection between the encoder and the laptop.

The acquired data are then converted into a format suitable for processing and stored locally for subsequent visualisation and analytical evaluation. This systematic data recording and the establishment of a digital archive not only streamline data management but also facilitate the comparison of test results and their application in future experimental or industrial scenarios.

Upon completing this final phase, the model is considered fully implemented in accordance with the rigorously defined methodology, ensuring the genera–tion of valid, reproducible, and objective results across all operational parameters and test phases.

To minimise the influence of external variables, the entire implementation is carried out in a controlled laboratory environment, ensuring the stability of the experimental conditions. This systematic approach enabled a consistent and objective evaluation of the encoders' measurement accuracy and their performance when subjected to vibrational influences.

3. RESULTS AND DISCUSSION

3.1 Results

The testing process was conducted under strictly defi–ned and maintained laboratory conditions, allowing for a high-precision characterisation of encoder behaviour under varying operational parameters. Such a controlled setting effectively eliminated potential external distur–bances, thereby reinforcing the relevance and objec–tivity of the obtained results. The primary focus of the analysis was placed on the identification of errors in angular position measurement, which serves as a direct indicator of the accuracy of the tested encoders.

During each 10-second test, an Excel file containing time-stamped data was automatically generated, inc–luding the instantaneous positions of both the encoder under examination and the reference encoder. In addition, key parameters such as the current measu–rement error, motor rotational speed, vibration frequ–ency, encoder resolution, and the root mean square value of the encoder measurement error over the entire interval were documented to provide a comprehensive understanding of the factors influencing measurement accuracy. These data serve as the basis for graphical representations illustrating the behaviour of the measurement error under predefined operating condi–tions (Fig. 5).

The graph represents the test duration along with the measurement error values of the encoder under test. The horizontal axis (x-axis) presents the time span of the test, expressed in seconds, with the measurement interval ranging from 0 to 10 seconds at 0.1-second increments. The vertical axis (y-axis) displays the measured angular error in degrees [°], calculated as the difference between the actual encoder position and the value recorded by the reference encoder.

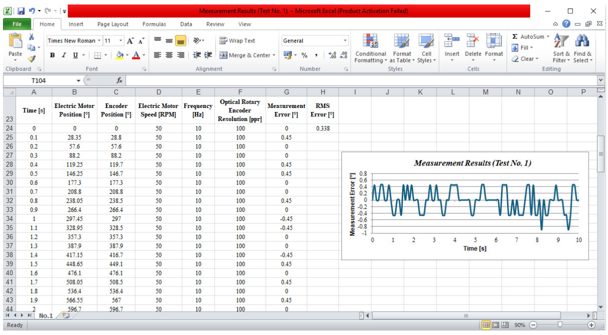

Figure 5. Measurement Results (Test No. 1)

The resulting graphs from the 36 test iterations provide a detailed visualisation of momentary fluctu–ations in measurement error over time, enabling an assessment not only of the error magnitude but also of its temporal stability and repeatability. Due to the large volume of data collected from the repeated iterations, the analysis of results (highlighting the fact that measurement error is neither uniform within a single encoder nor consistent across encoders of different resolutions) is presented using the root mean square (RMS) values of the measurement error obtained during each test session.

3.2 Assessment of Measurement Accuracy Using the Root Mean Square Error

The root mean square (RMS) is a fundamental statistical metric that quantifies the average magnitude of varia–tions in numerical data. It provides an objective assess–ment of the overall amplitude of fluctuations in a given signal, irrespective of the sign of individual values. RMS is widely applicable in the analysis of time-dependent signals and is particularly useful in charac–terising the content or intensity of stochastic processes and periodic disturbances, such as vibrations, oscilla–tions, and electrical or mechanical noise, which can significantly impact measurement accuracy [28].

When applied specifically to the evaluation of measurement accuracy, this metric becomes the root mean square error (RMSE), which is especially relevant for assessing the impact of dynamic and environmental influences on precision systems. From a methodological perspective, the RMSE is defined as the square root of the arithmetic mean of the squared differences between the reference values and the corresponding measured values over a given number of observations. Mathematically, it is expressed as [29]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(r_n^{ref} - r_n^{meas}\right)^2} \quad (1)$$

where r_n^{ref} represents the reference value, r_n^{meas} denotes the measured value at the same point in time, and N is the total number of measurements. This formulation captures the average magnitude of measurement error, regardless of its direction, and provides a reliable metric for evaluating the accuracy and consistency of measu–rement systems.

The utilisation of RMSE in experimental analysis constitutes a significant approach for quantifying results, and its application is well-documented in the scientific literature. For example, in the study conducted by Alejandre and Artés [16], the accuracy of an optical linear encoder under vibrational influence was inves–tigated. Their analytical methodology employed the RMSE to quantify measurement errors, allowing for comparison under varying conditions regardless of deviation direction. Thus, RMSE serves as a reliable indicator of overall measurement accuracy in complex and unstable environments.

As an integral part of the testing process, the RMSE was calculated to provide a quantitative assessment of the measurement error corresponding to each individual test iteration. These RMSE values were determined utilising data obtained from the relevant Excel files generated for each test series. In connection with (1), the resulting values are systematically presented in Table 2, aligned with the respective test iteration.

Table 2. Results for the RMSE values

	RSME value in the test series		
Test No.	First Test Series	Second Test Series	Third Test Series
1	0.338	0.311	0.168
2	0.347	0.287	0.210
3	0.380	0.383	0.277
4	0.338	0.302	0.165
5	0.543	0.448	0.225
6	0.641	0.320	0.280
7	0.410	0.568	0.296
8	0.829	0.440	0.288
9	0.408	0.491	0.380
10	0.488	0.590	0.382
11	0.543	0.674	0.433
12	0.791	0.419	0.457

These values were subsequently presented in graphical form, allowing for a visual analysis and comparison of the encoder accuracy under the varying vibration parameters. The graphs provided below illustrate the RMSE values during the testing of optical rotary encoders with different resolutions across each test series. In each graph, the horizontal axis denotes the sequence number of the test, whereas the vertical axis represents the corresponding RMSE values. These values reflect the average deviation of the measured angular position from the reference value, thereby serving as a quantitative indicator of the encoder's measurement accuracy under dynamic conditions.

The RMSE values of the encoder's measurement error for each individual test in the first test series are presented in Figure 6. The graph illustrates variability in the results, with values ranging from 0.338° to 0.829°. In the initial tests (specifically tests 1, 2, and 4), the measurement error remains relatively low, between approximately 0.338° and 0.347°, indicating that under moderate vibration conditions and reduced rotational speeds, the encoder demonstrates stable measurement performance.

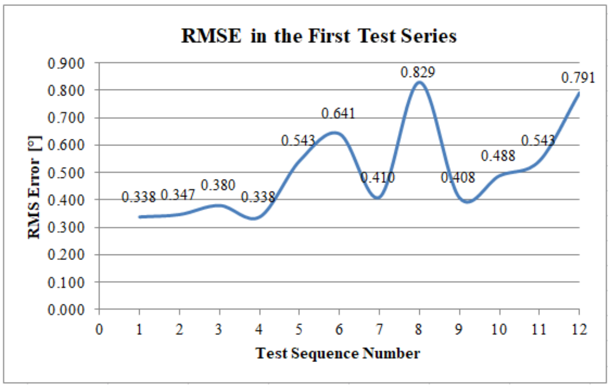

Figure 6. RMSE in the First Test Series

A gradual increase in the RMS error is subsequently observed, reaching its maximum value of 0.829° in test 8. This notable rise can be attributed to the presence of high-frequency vibrations and elevated rotational speed, which induce mechanical instability and adversely affect the encoder's measurement accuracy.

Although a reduction in RMSE is observed following the peak in test 8 (specifically in tests 9 and 10, where the values decrease to 0.408° and 0.488°, respectively), this does not indicate a sustained stabilisation of the measurement error. On the contrary, an increasing trend is again evident in the final tests. Notably, test 12 results in an error of 0.791°, approaching the maximum value recorded in test 8. This pattern indicates that the encoder, with a resolution of 100 PPR, exhibits limited capability to maintain consistent and accurate measurements under dynamic conditions, demonstrating susceptibility to variations in both vibration frequency and rotational speed.

The RMSE values of the encoder's measurement error for the second test series are illustrated in Figure 7. The graph shows that the initial tests exhibit relatively low RMSE values of 0.311°, 0.287°, 0.383°, and 0.302°. As the series progresses, the error values display gradual oscillations, although without the peaks observed in the results of the first encoder. Throughout most tests, the RMSE remains below 0.6°, indicating improved resistance of the 360 PPR encoder to vibration and rotational speed effects. The highest error, 0.674°, is recorded in test 11, followed by a decrease to 0.419° in the final test.

This gradual increase in RMS error observed throughout the series, especially between tests 6 and 11, suggests that the 360 PPR encoder is also affected by intensified vibrations and higher rotational speeds, although to a lesser degree compared to the lower-resolution encoder.

The RMSE values of the measurement error in the third test series are presented in Figure 8. As illustrated in the graph, these values are significantly lower compared to those of the first and second series. The initial tests, specifically the first four measurements, show exceptionally low RMSE values, ranging from 0.168° to 0.277°, with a brief decrease to 0.165° during the fourth test.

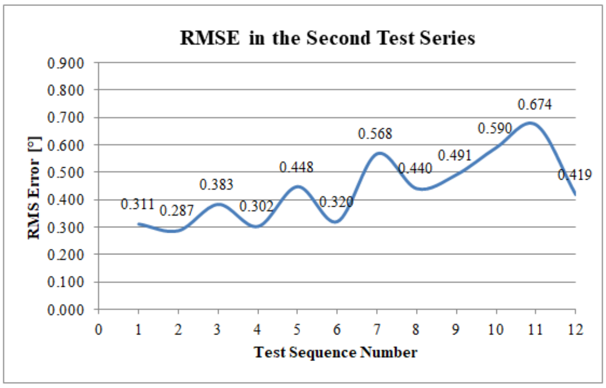

Figure 7. RMSE in the Second Test Series

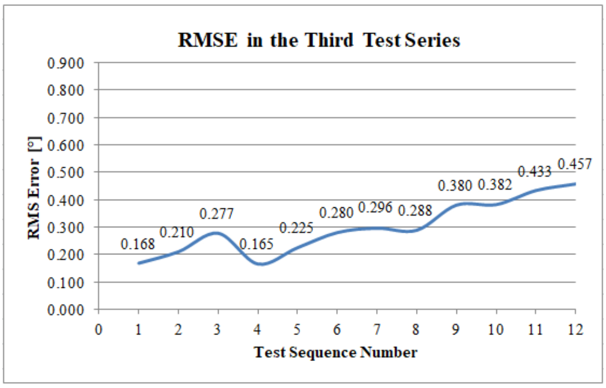

Figure 8. RMSE in the Third Test Series

The middle section of the graph, encompassing tests five through eight, shows stable RMSE values ranging from 0.225° to 0.296°, demonstrating the encoder's robust ability to maintain accuracy across a wider range of vibration conditions. Although minor fluctuations are present, the RMSE trend increases gradually without the peaks characteristic of the lower-resolution encoders. In the final part of the series, tests nine to 12 exhibit a slight increase in error, reaching 0.457° in the last test. Nonetheless, despite this moderate rise, the values remain significantly lower than the peak errors observed in the previous two series, further confirming the superior performance of the high-resolution encoder.

Comparative Analysis Based on RMSE Values

The results reveal distinct patterns in the measurement error behaviour, illustrating how variations in experimental conditions affect the encoder's sensitivity and accuracy. In the first test series, the encoder exhibited considerable variability, with several tests resulting in elevated RMSE values. This suggests increased susceptibility to changes in vibration frequency and encoder rotational speed, reflecting a limited tolerance to dynamic and rapidly fluctuating external disturbances.

Conversely, the second test series demonstrated a more gradual and progressive rise in RMSE values, indicating a decline in accuracy over time and with prolonged exposure to vibrations. Although this trend was less pronounced than in the first series, certain tests still produced notable errors, implying that the encoder's stability decreased as the intensity and duration of vibrations increased. These findings highlight the encoder's partial sensitivity to sustained, high-amplitude vibration inputs and its limitations in maintaining accuracy under complex vibrational conditions.

The third test series displayed the most stable and reliable performance, characterised by consistently low and smoothly varying RMSE values. The encoder's uniform results suggest that the applied vibration conditions remained within an optimal range for its resolution and structural design. The absence of distinct error peaks and the consistency of measurements indicate the encoder's capability to maintain high accuracy under dynamic environments where vibration parameters and rotational speed vary as functional inputs. This pattern of minimal fluctuations and low error magnitudes reflects the encoder's robustness and stability, particularly for a resolution of 1000 PPR, against external vibrational disturbances.

This comparative analysis confirms that the encoder's measurement accuracy is significantly influenced by the characteristics of the vibration profile. Moreover, it suggests that higher resolution, corresponding to smaller angular increments per pulse, enables more precise angular position detection, thereby contributing to reduced measurement error even under varying vibration and speed conditions.

3.3 RMSE Estimation Using the Response Surface Methodology

To visually represent the influence and interdependence of vibration frequency and rotational speed on the resulting RMSE values obtained during the three test series, an additional analysis was conducted based on the results presented in Table 2. For this purpose, Response Surface Methodology (RSM), a statistical modelling and optimisation technique, was employed to examine the effects of two input variables on a single output response.

By general definition, RSM comprises a set of statistical and mathematical tools that facilitate the development of models describing the relationship between independent variables and the system's response. This approach not only identifies significant factors and their interactions but also enables the prediction of system behaviour in unexplored regions of the design space. Moreover, RSM allows for the monitoring of process parameters to achieve desired outcomes and provides insight into the system's sensitivity to variations in individual factors [30-31].

Using this methodology, a MATLAB script was developed to enable advanced processing of the results presented in Table 2, illustrating the dependence of RMSE on vibration frequency and rotational speed. Through regression analysis, a surface model was constructed, allowing for the prediction of the RMSE even for parameter values not directly measured during the tests. This approach enabled both the analysis and visualisation of the results through the generation of three-dimensional response surface plots, facilitating the estimation of RMSE values for vibration frequencies and rotational speeds that were not explicitly included in the original dataset but fall within the investigated parameter range.

In this context, the vibration frequency (x_1) and the rotational speed of the electric motor (x_2) are considered as independent variables, while the RMSE of the encoder (y) represents the dependent variable. The functional relationship among these parameters is expressed as $y=f(x_1,x_2)$, where y denotes the RMSE as a function of the input factors x_1 and x_2.

This relationship, derived from the tests conducted on the three optical rotary encoders, is visualised through 3D plots. In these plots, the X-axis represents the vibration frequency in the range of 10 Hz to 150 Hz, the Y-axis denotes the rotational speed of the electric motor within the interval of 50 to 150 RPM, and the Z-axis displays the encoder's RMSE values, expressed in degrees [°]. The plotted surfaces correspond to a second-order polynomial (Quadratic Surface Model), reflecting the quadratic regression function obtained from the MATLAB-developed script.

Based on the results in Table 2, the corresponding 3D graphs are shown below. Specifically, Figure 9 presents the 3D model for the optical rotary encoder with a resolution of 100 PPR, Figure 10 illustrates the respective 3D model for the encoder with a resolution of 360 PPR, while Figure 11 depicts the 3D model for the encoder with a resolution of 1000 PPR.

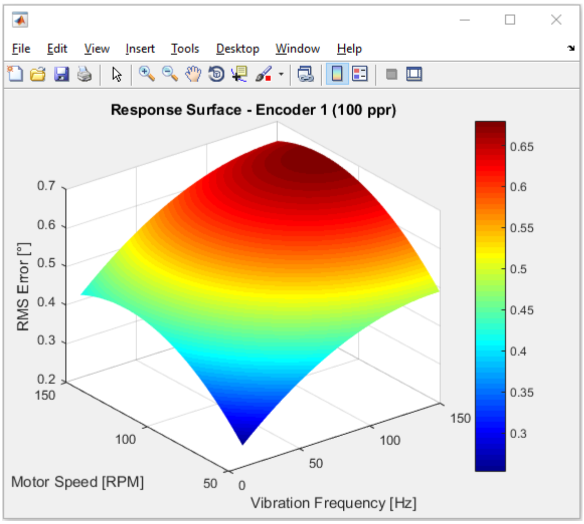

Figure 9. Response Surface in the First Test Series

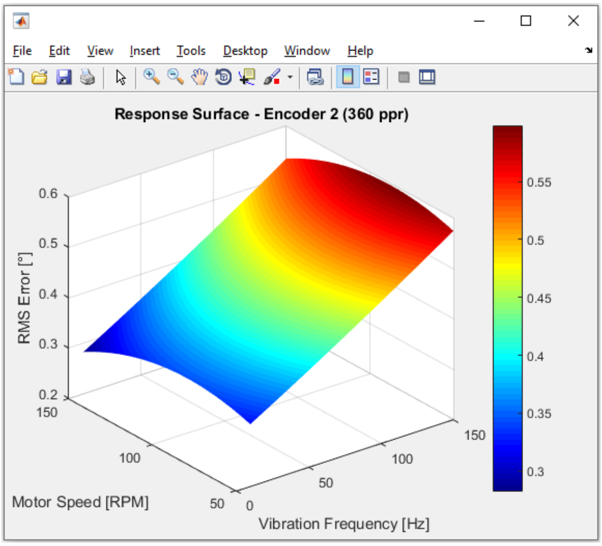

Figure 10. Response Surface in the Second Test Series

The format in which the results are presented in these graphs provides a detailed visual representation of the encoder's response under varying dynamic condi–tions. These visualisations clearly highlight the parame–ter regions corresponding to the variability of the RMSE values observed across the test series.

Furthermore, for each graph, the magnitude of the encoder's RMSE is represented by a colour scale, where blue regions indicate the lowest error values and red regions correspond to the highest. The gradual transition from blue to red illustrates the progressive increase in measurement error as a function of the influencing parameters.

Through this approach, it becomes possible to further analyse and assess the estimation of RMSE for encoder measurements, based on the previously presented results.

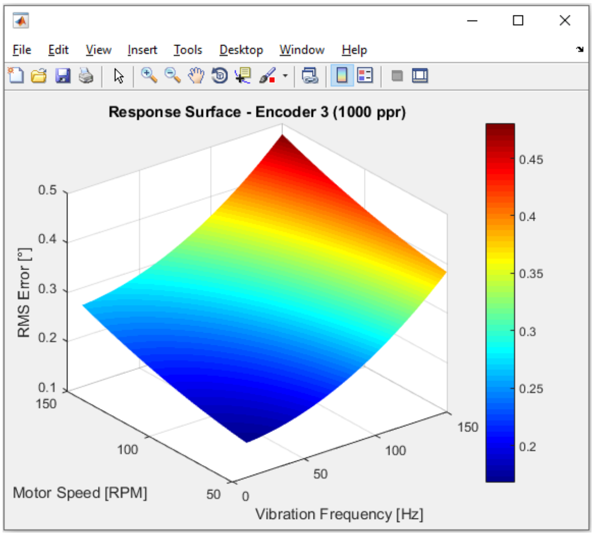

Figure 11. Response Surface in the Third Test Series

Specifically, by considering vibration frequency and rotational speed as the two independent input variables upon which the output response depends, it is feasible to assign any desired value to one or both variables. The corresponding RMSE value for the encoder measurement can then be predicted using the developed model based on the experimental data.

For instance, consider the estimation of the RMSE value error for the first encoder (100 PPR) under a vib–ration frequency of 75 Hz and a rotational speed of 125 RPM, where both variables represent new input condi–tions, not directly measured or included in Table 2. In this case, the MATLAB script employs the 'fitlm' function with the 'purequadratic' parameter, creating a second-order (quadratic) regression model without interaction terms. This model constructs a mathematical function based on all available data points, allowing the es–timation of the RMSE value for any combination of frequency and speed within the defined parameter range.

Given that the dataset for the first encoder includes only discrete combinations (e.g., 10, 50, 100, 150 Hz for vibration frequency and 50, 100, 150 RPM for speed), values such as 75 Hz and 125 RPM are internal points within this space, located between the existing measured values. Consequently, the estimation process involves bivariate interpolation, meaning the regression model predicts the RMSE value for a point that has not been directly tested but lies within the known domain.

When the input pair (75 Hz, 125 RPM) is provided to the MATLAB script, it computes the estimated RMSE value according to the derived quadratic function, resulting in a value of 0.6129°. This represents the expected RMSE for the encoder measurement under the specified parameters. It is important to emphasise that this value does not originate from the direct testing process but results from analytical interpolation based on the established regression model.

The visualisation of this estimation is shown in Figure 12, where a black marked point indicates the estimated point at coordinates (75 Hz, 125 RPM, 0.6129°) on the 3D surface plot. This plot represents the value of the RMSE as a function of vibration frequency and rotational speed.

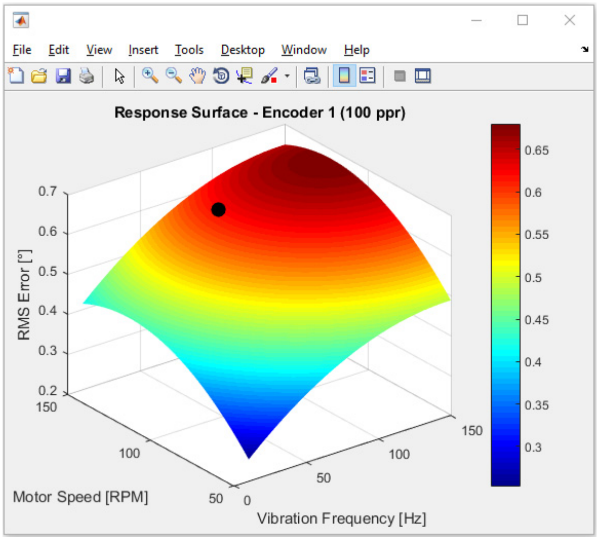

Figure 12. RMSE Response Surface with Interpolated Value

As an additional example, consider the estimation of the RMSE value for the encoder with a resolution of 360 PPR, at a vibration frequency of 85 Hz and a rota–tional speed of 150 RPM. In this case, the situation differs slightly because the frequency value of 85 Hz is not present among the original data points. Therefore, interpolation using the regression model is required. Conversely, the rotational speed of 150 RPM is included in the original dataset and has been directly measured across various frequencies. This means that the speed parameter is known and incorporated into the model without interpolation.

Mathematically, this case represents partial interpolation within a bivariate space. While two inde–pendent variables (frequency and speed) define the sys–tem, only one (frequency) requires interpolation. This corresponds to one-dimensional interpolation embed–ded within a two-dimensional quadratic regression mo–del. The model estimates the value at 85 Hz by inter–polating the observed variation of the RMSE across ad–jacent frequency values while preserving the established dependency on the rotational speed of 150 RPM.

By applying MATLAB's 'fitlm' function and the generated quadratic regression model describing the dependency of RMSE on the input variables, it becomes possible to calculate the expected error for any new input combination within the domain of the original data, such as this example of 85 Hz and 150 RPM. It is important to note that this is not a simple linear interpolation; rather, the model employs a multivariate quadratic approach, allowing for more flexible and realistic predictions.

The result of the interpolation, in this case, is an estimated RMSE of 0.4734°. This represents the predicted angular measurement error of the encoder for operating conditions not directly tested but falling within the boundaries of the investigated parameter space.

As a final step, this estimated value is also visualised on the 3D surface plot (Fig. 13) by a clearly marked point at coordinates (85 Hz, 150 RPM, 0.4734°). This provides not only a numerical estimation but also an intuitive graphical representation of the result, showing its position relative to other data points and the overall RMSE surface model.

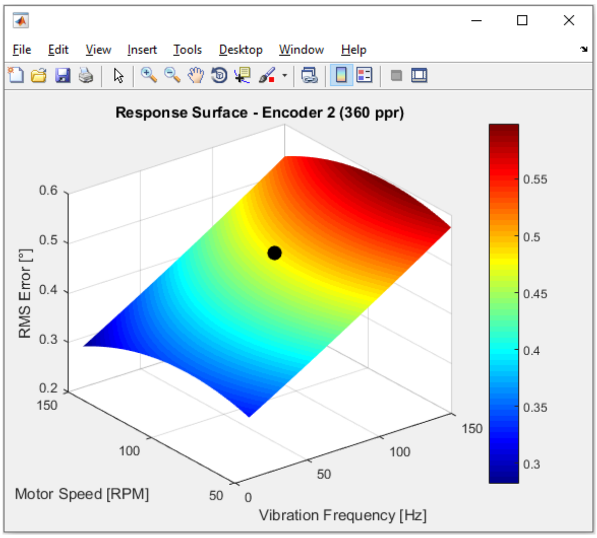

Figure 13. RMSE Response Surface with Interpolated Value

Model Validation and Applicability

From the perspective of result analysis within the framework of the developed model for assessing the accuracy of optical rotary encoders under vibration influence, the model's validity, applicability, adap–tability, and implementation potential are clearly de–monstrated.

The validation process extends beyond merely con–firming the model's formal reliability, it establishes a fundamental basis for its systematic integration into simulation studies and engineering analyses, particularly in the domain of systems incorporating optical rotary encoders. In this context, the validated model fulfils a broader purpose, not only as a replica of real systems but also as a standardised experimental platform that enables the simulation of diverse dynamic scenarios, effectively replacing the need for direct industrial testing under real operating conditions.

Defined in this way, the additional digital approach serves not only to replicate real operating conditions but also to identify critical instability points, conduct sensi–tivity and stability analyses, and support the develop–ment of compensation and optimisation strategies for the entire measurement process. Its reproducibility, adaptability, and capability for systemic behaviour analysis position the model as an integral part of the research methodology, providing a reliable platform for both qualitative and quantitative evaluation of key parameters critical to the functionality, accuracy, and dependability of measurement systems.

Based on the presented results and discussion, it can be concluded that the design and development of the model have been fully validated through its functionality. Its purpose, accurate representation of the behaviour of optical rotary encoders under varying dynamic operating conditions, makes it potentially applicable in situations where real-world measurements are technically complex or unfeasible.

Furthermore, the model's flexibility and robustness enable its use as a tool for testing new hypotheses, designing alternative system architectures, and deve–loping compensation techniques to improve measu–rement systems. This level of reliability and adaptability supports the model's positioning as a crucial component in the research processes, providing stable, dependable, and repeatable support across all stages of modelling, simulation, and analysis. Consequently, the designed and developed model represents not only a robust technical tool but also a significant contribution to enhancing scientific precision and engineering effecti–veness in the field of optical rotary encoder accuracy assessment under complex dynamic influences.

In this regard, the conceptual framework established through the development of this model offers oppor–tunities for further expansion and improvement, parti–cularly by integrating and testing additional parameters with variable characteristics. Additionally, data analysis and processing may be performed using alternative methodologies and different or complementary software tools.

Conclusively, this conceptual foundation serves as a platform for future scientific exploration and tech–nological implementation. In subsequent research, the experimental and digital approach could be extended and upgraded with adaptive error compensation sys–tems, analyses of the influence of temperature, and electromagnetic interference, as well as its application in non-invasive diagnostic tools for real-time sensor condition monitoring.

4. CONCLUSION

In this paper, an innovative model is designed and developed to evaluate the accuracy of optical rotary encoders under the influence of mechanical vibrations. The testing process involves three commercially available encoders subjected to vibrations with controlled parameters of frequency, amplitude, and duration. Reference values are utilised to determine the degree of deviation in the output signal and to identify the most sensitive frequency ranges. This approach enables a precise assessment of the reduction in measurement accuracy of optical rotary encoders under dynamic operating conditions, contributing to a deeper understanding of their metrological reliability in realistic industrial environments.

The comparative analysis of the results obtained from the three experimental test series provides an in-depth insight into the performance of optical rotary encoders with different resolutions (100 PPR, 360 PPR, and 1000 PPR) when subjected to vibrations with variable parameters. The analysis reveals the relationship between encoder resolution, output signal stability, and the device's resistance to external dynamic influences. Although all encoders were tested under identical experimental conditions, their capability to generate precise and reproducible angular position data differs significantly, leading to a series of important technical and practical implications.

The advanced functionalities of MATLAB in this study provide a foundation for a comprehensive approach to data processing and interpretation specific to this complex system. This includes multiple aspects, ranging from the characteristics and configuration of the system components, through the methodology for results analysis and processing, to the quantitative comparison and visual representation of the outcomes via appropriate graphical illustrations.

The implications of this analysis are multifaceted. From a technical perspective, the findings highlight that the selection of an optical rotary encoder must be carefully aligned with the specific application require–ments, particularly in operating environments charac–terised by vibrations. In cases where high resolution is not critical or where vibrations are minimal and well-controlled, lower-resolution encoders may offer a cost-effective solution. Nevertheless, in applications deman–ding high accuracy and stability, the use of high-resolution encoders becomes essential, alongside considerations for additional methods such as mecha–nical isolation and vibration compensation.

In this regard, the comparative analysis also opens perspectives for future research and improvements in encoder technology. The results suggest that the deve–lopment of next-generation encoders should focus not only on increasing resolution but also on integrating adaptive error correction algorithms, enhancing electromechanical stability, and developing embedded systems for self-diag–nosis and intelligent compensation of external influences.

In conclusion, the differences in performance among encoders with varying resolutions under vibra–tional influence underscore the importance of precise engineering design and careful component selection. Moreover, these findings lay the groundwork for advancements in future design methodologies and testing practices in the field of high-precision sensing and control applications.

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ДИЗАЈН И РАЗВОЈ МОДЕЛА ЗА ОЦЕНУ ТАЧНОСТИ И КВАНТИФИКАЦИЈУ ГРЕШКЕ МЕРЕЊА КОД ОПТИЧКИХ РОТАЦИОНИХ ЕНКОДЕРА ПОД УТИЦАЈЕМ ВИБРАЦИЈА

В. Крчева, С. Нусев, М. Томић

Ова студија представља развој и примену инова–тивног модела намењеног евалуацији грешака у мерењу код оптичких ротационих енкодера изло–жених механичким вибрацијама. Методолошки оквир обухвата анализу фактора који утичу на тач–ност и стабилност три комерцијална оптичка рота–циона енкодера, са циљем да се квантификују грешке мерења изазване вибрацијама. Ради пости–зања дубљег разумевања понашања енкодера у реалним динамичким условима, резултати су обра–ђени у MATLAB-у, што је омогућило напредну анализу одговора система на вибрациона узбуђења. Оваквим приступом побољшава се и тачност и поузданост модела, омогућавајући свеобухватну оцену перформанси енкодера под различитим условима вибрација. Модел осмишљен и развијен у оквиру ове студије представља значајан и ориги–налан допринос области анализе перформанси опти–чких ротационих енкодера у динамичким условима рада, са посебним нагласком на утицај механичких вибрација на тачност и стабилност мерења.