Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 9, S. 174-185, 9, 2025

Araştırma Makalesi

IJANSER

https://as-proceeding.com/index.php/ijanser
ISSN:2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 9, pp. 174-185, 9, 2025

Research Article

Vibration Effects on Optical Rotary Encoders: Development of a Model for Quantitative Error Analysis and Accuracy Validation

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(Received: 15 September 2025, Accepted: 21 September2025)

(2nd International Conference on Pioneer and Academic Research ICPAR 2025, September 15-16, 2025)

ATIF/REFERENCE: Krcheva, V., Nusev, S. & Tomić, M. (2025). Vibration Effects on Optical Rotary Encoders: Development of a Model for Quantitative Error Analysis and Accuracy Validation, *International Journal of Advanced Natural Sciences and Engineering Researches*, 9(9), 174-185.

Abstract **–** The precise measurement and quantification of errors in optical rotary encoders, particularly under vibrational influence, are critical for assessing their performance and operational reliability. Optical rotary encoders are widely employed in high-precision applications, including CNC machines, robotics, aerospace systems, and industrial automation, where accurate feedback and position control are essential. Even minor measurement deviations induced by external vibrations can lead to significant control errors, compromising system efficiency and, in extreme cases, causing operational failures. This study introduces a comprehensive analytical model designed to evaluate the accuracy of optical rotary encoders under varying vibrational conditions. The model incorporates multiple interconnected components, each representing a specific aspect of encoder behaviour, and integrates them into a unified framework capable of simulating real-world operational environments. Particular emphasis is placed on the dynamic interactions among the components, as these interactions critically affect the overall system response and the resultant measurement accuracy. The proposed methodology enables systematic assessment of encoder performance under realistic vibration scenarios, providing both qualitative insights and quantitative metrics. Furthermore, the model facilitates the identification of key factors contributing to measurement deviations, offering practical guidance for design optimisation and error minimisation strategies. By combining theoretical analysis with simulated operational conditions, the approach presented herein contributes to the development of more reliable and precise optical rotary encoders, ultimately supporting improved performance in precision-driven technological systems.

Keywords – Dynamic Disturbances, MATLAB & Simulink, Environment, Block Diagram, Blocks.

I. INTRODUCTION

Optical rotary encoders (Fig. 1a) have, over the past several decades, become indispensable devices in the field of precision measurement and control. They are designed to monitor and quantify key parameters of rotary motion, such as angular position, rotational speed, and direction of movement. At their core, these sensors operate as transducers, converting mechanical motion into electrical signals which can then be interpreted and processed by digital control units. This fundamental capability of transforming physical motion into interpretable electronic data explains their widespread adoption in modern engineering and scientific systems. From computer numerical control (CNC) machines to advanced robotic manipulators, from aerospace guidance systems to medical diagnostic equipment, optical rotary encoders play an essential role in ensuring accuracy, efficiency, and operational reliability.

In practical contexts, encoders are utilised to measure and regulate the rotation of vital machine elements such as motor shafts, drive spindles, gear assemblies, or robotic joints. Their contribution is most clearly illustrated in CNC machining, where the encoder is responsible for tracking the rotational motion of the spindle, thereby allowing precise and repeatable cutting operations. Without such feedback, the system would be unable to maintain the strict dimensional tolerances required for high-quality machining. In robotic systems, encoders deliver the feedback necessary for accurate joint positioning, enabling the end-effector to follow prescribed trajectories. Similarly, in electric vehicles, encoders monitor and regulate motor torque and speed to ensure smooth propulsion, while in medical imaging equipment, they secure the accurate alignment of scanning mechanisms. These examples collectively underscore the universality of encoders and their role as critical components of advanced technological systems.

Fig. 1 An optical rotary encoder [1]

The operation of an optical rotary encoder relies on the modulation of light through a patterned rotating disc (Fig. 1b). This disc is typically attached directly to the shaft whose motion is being measured and incorporates alternating transparent and opaque (or reflective and non-reflective) regions arranged in carefully designed geometrical patterns. A light source, usually a light-emitting diode (LED), projects a beam onto the disc. As the disc rotates, the patterned regions alternately obstruct or transmit the light. On the opposite side of the disc, photodetectors capture these fluctuations in illumination and convert them into electrical pulses. These pulses, interpreted by the control system, carry information on angular position, velocity, and rotational direction.

Modern optical encoders often adopt more elaborate designs to enhance resolution and precision. For example, they may employ multiple light beams, more advanced photodiode arrays, or discs with highly intricate patterns. The resolution of the encoder is directly related to the number of divisions on the disc and can reach thousands, or even tens of thousands, of pulses per revolution. This allows for extremely fine measurement of angular displacements, often at micrometre-level accuracy. Such high-resolution performance is vital in applications where minute positional errors can have disproportionately large effects, including semiconductor lithography, astronomical telescopes, and automated inspection systems.

A. Encoder configurations and signal processing

Beyond the intrinsic resolution of an optical rotary encoder, the specific arrangement and configuration of its signal channels play a critical role in ensuring reliable and precise motion detection. The architecture most commonly employed in modern encoders utilises two primary channels, conventionally designated as A and B, which are configured in a quadrature arrangement. This configuration involves the generation of sinusoidal or square-wave signals that are phase-shifted by 90 electrical degrees relative to one another. The quadrature relationship is fundamental, as it permits the precise determination of both the rotational speed and the direction of motion by analysing the temporal sequence of transitions between the signals. In effect, this arrangement transforms raw optical pulses into a continuous, directional measure of angular displacement, which can then be interpreted by the control system.

The processing of these signals is typically managed by microprocessors or programmable logic controllers (PLCs), which apply advanced edge-counting methodologies to enhance the effective resolution of the system. Depending on the specific counting strategy—whether single-edge, double-edge, or quadrature (four-edge) counting—the number of detectable positions per revolution can be increased substantially, sometimes by a factor of four relative to the nominal resolution of the disc. This capability is crucial for applications requiring high precision, as it enables the encoder to capture minute angular displacements and provides the control system with sufficiently detailed information to maintain accurate feedback and control.

In addition to channels A and B, most high-performance encoders incorporate a third channel, commonly referred to as the index or reference channel, denoted Z. The index channel generates a single pulse for every complete revolution of the encoder disc, serving as a reliable reference point. This reference is essential for tasks such as system initialisation, zero-point calibration, and recovery following power interruptions or system resets. By providing a repeatable positional marker, the index channel ensures that all subsequent measurements can be referenced consistently, thereby maintaining long-term operational accuracy and repeatability.

The combined functionality of channels A, B, and Z illustrates the sophistication of contemporary multi-channel encoder systems, as represented schematically in Fig. 2. This integrated design not only improves measurement fidelity but also enhances the robustness of the encoder under varying operational conditions. By providing a coordinated and multi-dimensional output, these channels allow control systems to accurately reconstruct motion trajectories, detect minute positional deviations, and respond effectively to dynamic changes in speed or direction. The interaction between the quadrature channels and the index channel thus exemplifies how modern encoders combine high-resolution measurement with practical system functionality, ensuring both precision and operational reliability in complex mechanical and automated environments.

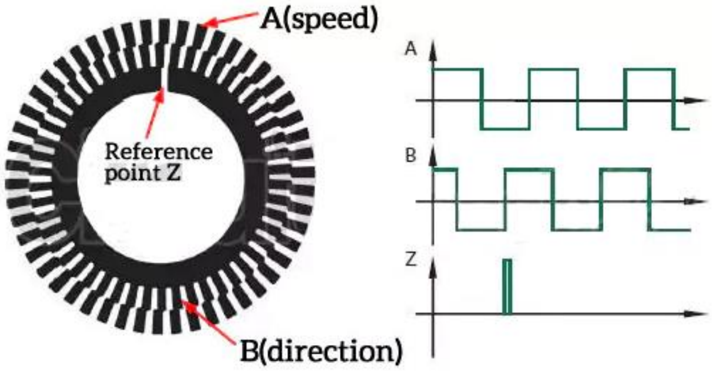

Fig. 2 Configuration of an optical rotary encoder [2]

The use of multi-channel configurations confers several advantages beyond enhanced resolution. They significantly improve measurement robustness by providing additional redundancy, allowing the implementation of error-detection and correction schemes. In dynamic industrial environments, where systems are exposed to noise, electromagnetic interference, or structural vibrations, this redundancy ensures that measurement reliability is not easily compromised.

B. Sensitivity to external disturbances

Despite their robustness, optical rotary encoders remain highly sensitive to external mechanical disturbances. Among these, vibrations are of particular concern due to their prevalence in real-world industrial and research environments. Vibrations are generated by diverse sources such as unbalanced rotating elements, cutting forces in machining operations, irregular surfaces in mobile systems, or structural resonances in high-speed assemblies. Several studies [3–10] have highlighted that encoder measurements are affected by metrological errors, with vibrations recognised as one of the most significant and practically relevant contributors to these errors.

The influence of vibrations on encoders is multifaceted. Even minute displacements, on the order of micrometres, can induce misalignments between the rotating disc and the photodetectors. Such misalignments may manifest as missed pulses, false activations, or phase distortions in quadrature signals. Consequently, the encoder's output becomes unreliable, undermining the fidelity of angular position, speed, and direction measurements. These effects are especially detrimental in high-precision applications. In CNC machining, they may reduce dimensional accuracy; in robotic manipulators, they can destabilise trajectories and reduce the accuracy of end-effector positioning; in mobile robots, they may impair odometric navigation. Even the index pulse (Z channel), intended as a stable reference, may become corrupted, reducing the reliability of system calibration.

The impact of vibrational disturbances is typically analysed with respect to three defining parameters: frequency, amplitude, and duration. Each of these parameters exerts a distinct influence on encoder performance (Fig. 3).

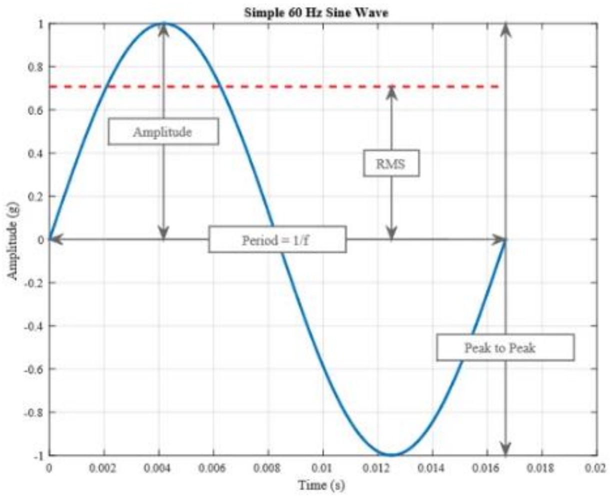

Fig. 3 Vibration parameters [11]

The frequency of vibration determines the temporal characteristics of signal distortion: low-frequency oscillations (<10 Hz) may affect long-term stability, mid-frequency vibrations (10–100 Hz) can introduce phase errors and pulse irregularities, while high-frequency vibrations (>100 Hz) may create spurious noise or cause false photodetector activations. Amplitude, even at very small values, can induce critical errors when combined with high-speed rotation, causing phase shifts and degraded pulse integrity. Prolonged exposure, finally, tends to accumulate errors over time, in some cases altering the thermomechanical stability of the encoder assembly.

C. Issues in dynamic environments

Dynamic operating environments, where speed, direction, and load conditions vary rapidly, impose particular issues on encoders. Maintaining precise alignment between optical elements and stable signal generation under such conditions is increasingly difficult. Conventional strategies, such as mechanical damping or electronic signal filtering, can reduce—but not completely eliminate—the effects of vibrations, especially when continuous, resonant, or high in amplitude.

This has prompted a growing focus on research methodologies that allow realistic assessment of encoder performance under controlled vibrational conditions, as conventional static tests fail to capture the complexity of dynamic signal distortions. Using vibration-generating platforms offers an effective solution, reproducing industrially relevant disturbances with precision and repeatability, enabling systematic evaluation of encoder behaviour, identification of error mechanisms, and development of compensation strategies.

Complementing physical testing, virtual simulation environments such as MATLAB & Simulink can become powerful tools for encoder analysis. Simulations reduce experimental cost and complexity while allowing reproducible and flexible evaluation across a wide range of scenarios. By modelling vibrations with adjustable frequency, amplitude, and duration parameters, simulations can generate comprehensive datasets invaluable for encoder selection, system design, and predictive maintenance.

D. Scope and contribution of this research

In this context, the present study introduces a structured and versatile model for investigating the effects of vibrations on optical rotary encoder performance. The model integrates multiple subsystems into a unified framework, capable of replicating real-world disturbances while maintaining experimental control and repeatability. Its primary contribution lies in providing both qualitative insights and quantitative metrics concerning signal deformation, accuracy degradation, and error occurrence under vibrational influence.

Furthermore, by implementing the model in a simulation environment, the study offers a reproducible platform that avoids the constraints of costly physical prototypes. This enables designers and engineers to evaluate and compare encoders systematically, to optimise encoder integration in early design stages, and to anticipate reliability issues before implementation. The model can also serve as a diagnostic tool post-integration, facilitating condition monitoring and predictive maintenance strategies.

The structure of this paper is organised as follows. After this introduction, the second section details the design and technical development of the proposed model. The third section elaborates on the methodology, operational principles, and functional capabilities of the system. The final section presents conclusions, discusses the implications of the results, and suggests possible avenues for extending the model to future applications.

II. MATERIALS AND METHOD

The development of a reliable and comprehensive model for evaluating the accuracy of optical rotary encoders under vibrational disturbances requires more than a straightforward simulation of measurement processes. It necessitates the creation of a coherent and methodologically rigorous conceptual framework that directly represents the conditions under which such devices operate in industrial practice. In this study, the model has been developed within the MATLAB & Simulink environment, selected for its flexibility and proven capability to reproduce complex dynamic systems through modular, block-based design. Constructing the model in this manner enables not only the simulation of the encoder's functional behaviour but also the imposition of carefully controlled external disturbances that replicate the types of vibrations encountered in real-world applications. The principal aim of this approach is to provide a robust virtual test system through which the interaction between encoder accuracy and vibrational influence can be studied systematically and in detail.

The conceptualisation of the model follows the principle of integrated system design, whereby each component is defined in the context of the broader system architecture. This ensures that the functional interactions between mechanical, electrical, and computational elements are preserved, allowing the simulation to reflect the complexities of actual operational conditions. At the core of the system stands the optical rotary encoder, serving as the primary sensing element, providing continuous feedback regarding angular position. To generate meaningful insights into the encoder's behaviour, the simulation incorporates additional components, each fulfilling a distinct role in introducing, transmitting, or processing both motion and disturbance signals.

Central to the setup configuration is the vibration generation machine, a dedicated subsystem capable of imposing vibrational profiles with variable frequency, amplitude, and duration. These profiles are designed to emulate industrially relevant scenarios, ranging from low-frequency oscillations to high-frequency mechanical resonances. By subjecting the encoder to these controlled disturbances, the model allows for a detailed examination of the extent to which vibrations compromise measurement integrity, while enabling the systematic assessment of encoder stability under varying operational conditions.

The encoder is mechanically coupled to an electric motor, which provides continuous rotational motion. This motor is controlled via a precision motor controller, permitting fine regulation of rotational speed in revolutions per minute (RPM). The inclusion of this motor and controller is essential, as it facilitates the investigation of how variations in rotational velocity, in conjunction with vibrational disturbances, influence the accuracy of the encoder. Such a configuration allows for the identification of dynamic interactions that may amplify errors or trigger resonance effects, insights that would be unattainable through static testing alone.

Torque transmission between the motor and encoder is facilitated by a coupling system, carefully selected to ensure efficient energy transfer while minimising backlash, misalignment, or other mechanical anomalies that could affect measurements. This design consideration ensures that the primary source of measurement error arises from the controlled vibrations rather than from unintended mechanical effects, thereby isolating the specific impact of dynamic disturbances.

Signals produced by the encoder, reflecting both rotational movement and vibrational effects, are captured via a USB-based multifunctional input/output (I/O) device. This interface acts as a critical bridge between the physical measurement domain and the digital processing environment, enabling real-time data acquisition. The acquired signals are subsequently transmitted to a computing station, where they are subjected to comprehensive conditioning, filtering, and analysis. Signal conditioning removes background noise and isolates relevant features, while advanced processing techniques allow for the quantification of phase shifts, pulse irregularities, and amplitude deviations. The processed data is visualised in real time, providing an intuitive and quantitative understanding of how variations in vibration characteristics and rotation speed affect encoder performance.

Within MATLAB & Simulink, each component of the model is represented as a distinct functional block. The electric motor, motor controller, vibration generator, encoder, coupling system, I/O interface, and computer are all modularly defined and systematically interconnected in a block diagram that mirrors the flow of energy, signals, and disturbances throughout the system. This modular design provides clarity and adaptability, allowing components to be refined, replaced, or extended without compromising the integrity of the overall model. The interconnected blocks culminate in a comprehensive visual representation that illustrates the flow of mechanical and signal interactions, facilitating both validation and understanding of the system's operational dynamics.

The resulting conceptual framework is more than a simple aggregation of components. It constitutes a structured and controlled environment in which the behaviour of optical rotary encoders under vibrational conditions can be examined with scientific rigour. By integrating regulated rotational motion, systematically generated disturbances, precise mechanical coupling, robust data acquisition, and advanced processing, the model captures the complexity and nuance of real-world encoder operation. Moreover, positioning this platform within a simulation environment ensures reproducibility, flexibility, and extendibility, providing a solid foundation for subsequent experimental and analytical research.

III. RESULTS

The results of the present study are derived from the systematic modelling and simulation of the proposed setup within the MATLAB & Simulink computational environment. The modelling process was carried out with a particular emphasis on achieving a high degree of conceptual fidelity between the virtual representation and the physical system under investigation. To this end, each major subsystem of the encoder test setup was abstracted into a corresponding Simulink block. These blocks were not only designed to encapsulate the essential operational principles of their physical counterparts but were also structured in a way that allowed for clear visualisation of the interactions and couplings between different components. By applying this modular approach, it was possible to construct a coherent block diagram that reflects the complex interdependencies observed in real mechanical and electromechanical systems.

A fundamental aspect of the modelling procedure was the accurate definition of interconnections between individual blocks. Special attention was devoted to ensuring that these interconnections closely reproduced the actual pathways of mechanical transmission and signal flow within the encoder testing system. This careful structuring facilitated the development of a simulation platform capable of reproducing the mechanical dynamics, feedback processes, and disturbance replication that would occur in practice. In particular, the simulation allowed for the monitoring of encoder behaviour under dynamic conditions, providing valuable insights into how the accuracy of measurement is affected by operational disturbances such as externally induced vibrations.

The complete structure of the system, as represented in the developed block diagram (Fig. 4), demonstrates a high level of architectural consistency with the physical layout. The diagram is therefore not only a simulation tool but also an analytical representation that helps identify the key pathways through which errors may be introduced into the measurement process. Within this framework, the primary focus of the study was to examine how vibrational disturbances, which are common in industrial environments and often unavoidable, influence the encoder's performance in terms of measurement accuracy, stability, and repeatability.

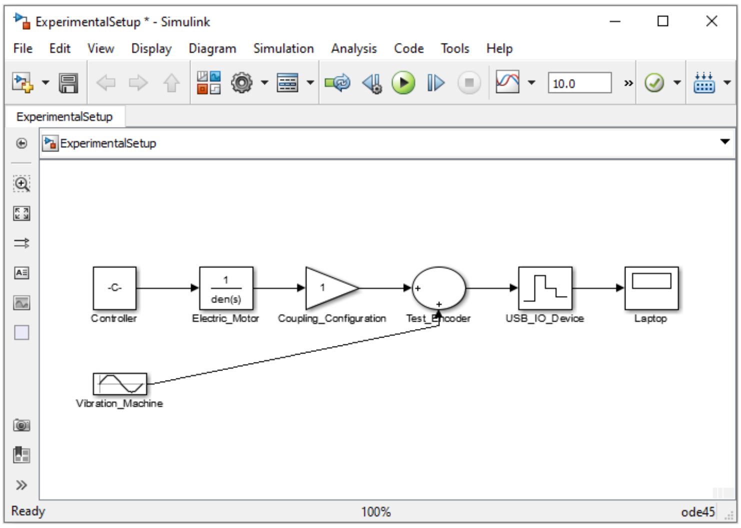

Fig. 4 Block Diagram Developed in MATLAB & Simulink

In the constructed model, external disturbances were introduced through the "Vibration_Machine" block. This block functions as a virtual representation of a mechanical vibration generator, capable of producing sinusoidal oscillations with controllable parameters. The three principal parameters defined for the simulation were frequency, amplitude, and duration (Fig. 5). The "Frequency (Hz)" parameter determines the number of oscillation cycles per second. In the reference configuration, a value of 70 Hz was applied, meaning the simulated vibrations occur seventy times per second. The choice of this value was intentional, as frequencies in this range are commonly encountered in heavy machinery and rotating industrial equipment. Testing the encoder at this frequency allows for the assessment of its robustness under relatively high-frequency oscillations, a scenario where errors are more likely to occur through mechanical interactions.

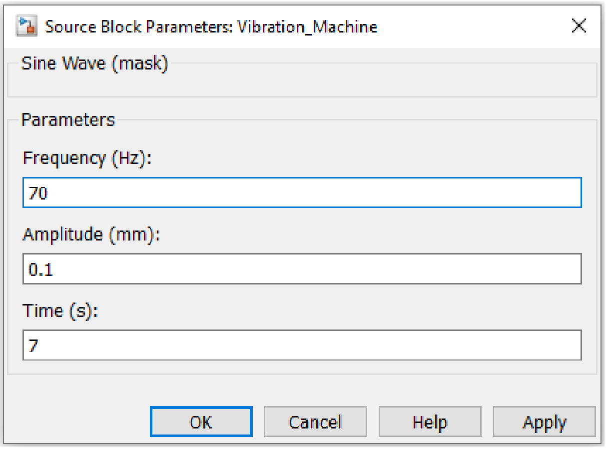

Fig. 5 Vibration parameters

The second parameter, “Amplitude (mm)”, specifies the maximum deviation of the vibration from its neutral position. An amplitude of 0.1 mm was selected for the baseline case. Although apparently small in magnitude, even such minimal displacements are capable of generating non-negligible distortions in sensitive measurement systems such as optical encoders. The amplitude essentially determines the mechanical severity of the vibration, and its influence is directly transmitted to the encoder shaft via the motor–encoder coupling. Therefore, variations in amplitude provide a means of simulating conditions ranging from minor operational vibrations to severe mechanical shocks.

The third parameter, “Time (s)”, defines the temporal extent of the simulation. For the setup presented in this work, the vibration source was configured to operate for a duration of seven seconds. This ensured that the encoder was subjected to a sufficiently long period of dynamic disturbance to allow for meaningful analysis of measurement errors and random behaviours. The ability to control simulation duration enables precise replication of both short-term and sustained disturbance conditions, each of which poses different issues to measurement reliability. The configuration window of the “Vibration_Machine” block, where these parameters are specified, is presented in Fig. 5.

The role of these three parameters — frequency, amplitude, and duration — is thus critical in determining the vibrational environment of the simulation. Their systematic variation provides a platform for analysing the encoder’s behaviour under a broad range of realistic conditions, thereby contributing to the generalisability of the results.

Parallel to the vibration subsystem, the system also incorporates a controller–motor configuration. The “Controller” block defines the reference command signal for the “Electric_Motor” block, which models the dynamic response of an electric motor through a transfer function. The motor dynamics are described by an integrator-type transfer function (1/s), where the angular position is mathematically derived as the integral of angular velocity. This formulation ensures that the simulation closely reflects the continuous nature of rotational motion. In the presented configuration, the motor was operated at a constant reference speed of 70 revolutions per minute (RPM), as specified in the “Controller” block (Fig. 6).

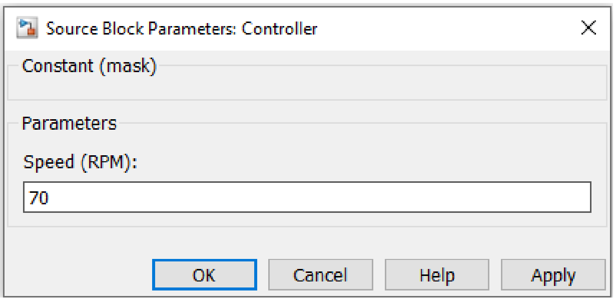

Fig. 6 Interface window of the “Controller” block

Maintaining a fixed rotational speed is of critical importance for this study. By stabilising the rotation speed, it becomes possible to isolate the specific effects of vibrational disturbances on the encoder, without introducing confounding variability from fluctuating motor dynamics. In practical applications, rotation speeds are often subject to external influences such as load changes or supply fluctuations, which can complicate the evaluation of sensor performance. In contrast, the controlled environment of this simulation ensures that the observed deviations in encoder output can be attributed exclusively to vibration-induced effects.

The encoder is represented through the "Test_Encoder" block. This block registers the rotational position of the motor shaft as transmitted through the "Coupling_Configuration" block, which models the mechanical connection between motor and encoder. The accuracy of torque and positional transmission in this block is essential, as it ensures that any difference between the reference signal and the encoder measurement can be legitimately interpreted as measurement error rather than modelling imperfection.

Data acquisition and error evaluation were implemented through the "USB_IO_Device" and "Laptop" blocks. These blocks facilitate the transfer of encoder data to an external computational platform, where real-time analysis and comparison with the reference values are performed. Upon execution, the system generates graphical representations of the encoder's measurement error over time. The output graph typically depicts angular deviation, expressed in degrees, as a function of time in seconds.

An illustrative representation of the encoder's performance under vibrational disturbance is provided in Fig. 7, where the temporal evolution of the angular error is plotted against the reference position. As can be clearly observed, the measured error remains consistently bounded within a narrow interval of approximately ±1°, despite the fact that the system is continuously subjected to externally induced vibrations. These vibrations are characterised by a frequency of 70 Hz and an amplitude of 0.1 mm, as configured through the "Vibration_Machine" block previously presented in Fig. 5. The persistence of such a confined error margin under these dynamic conditions constitutes a particularly significant result, as it highlights the ability of the encoder to preserve a high degree of measurement accuracy even when exposed to mechanical distortions of considerable magnitude.

The limited error interval observed in Fig. 7 is not merely a numerical outcome but also a meaningful indicator of system stability. In practical terms, maintaining an angular deviation within ±1° ensures that the encoder can be reliably implemented in industrial environments where operational vibrations are unavoidable. The stability of the error signal across the full duration of the vibration exposure further underscores the robustness of the system. Instead of exhibiting irregular or unstable deviations, which would suggest susceptibility to resonance or loss of synchronisation, the error signal demonstrates a consistent oscillatory behaviour. This steady oscillatory pattern implies that the encoder does not react to uncontrolled error amplification but instead responds in a predictable and well-contained manner.

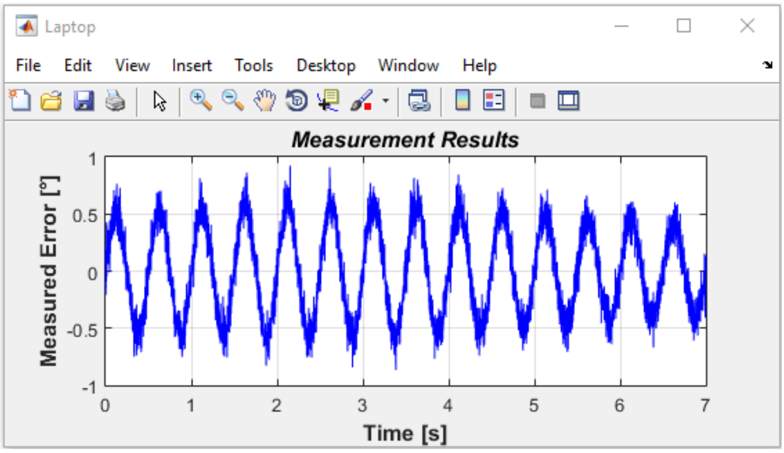

Fig. 7 Outcome of the developed model

Such behaviour is of particular importance when evaluating sensors for industrial applications. In real-world scenarios, encoders are frequently exposed to a spectrum of vibrational sources, ranging from low-frequency structural oscillations to high-frequency machine-induced disturbances. The evidence presented in Fig. 7 indicates that the tested encoder is capable of maintaining precision under at least one representative set of such conditions. Furthermore, the correlation between the vibrational characteristics defined in Fig. 5 and the observed response in Fig. 7 establishes a clear causal relationship, thereby validating the reliability of the simulation model itself.

Another noteworthy aspect of the result is its implication for long-term operational stability. A measurement error confined within a ±1° band, even under continuous disturbance, suggests that the encoder possesses inherent robustness not only to temporary distortions but also to sustained dynamic influences. This is particularly relevant for systems that operate for extended periods under constant exposure to mechanical stress, such as automated production lines, robotic manipulators, or precision positioning platforms. In such systems, even small uncorrected deviations can accumulate over time and compromise overall accuracy. The observed performance of the encoder therefore demonstrates its suitability for integration into these demanding environments.

IV. DISCUSSION

The results obtained from this study highlight not only the immediate utility of the proposed model but also its broader implications within the field of engineering sciences and applied system analysis. At the most fundamental level, the outcome demonstrates that the model possesses the capability to capture and interpret the performance characteristics of an optical rotary encoder when it is subjected to dynamic disturbances. This capacity extends well beyond the confirmation of theoretical assumptions or the simple verification of representational accuracy; rather, it positions the model as a methodological cornerstone for future investigations into system dynamics under complex, real-world conditions. In particular, the model facilitates a structured approach to examining the intricate interplay between mechanical vibrations, encoder accuracy, and system reliability—an interaction that often remains underexplored in conventional analytical frameworks.

From this perspective, the validation of the model is not merely an act of confirming its fidelity to the physical behaviour of encoders. Instead, it provides a critical connector through which the model can be systematically integrated into a diverse range of simulation-based studies and engineering evaluations. Such integration holds considerable promise for industrial applications, where encoders are frequently integrated within systems that are exposed to significant environmental and operational distortions. In these contexts, the model functions simultaneously as a precise digital replica of the physical system and as a forward-looking predictive tool. Its predictive capability allows engineers and researchers to anticipate potential deviations in encoder behaviour under varying load conditions, thereby enabling pre-emptive strategies for minimisation and system optimisation. This predictive function is particularly valuable when considering industrial environments that are inherently characterised by high levels of vibration, fluctuating operational demands, and the constant presence of uncertainty in measurement processes.

Furthermore, the role of the model extends considerably beyond the conventional expectation of replicating empirical conditions. By enabling the identification of critical instability ranges within operational spectra, the model contributes to a deeper understanding of thresholds at which encoder behaviour may transition from stable to disordered. This in turn provides insight into the sensitivity of the overall system to mechanical distortions, which is an essential aspect when designing robust feedback loops, error correction algorithms, or compensation mechanisms. Through such contributions, the model becomes instrumental in developing advanced methodologies for system optimisation, allowing not only for the improvement of measurement accuracy but also for the enhancement of system stability and long-term reliability.

A particularly important dimension of the model lies in its inherent adaptability and reproducibility. These qualities allow it to be applied across a broad spectrum of research contexts, ranging from controlled laboratory experiments to large-scale industrial case studies. By offering a versatile analytical platform, the model enables both qualitative insights—such as the detection of behavioural patterns under specific disturbance conditions—and quantitative evaluations, including the measurement of error magnitudes, frequency responses, and stability margins. Consequently, the model effectively bridges the gap between theoretical abstraction and practical application, offering a resource that is both academically rigorous and industrially relevant.

The implications of this are twofold. First, from a research standpoint, the model constitutes a valuable scientific asset that strengthens methodological robustness in the study of dynamic disturbances and vibration-induced effects. Its use ensures that examinations into optical encoder performance can be grounded in systematically validated simulations rather than relying exclusively on costly and time-consuming physical experiments. Second, from a practical engineering perspective, the model provides a concrete basis for the precision design and optimisation of encoder-based systems. This includes applications where high levels of accuracy and reliability are non-negotiable, such as CNC machining, robotics, aerospace navigation, automated manufacturing, and high-precision control systems.

In summary, the discussion of these results demonstrates that the value of the model lies not only in its capacity to replicate existing system behaviours but more importantly in its ability to anticipate, interpret, and generate responses to complex operational issues. By offering a comprehensive framework for evaluating encoder performance under dynamic disturbances, the model serves as a predictive, diagnostic, and optimisation tool. It thereby addresses both the theoretical requirements of scientific investigation and the practical demands of industrial engineering. Ultimately, the model emerges as a robust and indispensable framework, contributing to the advancement of knowledge and practice in the analysis, design, and optimisation of systems incorporating optical rotary encoders under dynamic and vibration-intensive conditions.

V. CONCLUSION

The development of a comprehensive and robust model for the assessment of accuracy and the quantification of measurement errors in optical rotary encoders subjected to vibrational disturbances represents a significant step forward in the systematic evaluation of these critical components. Implemented as a block-diagram framework within MATLAB & Simulink, this model offers a versatile and standardised environment for simulating dynamic distortions and examining the resulting behaviour of encoders, thereby overcoming the logistical issues, time constraints, and financial costs typically associated with extensive physical testing. By providing a controlled virtual platform, it enables a detailed investigation of the complex interactions between vibrational inputs and encoder responses, offering insights that would be difficult to obtain through an experimental approach alone.

Beyond reflecting observed empirical behaviours, the model functions as a predictive instrument, capable of revealing potential performance limitations and assessing the sensitivity of encoders to vibrational conditions. Its inherent flexibility and reproducibility render it especially beneficial during initial design stages as well as in subsequent operational diagnostics. Consequently, the model supports the enhancement of system robustness and facilitates the implementation of predictive maintenance strategies, contributing to the long-term reliability and efficiency of motion control systems.

Prospectively, there are numerous avenues for further enhancement and expansion. One promising direction involves extending its capabilities to multi-axis vibrational analysis, allowing for more comprehensive simulations of real-world scenarios. Incorporating real-time hardware-in-the-loop validation techniques would further enhance the model's applicability. Additionally, integrating advanced computational approaches, such as machine learning algorithms for predictive error correction, could substantially improve the model's predictive accuracy. Expanding the framework to incorporate a broader spectrum of encoder technologies and diverse mechanical interfacing conditions would also increase its relevance across multiple industrial domains, from precision manufacturing to robotics and automation.

In conclusion, the continued development and refinement of this model have the potential to transform it into a comprehensive, widely applicable tool for improving both the accuracy and stability of motion control systems. By analysing the effects of vibration on encoder performance and enabling predictive interventions, it enhances component-level reliability and contributes to the optimisation of entire electromechanical systems. In this context, the model represents not merely a methodological advancement but a foundational resource for engineers and researchers aspiring to superior performance, durability, and operational stability in environments characterised by dynamic mechanical conditions.

REFERENCES

[1] https://etching-meltec.com/optical-encoder/

[2] https://forum.digikey.com/t/understanding-rotary-encoders-key-types-technologies-and-use-cases/44606

[3] Lopez, J., & Artes, M. (2012). A new methodology for vibration error compensation of optical encoders. Sensors, 12, 4918–4933.

[4] Alejandre, I., & Artes, M. (2007). Method for the evaluation of optical encoders performance under vibration. Precision Engineering, 31, 114–121.

[5] Lopez, J., Artes, M., & Alejandre, I. (2011). Analysis under vibrations of optical linear encoders based on different scanning methods using an improved experimental approach. Experimental Techniques, 35, 3, 19–28.

[6] Lopez, J., Artes, M., & Alejandre, I. (2011). Analysis of optical linear encoders' errors under vibration at different mounting conditions. Measurement, 44, 1367–1380.

[7] Sanchez-Brea, L. M., & Morlanes, T. (2008). Metrological errors in optical encoders. Measurement Science & Technology, 19, 115104.

[8] Resor, B., Trethewey, M., & Maynard, K. (2005). Compensation for encoder geometry and shaft speed variation in time interval torsional vibration measurement. Journal of Sound and Vibration, 286, 897–920.

[9] Alejandre, I., & Artes, M. (2006). Thermal non-linear behaviour in optical linear encoders. International Journal of Machine Tools and Manufacture, 46, 1319–1325.

[10] Alejandre, I., & Artes, M. (2004). Machine tool errors caused by optical linear encoders. Journal of Engineering Manufacture, 218, 113–122.

[11] https://blog.endaq.com/vibration-measurements-vibration-analysis-basics