

NEW CONCEPTS AND ADVANCED STUDIES IN ENGINEERING



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Editor

Asst. Prof. Dr. Umut ÖZKAYA





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Rationale for Model Development in Accuracy Assessment of Optical Rotary Encoders Under Vibration: A Literature Perspective

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ABSTRACT

Optical rotary encoders are widely acknowledged as essential sensors for high-precision measurement and control in contemporary automation and manufacturing systems. Their extensive utilisation is primarily attributable to their capacity to provide accurate data on angular displacement and rotational speed. Nevertheless, despite their proven performance under controlled laboratory conditions, these devices remain susceptible to disturbances encountered in real industrial environments. Among such disturbances, mechanical vibrations constitute one of the most pervasive and influential factors, acting as a primary source of instability capable of compromising measurement reliability. The current literature evidences substantial progress in the development of optical encoder technologies, including advancements in resolution, signal processing, and multi-channel configurations. These improvements have enhanced robustness and reduced vulnerability to electrical interference and minor mechanical perturbations. However, under dynamic operational conditions, encoders continue to display limitations that have not been fully explored in either research or practice. While several studies have investigated the impact of vibrations, there remains a clear need for broader and more systematic evaluations of rotary optical encoders in dynamic contexts. This paper therefore provides a literature-based perspective on the rationale for developing dedicated models to assess encoder accuracy under vibrational influence. By synthesising existing findings, the discussion emphasises the importance of integrating vibration analysis into sensor metrology frameworks. Such integration is crucial not only for understanding the basic mechanisms of error generation but also for guiding the design of experimental methodologies and simulation models that more faithfully represent real-world operational conditions.

Keywords – Sensor metrology, Error propagation, Signal processing, Industrial reliability, Dynamic conditions, Automation systems, Experimental validation.

I. INTRODUCTION

The optical rotary encoder (Fig. 1) is a high-precision electromechanical sensor that plays a crucial role in modern automation, control, and measurement systems. It is specifically designed to determine angular position, rotational speed, and direction of motion with high accuracy. As a result of these capabilities, rotary encoders are widely implemented in applications requiring real-time data processing and fine measurement resolution, including computer numerical control (CNC) machining systems, robotics, servo mechanisms, motion control units, and a broad range of industrial automation processes.

The primary function of an optical rotary encoder is to convert mechanical rotational movements into electrical signals that can be processed by electronic controllers or computer-based systems. These signals are subsequently employed for precise monitoring, regulation, and analysis of rotational motion, thereby ensuring high levels of accuracy and automation in technical systems. Due to their excellent resolution and reliability, optical encoders have become the preferred choice in applications where dependable detection of position and speed variations is essential.

Beyond accuracy, these devices are characterised by their resistance to external electromagnetic disturbances and their ability to operate effectively in complex industrial environments. Their compact design, compatibility with multiple communication interfaces, and high measurement reliability make them suitable for sensitive applications that demand stability and precision. For this reason, optical rotary encoders are considered a key element in the design and implementation of advanced motion control and positioning systems in modern industry.



Fig. 1 An optical rotary encoder [1]

A. Applications of Optical Rotary Encoders

Optical rotary encoders represent indispensable components in contemporary machines and automated control systems. In CNC machining, for instance, they are integrated into the spindle drive to provide feedback on the rotational speed and position of the main spindle, which is central to the cutting processes. Since spindle motion directly affects machining accuracy and product quality, encoder feedback is critical for maintaining precise rotational speed and achieving consistent operation within defined process parameters.

With appropriate configuration, encoders can also support diagnostic functions within automated systems. In advanced CNC machines, they are used to verify reference positions during initialisation, detect lost steps in stepper motors, or identify mechanical blockages and transmission faults. In this way, encoders contribute not only to motion measurement but also to fault detection and system integrity.

In robotics, optical encoders serve as fundamental feedback devices for measuring angular displacement, speed, and rotation direction of moving joints and components. Embedded within servo or stepper motors, they

enable closed-loop control that ensures precise joint positioning, which is essential for tasks requiring high accuracy, such as assembly, manipulation, or finishing operations. In mobile robotics, encoders attached to wheels or drive systems are used to estimate distance passed and velocity, forming the basis for odometry and supporting navigation algorithms. Furthermore, they are essential in coordinating multiple axes in complex robotic systems, where synchronised motion is required.

Emerging applications such as collaborative and medical robotics benefit from encoders due to their ability to deliver stable, high-resolution feedback. This ensures safe interaction with humans, reliable calibration, and early detection of potential mechanical faults, thereby enhancing safety and trust in robotic operations.

Encoders also play a significant role in automated production and logistics systems. In conveyor systems, they monitor the position of products as they move through different processing or packaging stages, providing real-time feedback for activating manipulators, inspection sensors, or sorting mechanisms. Similarly, in automated warehouses, they are integrated into transport vehicles and lifts to enable safe and efficient material handling.

In addition, optical rotary encoders are applied in precision measurement and quality control systems. When combined with high-accuracy positioning sensors, they enable exact alignment of measuring heads, support laser-based machining, and assist in automated calibration tasks. These features position optical encoders as vital contributors to higher levels of automation, safety, and adaptability across a broad range of monitoring and control applications.

Taken together, these characteristics highlight that optical rotary encoders are not merely sensors for measuring angular position or speed but integral components of intelligent control, monitoring, and diagnostic systems. Their applications extend from conventional CNC machining to advanced robotic platforms, enhancing precision, reliability, and automation in industrial and technological processes. With their ability to provide robust and high-resolution feedback, they form a foundation for adaptive and synchronised motion-tracking systems, which are indispensable for Industry 4.0 and modern automation.

B. Operating Principle of Optical Rotary Encoders

The fundamental operation of an optical rotary encoder relies on the interaction between a light source and a precisely engineered rotating disc, which is mounted on the rotational axis of the object whose angular displacement is being measured (Fig. 2). This disc features alternating regions with distinct optical characteristics, such as transparent and opaque sections or reflective and non-reflective surfaces. As the disc rotates in unison with the target component, it enables continuous real-time measurement of angular movement.

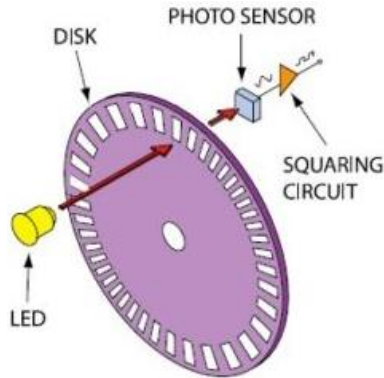


Fig. 2 Operating principle of an optical rotary encoder [2]

Typically, the light source is a monochromatic LED that either passes through or reflects off the surface of the disc, depending on the specific optical design. As the disc spins, the light is intermittently transmitted or blocked by these patterned regions, producing a series of periodic interruptions or pulses in the light signal. These variations are captured by photodetectors, most commonly photodiodes or phototransistors, positioned opposite the light source.

The photodetectors convert changes in light intensity into electrical signals, which are then processed as digital pulses. Each interruption or passage of light generates an individual pulse, forming a sequence that encodes the rotational information of the disc. By analysing the frequency, order, and phase difference of these pulses, the encoder can accurately determine the angular position, direction, and speed of the rotating element.

C. Configuration of Optical Rotary Encoders

The structural configuration of optical rotary encoders represents a critical determinant in ensuring accurate, reliable, and repeatable measurement of rotational motion. Within contemporary industrial and research-orientated applications, the escalating demand for high precision and operational dependability has driven both the refinement and widespread implementation of encoders with multi-channel architectures. These advanced arrangements embody a significant technological progression compared with the more conventional single-channel solutions, providing not only enhanced resolution but also expanded functional capacity.

Typically, the most widely adopted configurations incorporate two or three distinct channels, conventionally denoted as A, B, and Z, each of which performs a specific role within the system (Fig. 3). These channels are carefully synchronised, both with one another and with the associated control unit, to guarantee coherent and precise operation. Channels A and B form the foundation of motion detection, generating quadrature signals offset by 90 electrical degrees. This deliberate phase displacement enables the

encoder to differentiate rotational direction – whether clockwise or anticlockwise – through the sequential activation and deactivation of signals. The order in which the transitions occur provides the control system, frequently realised by microcontrollers or programmable logic controllers, with unequivocal information for determining both velocity and orientation of rotation.

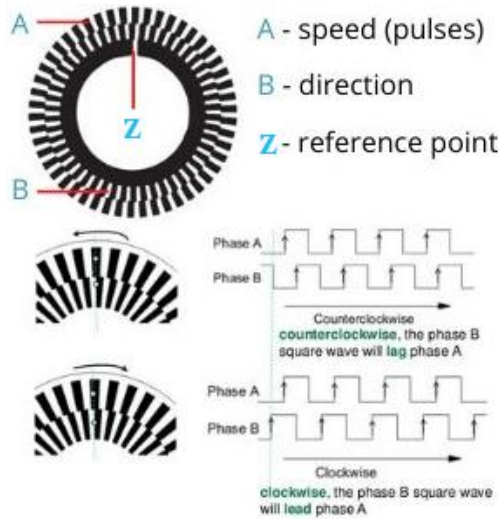


Fig. 3 Configuration of optical rotary encoders [3]

In addition to the enhanced resolution and the capability for precise directional detection, multi-channel configurations also serve a critical role in improving the overall reliability of encoder-based measurement systems. Their design inherently offers greater resilience through redundancy, signal verification, and error-checking mechanisms, thereby mitigating the risks posed by electrical interference or minor mechanical disturbances. Such robustness ensures that encoders remain dependable components across a wide variety of technical applications.

D. Mechanical Vibrations as a Source of Instability in Sensor Metrology

Within the framework of optical rotary encoder systems, it is essential to carefully examine the challenges associated with their performance under real-world dynamic conditions, which often impose complex technical constraints and act as potential sources of measurement error. In both scientific literature and industrial practice, such dynamic influences are most commonly characterised as mechanical vibrations, which are widely recognised as the primary and representative factor causing disturbances in industrial environments.

This perspective is included by several studies [4–7], where mechanical vibrations can be considered as a reliable and practical approximation of real operating conditions.

Although optical rotary encoders are engineered to deliver high-resolution and reliable measurements, their susceptibility to external dynamic influences—particularly vibrations—remains a critical consideration. These disturbances can significantly affect measurement accuracy, making vibration analysis an indispensable component of sensor metrology and system design. In this regard, however, it becomes evident that while previous research has provided valuable insights into the influence of vibrations, the scope of these investigations remains limited, highlighting the need for further expansion and more systematic evaluation of encoder performance under dynamic conditions.

E. Scope and contribution of this research

A review of the existing literature reveals a notable gap regarding the systematic evaluation of optical rotary encoder performance under vibrational influence. Despite their expanding implementation—particularly in CNC machining, high-precision manufacturing, automation, and robotics—their sensitivity to mechanical vibrations remains insufficiently explored. Given the rapid pace of technological advancement and the increasing integration of these devices across diverse industrial applications, ensuring their optimal performance has emerged as both a critical challenge and a priority for research.

This underscores the necessity for the development of novel methodologies to analyse measurement errors and assess the performance of optical rotary encoders under dynamic operating conditions. Within this context, it is particularly important to conduct comprehensive and systematic investigations that encompass not only quantitative metrics such as accuracy and repeatability, but also a qualitative understanding of encoder behaviour in vibratory environments.

Consequently, there is a clear need to establish an innovative model capable of evaluating and predicting encoder performance across varying vibration amplitudes and frequencies. Such a model would enhance insight into their real-world behaviour and provide essential data for assessing their reliability in dynamic systems. Focusing research efforts in this area is crucial for improving measurement precision, ensuring system dependability, and reinforcing the overall trustworthiness of applications that incorporate optical rotary encoders.

The structure of this paper is organised as follows. After this introduction, in the second section, the procedure for identifying and reviewing relevant literature is outlined. In the third section, research addressing the fundamental principles and applications of optical rotary encoders is reviewed, and the main limitations of existing studies are identified. In the discussion chapter, the insights obtained from the literature review are analysed, with emphasis placed on the research gaps. Finally, in the conclusion, the principal findings are summarised, the key outcomes of the

review are discussed, and potential directions for future research are presented.

II. MATERIALS AND METHOD

The methodology applied in this review was designed to ensure both breadth and depth in the identification, selection, and analysis of the scientific literature dealing with optical rotary encoders and their measurement accuracy under vibrational influence. Unlike empirical studies, where the focus lies on laboratory procedures or numerical simulations, the present work places its emphasis on establishing a systematic framework for the evaluation of previously published knowledge. Although the overall procedure comprises several stages, for the purposes of this review, particular attention is given to a selected set of key phases, namely: (i) comprehensive database search, (ii) keyword formulation and refinement, (iii) application of inclusion and exclusion criteria, and (iv) classification and analytical synthesis of the selected academic literature.

A. Literature Search Strategy

The initial step was to identify and review a broad range of scientific databases that provide reliable coverage in the fields of engineering, automation, signal processing, and measurement science. Several platforms were systematically searched, among which the most prominent were IEEE Xplore, Scopus, Web of Science, and ScienceDirect. These repositories, along with additional specialised sources, were selected due to their international recognition, extensive indexing of peer-reviewed journals, and comprehensive coverage of both theoretical and applied research in measurement technologies.

The search process was conducted in an iterative manner. In the first iteration, broader search terms associated with optical rotary encoders, encoder accuracy, and similar expressions were applied. This generated a wide pool of references, many of which only partially aligned with the core research focus. To refine the results, subsequent iterations introduced a larger set of possible terms with a higher likelihood of relevance, like vibration influence, measurement error, frequency response, etc. Different combinations of these and related terms were explored as potential variants for searching, allowing a more targeted selection of studies that addressed the effects of vibrational disturbances on encoder performance.

The search encompassed a wide range of sources, including publications written in English, as it remains the predominant language of technical and engineering research. Additionally, multiple databases were consulted to include journal articles, conference proceedings, and doctoral dissertations, recognising that these sources often contain original findings and complementary perspectives that may not yet be reflected in journal publications.

B. Inclusion and Exclusion Criteria

The refinement of the initial literature required the application of rigorous selection criteria. Studies were considered eligible for inclusion if they met the following requirements:

- They were published in peer-reviewed journals, conference proceedings, or reputable scientific monographs;
- They explicitly addressed the issue of measurement accuracy, performance evaluation, or error quantification in optical rotary encoders;
- They investigated external influences that could compromise measurement reliability, such as mechanical vibrations, thermal fluctuations, or misalignment errors;
- They presented empirical findings, numerical simulations, or analytical models that could be critically evaluated.

On the other hand, publications were excluded if they:

- Focused exclusively on incremental or absolute encoders without consideration of measurement errors;
- Dealt solely with design and manufacturing aspects without testing performance under real-world disturbances;
- Provided descriptive information without quantitative or analytical results;
- Or were published outside the defined temporal window of interest.

Although the time frame was not strictly confined to a single decade, preference was given to studies published in the last 15–20 years, reflecting the rapid technological advancement of encoder systems and the increasing importance of vibration resilience in modern automation.

The process of inclusion and exclusion was carried out in multiple stages, allowing for flexibility in selection. Initially, titles and abstracts were reviewed to identify sources that appeared relevant, while acknowledging that some sources might be reconsidered in later stages. Subsequently, the full texts of potentially pertinent articles were examined, with multiple criteria considered rather than strictly enforced rules. The resulting selection reflected a diverse and adaptable corpus of literature suitable for systematic analysis.

C. Classification of Selected Studies

To facilitate structured analysis, the final set of sources can be classified into three principal categories:

1. Experimental investigations – studies in which encoders were tested under controlled laboratory conditions or within industrial settings. These works typically involved the application of artificial vibrations through electromechanical shakers or the measurement of encoders in situ under operational disturbances. Reported metrics included data

for angular deviation, RMS error, amplitude–frequency characteristics, etc.;

2. Simulation-based studies – publications in which mathematical or computational models were developed to predict encoder behaviour. These studies often involved the use of finite element methods (FEM), signal-processing algorithms, or control-system simulations implemented in environments such as MATLAB/Simulink, etc.;
3. Hybrid approaches – research combining experimental measurements with analytical or numerical models. This class of studies is particularly valuable, as it bridges the gap between theory and practice by validating predictive models against real-world data.

By applying this classification, it is possible to identify patterns across methodologies, highlight recurring analytical techniques, and compare the strengths and weaknesses of different approaches.

D. Analytical Framework

Once the relevant studies are categorised, a structured analytical framework can be employed. This framework sought to extract information under several dimensions:

- Type of encoder: including incremental versus absolute, resolution levels (measured in pulses per revolution – ppr), and the specific application context (robotics, CNC machinery, aerospace, automotive systems, etc.);
- Nature of external influence: with an emphasis on vibrational characteristics (frequency, amplitude, duration), but also considering additional factors such as thermal effects, electromagnetic interference, and mechanical misalignments, etc.;
- Evaluation metrics: error quantification techniques such as root mean square error (RMSE), Fourier and spectral analysis (FFT), time-domain deviation analysis, or calibration-based correction models, etc.;
- Limitations and future recommendations: as reported by the authors themselves, which provide a valuable indication of current research gaps.

This framework enables not only a systematic comparison of methodologies but also the identification of inconsistencies across studies. For instance, while some authors relied heavily on frequency-domain analysis to capture vibration-induced errors, others focused on time-domain error propagation, making direct comparisons difficult. Similarly, while experimental studies often dealt with limited parameter ranges due to technical constraints, simulation-based works tended to simplify the encoder–environment interaction, raising concerns about real-world applicability.

E. Identification of Research Gaps

The final step of the methodological approach is the synthesis of gaps and limitations. Several issues can emerge consistently:

- A lack of a unified modelling framework that integrates experimental, analytical, and simulation-based insights into a coherent structure;
- Limited availability of systematic testing protocols, with most studies employing ad hoc setups rather than standardised procedures;
- Insufficient attention to parameter variability, such as simultaneous changes in rotational speed, vibration frequency, and amplitude;
- A scarcity of long-duration studies that investigate the cumulative effects of vibrations over extended operational periods.

By systematically highlighting these gaps, the methodological framework lays the foundation for the development of a new innovative model of encoder performance assessment, which is the broader aim of this research effort.

III. RESULTS

The following section presents a systematic synthesis of the key findings extracted from the reviewed literature. Emphasis is placed on the performance characteristics of optical encoders, the factors influencing their measurement accuracy, and the impact of dynamic operational conditions, particularly vibrations. The analysis is structured to provide a clear overview of both the established knowledge and the gaps identified across experimental, simulation-based, and hybrid studies. By organising the results thematically, this section aims to highlight the critical aspects that govern encoder behaviour, thereby setting the stage for a detailed discussion of mechanical, thermal, and vibrational influences in subsequent subsections.

A. Application and Relevance of Optical Encoders in Modern Systems

The evaluation of performance and the assessment of measurement errors in optical encoders constitute a fundamental aspect of research in domains where precision and accuracy are of paramount importance. Owing to their capability to provide highly accurate and reliable information regarding angular or linear positions, optical encoders are regarded as essential components within systems designed for position and velocity measurement and control. Their extensive utilisation across industrial, scientific, and technological settings underscores their significance as integral elements of contemporary automated systems.

Their role is particularly pronounced in modern CNC machining centres, where they are employed to monitor relative displacements and ensure the precise positioning of moving components [8]. These sensors facilitate automatic correction and minimisation of errors during the machining process, which is crucial for the manufacture of components with complex geometries and stringent quality requirements.

In robotics, optical encoders play a central role in motion control systems for robotic manipulators [9]. Their precise measurement capability enables

the synchronisation of movements, which is a key factor in optimising and enhancing the efficiency of production processes.

Moreover, optical encoders are employed as sensors for determining the position and velocity of moving objects within tracking systems [10]. This application allows for trajectory analysis and real-time adjustment of control strategies, thereby ensuring high accuracy and rapid responsiveness under dynamic operating conditions.

The inherent precision and reliability of these devices also permit their deployment in a variety of other domains, highlighting the critical importance of encoder performance as a determinant of overall system functionality. Investigations into this topic emphasise the necessity of analysing the factors that influence measurement accuracy. According to the study conducted in [5], the principal factors affecting the performance of optical encoders include mechanical deformations, thermal variations, and exposure to vibrations within the systems in which they are integrated.

B. Mechanical Factors and Their Influence on Optical Encoder Accuracy

Mechanical deformations and thermal variations constitute critical factors influencing the measurement accuracy of optical encoders. In [11], a methodology is presented for quantifying and modelling thermally induced deformations that contribute to positioning errors in multi-axis machining centres. The study further introduces a structured framework for minimising encoder-related errors through a detailed analysis of both the spatial temperature distribution and the rigid body kinematics, thereby offering a systematic approach to mitigating measurement inaccuracies associated with thermal effects.

Furthermore, the impact of thermoelastic deformations, originating from diverse thermal sources, as well as ambient temperature fluctuations, on the accuracy of optical linear encoders has been investigated in [12]. A real-time model for geometric and thermal error compensation was developed, which, when implemented on an FPGA platform, demonstrated a significant reduction in measurement errors—reported to reach up to 98%. Similarly, the influence of thermally induced deformations, caused by heat generation in linear motor systems, on both encoder accuracy and the structural integrity of machining centres has been examined in [13]. The study identified the principal sources of thermal errors, including thermal expansion, linear scale displacement, and deformation of machine components.

The consequences of prolonged machine operation, particularly the effects of continuous thermal loading on moving components during extended work cycles, were explored in [14]. It was observed that the heat generated during operation induces structural expansion, resulting in diminished positioning accuracy of moving elements. Consequently, extended utilisation of machining centres leads to increased cumulative error in encoder

measurements, accompanied by a reduction in operational precision and efficiency.

In a related investigation, structural analysis of CNC machining centres, with emphasis on deformations and thermal fluctuations as primary contributors to encoder measurement inaccuracies, was conducted in [15]. This research combined finite element models with experimental calibration techniques to enable precise quantification of these phenomena. Special attention was given to the interaction between power control systems, machining conditions, and the structural dynamics of the machines. The study confirmed that both temperature fluctuations and mechanical deformations constitute key factors in the degradation of positional accuracy within CNC systems.

C. The Influence of Vibrations on Measurement Accuracy

Although extensive attention has been devoted to the effects of deformations and thermal variations, comparatively fewer studies have investigated the behaviour and performance of encoders under the influence of vibrations. Within this context, which remains a relatively underexplored scientific domain, research was conducted in [8], where—alongside the analysis of errors in optical linear encoders induced by deformations and temperature changes—the impact of vibrations on their operational reliability was also examined. The study focused on the identification, classification, and quantitative evaluation of vibration effects, with the aim of gaining a deeper understanding of the limitations and potential applications of these devices across diverse technical and industrial contexts.

The examination of encoder measurement errors occurring during the operation of CNC machine tools, particularly in relation to the synchronisation of moving components and their accurate positioning, has traditionally been concentrated on the structural properties of the machines themselves. This line of research encompasses the study of design imperfections, weaknesses in the mechanical layout, damping characteristics, and the effects of clearances in joints, transmission mechanisms, and other structural elements.

In this regard, in [16] respectively [17], a method for assessing geometric errors in multi-axis CNC machine tools was proposed. Their approach relied on measurements of three-dimensional volumetric lengths and the development of a universal error model applicable across different machine configurations. Considering the significance of measurement accuracy, the implementation of the proposed model enables software-based error compensation as well as precise diagnosis of machine tool functional deficiencies. Within this methodological framework, high-precision length measurements combined with straightforward execution were identified as the most suitable technique for determining positioning errors. Moreover, it was confirmed that the design of the measurement system and the precise

formulation of the error model—aligned with the correlation of influential parameters—play a crucial role in ensuring accurate diagnostics and enhancing the reliability of measurement outcomes.

D. The Optical Encoder as a Potential Source of Error

While errors in the synchronisation of motion and in the accurate positioning of moving components in machine tools are most frequently associated with the structural design and performance of the machines themselves, relatively few investigations have directly addressed the encoder as a potential source of error. Nevertheless, several studies suggest that the encoder may indeed represent a contributing factor, thereby opening new perspectives for the analysis and enhancement of the precision of such devices.

In this regard, the application of a digital time-interval technique for measuring torsional vibrations in rotating shafts was examined in [4]. Within this study, a calibration method for encoders under real operating conditions was proposed, whereby a reference sequence corresponding to the true angular intervals of the encoder was generated. To minimise errors, a resampling algorithm was employed, producing a sequence of samples at constant time intervals. The results demonstrated that the method effectively reduces the impact of frequency dispersion—caused by variations in rotational speed—even when using high-precision optical encoders.

Furthermore, devices and methods designed to isolate encoders from vibrational influences through the application of external flexible elements and other structural components were introduced in the patents [18] and [19]. These contributions emphasise the significant role of vibrations as a factor that degrades encoder performance. However, a review of the available literature reveals that information concerning the specific performance of encoders within their operational frequency ranges under dynamic conditions remains limited.

E. Modern Methods for Evaluating the Performance of Optical Encoders under Vibrational Influence

According to the findings in [5], optical encoders are generally regarded as highly precise devices, even when exposed to vibrations. Deviations in measurement are most commonly attributed to the CNC machine tools themselves, including their components, gears, belt drives, and other mechanical elements. However, it is emphasised that this assumption is not universally valid, highlighting the necessity for methods specifically designed to evaluate the accuracy and performance of optical encoders under vibrational conditions, thereby ensuring optimal functionality across diverse operational scenarios. To achieve this purpose, an innovative approach is presented for assessing encoder performance under vibrational influence.

This method differs from traditional approaches by not merely identifying resonant frequencies and signal acceleration but also introducing the concept

of “measuring error for a frequency range”. Such a perspective enables a more comprehensive evaluation of performance, demonstrating that, under real operational conditions, signal acceleration is less critical compared to the measurement errors induced by vibrations in optical encoders.

The methodology represents a significant advancement in this research area, as it considers two critical aspects: first, the magnitude of encoder measurement errors at resonance; and second, the errors occurring in non-resonant frequency ranges. Successful implementation relies on several key factors, including the choice of signal type, analysis of non-linear signal variations, sampling frequency specification, and signal composition. These elements are fundamental to accurately assessing encoder performance and ensuring their functionality under varying operational conditions.

Application of this method produces a high-resolution spectrum of encoder behaviour, allowing the identification of multiple instability zones within the examined frequency range. Parameters for these evaluations are based on the European standard in [20], facilitating the identification of critical frequencies during durability testing. Under dynamic loading, the device is exposed to continuously variable frequencies within an adopted range of 55 Hz, though testing may also extend to other ranges according to the capabilities of the vibration-generating equipment. Additionally, the amplitudes of vibration for different encoder types are adjusted individually. For visualisation of mechanical effects, an acceleration amplitude of 200 m/s² was considered appropriate, consistent with specifications from several commercial encoder manufacturers. Testing duration was initially set to over five minutes, resulting in substantial data files; to maintain manageable file sizes for numerical processing, the duration was limited to 90 s, with recording activated at the onset of testing.

The results indicate multiple instability zones within the specified range, significantly influencing measured values and increasing total measurement error. Analysis demonstrated that errors could reach up to three times the declared encoder accuracy, confirming that optical encoders can constitute significant sources of measurement error in high-frequency vibrational environments, even when these comply with international environmental testing standards. The proposed methodology not only identifies performance weaknesses but also provides practical guidance for improvement, offering substantial value to manufacturers seeking design enhancements and end-users aiming to optimise performance through validation.

In a related study [6], a detailed investigation is conducted into the measurement errors of optical linear encoders under vibrational influence across various mounting conditions. Three commercial encoders from different manufacturers were examined to yield representative and generalisable results. The methodology aimed to quantify accuracy

degradation under vibrational load and its dependence on mounting conditions.

Several fundamental parameters were defined for testing, including frequency range, vibration amplitude, and test duration. Parameter selection followed the recommendations in [20], which enables precise assessment of system stability through the identification of critical frequencies. The frequency range was chosen to comprehensively characterise encoder measurement error relative to vibration frequency, corresponding to the minimum and maximum resonant frequencies of machine tool structures, as reported in [21]. The standard also allows variation in vibration amplitude according to the specifications of the tested commercial encoders, as confirmed in [5]. A maximum acceleration amplitude of 100 m/s^2 was selected to ensure proper encoder operation without additional vibration protection. At low frequencies (20–82.3 Hz), vibration was controlled via a constant displacement of 0.75 mm, with a $\pm 3 \text{ dB}$ tolerance. Below 82.3 Hz, improved control could be achieved by reducing the frequency ramp rate while considering test duration, which depends on the size of the data archive storing encoder signals. A linear frequency ramp of 22 Hz/s was applied to establish a direct relation between frequency and test duration while maintaining an optimised archive size.

The results revealed that the dynamic characteristics of optical linear encoders vary significantly with vibration direction. In certain positions, errors exceeded nominal accuracy, even at acceleration levels for which additional anti-vibration measures were not recommended. Mounting position could also introduce new resonances, producing substantial errors. Results were presented in diagrams showing encoder measurement errors as a function of vibration frequency.

Analysis demonstrated that vibration-induced encoder errors primarily arise from the relative motion between the two gratings forming the interference pattern—the fundamental measurement mechanism. Improper encoder installation in machine tools further amplifies measurement errors. Encoders operating within specifications under different mounting conditions may exhibit errors exceeding allowed tolerances. These findings underscore the importance of proper installation and monitoring of operational conditions to achieve high precision when employing optical linear encoders.

IV. DISCUSSION

A comprehensive examination of the research confirms the fundamental role of optical encoders as indispensable components within modern systems of measurement, positioning, and control. Their contribution extends far beyond the function of mere sensing devices; rather, they represent the foundation of many industrial processes where accuracy, stability, and repeatability are essential. High levels of precision and reliability are not

simply desirable characteristics but indispensable prerequisites for the efficient operation of complex automated systems, including CNC machine tools, robotics, aerospace platforms, and a variety of mechatronic applications. Within such domains, optical encoders act as the link between mechanical motion and digital interpretation, thus enabling real-time monitoring and decision-making. Consequently, the extent to which their functionality is preserved under dynamic working environments becomes a subject of critical importance for both scientific investigation and industrial practice.

Previous research consistently indicates that the accuracy of optical encoders, and more broadly their ability to provide highly stable measurement outputs, is particularly sensitive to external factors. Among these, vibrations have emerged as one of the most frequent and severe sources of disturbance. Dynamic conditions, characterised by rapid changes in position, speed, or direction, introduce mechanical and electronic challenges that affect the stability of measurement signals. In such environments, additional factors, including mechanical loads, thermal fluctuations, electronic interference, and long-term wear of components, further exacerbate instability. The combined effect of these influences manifests in increased measurement error, signal degradation, loss of synchronisation, or even physical damage to the encoder structure. From a systems perspective, such inaccuracies may propagate through control loops, producing deviations in machine performance, reduced product quality, or, in some cases, complete process failure.

Specialised attention in the literature has been directed towards optical linear encoders, where it has been repeatedly demonstrated that their measurement precision is vulnerable to vibrational excitation as well as the conditions under which they are mounted. Empirical results suggest that high-frequency vibrations or sudden shocks can lead to abrupt signal losses, reduced stability of the optical interference pattern, and, in severe cases, structural degradation. These findings underline the critical importance of both robust mechanical design and meticulous installation practices as preventive measures. The implication is that even relatively small deviations in mounting alignment or inadequate damping of vibrations may drastically compromise overall accuracy. Consequently, in high-precision manufacturing and automation, encoder design and installation procedures must be approached with the same rigour as the calibration of the measuring system itself.

Despite these insights, a closer review of the scientific literature reveals a substantial gap regarding the systematic evaluation of optical rotary encoders under the influence of vibrations. While their deployment in industrial environments continues to expand—most notably in CNC machining, robotic automation, and precision assembly—the extent to which they are affected by dynamic excitation remains underexplored. This lack of detailed

understanding contrasts with the growing technological demand for robust, vibration-resistant measurement systems. The rapid advancement of digital manufacturing, the rise of Industry 4.0, and the integration of intelligent monitoring systems all emphasise the need for encoders capable of maintaining accuracy under increasingly complex operating conditions. The insufficient exploration of their vibrational sensitivity thus represents not only a scientific limitation but also a pressing industrial concern.

Addressing this deficiency necessitates the development of new methodologies for analysing measurement errors and evaluating the performance of optical rotary encoders under dynamic conditions. Such methodologies must transcend simple accuracy checks, incorporating both quantitative and qualitative aspects of encoder behaviour. Quantitative dimensions include frequency response, measurement deviation, and error propagation over time, while qualitative insights pertain to understanding how encoders react to varying modes of excitation, resonance phenomena, and mounting configurations. Without this dual perspective, evaluations remain incomplete and risk underestimating the limitations of encoders in real-world scenarios.

The literature review also highlights that while considerable effort has been directed towards identifying the influence of temperature variations, structural deformations, and machine imperfections, the effects of vibrations on rotary encoders have not received equivalent systematic attention. This imbalance indicates that although the scientific community acknowledges multiple external influences on encoder performance, the vibrational component is yet to be fully integrated into standardised evaluation procedures. Initiatives do exist to model encoder accuracy in dynamic conditions, yet there remains no universally accepted framework that encompasses both the frequency spectrum and the range of potential measurement errors. This absence of a standardised, comprehensive model leaves a significant research gap and underscores the importance of extending inquiry into this area.

Developing an innovative model for assessing the performance of rotary encoders under various levels and frequencies of vibration is therefore not merely desirable but essential. Such a model would not only provide researchers with the tools to quantify and interpret encoder behaviour under realistic conditions but would also generate practical guidelines for industrial users. By simulating dynamic excitations, identifying resonance zones, and quantifying error propagation, it would be possible to predict performance degradation before it compromises system reliability. Furthermore, the model could inform the design of next-generation encoders with enhanced vibration resistance, whether through structural reinforcement, improved signal processing algorithms, or advanced mounting technologies.

In essence, the discussion underscores that optical rotary encoders occupy a position of growing strategic importance within advanced technological

systems. Their ability to deliver accurate, repeatable measurements in environments characterised by dynamic stress will directly influence the reliability of industrial automation, robotics, and precision manufacturing. At present, the absence of comprehensive models and systematic evaluations represents a limitation in both the academic and industrial knowledge base. Consequently, addressing this gap is not only a scientific opportunity but also a prerequisite for ensuring that optical encoders can continue to serve as trustworthy components in the rapidly evolving landscape of modern engineering applications.

V. CONCLUSION

The analysis of the available literature demonstrates that optical rotary encoders constitute critical elements within modern measurement and control systems, particularly in applications where accuracy, stability, and reliability are non-negotiable. Their widespread use across domains such as CNC machining, robotics, aerospace, and precision manufacturing reflects both their technological sophistication and their indispensable role in enabling digital transformation within industry. However, this review has also revealed a pronounced research gap: despite their prominence, the performance of optical rotary encoders under vibrational influence remains insufficiently examined in a systematic manner.

The findings consistently underline that vibrations, whether originating from machine dynamics, environmental disturbances, or structural imperfections, represent one of the most persistent and disruptive factors affecting encoder accuracy. While certain studies have explored the impact of temperature variation, thermal expansion, and mechanical alignment on encoder performance, vibrational effects have not been addressed with the same depth or methodological rigour. This imbalance has created a fragmented knowledge base in which partial insights exist, yet a holistic and standardised framework for evaluating encoder behaviour under dynamic conditions is still absent.

Against this backdrop, the rationale for model development becomes clear. The need is twofold: on the one hand, to provide researchers with analytical tools capable of quantifying measurement errors, identifying resonance effects, and simulating encoder behaviour across different frequency domains; on the other, to offer practitioners practical guidelines for selecting, installing, and operating encoders in environments where vibration is inevitable. A comprehensive model would therefore bridge the existing gap between theoretical understanding and industrial application, while also fostering innovation in encoder design, calibration, and error mitigation strategies.

Furthermore, the urgency of such development is heightened by the accelerating pace of technological progress. The expansion of intelligent manufacturing, cyber-physical systems, and autonomous platforms requires

measurement devices that can withstand increasingly complex operating conditions. Without robust methodologies for evaluating and predicting encoder accuracy under vibration, the reliability of entire systems may be compromised, undermining the very foundations of precision-driven industries.

In conclusion, the literature perspective presented here underscores both the critical role of optical rotary encoders and the inadequacy of current approaches to assessing their accuracy in vibrational environments. The development of a systematic, standardised model is therefore not merely an academic exercise but a strategic necessity. Such a model would enhance scientific understanding, inform industrial practice, and ultimately ensure that optical rotary encoders continue to serve as reliable, high-performance components within the progressing domain of modern engineering and automation.

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