

Eddy Current-Based Proximity Measurement for High-Precision Vibration Detection and Industry Applications

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ABSTRACT

Eddy current proximity sensing is a well-established non-contact method to measure linear and angular displacement, motion, and vibration, commonly employed in automotive and industrial settings due to its precision and reliability. In this paper the basic principles of eddy current proximity measurement is outlined, the peculiarities between the digital and analog methods are compared. It further explores the benefits and challenges of digital proximity systems, followed by an explanation of their application in vibration monitoring. Finally, it highlights current trends in digital proximity sensing technologies.

Keywords: *proximity sensors, eddy current, vibration measurement, IoT*

1. INTRODUCTION

One of the most developed methods for accurately measuring linear or angular displacement, metal position, vibration, compression, and motion in a variety of applications, such as automotive, medical, industrial, and security, is eddy current proximity sensing. The method has superior performance and better reliability compared to alternative methods of proximity sensing because it is contactless. It possesses numerous advantages relative to other methods. Firstly, its implementation is straightforward, as the sensor does not necessitate direct contact with the metallic target material, nor does it demand the presence of a coupling medium. Secondly, it demonstrates its applicability across a diverse array of applications due to its elevated detection sensitivity and linear response to variations in the size, shape, or spatial displacement of the target metallic material. Third, this sensing technology is both portable and economically viable, as the associated sensing apparatus is notably compact and lightweight. Ultimately, the automation of

eddy current proximity sensing is feasible due to the straightforward modulation of its electrical properties. Among various utilizations, vibration measurement serves as a prominent application wherein eddy current-based detection is extensively utilized. A lumped parameter RLC circuit can be used to simulate an eddy current proximity probe system (Du, 2014). When an oscillating current traverses a probe coil, it induces an eddy current upon the surface of an electrically conductive target material. Subsequently, this eddy current exerts a counteracting influence on the probe's R-L-C "tank." A notable phenomenon is that the inductance and the resistance exhibit variations in response to changes in the physical distance between the metallic target and the probe. Conversely, a sensing electronic circuit translates these alterations in inductance or resistance into voltage, yielding an output signal that is proportional to the physical separation. The schematic representation of the eddy current probe system is depicted in Fig. 1.

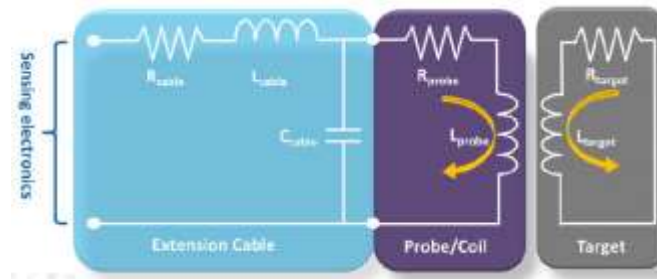


Fig. 1: Probe system for eddy current sensing

2. PRINCIPLE OF DIGITAL PROXIMITY SYSTEM

The predominant category of proximity probe systems can be classified as devices that fundamentally measure impedance. At the designated resonance frequency, the impedance becomes a function of the attributes of the R-L-C

“tank” and the relationship is as depicted in equation 1.

$$Z = \frac{L}{RC} \quad (1)$$

and the intended material. The American Petroleum Institute (API) standard 670 delineates the fundamental prerequisites for a machinery protection system (MPS) tasked with the

measurement of shaft vibration and positional parameters. This standard stipulates that the output voltage generated by the sensing electronic components must exhibit linearity and remain within $\pm 5\%$ of 200 mV/mil across the complete operational spectrum (10 mil to 90 mil) of a proximity probe system (wherein one mil is defined as one thousandth of an inch).

The primary function of the sensing electronics is to quantify the variations in impedance and subsequently produce a corresponding output voltage. In the event that a linear correlation is established between the alterations in impedance and the modifications in gap, it would facilitate the process for the sensing electronics to effectively correlate the gap alterations to the resultant output voltage. Nevertheless, it is essential to recognize that the impedance response to variations in gap distance exhibits a nonlinear or logarithmic relationship. Once the gap attains a specific threshold, the probe ceases to detect the target, resulting in subsequent alterations in the gap having no influence on the impedance. A representative graph illustrating the relationship between impedance variation and gap alteration is depicted in Fig. 2.

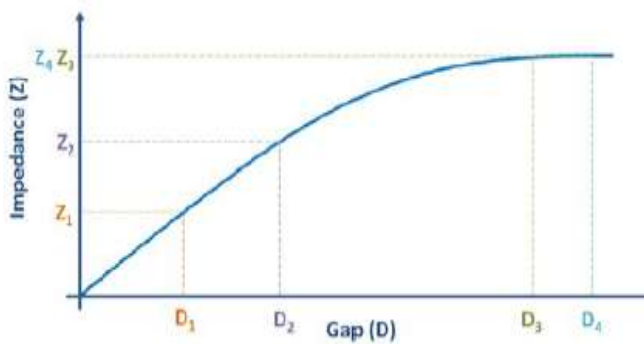


Fig. 2: Impedance – gap relationship

Digital proximity sensors have shown promising performance in smart vibration sensing

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applications when integrated with machine learning techniques (Lee & Choi, 2019). Various digital signal processing algorithms have been developed to improve the linearity and accuracy of inductive proximity sensors, ensuring more reliable system performance (Wang & Tan, 2020). In predictive maintenance applications, smart vibration sensing using digital proximity technology has proven effective for identifying incipient mechanical faults (Lee & Choi, 2019).

2.1 Analog Approach

The primary challenge, therefore, lies in the methodology employed to linearize the observed variation in impedance in such a manner that the resultant output voltage is both linear and directly proportional to the gap across an extensive range. An analog circuit can be used to linearize the nonlinearity as illustrated in Fig. 3. However, executing the requisite compensation presents a formidable challenge. Initially, it is essential to meticulously select the appropriate circuit components. Subsequently, a specific assemblage of components is effective solely for a distinct combination of target material, cable length and probe tip diameter (Silva, 2016).

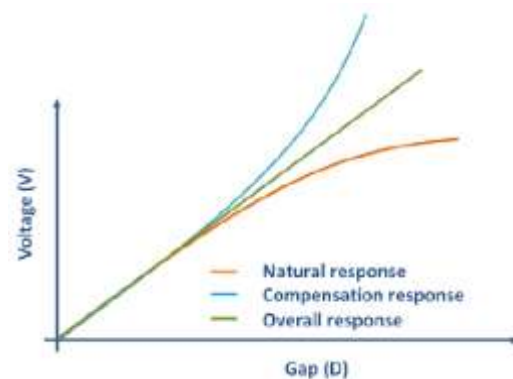


Fig. 3: Analog compensation of a nonlinear graph

2.2 Digital Method

A software-based method for linearizing nonlinear impedance input involves developing a digital algorithm. This intelligent algorithm enables direct mapping of each specific input to

a corresponding output. The process is simple and efficient. Fig. 4 presents the functional block diagram of this digital approach.

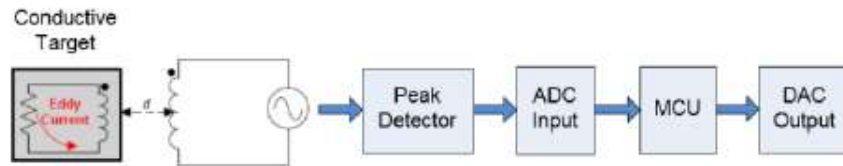


Fig. 4: Digital proximity measurement system

The digital proximity sensing system consists of five main components. The oscillator is an R-L-C "tank" circuit that generates continuous oscillations at a specified frequency. The peak detector captures the peak-to-peak amplitude of these oscillations as the distance varies. The Analog-to-Digital Converter (ADC) transforms the analog peak values into digital signals, which are then processed by the Microcontroller Unit (MCU)—the system's core—executing an algorithm to convert nonlinear input data into a linear digital value. Finally, the Digital-to-Analog Converter (DAC) outputs this processed digital value as an analog voltage.

2.2.1 Merits of Digital Proximity Sensing

The digital proximity system possesses the capability to integrate the functionality of complete API 670 compliance and can be digitally configured across various manufacturers, probe tip diameters extension cable lengths, linear ranges and target materials (API, 2014). It has the following advantages over the analog counterparts:

1. The oscillatory characteristics of the R-L-C resonant circuit may be fine-tuned to realize an optimized dynamic nonlinear range that

fulfills the specifications of various materials and system dimensions.

2. The output from the peak detector can be calibrated to align with the input specifications of the Analog-to-Digital Converter (ADC) within the context of system architecture.
3. A high-resolution analog-to-digital converter (ADC) can be employed to attain superior accuracy.
4. The intelligent algorithm implemented in the software exhibits flexibility, thereby allowing the system to be calibrated either during the manufacturing process or in the field by the end users.
5. The output from the digital-to-analog converter (DAC) may be represented as either a current or a voltage signal.

2.2.2 Challenges of the digital proximity system

While the digital proximity system offers several advantages over its analog counterpart, certain challenges still need to be addressed before it can be considered a fully practical solution.

1. Temperature compensation:

The algorithm table typically performs reliably at room temperature. However, significant temperature fluctuations can alter electrical properties, causing the actual nonlinear response to deviate from the reference curve used for initial linearization. Without an effective temperature compensation algorithm, the measurement results may diverge considerably from the API 670 standard.

2. Interchangeability:

The R-L-C "tank" plays a vital role in the digital proximity system. However, manufacturing tolerances make it nearly impossible to produce identical probes, cables, or sensing electronics. Replacing any component in the system can lead to variations in inductance, capacitance, or resistance, which in turn may cause the actual nonlinear response to differ from the one used to generate the original linearization table. To achieve true system interchangeability, an advanced compensation mechanism is necessary.

3 DIGITAL APPROACH FOR PROXIMITY SENSING

Vibration analysis is a cornerstone of predictive maintenance programs and is extensively used to detect and monitor early-stage and advanced faults in components like shafts, bearings,

couplings, rotors, and motors. The wide range of applications involves diverse conductive materials, varying sensor-to-machine distances, and a broad selection of sensor sizes. Eddy current proximity sensing effectively meets these demands. With appropriate design, its oscillation frequency can be tuned to match the penetration depth required for different conductive surfaces.

Being an inductive method, the technology is well-suited for applications involving the detection or monitoring of a conductive target's position—particularly in harsh or contaminated environments. Due to its high precision and ability to operate at very close ranges, it is more commonly employed to capture the dynamic behavior of continuously moving targets, such as vibrating components. When equipped with well-designed hardware, an effective software linearization method, and a reliable compensation algorithm, the method can detect targets with sub-mil accuracy and produce an incremental scale factor (ISF) established by Frank & Guoxing (2017). As shown in Fig. 5, the system delivers outstanding performance and interchangeability. This level of precise vibration monitoring at the micro scale significantly contributes to asset protection and improved operational efficiency.

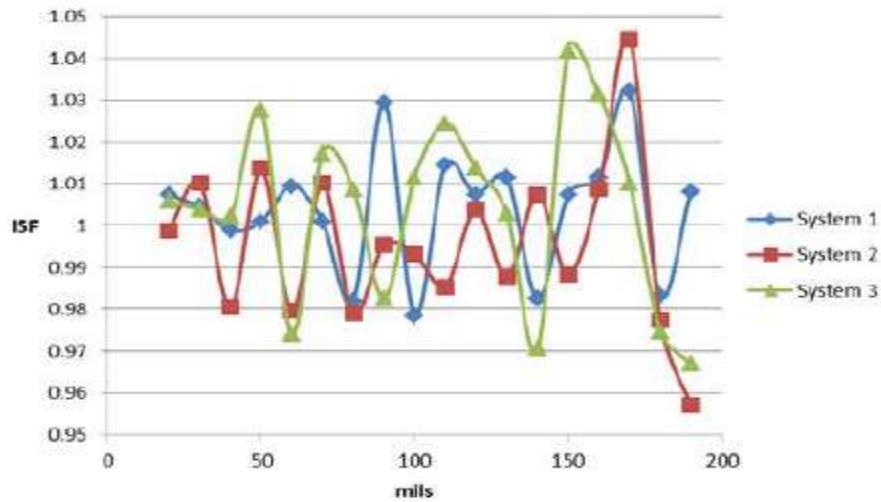


Fig. 5: Incremental Scale Factor Linear output of digital method of proximity sensing

4 ADVANCES IN DIGITAL PROXIMITY SENSING TECHNOLOGY

The world is on the brink of a technological revolution, with innovation accelerating at an unprecedented pace. Companies are leveraging advanced integrated circuit (IC) technology, the Internet of Things (IoT), and embedded intelligence to develop effective methods and gain a competitive advantage.

Integrated circuits have entered the nanotechnology era, with their physical size shrinking year by year. In contrast, their capacity and density continue to grow significantly. As a result, the cost-to-performance ratio keeps improving. Today's advanced IC technology enables the integration of various sensor types on a single chip. Texas Instruments (TI) leads the industry in this area, with its LDC1x series devices offering significant potential for innovative system design in proximity sensing

(TI, 2017). However, these devices need to be optimized or tailored to meet the specific needs of different applications.

As the IoT market is expected to grow rapidly in the coming years (Intel, 2017), incorporating the digital proximity system into the IoT ecosystem could unlock significant potential for brand development and customer engagement. Cloud computing further enhances this by making all features of the digital proximity system accessible through mobile devices, whether via native or web apps.

As mentioned earlier, an intelligent algorithm is essential to ensure the system is flexible, configurable, reliable, and repeatable. This is a complex task, particularly when considering probe interchangeability and temperature fluctuations. The algorithm must be capable of converting varied nonlinear inputs into a consistent linear output. Therefore, developing

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proprietary intelligence in this area is crucial for achieving superior performance and maximizing customer satisfaction.

5 CONCLUSION

Eddy current-based proximity measurement is a contactless technology that enables precise measurement of position and displacements for conductive targets. While analog method offers simple design and less precise solution, digital proximity sensing combines sophisticated electronic designs with advanced algorithms to deliver a more precision in vibration and displacement measurements for modern industrial operations. By integrating other state-of-the-art technologies, such as integrated circuits (IC) and the Internet of Things (IoT), into digital proximity sensing systems, significant potential is unlocked for the advancement and broader application of this technology.

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