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Research on the intelligent fatigue detection of metal components in vehicles

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Abstract. With the acceleration of transportation speed, heavy loading of trucks has higher requirements for the quality of wheel axles, and the detection of wheel axles on trucks has become a key focus in corrective maintenance. The automotive industry requires timely detection of vehicle components. Nondestructive testing (NDT) technology provides a method of detecting and analyzing physical quantities on the internal surface of an object without causing damage. It can determine the presence of defects or abnormal conditions. The application of nondestructive testing (NDT) is essential in the automotive industry to guarantee the safety and dependability of vehicles. This article provides an overview of the principles and applications of phased array ultrasound imaging and eddy current testing, focusing on intelligent monitoring solutions for axles. This article proposes an enhanced intelligent monitoring approach that utilizes existing detection methodologies to provide vehicle owners with real-time feedback regarding the fatigue strength of individual automotive parts. This approach aims to prompt the replacement of auto parts when the fatigue trend approaches predetermined warning thresholds.

Keywords: phased array ultrasound imaging, eddy current testing, metal fatigue testing, intelligent monitoring, Nondestructive testing

1. Introduction

The components of a car can experience wear, cracks, and other issues after prolonged use. Among these components, the axle is a critical part of a motor vehicle that directly impacts driving safety. If these parts develop problems that are not detected in a timely manner, the issues can escalate and lead to more dangerous accidents, potentially causing severe consequences [1].

The automotive industry nowadays requires an intelligent inspection solution capable of detecting vehicle components. By doing so, it aims to address the challenge of timely replacement for critical components [2]. Nondestructive testing (NDT) technology refers to a method of detecting and analyzing physical quantities on the internal or surface of an object without causing damage, in order to determine the presence of defects or abnormal conditions. NDT offers several advantages, such as non-contact measurements, nondestructive nature, and high precision. It has found widespread applications in various industries, including aviation, aerospace, automotive, power generation, and petrochemical sectors. NDT techniques involve the use of advanced equipment and methodologies to assess the integrity and reliability of critical components and structures. By utilizing physical principles to detect and analyze signals, NDT enables the identification of defects or anomalies that may compromise the safety or functionality of the object being inspected. The non-contact nature of NDT minimizes the risk of damage to the object, allowing for safe and repeated inspections [3]. In order to achieve the objective of assessing the service life of these components, the first step is to select suitable inspection instruments. Currently, commonly used nondestructive testing techniques in the world include ultrasonic testing techniques, which are divided into phased array ultrasonic testing and conventional single probe ultrasonic testing, radiographic testing techniques, eddy current testing techniques, magnetic particle testing techniques, and penetrant testing techniques. Among them, eddy current testing and ultrasonic testing techniques are most in line with the current research direction.

As compared to traditional imaging techniques, phased array ultrasound imaging offers the advantage of beam translation, deflection, focus, and scanning without the need for physical movement of the transducer. This enhances efficiency and reliability. On the other hand, eddy current testing imaging provides non-contact inspection and high sensitivity. Based on these advantages, this paper aims to provide an overview of the principles and applications of phased array ultrasound imaging and eddy current testing. Regarding the selection of components, an intelligent monitoring solution will be designed for the axle of vehicles.

This article will first introduce existing non-destructive testing techniques, then proposes an enhanced intelligent monitoring approach that is capable of providing real-time feedback to vehicle owners regarding the fatigue strength of individual automotive parts, building upon the existing detection methodologies. Afterwards, a feasibility analysis of the plan will be conducted. Finally, an explanation of specific problems encountered in the research and the future research direction will be listed.

2. Discussion

2.1. Monitoring Schemes for Metallic Fatigue

2.1.1. Phased Array Ultrasonic. Since 1934, commercialized pulse-echo ultrasonic flaw detectors have been available in the market. Due to their nondestructive properties in part testing, the use of ultrasonic principles for detecting the interior of metal components has become a common and reliable method. With the advancement of technology, various subdivision schemes have been developed for ultrasonic testing to meet the testing needs under different conditions. In line with the research objectives of this article, we have employed phased array ultrasonic technology (PAUT) to test key automotive components [4,5]. Our team utilized the Olympus FOCUSPX Phased Array Ultrasonic detector equipment. The difference between phased array-electronic focusing and phased array-electron detector is shown in figure 1.

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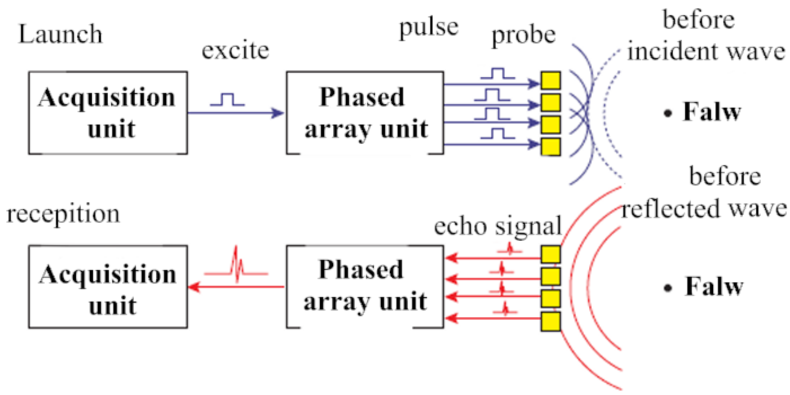

Figure 1. Phased array-electronic focusing and phased array-electron detector

Among the numerous components in automobiles, brake pads play a critical role. We have focused on the metal testing of semi-metal brake pads, which offer good braking performance and wear resistance and are widely used in private cars and some transportation vehicles. PAUT technology primarily employs linear scanning and sector scanning [6], and we believe it yields excellent results in the metal inspection of semi-metal brake pads. Our design approach aims to quickly, sensitively, and accurately detect brake pads using a probe at a fixed point while ensuring it does not affect their normal use. We have conducted ultrasonic phased array detection tests using both straight and angled probes on surfaces with different diameters. The experimental results were obtained with the gain value as the Y-axis and the surface diameter as the X-axis, as illustrated in the figure 2. Consequently, our research team intends to utilize a straight probe as the testing tool for brake pads.

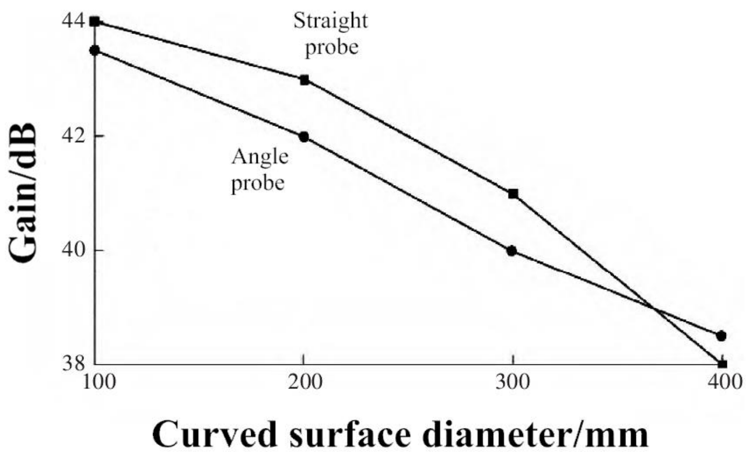

Figure 2. Ultrasonic phased array detection tests

2.1.2. Eddy Current Testing. The growing attention towards pulsed eddy current (PEC) nondestructive testing and evaluation (NDT&E) is due to its significant potential benefits. One key advantage is its inherent broadband range of frequencies, which sets it apart from single-frequency eddy current testing (ECT) [7]. This broad frequency range is advantageous for any eddy-current-based NDT&E techniques, as it takes into account the frequency-dependent skin effect.

Another benefit is that PEC signals are comparatively easier to interpret. In contrast, conventional ECT signals, presented in the impedance plane trajectory, require operators with specialized skills for interpretation. Conventional ECT relies on a single excitation frequency, limiting its ability to reliably detect both surface and sub-surface defects. On the other hand, the improved technique of multi-frequency ECT applies different excitation frequencies sequentially. In comparison to multi-frequency ECT, PEC has the potential to significantly reduce inspection time for different depths. This is achieved by applying a wideband of frequencies in a single pulse, allowing for the minimum measurement time required based on the characteristics of the sample.

The method known as ECT has been widely used for nondestructive testing (NDT) [8] purposes and is commonly employed to examine the integrity of conductive materials. However, the use of coils to detect the magnetic field (MF) as a primary indicator [9] has limitations when it comes to detecting subsurface defects and requires sensitivity at low frequencies for materials of varying thickness. To address the poor sensitivity issue associated with traditional eddy current probes, NDT technology has the advantage of utilizing magnetometer (MR) sensors to gather comprehensive information from the tested component [10]. Numerous research studies have proposed various ECT structures for material inspection. Lee et al. introduced the use of bobbin coils to induce eddy currents in small piping [11], with the MF being detected by a Hall sensor array.

This technique enables the visualization of the distorted electromagnetic (EM) field surrounding the outer diameter of stress corrosion cracking, eliminating the need for a rotating apparatus. Sorting test pieces into two categories, good or bad, is the primary function of basic eddy current equipment. These instruments are cost-effective and include essential controls and basic displays, with the option to connect to an oscilloscope. They typically have one or two physical channels that can be time multiplexed to enhance their functionality.

In production line settings, these instruments that meet the basic requirements can perform various tasks. They can detect composition in alloys, measure parameters like hardness, case depth, and temper in heat treatments, measure sinter density, and identify structure variations. Different enclosures are available, and RS232/V24 interfaces enable communication with mainframe computers. Additionally, some instruments offer opto-isolated inputs and outputs for connecting with other systems. Manufacturers also produce portable instruments that feature a compact enclosure housing the screen, controls, and connectors, as shown in Figure 3.

Figure 3. Portable eddy current testing instrument [12]

2.2. Enhanced Intelligent Monitoring Approaches

The contact-based detection method requires the use of eddy current testing equipment to detect defects on the outer surface of the vehicle axle. The complete axle testing system consists of an eddy current testing AC power supply, an eddy current testing computer, and an eddy current testing probe. The AC power for eddy current testing can be provided by the vehicle's generator, which supplies power to the testing equipment when the vehicle is running. The eddy current testing computer is installed in the front control panel of the vehicle and is responsible for storing and processing the detection data from the eddy current testing coils. It processes and analyzes the detection signals to determine the presence of

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defects, thickness, or conductivity information on the metal surface. The detection probe is used to generate the electromagnetic field and induce eddy currents. When the magnetic field contacts the metal surface, eddy currents are generated. The changes in magnetic field distribution caused by the eddy current induction alter the inductance or resistance of the electromagnetic coil. These changes are captured by the probe and the data is transmitted to the eddy current testing computer. The eddy current testing computer receives data from other computer systems on the vehicle to control the eddy current testing process only when the vehicle is in a safe state. By comparing the detected data with the original data, it can determine the existence of damages. The contact-based detection method provides indirect information about axle damage. By simply installing the testing probe on the exterior of the axle, the detection can be completed, reducing unnecessary procedures, and increasing work efficiency. As the axle is coated, eddy current testing can also measure the thickness of metal or non-metal coatings, thereby detecting coating damages with high accuracy. The schematic diagram of the entire system is shown in Figure 4.

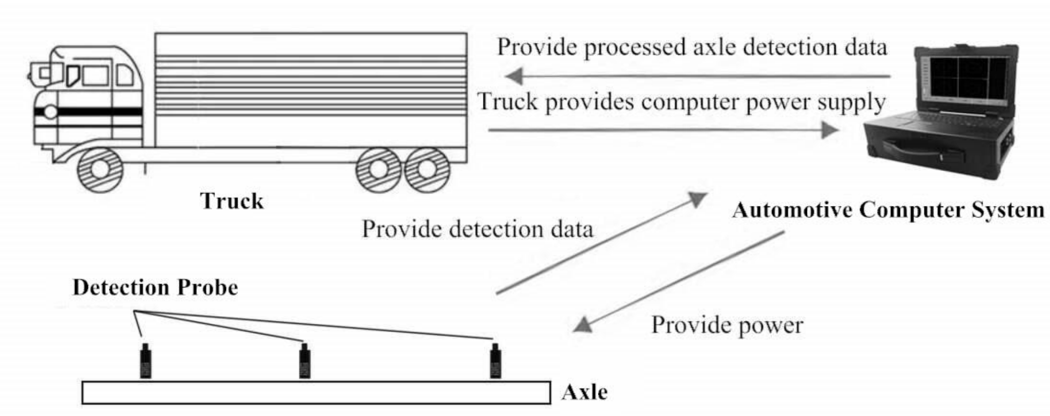

Figure 4. Diagram of an enhanced intelligent monitoring approach

2.3. Feasibility and issues

There are some key factors to pay attention to when applying the two non-contact nondestructive testing technologies mentioned above to the detection of automotive parts. For eddy current testing, the tested part must be a metal and conductive. The core principle of eddy current testing technology is Lenz's law. The probe can detect cracks and other damages by detecting the magnetic field generated by eddy current in the part, and Lenz's law only works in metal conductors. Eddy current testing technology has a good effect on detecting the surface of the part, so the detection effect of the deep crack of the part needs to be further tested. For eddy current testing, the change in the temperature of the part will affect the resistivity, thus affecting the intensity of the generated magnetic field.

Therefore, for parts with large temperature changes, it is necessary to further confirm the feasibility of eddy current testing technology through experiments. Due to long-term use, some parts of the car may accumulate impurities, such as dust, affecting the detection effect of the probe. Therefore, it is necessary to avoid the influence of impurity accumulation on the detection effect. The probe can be isolated from the external environment, or a detachable probe can be designed to facilitate cleaning. The specific scheme is selected based on the characteristics of different parts, which needs to be further confirmed by experiments. For the detection of moving parts, the probe can be placed in two ways: following the movement of parts and static. The implementation of the following part movement is usually relatively difficult. For the stationary probe, whether it should be detected during the motion of the part or wait for the part to be completely stationary also needs to be further confirmed by experiments. In conclusion, the realization difficulty of applying the above two non-contact nondestructive testing technologies to the detection of parts in vehicles varies greatly for different parts.

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3. Conclusion

In conclusion, nondestructive testing (NDT) techniques, such as phased array ultrasound imaging and eddy current testing, play a crucial role in the automotive industry for detecting and analyzing defects or abnormalities in vehicle components. These techniques offer advantages such as non-contact measurements, high precision, and nondestructive nature, making them suitable for assessing the integrity and reliability of critical components. Phased array ultrasound imaging provides efficient and reliable results by allowing beam translation, deflection, focus, and scanning without the need for physical movement of the transducer. On the other hand, eddy current testing offers non-contact inspection and high sensitivity, making it a valuable tool for detecting defects in conductive materials. The research presented in this paper focuses on the application of phased array ultrasound imaging and eddy current testing for monitoring the fatigue strength of automotive parts. The intelligent monitoring solutions can provide real-time feedback to vehicle owners regarding the condition of these parts.

By promptly detecting fatigue trends and providing warnings when predetermined thresholds are approached, the proposed enhanced intelligent monitoring approach aims to ensure timely replacement of auto parts, thereby enhancing driving safety and preventing potential accidents. In conclusion, the combination of phased array ultrasound imaging and eddy current testing offers promising solutions for the automotive industry in terms of component inspection and monitoring. Further research and development in this field will contribute to improving the overall safety and reliability of motor vehicles.

Acknowledgement

Zhaoran Xue is the first author, Qiren Chen, Esu Xian and Hongde Du are the co-second author

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