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EDDY CURRENT AND ULTRASONIC NONDESTRUCTIVE TECHNIQUES FOR STRUCTURAL INTEGRITY MONITORING

Abstract. The article presents comprehensive research results on improving non-destructive testing technologies for monitoring the integrity of critical structures operating under high static, cyclic, and thermal loads of advanced eddy current and ultrasonic techniques.
Keywords: non-destructive testing, eddy current, ultrasonic testing, structural integrity monitoring, crack detection.

Monitoring the integrity of critical structures using nondestructive testing (NDT) is essential for preventing catastrophic failures with significant economic and environmental consequences, particularly in structures operating under high static and cyclic loads, pressure, and elevated temperatures in thermal and nuclear power engineering, transportation, oil and gas industries, and aviation. This paper presents comprehensive research and development of advanced eddy current (EC) and ultrasonic NDT techniques for structural integrity assessment, conducted at the G.V. Karpenko Institute of Physics and Mechanics of the National Academy of Sciences of Ukraine, Ivan Kozhedub National Air Force University, and King Danylo University. The study focuses on developing and applying enhanced eddy current methods for detecting surface and subsurface defects in critical structural components. A novel high-frequency parametric pencil-type eddy current transducer (ECT) with a 1.0 mm diameter ferromagnetic core was developed, featuring an initial magnetic permeability μ = 500 and optimized geometry for detecting surface cracks longer than 2.0 mm (Fig. 1).

Fig. 1. (a) parametric ECT of the "pencil type"; (b) portable eddy current flaw detector Eddycon with a rotary scanner for hole inspection.

The transducer design incorporates a 0.5 mm distance from winding start to working end, ensuring high wear resistance during surface scanning operations.

Experimental validation was performed using D16T aluminum alloy standard samples with artificial defects ranging from 0.1 to 2.0 mm in depth and 30 mm in length, created using electro-erosion methods to achieve consistent 0.1 mm crack widths. Testing utilized universal Eddycon C eddy current flaw detectors operating at frequencies up to 700 kHz. The developed EDDYLINE-type EC probes demonstrated significant improvements in inspection productivity, achieving 4-5 times faster inspection rates than conventional methods.

Key findings include enhanced defect detection capabilities through signal differentiation in the complex plane, enabling improved reliability by distinguishing between actual defects and lift-off interference. Fig. 2 shows the characteristic sensitivity distributions obtained experimentally using a double differentiation ECT of the MDF 1201 type during sequential scanning of a local defect zone simulated by drilling with a diameter of 1.0 mm.

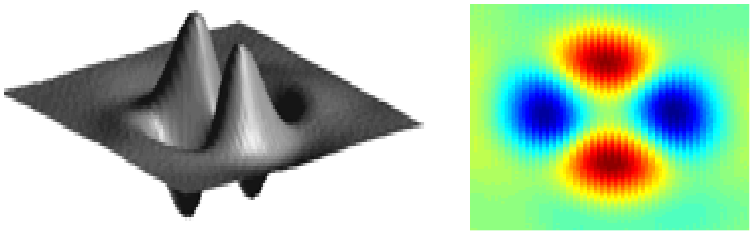

Fig. 2. Four-point spatial signal distribution with two positive and two negative peaks for local defects.

The research addresses limitations of existing NDT methods, including sensitivity variations across different materials, interference from structural variations, thickness changes, curvature effects, and coating properties. The developed methodologies demonstrated successful application in real-world scenarios, including gas turbine compressor blade inspection with 4 mm long, 0.2 mm deep artificial defects, achieving high repeatability and clear signal orientation within automatic signaling sector frames. The techniques effectively detected surface-breaking cracks in aircraft structures and multi-layered assemblies.

Acoustic NDT techniques were also investigated for pipe product inspection in diversified industrial sectors. The acoustic inspection method is widely used in various industries, primarily in ultrasonic flaw detection and thickness measurement of structures, equipment and materials. One of the main characteristics of the acoustic inspection method is sensitivity - the ability of the method to detect defects of minimal size. A feature of the acoustic method of control is the conditions for the propagation of ultrasonic vibrations (USV) in controlled structures, which is the fact that when the USV hits the surface of the interface of the media (piezoelement - contact liquid layer - TO), acoustic vibrations that propagate in the media according to the laws of acoustic optics have the property of being reflected (reflected), refracted and transformed into other types of waves (longitudinal, transverse, surface and others), which significantly reduces the power (up to 90% or more) of the generated volume of the USV power, even with their normal input (incidence) on the controlled surface, there is a so-called deterioration of the transverse (frontal) resolution and a decrease in the intensity of the USV beam and, as a result, a decrease in the sensitivity of the method. In addition, in practice, up to 80% of the inspected products are those that have a curved (cylindrical, spherical) surface, which, due to the above-mentioned properties of the propagation of ultrasound, as well as their defocusing by the outer and inner surfaces of the pipe, the amplitude of the signal emitted by the piezotransducer is significantly attenuated even more significantly, up to 98%.

It was suggested that the task of increasing the sensitivity of control can be solved by increasing the fraction of ultrasonic energy of the ultrasonic beam, which is introduced into the pipe product. One way to implement this task can be to fulfill the condition if all elementary rays of the ultrasonic beam are introduced into the TO normal to its outer surface, that is, there will be no phenomena of reflection, refraction and transformation of the ultrasonic waves will be absent or minimized.

As a result of studies of the propagation of high-frequency elastic waves in stressed-deformed media with a complex inhomogeneous stress distribution, a new approach was developed, which uses the introduction of an effective medium with reduced elastic moduli, depending on the spatial distribution of transverse stresses. This made it possible to reduce the problem of wave propagation in media with an inhomogeneous stressed-deformed state to wave propagation in weakly inhomogeneous media, and also to use the beam method to study the laws of elastic wave propagation in media with a flat and cylindrical-layer stress distribution. Using the results of the above studies, a series of different designs of focusing piezotransducers (Fig. 3) and special scanners for their retention on controlled pipe products were developed, tested and implemented.

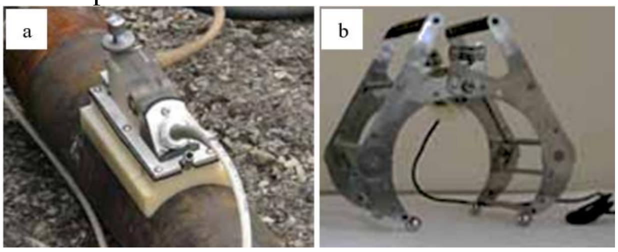

Fig. 3. (a) focusing piezotransducer; (b) special scanner

These piezo transducers were equipped with specialized mobile and portable installations for non-destructive testing of oil pipelines. With the help of these devices, defects of operational (corrosion-fatigue cracks, non-penetration, etc.) and factory origin (various inclusions, fiber bends, etc.) were reliably detected.

A technology for focusing piezoelectric transducer prisms was developed, ensuring near-normal introduction of ultrasonic waves into cylindrical surfaces and enabling reliable detection of corrosion-fatigue cracks in drill pipe threads. Based on studies of contact mechanics, new diagnostic indicators for evaluating threaded connection quality were proposed, including stress relaxation phenomena, actual contact area, and radial deformation characteristics.

Threaded connections are widely used in various fields of technology due to their universality, ease of manufacture, reliability, ease of assembly and disassembly, and complete interchangeability. Threaded connections are divided into detachable and non-detachable. Detachable connections require special attention, as they allow assembly and disassembly without damaging the material of the parts.

Such connections are widely used in the oil and gas industry during the drilling of oil and gas wells. Drill pipes, 8-12 meters long, are connected using threaded connections, which are subjected to repeated screwing and unscrewing during the process of replacing drill bits.

The conditions for ensuring the operational reliability of threaded connections should be the following: the possibility of quality control of the screwing process to achieve the regulated screwing torque; assessment of the operational characteristics (strength and tightness) of the threaded connection after screwing at different stages of operation when exposed to the entire range of loads (alternating stresses, corrosive environment, temperature fluctuations, etc.).

At the present stage, quality control of threaded connections usually involves checking the compliance of dimensions, thread profile, surface cleanliness, and the correct assembly of the connection. For this, a visual inspection, a measuring tool (for example, gauges) is used, and strength and tightness tests are also carried out, depending on the purpose of the connection.

However, these methods do not ensure the operational reliability of threaded connections, which leads to the occurrence of stress corrosion cracks (Fig. 4, a) or separation of the threaded connection - in case of failure to reach the regulated screwing torque, or destruction of the thread profile - in case of exceeding the values of the regulated (load) screwing torque.

We conducted research into the features of contact between roughness surfaces that occur in threaded connections, namely the phenomenon of relaxation of contact pressures. It has been established that with an increase in torque and reaching the limit of proportionality, permanent deformation occurs and the moment comes when the increase in the deformation value occurs without an increase in load (torque), and stresses close to the yield strength occur in the joint material. Thus, the moment of reaching stresses close to the yield point in a threaded connection can be taken as a diagnostic sign of the quality of threaded connections (Fig. 4, b).

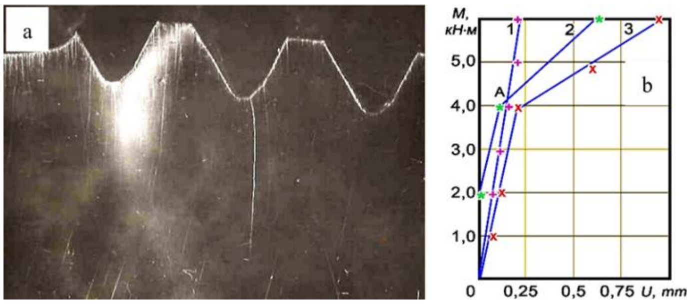

Fig. 4. (a) stress corrosion cracks of threaded connection; (b) dependency between torque and elastic (1), plastic (2), total (3) deformations

Since the contact of solids occurs discretely through the protrusions of the stiffeners, the actual contact area is represented by the zones of setting and the zones of tight contact, with a width, as a rule, from 0.1 to 2 microns. To measure the actual contact area, it was proposed to use an acoustic method. Methods for acoustic quality control of screwing threaded connections of drill pipes, a method for controlling the tightness of threaded connections, and others were proposed.

Based on the research, technical means (specialized piezo transducers and scanners) were developed, manufactured, and industrially tested for quality control of various types of threaded connections.

The conducted research demonstrates significant advancements in the field of non-destructive testing of critical structures, particularly through the refinement of eddy current and acoustic inspection methods. The development of new parametric, double-differential, and specialized eddy current transducers has substantially increased the sensitivity, selectivity, and reliability of flaw detection in materials with varying electrical and magnetic properties. These solutions enable effective detection of both surface and subsurface cracks, including short and “zero-opening” defects, and allow inspection of complex-geometry components without dismantling, which is essential for aviation and power engineering applications. Acoustic testing improvements, particularly the development of focusing piezoelectric transducers and new approaches to ultrasonic beam introduction, have addressed the long-standing problem of sensitivity loss in curved and threaded components. The proposed diagnostic criteria based on contact mechanics - actual contact area, stress relaxation, and radial deformation parameters. Overall, the results obtained confirm the effectiveness of the proposed technologies and demonstrate their high potential for improving the reliability, safety, and efficiency of NDT across multiple industries. The new methods and instruments can be successfully applied not only in aviation and energy sectors but also in oil and gas production, mechanical engineering, and other fields requiring high standards of structural integrity monitoring.

Results indicate that integrating advanced eddy current and ultrasonic techniques provides comprehensive solutions for structural health monitoring, enabling early detection of critical defects and supporting preventive maintenance strategies. The research contributes to improved safety and reliability of critical infrastructure through enhanced NDT capabilities, addressing the growing demand for effective structural integrity assessment methods in industrial applications. The developed techniques offer significant advantages regarding inspection speed, reliability, and applicability across diverse structural configurations and materials.