

елемента забезпечується. Однак, при цьому спостерігається нерівномірність розподілу напружень по висоті пружного елемента, що не задовольняє умовам рівномірності конструкції.

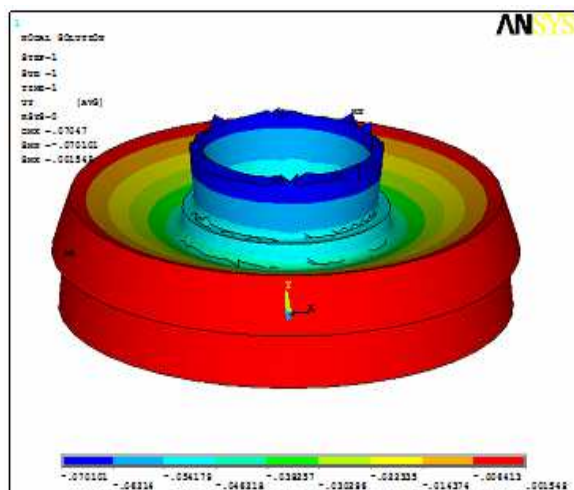


Рис. 5 Вертикальні переміщення в пружному елементі датчика сили

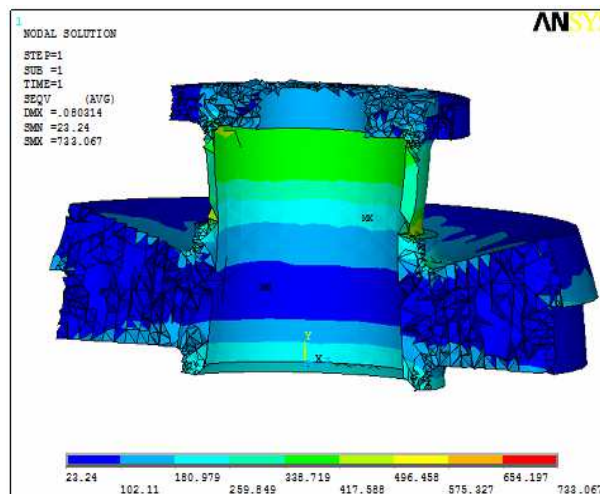


Рис. 6 Еквівалентні напруження за гіпотезою Губера-Мізеса

Ключові слова: авіаційна техніка, випробування, тензометричний датчик, напруження, переміщення, аналого-цифровий перетворювач.

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UDC 620.179.16:681.5

MODERN TRENDS IN AUTOMATION OF MAGNETIC PARTICLE INSPECTION

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Magnetic particle inspection (MPI) is one of the most effective non-destructive testing methods widely used to detect surface and subsurface defects in ferromagnetic materials. Due to its high sensitivity, ease of use, and the ability to inspect parts of complex shapes, this method is used in many industries, including the automotive, aviation, railroad, and energy sectors [1]. In general, according to the statistics of the American Society for Non-Destructive Testing (ASNT), more than 35% of all NDT procedures in heavy industry are performed by MPI. This is due not only to the

technical effectiveness of the method, but also to the relatively low cost of implementation compared to other methods, such as ultrasonic or radiographic inspection.

However, traditional methods of conducting MPI often depend on the human factor, which can affect the accuracy and repeatability of the results. In addition, the typical disadvantages of traditional MPI are insufficient documentation of results and the complexity of their archiving. In the case of an automated approach, it is possible to capture a visual image of the defect with reference to the coordinate grid of the part, which allows you to create digital "passports" of components and track the dynamics of wear throughout the entire life cycle of the product. That is why automation of the magnetic particle inspection process is becoming increasingly important. Modern technologies, such as robotic systems, machine vision, artificial intelligence algorithms, and automated magnetization systems, can significantly increase the speed and reliability of inspection. It is relevant to analyze the current level of automation of the magnetic particle inspection process, study existing technologies and evaluate their application in industry.

Magnetic particle inspection is one of the most common non-destructive testing methods used to detect surface and subsurface defects in ferromagnetic materials. It is widely used in industry due to its high sensitivity to microcracks, ease of use, and the ability to inspect parts with complex shapes.

The method is based on the creation of a magnetic field in the controlled object. In the areas of defects (e.g., cracks), the magnetic field is scattered, forming local magnetic poles. When a magnetic powder or suspension is applied, the particles concentrate in these areas, forming a visible indication of the defect.

However, despite the efficiency of the method, there are a number of problems associated with its traditional implementation. The biggest threat is the human factor - the quality of control largely depends on the experience, attention, and qualifications of the operator. Also, the process is labor-intensive, can take considerable time, and does not always ensure high repeatability of results

The relevance of the study is due to the need to improve the accuracy, productivity, and reliability of magnetic particle inspection, especially in conditions of mass production, limited inspection time, and complexity of the objects under inspection.

In this regard, the automation of MPI is a logical and necessary step. It reduces the influence of the human factor, ensures the consistency of control conditions, and speeds up the processing of results and defect detection. The use of computer vision, artificial intelligence algorithms and robotic systems opens up new opportunities for high-quality diagnostics of ferromagnetic materials in various industries.

Various AI approaches are actively used in automated magnetic particle inspection systems. First, convolutional neural networks (CNNs), such as the U-Net and ResNet architectures, are used to segment magnetic field scattering zones in the acquired images. This allows for automatic outline detection of even very small

defects at low contrast. Secondly, object detectors such as YOLOv5 and Faster R-CNN detect and localize multiple defects in a single frame in real time, which is critical for high-speed inspection [2]. Additionally, classical machine learning algorithms such as Support Vector Machine (SVM) and Random Forest are used to pre-classify defects by shape and size, which speeds up the sorting of inspected areas.

Certain hybrid approaches, such as combining CNN with the DBSCAN clustering algorithm, automatically adjust sensitivity thresholds depending on the noise level in the images and thus improve diagnostic accuracy. Methods for amplifying weak defect signals using super-resolution image algorithms (SRGAN, ESRGAN) are also being investigated to improve the quality of indications in low definition or noisy environments. This is especially relevant for parts operating in high-temperature or vibration conditions, where surface damage often has a fuzzy morphology.

In the automotive and aviation industry, Airbus (France) has introduced a robotic station based on the KUKA KR 16 manipulator with an integrated Magnaflux Automated MQC system. Images from Basler 8 MP cameras are processed by the YOLOv5 detector, and the magnetization process is controlled by the PulseBurst module with CNN-based control [3].

In rail transport, the German company DB Cargo uses the RoboMPC mobile complex based on the MobiBot platform with the built-in ResNet50 network. The system provides a real-time "green" or "red" decision on the suitability of wheel sets and axles [4].

In the machine building industry, Siemens Energy (Germany) has integrated an MPI station directly on the assembly line. FLIR cameras capture images that are analyzed by Faster R-CNN for multi-center defect detection, and the results are synchronized with the company's MES system. In China, CRRC Zhuzhou uses the MPC-Smart adaptive system with ActiveMagSense module, which dynamically changes the magnetic field configuration depending on the type of axle or frame being inspected. The system uses deep learning methods to detect material degradation patterns and has API integration with the company's ERP system for automatic reporting.

The Fincantieri shipyards (Italy) use a modular MagNoScan system with a hybrid CNN + DBSCAN architecture. This system automatically adjusts the sensitivity of the sensors to the metal thickness of the hull sections being welded [5].

In the oil and gas industry, Schlumberger (USA) operates a mobile laboratory called NDT Explorer. They use Poisson-Net to segment defects in pipelines and Random Forest to classify the finished images, which allows them to instantly generate reports right on the spot.

Automation of magnetic particle inspection is an important area of non-destructive testing development that can significantly improve the efficiency and accuracy of defect detection in ferromagnetic materials. The use of robotic systems, machine vision, and artificial intelligence algorithms minimizes the human factor, reduces inspection time, and improves the reliability of the results [6].

Automated systems are already actively used in industry, in particular in the aviation, automotive, energy, and railway sectors, where high accuracy of control of critical components is required. Thanks to the introduction of mobile and stationary automated systems, magnetic particle inspection is becoming more accessible to large-scale facilities and hard-to-reach areas [7].

Further development of technology, including improved image analysis methods and integration with modern information systems, opens up new opportunities for even more accurate and faster inspection. This helps to improve equipment safety and reduce production costs, which is a key factor for many industries.

Keywords: magnetic particle inspection, non-destructive testing, machine vision, artificial intelligence.

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УДК 681.518

СУЧАСНІ ПІДХОДИ ДО РОЗРОБКИ АВТОНОМНИХ СИСТЕМ КЕРУВАННЯ МОБІЛЬНИМИ РОБОТАМИ

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Сучасні мобільні роботи активно інтегруються у промисловість, логістику, сільське господарство, оборонну та побутову сфери. Проте ефективне функціонування роботизованих систем у реальних умовах вимагає не лише