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Ultrasonic and electromagnetic inspections of railway hollow axles

Ultradźwiękowa i elektromagnetyczna inspekcja kolejowych osi drążonych

Abstract

The structural integrity of wheelsets used in rolling stock is of great importance to the safety. In this paper, new inspection technologies based on Ultrasonic Testing and Electromagnetic techniques suitable for the inspection of hollow axles have been developed. The key difference between the developments of this technology compared to other existing manual inspection techniques is that the inspection can be conducted in-situ without removing the axles and associated bogies from the train and with minimal disassembly of the wheelset. Both kinds of probes (UT and EM) have been developed to detect cracks of 0.5 mm deep anywhere within the axle. Ultrasound technique can be utilized to inspect the whole axle, but it is not sufficiently sensitive to the surface breaking shallow defects. Therefore, the electromagnetic technique is used to detect surface breaking cracks that cannot be detected by ultrasonic technique.

Streszczenie

Integralność zestawów kołowych taboru kolejowego ma ogromne znaczenie dla zapewnienia bezpieczeństwa. W niniejszej pracy zostały przedstawione nowe technologie kontroli oparte na metodzie ultradźwiękowej (UT) i elektromagnetyczną (EM) dostosowane do kontroli osi drążonych. Zasadniczą różnicą w porównaniu z metodami ręcznej kontroli jest to, że kontrola może być przeprowadzona bez demontażu osi i przy minimalnym demontażu kół. Oba rodzaje czujników (UT i EM) zostały opracowane w celu wykrywania pęknięć o głębokości nie mniejszej niż 0,5 mm i znajdujących się w dowolnym miejscu na osi. Zasadniczo, technika ultradźwiękowa może być wykorzystywana do kontroli w całej objętości osi, ale nie jest wystarczająco czuła na płytkie defekty powierzchniowe. W związku z tym technika elektromagnetyczna została wykorzystana do wykrywania tego typu pęknięć.

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Introduction

The structural integrity of wheelsets used in rolling stock is of great importance to the rail industry and its customers. In the last 15 years, 33 deaths and 48 injuries have occurred in Europe alone because of train axles failures. This is not to mention the financial aspect of some reported derailments, which fortunately did not result in deaths or injuries but burdened the train operators with huge expense and disruption to their services. This has led to increased demands for the inspection and maintenance of axles.

In this paper, new inspection technologies based on Ultrasonic Testing (UT) and Electromagnetic (EM) techniques suitable for the inspection of hollow axles have been developed with the overall idea of improving the efficiency in the use of axles by extending their life and monitoring their safe deployment. The key difference between the developments of this technology compared to other existing manual inspection techniques is that the inspection can be conducted in-situ without removing the axles and associated bogies from the train and with minimal disassembly of the wheelset. For hollow axles, probes based on conventional (UT) and EM inspection techniques have been developed to detect cracks of 0.5 mm deep anywhere within the axle. Ultrasound technique is utilized in many automatic inspection systems [1], but it is not sufficiently sensitive to the surface breaking defects. The electromagnetic technique is used to detect surface breaking cracks that cannot be detected by ultrasonic technique. Data fusion can be used to combine UT and EM results to give 100% coverage of hollow axles.

Ultrasonic inspection system

The hollow axle scanner and manipulator are designed to be used when conducting in-service inspections of hollow railway axles from within the bore. The axle bores are approximately 1.99 m long and Ø30 mm. The axles are forged from ferritic steel and shall, as much as is feasible, be inspected in-situ. The scanner includes the circumferential and axial drive mechanisms, and a suitable mounting mechanism. The unit is designed to operate with any control/flaw detection systems which utilizes DC Servo Drives and has capacity for 2 A, 24 V motors. The manipulator is combined with a motion controller and flaw detector to complete the inspection system. Figure 1 shows the hollow axle inspection system that comprises from the scanner, the UT probe lances, motion controller and the ultrasonic pulser-receiver.

The inspection configuration that was selected from the ultrasonic simulations will host 4 UT single crystal probes with 10 mm diameter, 4 MHz frequency and 40 mm crystal curvature radius. The hollow axle scanner will host two pairs of probes with angles ±45° and ±70°.

Figure 2. shows the schematic diagrams for the ultrasonic beam paths generated from the ±45° and ±70° ultrasonic probe lances during the scanning. The UT probes in the lance are facing in opposite directions in order to ensure full coverage of the axle critical areas, which are the areas of cross-sectional changes.

Figure 3a. presents the 3D CAD model of the hollow axle and the UT probe lance. Furthermore, a hollow

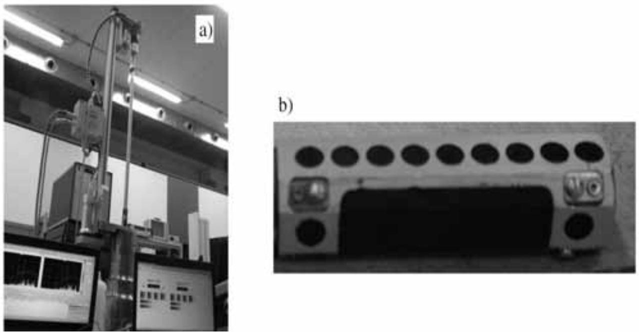


Fig 1. Hollow axle ultrasonic inspection system: a) automatic scanner b) UT probes lance

Rys. 1. Ultradźwiękowy system do inspekcji osi drążonych a) automatyczny skaner b) sztyca sondy UT

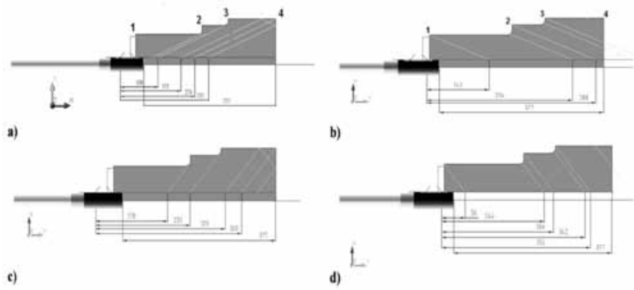


Fig. 2. Schematic diagrams of the ultrasonic sound paths for a) 70° facing forward b) 70° facing backward c) 45° facing forward (d) 45° facing backward

Rys. 2. Schematyczny diagram rozchodzenia się fal ultradźwiękowych z głowicy kątowej skierowanej a) 70 ° do przodu b) 70° do tyłu c) 45 ° do przodu d) 45° do tyłu

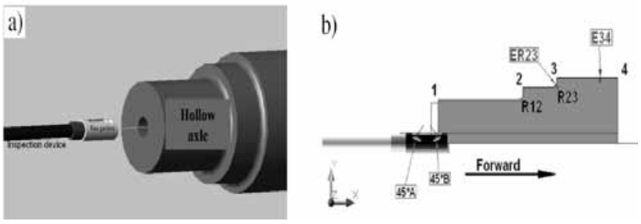


Fig. 3. Inspection set up: a) hollow axle CAD model b) defect plan and geometrical features.

Rys. 3. Widok elementu testowanego a) model CAD osi drążonej, b) rozmieszczenie wad

axle sample was used to introduce artificial defects of known sizes and locations. Figure 3b shows the defect plan of the hollow axle that identifies that location of the defects with respect to the geometrical features of the axle. The defects have been introduced into the corner No. 3 of the axles as well as away from areas of cross-sectional changes. The defect depths are 1 mm, 3 mm and 5 mm.

Figure 4 presents the Graphical User Interface (GUI) developed for the scanner motion control. The developed software allows the use of both raster and helical scans that provides flexibility during the inspection process. Furthermore, the motion control software allows setting up the scanning parameters such as: speed, resolution, scanning length. The use of these parameters allows optimizing the data quality acquired as well as determining the best inspection configuration.

Using the experimental set up shown in Fig. 1, testing of the hollow axle was carried out. Fig. 5 shows some of the results acquired from the inspection system. Fig. 5 shows the reflected A-scan signal obtained from the axle and presents the data from the 1 mm and 3 mm defects introduced into the axle. There are a number of reflections present in the A-scan and it is important to identify them in order to distinguish between the defect response and the axle geometrical reflections.

The experimental results obtained from the two defects can be summarized as follows:
– Advancing 210 mm (222º), SNR: 20/1, sound path 70 μs (104 mm), 3 mm depth notch ER23 (222º)
– Advancing 210 mm (342º), SNR: 4/1, sound path 67 μs (100 mm), 1 mm depth notch ER23 (342º)

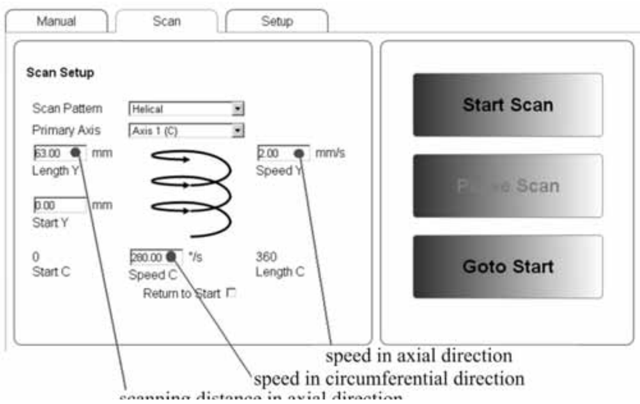


Fig. 4. Inspection parameters used in the scanner motion controller for the ultrasonic testing of the hollow axle
Rys. 4. Parametry użyte w kontrolerze ruchu skanera do ultradźwiękowego badania drążonych osi

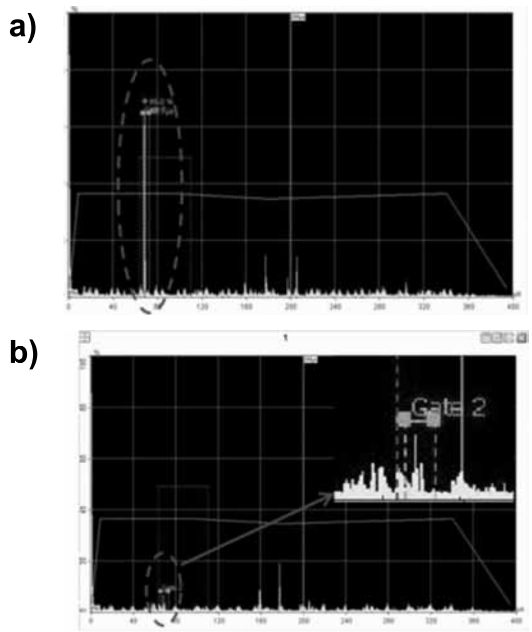


Fig. 5. A-scan response using the 45° incidence probes from: a) 3 mm deep notch, b) 1 mm deep notch.
Rys. 5. A-scan uzyskany za pomocą sondy kątowej 45° dla nacięcia o głębokości: a) 3 mm b) 1 mm

Electromagnetic inspection system

Structure of the subsystem

The proposed electromagnetic subsystem for non-destructive inspection of hollow axles consists of: a PC class computer with data acquisition (DAQ), a power amplifier, preamplifiers and lock-in amplifiers. The block diagram of the subsystem and a photography are presented in Figure 6. The PC computer working as a system's server runs a dedicated software under NI LabVIEW environment. The system is capable of acquiring complex response signals and can be controlled locally as well as remotely via Ethernet using TCPIP protocol. The main part of the system is a dedicated FLUFAH transducer. The simplified synthetic view of the transducer is shown in Figure 7. The transducer consists of two units: an excitation and a pick-up. The excitation section consists of a coil which generates alternating electromagnetic field. The alternating field excites eddy currents in the axle and in consequences a respond magnetic field is measured by pick-up unit elements. Dimensions of the excitation coil and frequency was decided based on results of Finite Element Method analysis. Taking into account all construction restrictions and carried out FEM simulation the following parameters of the excitation unit were assumed:
– the quasi optimal length of the coil is in the range 30-40 mm
– the testing frequency should be around 6 kHz.

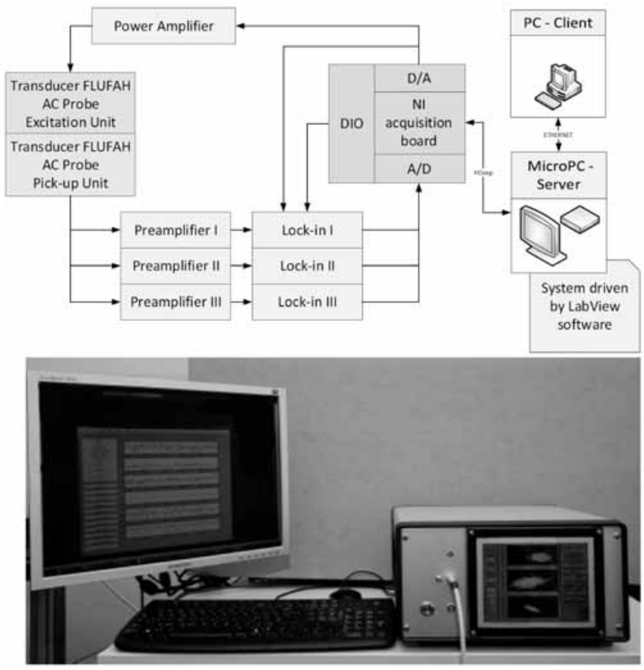
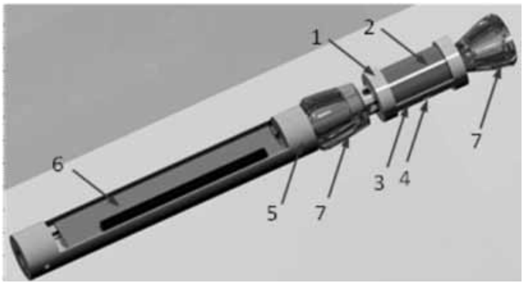


Fig. 6. Block scheme and a photo of the electromagnetic subsystem
Rys. 6. Schemat blokowy i zdjęcie podsystemu do badań elektromagnetycznych



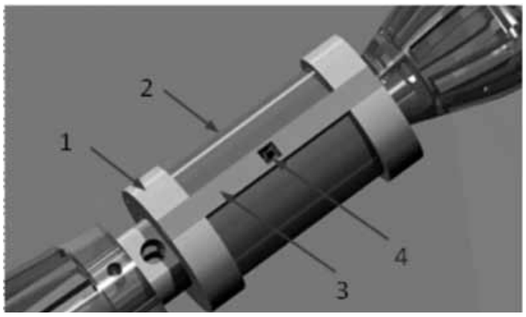


Fig. 7. Simplified view of the transducer; 1 – plastic bobbin, 2 – excitation coil, 3 – support plastic element for Hall effect sensors, 4 – 3 x Hall effect sensors, 5 – plastic compartment for electronic boards, 6 – electronic board, 7 – front and rear plastic centering elements
Rys. 7. Uproszczony widok przetwornika; 1 – plastikowy karkas, 2 – cewka wzbudzenia, 3 – element z tworzywa stanowiący wsparcie dla czujników Halla, 4 – 3 x czujniki Halla, 5 – plastikowy pojemnik z układami elektronicznymi, 6 – płytka z elektroniką, 7 – przednie i tylne plastikowe elementy centrujące przetwornik

There are two sections of pick-up unit. Each contains three Hall effect sensors. The pick-up units are mounted symmetrically on the opposite sides of the excitation coil. Each of the Hall effect sensors is measuring one of the magnetic field component (Hx, Hy and Hz). Two corresponding sensors from both pick-up sections measuring the same specific field component are connected in series. Therefore, in case of a homogeneous material the output signal from differentially connected sensors is close to zero. The differential signal from each pair of the sensors is provided to the instrumentation amplifier. Three identical circuits are manufactured for each component (Hx, Hy and Hz). Then, the output signals from amplifiers are provided to the three lock-in amplifiers in order to remove noises and extract information about real and imaginary part. The DC signals from all lock-in amplifiers are acquired and converted to digital form by A/D converter (Fig. 6). In order to protect the transducer against moisture all elements were covered by the epoxy resin.

Hollow axle sample inspection results

The performance of the transducer were verified using a hollow axle sample. The sample design, dimensions and orientation of the EDM notches manufactured into the axle are shown in Figure 8. The electro discharged machined (EDM) defects in the form of notches having a length of 5 mm and width of 0.2 mm were arranged in the axial and circumferential direction. The depth of the EDM notches was respectively 1 mm, 0.5 mm and 2 mm.

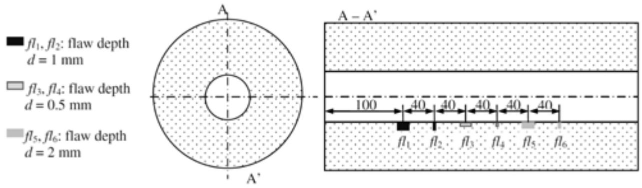


Fig. 8. The view with dimensions of the hollow axle sample
Rys. 8. Wymiary próbki osi drążonej

During the examination of the hollow axle sample signals corresponding to the three components x, y and z of the magnetic field were collected. The measurements were carried out in axial (l) and circumferential (α) direction. First, the acquired signals were post processed and normalized to the sensitivity range of the transducer, which depends on the A/C converters dynamic range and is limited by 15 V. Then, the norm value of all three normalized components was computed.

The selected results obtained for the hollow axle sample are presented in Figures 9 and 10. The figures present the results obtained for one half of transducer rotation (180 degrees). The results confirmed the detection ability of the measuring system. Considering the results shown in Figure 9, it can be noticed that each field component delivers different information about the detected notch. The x component can be utilized to estimate the depth of the flaws, while the y and z correlate with the width and the depth of the flaws. The probability of flaw detection can be increased by using data fusion algorithms. In example, the norm value of the components allows to combine the information and can be used to improve the identification process.

The results of norm value computation obtained for different notches are presented in Fig. 10. The evaluated SNR level obtained for norm values were between 26 dB and 50 dB. Considering the levels of the response signals acquired for different flaws it can be confirmed that the detection of both shallow and deep defects is possible utilizing the system.

Conclusions

The preliminary results achieved from the tests confirm the capabilities and usability of both methods and the whole system. In case of EM Inspection it was confirmed that defects having a depth of 2 mm and 1 mm can be detected regardless of the orientation (axial or circumferential). The defect with a depth of 0.5 mm is visible but, because of the rough surfaces of the sample, additional signal processing is required in order to identify the defect. Further work will be done to improve the results by the application of data fusion algorithms in order to combine results achieved from UT and EM method.

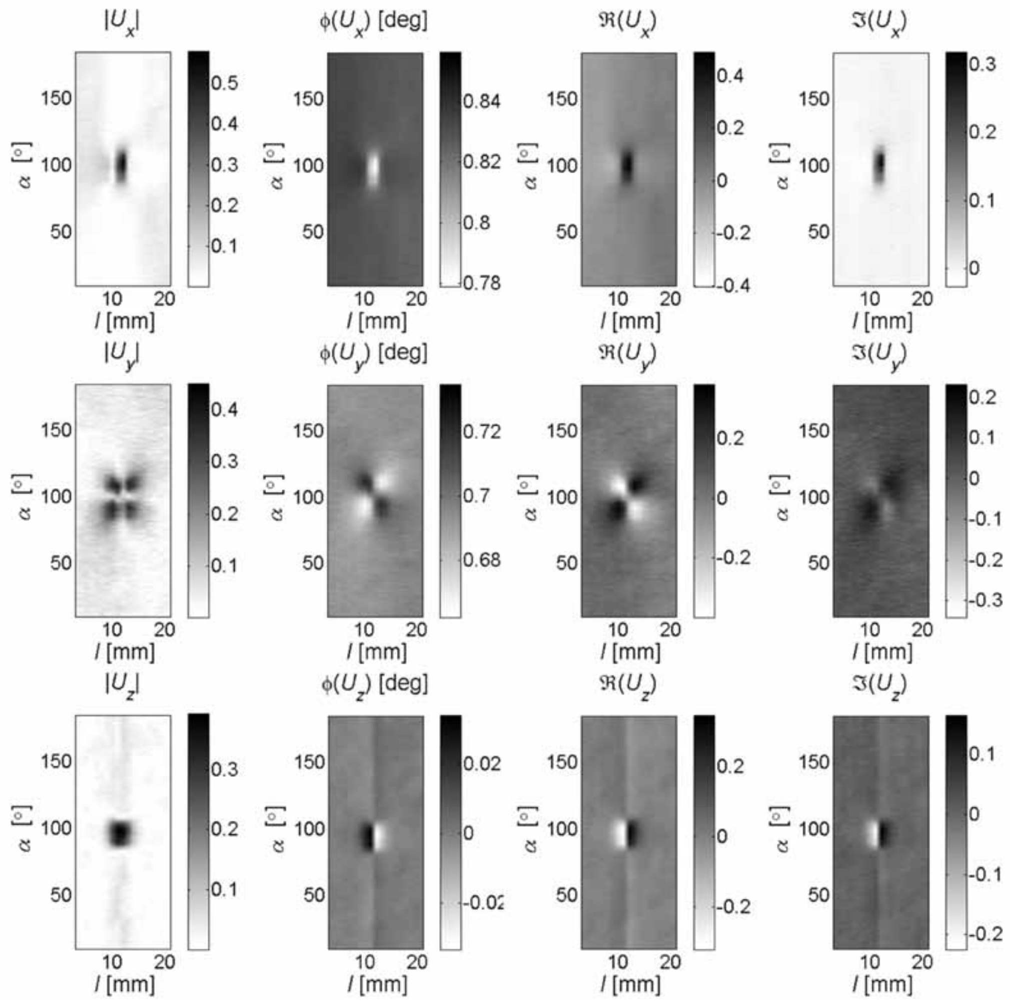


Fig. 9. Results of magnitude, phase, real, and imaginary part of the x, y and z component's signals obtained during 2D scanning for EDM notch no. 1 (1 mm depth)

Rys. 9. Wynik pomiaru modułu, fazy, części rzeczywistej i urojonej składowych x, y i z pola pomierzonego w trakcie skanowania 2D nacięcia nr. 1 o głębokości 1 mm

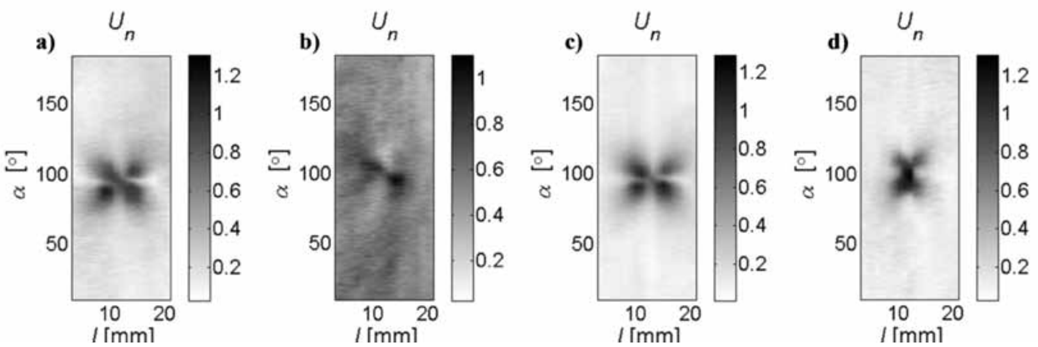


Fig. 10. Norm values of the measured x, y and z components signals obtained during 2D scanning of: a) notch no.1 (1 mm depth), b) notch no.3 (0.5 mm depth), c) notch no.5 (2 mm depth), d) notch no.2 (1 mm depth).

Rys. 10. Moduły składowych x, y i z pola pomierzone w trakcie skanowania 2D: a) nacięcia nr. 1 o głębokości 1 mm, b) nacięcia nr. 3 o głębokości 0,5 mm, c) nacięcia nr, 5 o głębokości 2 mm, d) nacięcia nr, 2 o głębokości 1 mm

Literature

[1] W. Shengyun, Z. Wenxian, L. Shiyuan "Research for Digital Automatic Test Technology of Hollow Axle in Motor Train Unit," Second International Conference on Digital Manufacturing and Automation (ICDMA), 5-7 Aug. 2011, pp. 922 – 925.

Acknowledgements

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