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Eddy Current System for Complex Geometry Inspection in High Speed Application

System wiroprądowy do kompleksowej kontroli geometrii w zastosowaniach z dużą prędkością

ABSTRACT

Rigid pipelines installed in offshore structures for oil and gas production are built from pipe sections connected by circumferential welds. Such welds are generally points of stress concentration and therefore the regions that most demand periodic inspection. The weld geometry and the inspection speed required for in service inspection are the main challenges associated to the inspection procedure. In the present work an eddy current transducer with sensing coils placed orthogonally and connected in differential mode was introduced to evaluate fatigue cracks in weld root. A dedicated embedded electronic hardware was developed to drive the transducer and measure the electrical complex impedance of the coils and was specifically designed for operation under autonomous in-line inspection tool in a speed range between 0.5 – 1.0 m/s. The achieved results have confirmed that the introduced eddy current transducer is a potential solution for fatigue crack detection in irregular surfaces like weld root, while the hardware developed presented a reasonable SNR and achieved the data rate required to be incorporated in an autonomous in-line inspection tool.

Keywords: *fatigue crack; weld root; eddy current testing; in-line inspection tool*

STRESZCZENIE

Sztywne rurociągi instalowane w morskich konstrukcjach do produkcji ropy i gazu budowane są z odcinków rur połączonych spoinami obwodowymi. Takie spoiny są zwykle punktami koncentracji naprężeń, a zatem regionami, które w największym stopniu wymagają okresowej kontroli. Geometria spoiny i prędkość kontroli wymagana do przeprowadzenia badania serwisowego stanowią główne wyzwania związane z procedurą inspekcji. W niniejszej pracy, w celu oceny pęknięć zmęczeniowych w rdzeniu spoiny, zaproponowano przetwornik wiroprądowy z cewkami pomiarowymi umieszczonymi ortogonalnie i połączonymi różnicowo. Opracowano specjalny wbudowany system elektroniczny do sterowania przetwornikiem i pomiaru impedancji złożonych cewek elektrycznych. System został zaprojektowany specjalnie do pracy jako autonomiczna jednostka inspekcji linii w zakresie prędkości od 0,5 do 1,0 m/s. Uzyskane wyniki potwierdziły, że wprowadzony przetwornik wiroprądowy jest potencjalnym rozwiązaniem umożliwiającym wykrywania pęknięć zmęczeniowych na nieregularnych powierzchniach, takich jak rdzeń spoiny. Ponadto opracowany sprzęt zapewnia odpowiedni współczynnik stosunku sygnału do szumu SNR i osiąga prędkość transmisji wymaganą dla zastosowania w jednostkach niezależnej kontroli w linii.

Słowa kluczowe: *pęknięcie zmęczeniowe; rdzeń spawu; testowanie wiroprądowe; jednostka kontroli inline*

1. Introduction

Rigid pipelines installed in offshore structures for oil production are built from pipe sections connected by circumferential welds. The application of clad material to subsea rigid pipelines is recently gaining ground in deep water oil exploration. Its bimetallic configuration presents an attractive combination of mechanical strength and corrosion resistance, ensuring the safety and integrity of pipelines that connect the reservoir to oil rig. The clad material for oil exploration consists of a base material, usually carbon steel, inner coated with a thin layer of corrosion resistance alloy (CRA), turning into an attractive economical solution for deep water exploration since only a small portion of the noble anti-corrosive alloy is required. Clad material has a metallurgical bond between the CRA and the base material attained by the carbon diffusion during the hot rolling process [1].

The potential for fatigue cracks to occur in pipeline structures due to cycling loads inherent of any offshore oil production, such as, tide variation, waves, ocean current, platform movements, etc., makes necessary have an inspection tool to carry out periodic nondestructive inspection in the inner pipe surface, figure 1A and B. It is worth mentioning that the inspection tool highlighted in figure 1A flows inside the pipeline propelled by the oil flow at a velocity which at the most times exceed 0.5 m/s.

In case of clad material, it is crucial to detect fatigue crack on its initial stage because if the crack propagates through the layer of the CRA and reaches the carbon steel a strong galvanic couple is completed accelerating exponentially the fatigue corrosion process [2]. In this context, the weld geometry and the inspection speed required for in service inspection are the main challenges associated to the inspection procedure. Figure 2 shows the influence of the weld geometry associated with the inspection speed. Assuming a high-speed condition and a crack in the opposite side of the weld root, in such circumstance the sensor path may not pass exactly through the crack contour surface.

In the present work an eddy current transducer with coils placed orthogonally and differentially connected was introduced to evaluate fatigue cracks in weld root. A dedicated embedded electronic hardware was developed to drive the

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transducer and measure the electrical complex impedance of the coils and was specifically designed for operation under autonomous in-line inspection tool in a speed range between 0.5 – 1.0 m/s. In the laboratory experiments, an automated inspection was performed with the goal to evaluate transducer's detectability and different scanning speed was tested to reproduce in service situation.

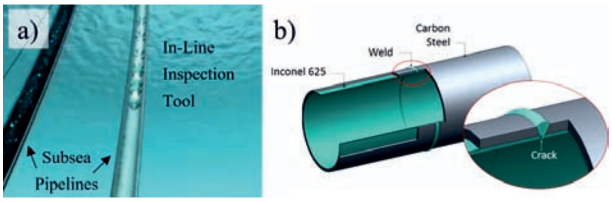

Fig. 1. A) Subsea pipelines and the in-line inspection tool (PIG), and B) Clad pipe section with the inspection region highlighted.
Rys. 1. A) Rurociągi podmorskie i jednostka inspekcji in-line (PIG) i B) Wybrany odcinek rury z powiększonym obszarem kontrolnym.

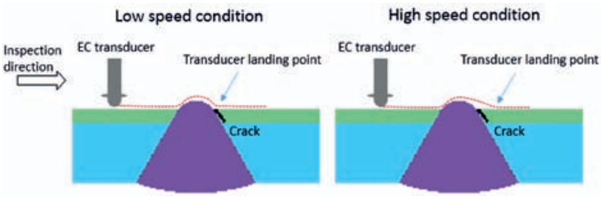

Fig. 2. Influence of the weld geometry and the inspection speed in the crack detectability.
Rys. 2. Wpływ geometrii spoiny i prędkości kontroli na wykrywalności pęknięć.

The techniques instrumented in the commercial in-line inspection tool, such as, MFL (Magnetic Flux Leakage), Ultrasound, EMAT (Electromagnetic Acoustic Transducer), are very effective in inspection of general corrosion or micro cracks in the base metal of carbon steel pipelines [5-7]. However, because of some practical limitation, such techniques are not efficient in micro cracks detection, especially in welded parts. Reber et.al. [8] have shown an ultrasonic configuration for crack detection in carbon steel pipeline girth welds and presented significant experimental results demonstrating the technique capability. The authors highlighted in their conclusions that the application of such technique in in-line inspection tools is still a challenge. Such challenge gets more complex in case of clad material inspection, where the anti-corrosive layer results in an additional interface for the ultrasonic wave propagation, interfering directly in the incident and refracted wave. Moreover, Cheng et.al. [9] pointed out that ultrasonic testing is not effective for inspections of Inconel welds because of its strong inhomogeneity and anisotropy. Once the ultrasound wave is sensitive to grain structures [10], Inconel welds significantly scatter the waves so that clear echoes due to defects cannot always be noticed.

Such challenge motivates the feasibility study of an in-line inspect tool development to detect fatigue cracks in the circumferential welds of clad pipelines based on eddy current concept. Yusa et.al. [11, 12] and Todorov et.al. [13] presented the capability of the EC transducer for fatigue crack detection in welded joints. Among the publications analyzed [11-18], it was verified that the EC transducer with orthogonal configuration of coils exhibits the most relevant inspection results. Its differential configuration and the fact that the coils are located in close proximity to each other, minimizes the influence of the weld root profile in the inspection signal. Besides the relevant results completed with such orthogonal transducer, none of the studied authors evaluated its behavior and performance when operating at high speed condition, relevant for field application for pipeline inspection. In addition, the tests performed in the examined studies used commercial or lab EC equipment, which restricts the application in tools that demands embedded electronic hardware.

Thus, the goal of the present work is evaluate the capability of an EC transducer to successfully meet the previously described requirements: detect fatigue cracks in the circumferential weld root of clad pipelines when operating at different inspection speed. It is worth mention that the in-line tool is propelled by the oil flow, which is inherently inconstant. An orthogonal coils EC based transducer was manufactured and tested, and a specific electronic hardware was developed to drive the transducer and measure the testing coils electrical complex impedance.

2. Materials and measuring system

A clad plate with substrate of carbon steel high strength low alloy, API 5L X65, and clad layer of Inconel 625, with dimensions 120x80x15mm, was manufactured with a 45° bevel to receive a weld bead from GTAW (Gas Tungsten Arc Welding) weld process. An Electrical Discharge Machining (EDM) notch with dimensions of 10.0x1.5x0.2mm was machined in the central part of the Inconel side between the weld root and the Inconel base material. Figure 3a presents a photo of the testing sample with the EDM notch indication, while 3b a metallographic image of the weld cross section after mechanical grinding, polishing and etching with chromium nitride solution. One may note the thickness of the carbon steel layer, 12mm, and the Inconel 625 clad of 3mm.

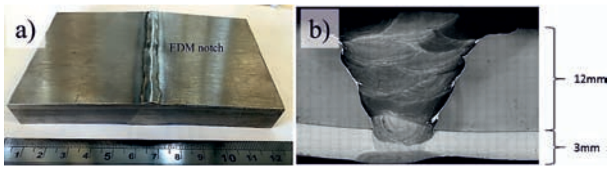

Fig. 3. a) Clad sample with the weld bead and EDM notch; b) metallographic image of the weld cross section.
Rys. 3. a) Próbka warstwowa (materiał platerowany) ze spoiną i nacięciem EDM; b) obraz metalograficzny przekroju spoiny.

The transducer manufactured to inspect the notch, consists of the testing coils placed in orthogonal configuration with layers interweaved, wounded over a dielectric core as shown by figure 4a. The coils are differentially connected thereby reducing spurious signals caused by variation of the distance to examined material during the inspection process [18]. When compared with EC pencil probes, orthogonal coils present low sensitivity to lift-off, allowing reduction of its influence rate from 40 dB/mm to 8 dB/mm. For weld inspection orthogonal coils configuration present relevant results because spurious signals arising from some specific materials characteristics or from some physical structures that are common to both coils are annihilated thereby providing no undesirable response. Each manufactured coil present 5 interleaved layers with 15 turns per layer, and an average inductance of 36.1 μH. The transducer testing frequency was 400 kHz and to assist the inspection, a KUKA robotic arm model Hollow Wrist with KRC4 controller was used (Figure 4b). With a payload of five kilograms, the robotic arm carry the sensors and tests different inspection speed from 0.05 m/s to 1.0 m/s.

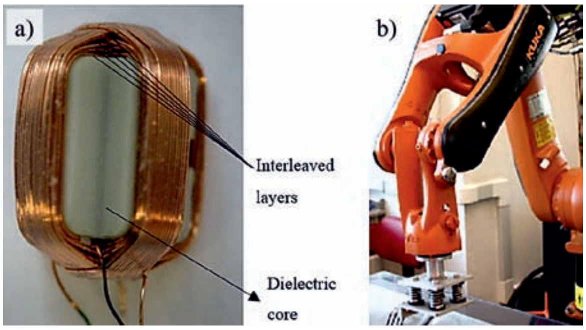

Fig. 4. A) Orthogonal coils with the layers interweaved, and B) KUKA robotic arm for automated inspection.
Rys. 4. A) Cewki ortogonalne z przeplotem warstw i B) Ramię robota KUKA do zautomatyzowanej kontroli.

The electronic hardware was developed to drive the EC sensors and measure the electrical complex impedance of the testing coils. Figure 5 present the basic concept of the EC coils impedance calculation procedure. First, in order to conduct the calculations, both voltage and current of the testing coil were measured. For that purpose, the shunt resistor was utilized and two complex potentials (V1, and V2) were sensed. Then, the Ohm's law in phasor form is applied to obtain the magnitude (eq. 6) and angle (eq. 7) of the complex impedance as demonstrated by equation 1- 7.

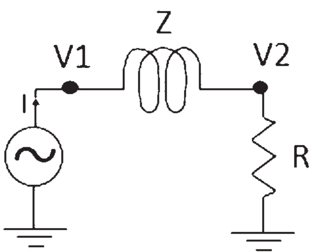

Fig. 5. Electrical scheme of a coil.
Rys. 5. Schemat zastępczy układu cewki.

$$V_1 = |V_1| e^{j\varphi_1} = |V_1| \cos(\varphi_1) + j|V_1| \sin(\varphi_1) \quad (1)$$

$$V_2 = |V_2| e^{j\varphi_2} = |V_2| \cos(\varphi_2) + j|V_2| \sin(\varphi_2) \quad (2)$$

$$V_2 = RI \rightarrow \frac{V_2}{R} = I \quad (3)$$

$$V_1 - V_2 = Z.I = \frac{Z.V_2}{R} \quad (4)$$

$$\frac{R(V_1 - V_2)}{V_2} = Z \quad (5)$$

$$|Z| = R\frac{\sqrt{\left(|V_1|\cos(\varphi_1) - |V_2|\cos(\varphi_2)\right)^2 + \left(|V_1|\sin(\varphi_1) - |V_2|\sin(\varphi_2)\right)^2}}{\sqrt{\left(|V_2|\cos(\varphi_2)\right)^2 + \left(|V_2|\sin(\varphi_2)\right)^2}} \quad (6)$$

$$\angle Z = \arctan\left(\frac{|V_1|\sin(\varphi_1) - |V_2|\sin(\varphi_2)}{|V_1|\cos(\varphi_1) - |V_2|\cos(\varphi_2)}\right) - \arctan\left(\frac{|V_2|\, sin(\varphi_2)}{|V_2|\cos(\varphi_2)}\right) \quad (7)$$

Figure 6 presents the block scheme of the measuring system while figure 7 shows a photo of the developed electronic Printed Circuit Board (PCB). As shown in the block scheme, the excitation signal is a sine wave with parameters defined in the form of the table and store in the microprocessor, which follows to a digital-to-analog converter (DAC) and a power amplifier to finally drive the coils. The hardware measures signals that are scaled versions of the voltage over the coils and their currents. These signals are digitized by an analog-to-digital converter (ADC). Then, in order to turn the digitized waveforms into phasors, a Fast Fourier Transform (FFT) or a similar algorithm, allowing processing the analysis in frequency domain, is applied.

Initially the algorithm implemented in the microprocessor ARM 32-bit to calculate the magnitude and phase of the complex impedance was the Fast Fourier Transform (FFT). However, in order to improve the hardware processing time and consequently the experimental data rate, the FFT was replaced with the Goertzel algorithm. The Goertzel algorithm is an efficient evaluation of individual terms of the Discrete Fourier Transform (DFT). When the full spectrum analysis needs to be carried out, the Goertzel algorithm is less efficient, because it presents a higher order of complexity than FFT. On the other side, in case of computing a small number of frequency components, it is more numerically efficient (then using the FFT), being very useful for small processors and embedded applications [19]. In the case of conventional EC testing, where the transducer is excited by a single known frequency, the Goertzel algorithm seems to be very suitable to calculate the coil impedance variation.

Equation 8 [19] presents the computed DFT term for the input sequence x[n] in the chosen frequency range ω_0 using the Goertzel analysis. The index k indicates the frequency bin of the DFT. If, for instance, a sine wave with 8 points was used, then the 8th bin of the FFT will have the real and imaginary information that can be turned into magnitude and phase. However, if, instead of using FFT to calculate all the bins, it is possible to use the Goertzel algorithm to calculate only x[7], where less computational effort is conducted.

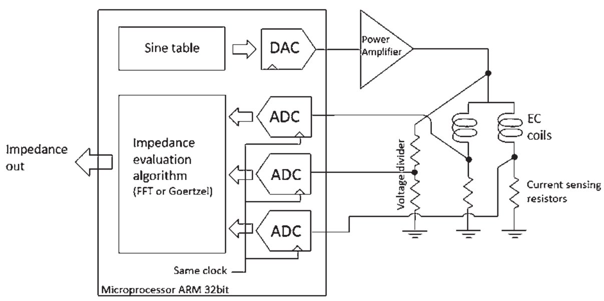

Fig. 6. Schematic block of the hardware to drive the eddy current coils and evaluate the impedance variation.
Rys. 6. Schemat blokowy układu do zasilania cewek wiroprądowych i pomiaru zmienny impedancji.

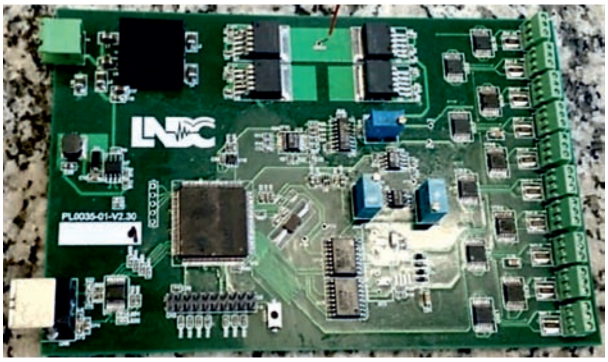

Fig. 7. Photo of the electronic hardware developed to drive and measure the EC transducer impedance variation.
Rys. 7. Zdjęcie układu elektronicznego opracowanego do zasilania i pomiaru zmienny impedancji przetwornika EC.

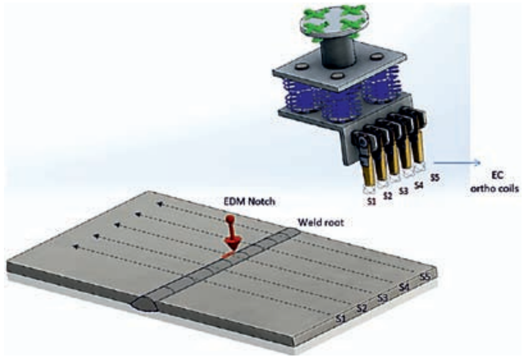

Fig. 8. Inspection result of the clad sample with the notch besides the weld bead.
Rys. 8. Wynik kontroli platerowanej próbki z wycięciem poza ściegiem spoiny.

$$y[N] = \sum_{n=0}^{N} x[n]e^{-j\omega_0} \tag{8}$$

where: $\omega_0 = 2\pi\frac{k}{N}$ and $k \in \{0, 1, 2, \dots, N-1\}$.

The use of the Goertzel algorithm offered a significant improvement in the hardware data streaming. In comparison to the FFT, the Goertzel analysis resulted in a calculation speed six times faster. On the other hand, while it provides only a single term of the DFT some relevant information, especially concerning harmonics content, is lost. If the excitation signal saturates the ADC it can be easily noticed by the distortion caused in the FFT spectrum and can be evaluated based on the harmonics analysis. In such case, the total harmonic distortion (THD) coefficient can be used. It defines the ratio between main and other harmonics and gives evidences about the behavior of the coil input excitation signal. However, according to the properties of the Goertzel algorithm, the calculation of THD is limited then. Nevertheless, it was decided to work with the faster algorithm in order to increase the hardware data streaming, which is quite relevant for high speed application. Finally, with the faster calculation and less data in the streaming package (THD data is only calculated in the FFT version) allowed the total data rate of the electronic hardware to be increased from ≈50 Hz (1/10.5 ms) for FFT to ≈100 Hz (1/19 ms) for Goertzel.

3. Results and discussion

The testing sample was scanned with different scan speed, 0.2, 0.5 and 1.0 m/s, using the orthogonal EC transducer operating at 400 kHz. Figure 8 presents the experimental schematic where an array of five EC transducers scanned the clad sample. The notch was set in the opposite side of the weld root so that the array must pass over the weld before passing through the notch. The transducer were excited and its response signal measured using the hardware developed. To scan the sample the transducer were set in longitudinal alignment with a lateral spacing of 1 mm, reaching the high scan resolution for in-line inspection tools defined by Barbian et.al. [20]. Although the tests were performed on flat plates, it is considered representative for a circumferential inspection condition. The flat arrangement is mainly used because it simplifies the mechanical arrangement and consequently the tests with different scan speed.

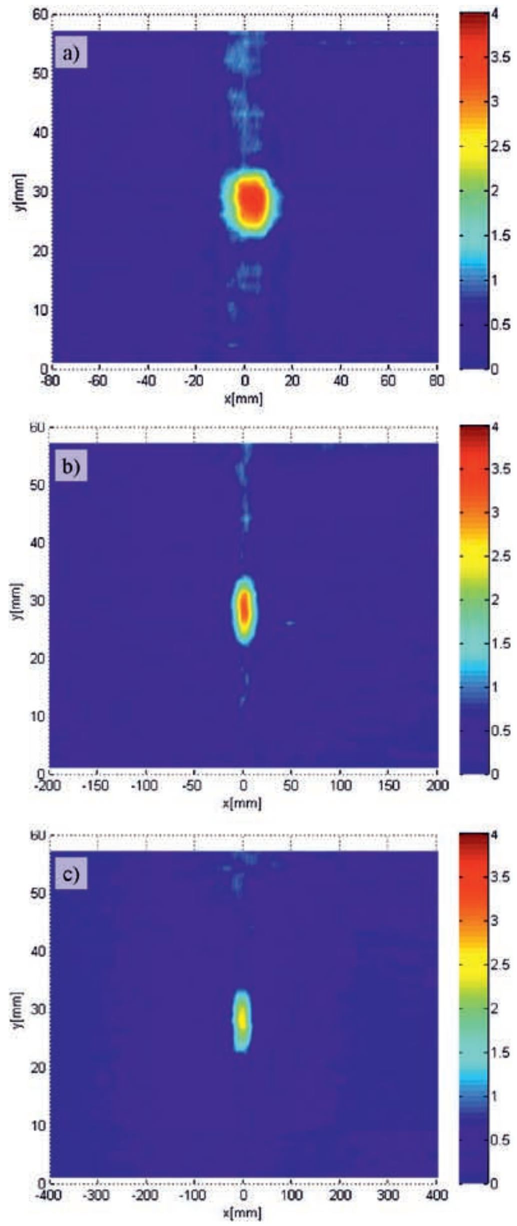

Fig. 9. Inspection results of different scanning speed of the clad sample, where: A) 0.2 m/s, B) 0.5 m/s and C) 1.0 m/s.
Rys. 9. Wyniki kontroli otrzymane dla różnej prędkości skanowania próbki platerowanej: A) 0,2 m/s, B) 0,5 m/s oraz C) 1,0 m/s.

During the movement of the array, the output signal of each transducer was measured, and the two-dimensional distributions of the signals' amplitude are shown in Figure 9a, b and c. One can observe that in all speed condition, the EDM notch can be clearly distinguished from the weld bead and, as the scanning speed increases, the notch signals amplitude are significantly attenuated.

Besides the clear identification of the notch, these results corroborates the fact that as higher the scanning speed, higher is the weld geometry influence in the inspection results. As presented in figure 2, according to the inspection speed there is a transducer trajectory associated in the weld root region. The present results made it explicit that even in high-speed condition, 1.0 m/s, it is possible to detect the notch with the suggested EC array and the developed hardware. It is worth mention that the presented experiments were performed with no lift-off, which in case of long distance inspection might result in a severe abrasion of the transducers along the pipeline inner wall.

4. Conclusions

A dedicated hardware was developed to drive the EC transducer and measure the electrical complex impedance. The Goertzel algorithm implementation improved the hardware data rate, which seems to be a relevant alternative for high-speed inspection tools where only a single frequency is evaluated. Different inspection condition was tested and as the speed is increased the notch identification signal attenuates, mainly because of the weld penetration geometry which makes difficult to proper profile the weld bead. The suggested EC system using the developed hardware and the transducer with orthogonal configuration presented the possibility to implement an in-line inspection tool to detect fatigue cracks in clad pipelines.

5. Acknowledgments

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