Industrial Eddy Current Array Testing Solution for Cylindrical Products

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Abstract. Electromagnetic inspection methods have become an effective approach for controlling the production processes of electrically conductive cylindrical products such as billets, bars, and tubes. However, most surface inspection solutions found on the market today have strict limitations regarding product geometrical tolerances (straightness, diameter, etc.), and they typically offer only partial coverage in terms of surface inspection (longitudinal and transverse defects only, significant dead zones at the product’s ends, etc.), as well as high maintenance costs.

Olympus has developed an eddy current array (ECA) solution for the surface inspection of carbon steel and stainless steel products. The aim of this new ECA system is to minimize the aforementioned limitations and respond to market needs for an affordable, high-performance, reliable, and low-maintenance requirement. Mounted on the same automated rotating cylindrical-product inspection system as the phased array ultrasonic testing (PAUT) probe, the ECA probe can detect surface indications in all orientations with a minimum detectable notch depth of 0.2 mm and length of 15 mm. Its rugged design with ceramic protection makes it virtually indestructible. In addition, an innovative integrated probe-check feature monitors the integrity of the inspection system between inspections in order to detect damaged coils. The solution includes mechanisms that prevent carbon steel and high-value alloy product surface finishes from being scratched.

This paper presents this innovative ECA solution and provides some inspection results to illustrate actual system performance.

1. Introduction

Eddy current (EC) is a very useful and powerful technique for the surface inspection of electrically conductive cylindrical products. Though ECT has several strengths and advantages, certain limitations, such as minimal notch depth or notch angle coverage, prevent its wide industrial application. Olympus has developed a new solution for the surface inspection of carbon steel and stainless steel products, improving upon existing solutions to better respond to market needs. This solution, which is based on the eddy current array (ECA) principle, features sensitive sensors positioned at different axes, enabling the detection of flaws as small as 0.2 mm and with orientations from zero to 360 degrees.

In addition to powerful detection capability, the ability to determine or verify the integrity of the eddy current inspection system is another market demand. This integrity validation applies to the system’s entire acquisition chain including the driver and receiver arrangement. This is especially true when the eddy current array has several coils, which makes it difficult to locate the broken ones in the system. Since non-destructive testing is
typically performed on critical components, the ability to confirm that an inspection system is functioning properly has a direct impact on the safety level of the inspected component by eliminating the risks associated with inspection system malfunctions. To meet this need, the probe in the Olympus solution includes an innovative self-check functionality.

This paper presents the details of this Olympus ECA solution with probe integrity check and provides some inspection results to illustrate actual system performance.

2. Design Details

2.1 ECA Probe Details

The probe design is based on the previous Olympus multidirectional hexagonal coil design (Ref.1). In the multidirectional hexagonal coil design, there are three coils; each of the coils is wound across the two opposing sides of a six-sided right-angled polygonal prism, such as a hexagonal core (see Fig. 1- on the left). As a result, the coils are oriented at ±60 degrees from each other. At each time interval, two of the three coils are used as driver coils, and the remaining one as the pick-up coil. The drivers, being charged simultaneously with electric current driven in coherent directions, induce a combined eddy current that is orthogonal to the receiver coil. Each coil functions alternately as the receiver coil, according to a predetermined switching sequence. Since each coil is shifted by 60 degrees with respect to its neighboring coils, the directional sensitivity of each channel rotates for each of the three resulting channels.

Since the maximum sensitivity of all channels is basically identical, a given flaw aligned with the directional sensitivity of any channel can be detected with the same signal amplitude. Therefore, flaws oriented at or close to angles of ±15°, ±45°, ±75°, ±105°, ±135° and ±165° (practically the entire 360° range) on the test surface, will be detected with sufficient sensitivity by one of the channels (see Fig. 1- on the right).

Fig. 1. Left: Conventional (three-dimensional) multidirectional hexagonal coil design; right: Optimum sensitive axes of all channels in the hexagonal probe.

Probes equipped with these conventional multidirectional HEX coils offer the advantage of inspecting a test surface for flaws of any orientation with only one scan pass, providing sufficient sensitivity and desirable noise cancellation in all directions.
The ECA probe presented in this paper is a two-dimensional structure of the three-dimensional conventional hexagonal coil design (Ref.2). Using a 2-D configuration enables the use of printed circuit board technologies for the manufacturing of these EC sensors. In this probe, there are 30 channels, each with three sensitive modes: 15, 45, and 75 degrees. The probe’s total coverage is 129 mm (width) with a resolution of 4.3 mm (distance between channels) (Fig. 2).

![A schema of 30 channels with 129 mm coverage](image)

Fig. 2. A schema of the ECA probe channels and their sensitive axes

As with the conventional HEX coil, various detection angles can be obtained by adapting the driver/receiver configuration within the structure. Thus, each channel provides three different sensors, each optimized for detecting defects at predefined orientations, resulting in 6 axes of optimal sensitivity (Fig. 2).

This ECA probe solution includes two special probe-housing designs to cover a wide range of product types: one probe-housing design for carbon steel products with rough surfaces and a second probe-housing design for high-value alloy (HVA) products with very smooth finishes (Fig. 3). While the carbon steel solution has the advantage of being virtually indestructible owing to its rugged design and integrated ceramic coating, the HVA solution is designed to protect the finished surface of the part from scratches. Variations in product geometry have a limited impact on the detection performance of both of these solutions because of their multi axis yoke designs.

![Probe housing design for carbon steel (left) and high-value alloy (right) products](image)

Fig. 3. Probe housing design for carbon steel (left) and high-value alloy (right) products
2.2 ECA Probe Integrity Check

In addition to the aforementioned evolution in this ECA probe’s design, a probe integrity check has been added to enable the user to verify the functionality of the whole inspection system.

The ECA probe integrity check solution is based on the eddy current response. When a shielding loop is positioned around an eddy current test coil, a signal is induced in the loop and this signal changes the magnitude and phase of the current flowing in the coil. Detecting these changes enables the verification of the ECA inspection system’s functionality. The impedance plane diagram in Fig. 4 shows how the probe integrity check solution works.

![Impedance plane](image)

Fig. 4. Impedance plane

In the impedance plane, each acquired data point corresponds to a single point on the plane (operation point). This operation point is directly related to the global condition of the inspection system, the probe, and the test material.

For this application, it is necessary to define a reference signal, which is presented here as reference signal ($\vec{V}_{ref}$). This reference signal is obtained by activating the test loop when the inspection system is working properly. Then the reference signal ($\vec{V}_{ref}$) can be compared with the eddy current signal from the system check evaluation signal ($\vec{V}_2$) to monitor the integrity of the inspection system. For this purpose, a probe integrity test value (PITV) was defined. For the PITV, $|\vec{V}_2|$ is calculated and compared with $|\vec{V}_{ref}|$ for each of the ECA channels in between bar inspections. A predetermined threshold allows us to identify damaged probes. For more detailed information relating to this method, see Ref.3.
3. Experimental Results

The experimental results are divided in two main sections:
In first section, the results show the probe performance for different notch and natural flaw detection. The second section provides the results of probe integrity check.

3.1 ECA Probe Performance Evaluation

In this part, the performance of Olympus carbon steel and HVA solutions for different notch and natural flaw detection are presented.

3.1.1 Carbon Steel Probe Performance Evaluation

A carbon steel tube (128 mm in diameter and 17 mm WT) with notches at different orientations and depths was used for validation testing. The objective of the testing was to evaluate the performance of the probe for different notch orientations and depths. For this purpose, two different inspection speeds (1000 m/s and 1800 m/s) were used.

Fig. 5 summarizes the results obtained during 10 runs at 1000 mm/s (in blue) and 1800 mm/s (in yellow) in terms of detection performance and reproducibility. Reproducibility is calculated using following equation:

\[
\text{Reproducibility} = 20 \times \log (\text{Max/Min})
\]

Where “Max” is the maximum amplitude reading and “Min” the minimum reading obtained on 10 runs for the same defect and detection group.
The results show that the average notch detection performance is always higher than 15 dB. Moreover, the variation of notch detection reproducibility is always $\leq 3$ dB, regardless of the inspection velocity.

In addition to the tube results, a carbon steel sample bar with a diameter of 120 mm and with notches at different depths was used to evaluate the probe’s depth detection performance, particularly at around 0.2 mm deep. Fig. 6 shows a scan of whole bar.

![Fig. 6. Notch detection for different notch depth](image_url)
As it is presented in Fig. 6, the notch located at a depth of 0.2 mm is clearly detected. Note that the evaluated bar surface was very rough (Ra = 8.6 μm) and included many natural defects. Therefore, for comparison purposes, part of the bar was grinded prior to defect machining to attain a smooth surface (Ra = 1.2 μm).

3.1.2 HVA Probe Performance Evaluation

As an example the results of the HVA probe’s performance evaluation on an austenitic high-temperature superalloy is presented in this paper. The tests are performed on the client’s production line in industrial conditions.

For this bar inspection, the system was calibrated on a longitudinal notch (at a depth of 0.5 mm) and the alarm was set at half of the calibrated signal. The SNR of the calibration notch detection is 16.3 dB. Fig. 7 shows an example of the results. As is presented in the figure, all defects were natural defects.

![Fig. 7. HVA probe test in industrial conditions](image)

3.2 Validation of the ECA Probe Functionality Check

To validate the performance of the probe functionality check, we intentionally damaged different channels to see if the proposed method is capable of distinguishing a damaged probe from an undamaged one.

In this regard, the following approach was deployed:

A) The PITV was calculated when the probe was undamaged (Fig. 8).

B) The probe was damaged in two steps (step 1 and step 2) and the PITV was recalculated after each step:
   1. For step 1, we damaged the probe so that channel 1 was affected. Then we calculated the PITV.
   2. For step 2, we damaged the probe so that in addition to channel 1, channel 4 and channel 5

Fig. 8 shows the PITV values for the undamaged probe. As is shown in the figure, the PITV did not exceed 0.1 for any of the channels.
Fig. 8. PITV value for the undamaged probe

Fig. 9 shows the results of the PITV for the first and second damage steps. Initially, it was expected that in first step, the damage would only affect channel 1, and in second step, the damage would only affect channel 4 and channel 5. As is shown in the figure, the PITV value of the anticipated channels increased significantly. It should also be noted that when more than one channel of this probe is damaged, other channels in different modes are affected as well. Comparing Fig. 8 with Fig. 9 confirms that it is possible to easily identify a damaged probe using this probe functionality check solution.

4. Conclusion

Based on the presented results, Olympus offers an affordable, high-performance, and reliable solution for the surface inspection of electrically conductive cylindrical products. For this solution, two different probe housings were developed to meet market needs (carbon steel solution and HVA solution). While the carbon steel solution has the advantage of being virtually indestructible owing to its rugged design and integrated ceramic coating, the HVA solution is designed to protect the surface of finished products from being scratched. Both solutions have the following technical features:
- Limited impact from product geometry variations on detection performance
- Ability to detect defects in all the directions, from 0 to 360°
- Ability to detect defects down to 0.2 mm depth
- Ability to check and confirm the probe’s functionality anytime during the inspection process
References

