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DEVELOPMENT OF A MULTIFREQUENCY EDDY CURRENT SYSTEM FOR INSPECTION OF THICK MULTILAYERED STRUCTURES

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Abstract

A laboratory system for Multifrequency Eddy Current nondestructive testing has been developed in the frame of the BRITE-EURAM project n° BE95-1778, contract N° BRPR-CT 96-0200, Cost reduction by Advanced Non-Destructive Inspection of Aeronautical structures (CANDIA), with the aim to detect and asses sub-surface corrosion in aluminum thick multilayered structures. The system is based on the use of optimized Eddy Current (EC) probes and ordinary laboratory instruments (arbitrary waveform generator, oscilloscope analyzer, lock-in amplifiers, scanning equipment) harmonized and governed through an analogic signal processor interface device specifically designed by AGUSTA to drive and merge the electromagnetic signals.
The main input requirements for the development of this laboratory system were:

- the capability to drive the optimized probes, specifically designed and manufactured by CISE (as sub-contractor of AGUSTA in this project) under AGUSTA specification,
- the capability to interface with an existing scanning equipment, partially modified to carry out Multifrequency Eddy Current inspection of helicopter structures in automatic mode,
- the capability to obtain a "fast and reliable" C-scan mapping of inspected structure (typically: complex multilayered structures) eliminating the interference due to unwanted signals,
- reduction of time/cost for helicopter maintenance inspections.

An existing scanning equipment (Versiscan) composed by a mechanical scanner-frame and an A/D converter was modified and adapted to carry out automatic Multifrequency Eddy Current inspections and mapping representations on the AGUSTA structures. The general structure of the laboratory system was built with two frames:

- the "sample-scanning and image processing" frame;
- the "signal-generation and processing" frame.

This common structure could be used in different configurations to better fulfil the different inspection cases. As approach for this research, AGUSTA has identified the requirements on Eddy Current equipment and probes for the inspection of "hidden corrosion" in representative set of multilayered samples and structures. The design activities for the realization of specific EC probes were developed with the use of Finite Element electromagnetic Modeling (FEM) together with experimental activities with standard instruments and devices.

Design activity was carried on and all the optimized EC probes were also manufactured, tested and characterized by AGUSTA subcontractor (CISE). Existing systems and instruments were adapted or assembled to perform Multifrequency EC testing inspections with automatic scanning and fast mapping representation of the inspected zone in which the defect extension can be easily recognized.
This system was used to validate the developed techniques carrying out automatic inspections and mapping on AGUSTA samples and structures getting methods and procedures that allow a fast and reliable testing, with consequently reduction of time and costs for in-service inspections.

Introduction

The work here presented is part of the AGUSTA's activities carried out in the framework of the BRITE EURAM project CANDIA.
Detection and assessment of corrosion in metallic parts have always been a problem in all industrial fields and mainly in aeronautics; for this purpose the NDTs have always played one of the most important roles and consequently many NDT techniques have been developed and improved with the aim to increase precision and reliability. In particular, Eddy Current inspection has made huge steps and has been considered one of the most practical and reliable ways to get rid of this issue, mainly for in-service inspection. This kind of testing is well used with metallic parts, because it allows the measurement of many parameters of the material (conductivity, magnetic permeability, grain size, etc.), the detection of discontinuities and the determination of thickness of coatings [1].
A particularly difficult problem to solve is when the corrosion is present in a not directly accessible area; i.e., when it is hidden by other parts like in multilayered structures. In this case the Multifrequency Eddy Current technique has been found as one of the most powerful tools because it allows penetration at different depths as a function of the selected frequency giving the possibility of choosing the layer to investigate, eliminating the unwanted signals coming from the others, and increasing signal to noise ratio [2], [3]. The typical use is to employ a higher frequency to get and store information from the uncorroded, and closest to surface, layer and then use them to "clean" the information coming from a lower frequency. The latter, in facts, given that can reach the thicker layers, integrates information from the surface and the deeper layers, where the corrosion is present.
However Multifrequency Eddy Current techniques are not limited to the corrosion investigation, in fact can be used in investigating other cases where the discontinuity is not directly accessible such as cracks in a metallic part under an insert (a specific case could be the crack detection in an aluminum part under a bronze bush whose roundness and trueness are variable).
For this work, the Multifrequency Eddy Current technique was used to detect corrosion on a quite difficult case: an hypothetical situation where the corrosion was on a lower surface of a 4 mm thick aluminum plate covered with an aluminum sheet bonded on it and beside a 1.5 mm thick lead plate (also bonded) [4]. It was supposed that the corrosion would have reduced the thickness of the aluminum plate by a quantity of no more than 0.8 mm, starting from the internal surface, which is not accessible for inspection. This case was particularly interesting and difficult to solve because it's not simple to detect such a small defect under such a thick plate. An actual specific sample was manufactured to simulate the problem according to the sketch of figure 7.
The decision of assembling a laboratory system using ordinary instruments, such as an oscilloscope, a wave form generator and two lock-in amplifiers, was taken because an instrumental chain with versatile instrumentation has the capability to allow the greatest flexibility in terms of frequency range, drive the optimized probes, specifically designed and manufactured with respect to the requirements of this particular case, and interface with an existing scanning device, partially modified to carry out Multifrequency Eddy Current inspection in automatic mode.
The heart of this system is a signal processor interface device specifically designed and manufactured for mixing signals with different frequency, obtaining the real useful output signal whose parameters can be programmed and controlled in a wide range. This allows enough versatility to approach different kind of inspection cases, and not only in this particular contest. In fact, with minor modifications, the system could be employed, in future, for investigating in other fields, for example residual stresses state evaluation in metals [5]. In effect, an instrumental chain gives a wide choice of employment in different fields, although it's not compact and requires skilled people to be managed.

Instrumentation

A laboratory system (figure 1) was assembled putting together a chain of instruments consisting of two lock-in amplifiers, a wave form generator and a digital oscilloscope, implemented with a Signal Processor Interface Device (SPID) appositely built.

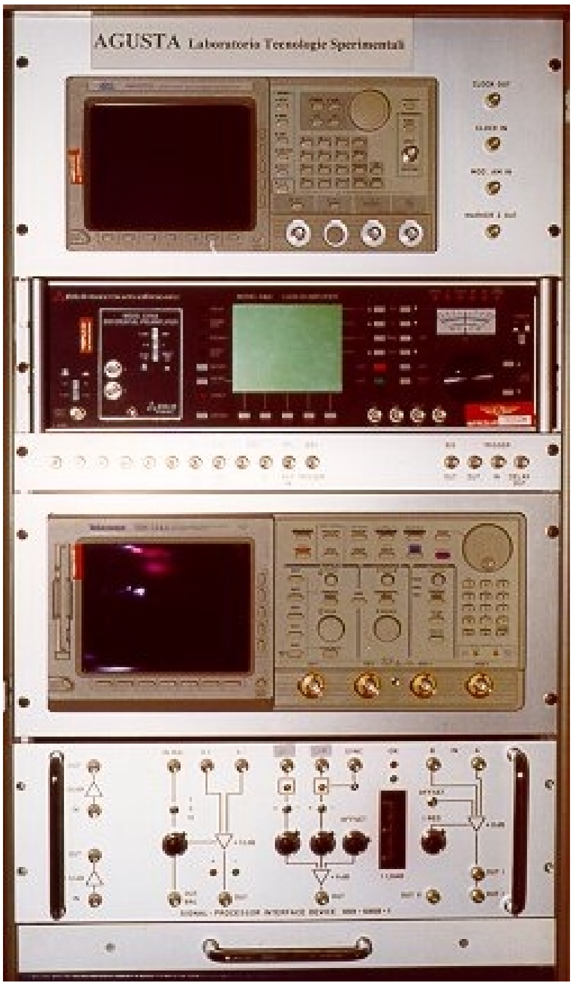

Figure 1: Front chassis view of the signal generator and processing frame (one lock-in version).

The introduction of the SPID in the chain was necessary for solving three major problems that with conventional EC instruments were difficult to deal with. First of all, this device was used to sum and pilot the probe's current, because with commercial instruments was difficult to work at low impedance ($\leq 1\Omega$), because there's big distortion in the signal. The necessity of working at low impedance was due to the fact that the probe had to be of very small dimensions and to have a wide frequency band, it was also essential to control the current going through the probe in order to keep under control the heating of the probe due to current flow. The section dedicated to the amplification of the signals was useful to raise the signal to noise ratio, in facts, in here, the windings are kept separated giving the possibility of inserting the preamplifier, which increases the output and lowers the impedance improving the quality of signals. The last and most important capability of the device is the possibility of combining algebraically the components (diagnostic signals $Y_{1,2}$) of the impedance vectors related to the two different frequencies.

All the chain's loops were connected according to the scheme of figure 2.

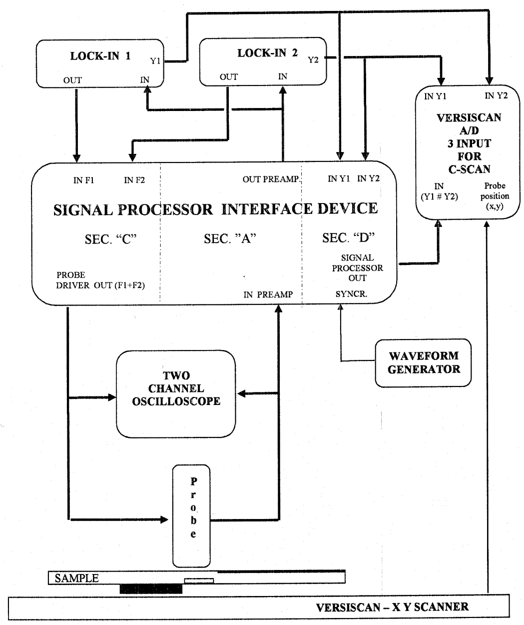

Figure 2: Scheme for instrument connection.

The first loop of the chain was made of two phase-sensitive lock-in amplifiers (5032) which had a frequency range that went from 10^{-3} Hz up to 10^{6} Hz, then there were an arbitrary wave form generator (AWG2021), with a frequency range from 1 Hz to 2.5 MHz, and a two-channel digitizing oscilloscope / wave form analyzer (TDS724A). All loops were connected to the SPID (P/N 999-6808-01) that was supposed to solve different tasks.

This unit is divided in four sections:

A. *Preamplifiers*
B. *Differential preamplifier*
C. *Probe power amplifier*
D. *Signal processor*

In section A two signal preamplifiers are present, both with a gain of 12/24 dB, an input impedance Z>1 MΩ, low output impedance and a band width that goes from DC to 220 kHz. Section B (optional for this application) contains a differential amplifier with balancing unit (DC/AC) and "level-off" visual warning (LED), has a gain of 6 dB, and all the other characteristics as in point A. Section C is the probe "driver" with two signal inputs, an offset level control, a regulation to get an output current proportional to the input voltage and a "bar-graph" indicator to check the actual current to the probe. This element has an input impedance of Z=1 MΩ, very low output impedance with current limitation variable from 0 to 500 mA, and a band width from

DC to 60 kHz. The last section is the most important because contains the processor that takes the input data and delivers an output signal as a linear combination given by the equation:

$$V_{out} = 2 \cdot \left[\left(\pm Y_1 \cdot k_1 \right) + \left(\pm Y_2 \cdot k_2 \right) + k_3 \right].$$

Where

- $Y_{1.2}$ are the signals from the lock-in amplifiers
- $0<k_{1,2}<1$ are arbitrary coefficients
- $-500\ mV \le k_3 \le 500\ mV$ is an offset variable.

The system was designed to drive the optimized Eddy Current probe with a signal that is a combination of two frequency-different sinusoidal waves. As indicated, everything started from the two lock-in amplifiers that generated two signals with an amplitude of 5V and a frequency of, respectively, $F_1=1kHz$ and $F_2=5kHz$ (see below for frequencies selection). These were sent to the probe power amplifier (sect. C) of the SPID, combined in a Multifrequency signal and then sent to the EC probe, as shown in figure 3.

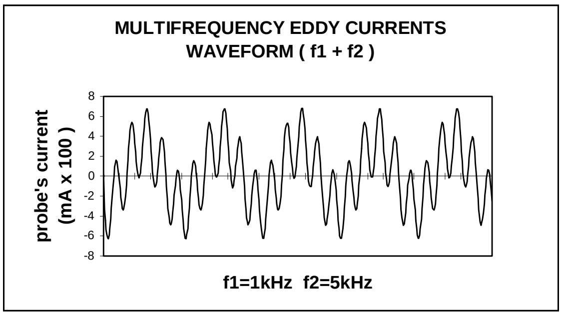

Figure 3: Input waveform.

The outputs of the coil were transmitted back to the SPID (sect. A) to be amplified before returning to both amplifiers, where each of them analyzed and processed the part of signals related to its frequency, sending to the SPID (sect. D) the respective impedance vectors components ($Y_{1,2}$) of the probe/sample interaction signal. Then the processor operated according to the equation described earlier and gave three types of analogic output voltages that reach the Versiscan A/D converter in order to obtain three different C-scan maps: two of them containing the voltage proportional to the component $Y_{1,2}$ of the signal $F_{1,2}$, while the third was proportional to an arbitrary linear combination of the previous signals. The waveform generator and the oscilloscope kept a collateral, but not less important, role; in fact, the first was employed to create a sequence of two signals used to synchronize the signal processor, while the other was necessary to visualize the inputs and the outputs of the probe. The oscilloscope was particularly useful in controlling the signals produced by the lock-in amplifiers in first place to avoid sending an inappropriate signal to the probe.

The system was kept in the analogic mode, but it's possible to improve it by switching to digital mode by introducing the devices and connections to control the chain from a computer.

Optimized Probe

On AGUSTA requirements, a specifically designed and manufactured EC prototype probe was realized and characterized by CISE [5]. It turned out that the probe was in compliance with the requests of this problem, having both good penetration, to separate the signal from background noise, and a reduction of lateral and axial resolution, to increase sensibility and minimize edge effect. This probe was built with absolute autobalancing, that means that a primary sensor (absolute receiving-transmitting coil, iron rolled and with C form) is placed in contact with the specimen, while an identical secondary sensor, built in the probe too, is put in contact with a reference plate made of the same material as the specimen (AL2024). Each sensor is made with a single transmitter, wound around the C-core, and a receiver positioned next to one of the terminations of the C-core, as shown in figure 4.

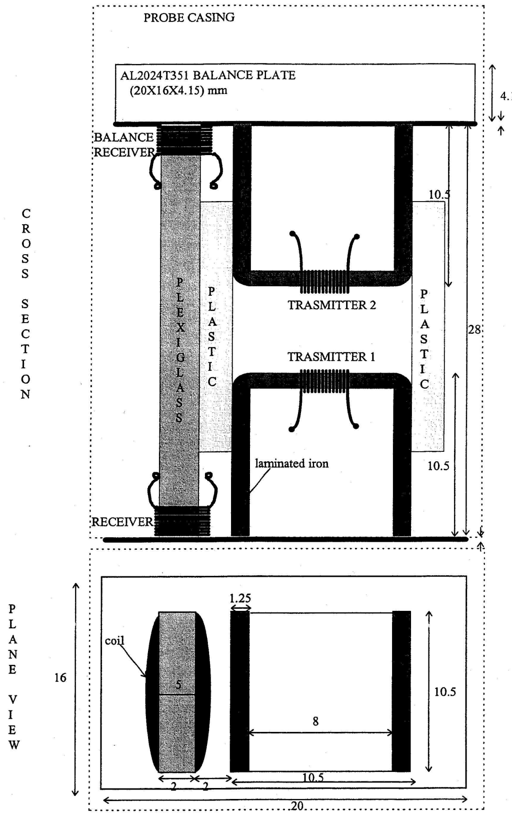

Figure 4: Probe's scheme

For a correct use of the probe, the first thing to do is the autobalancing; to do this it is necessary to put the

probe on a metal identical to the internal reference. In this way both the primary and the secondary elements can “feel” the same material and, consequently, minimize the output signal.
It’s very important to verify the position of the receiver’s coil because it must give the opportunity of collecting even the deepest flux lines; these, in facts, are those that most likely will interact with the defects. For this reason, it has been necessary to test the probe even with a rotation of 90°. Probe characterization was carried out by CISE itself to determine the best frequencies to work at, and, as shown in the following figure, it was found out that the “impedance knee” is in between 1-2.5 kHz, while there is a resonance at F>100 kHz.

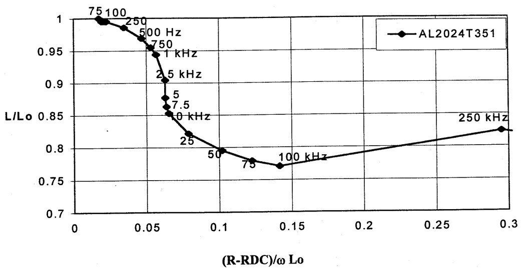

Figure 5: Probe's impedance as a function of working frequency.

Normalization parameters used here are $R_{DC}=3.952\Omega$ and $L_0=1.06mH$ (taken both at 60 Hz in air).

Modified C-scan system

For “sample-scanning and image processing” it was used a commercial Versiscan PC/2, modified and adapted for the AGUSTA needs.
This machine employs a PC with a custom designed, easy to use software package for controlling an X-Y scanning frame. It displays graphics in both the color and gray scale mode of the part being non-destructively inspected and obtains hard copy color or black and white printouts of the results. This frame is capable of being used for laboratory and in-field inspection. There is also the possibility to insert data file information into data analysis reports.
A simple “teach and learn” process allows to memorize and execute different X-Y rectilinear patterns. Using multiple-channel or multiplexed NDT instrumentation, up to eight channels of data can be acquired simultaneously and saved in one record. An eight color interactive graphics mode allows the part to be electronically rescanned at various sensitivities with the scaling in dB, Voltage, percentage or 0-248 levels. This scaling flexibility allows the analysis to be specifically referenced to the NDT instrumentation analogic output.
The A/D converter accepts only analogic levels (DC) of 0-10 V, 0-1 V, 0-100 mV and 0-20 mV. Any of the four ranges may be selected and assigned to anyone of the 8 input channels on Versiscan to accommodate external NDT instrumentation (usually: Ultrasonic or Mechanical Impedance Analyzer) that has an output which fits within the appropriate range. To connect without risks the Multifrequency Eddy Current “signal-generation and processing” laboratory frame with this system it was necessary to introduce a modified output-input connection based on a protection filter-circuit that limits between 0 and 10 Volts the largest voltage variation for the signals that could reach the A/D converter; moreover, to reduce at minimum the electric network disturbances, in the same circuit a time constant was introduced through a condenser.
Image processing functions that supply contrast adjustment are provided. C-scan images can be enhanced with digital filtering techniques to perform edge enhancements, accentuate low level but frequently occurring signals due to sharp defects and weigh them against higher signals due to other defects or the presence of different materials. The algorithms used to filter/alter/enhance the data are similar to those found in standard image processing systems for NDT.
Four images can be compared concurrently by choosing between those currently stored in each of the (4) 512 x 512 frame buffers. This feature allows a very rapid recall and image comparison function since each image that is stored in video RAM can be instantly displayed.

Inspection and results

The first issue to consider, before starting with the inspection of the Versiscan, was to find the right frequencies to work with. An optimal operating frequency of about 2 kHz was suggested by the FEM-Finite Element Modeling approach, in order to grade different levels of sub-surface corrosion in aluminum plates, and to avoid influence from the presence of the lead plates adhesively jointed to the bottom of the aluminum plate, in a position adjacent to the corroded areas; the possible disturbing effect due to a variation in the thickness of the glue layer between an upper sheet and the aluminum plate could be reduced by adopting a second frequency higher than the optimal one. Besides, some experimental tests were carried out to define the best combination of working frequencies. After several tries, it has been found that to reach the requested

depth it was useful utilize a frequency of 1 kHz, while to limit the investigation to the bonded aluminum sheet, it was better stay at 5 kHz.
Once found the correct frequencies, there were the mechanical problems to solve before starting scanning, and in particular the need of minimizing the presence of “lift-off” (i.e., the disturbance to the signal due to a change of distance between probe and specimen’s surface). For this reason, the probe was put in a probe-holder stabilizer that prevented the coil from tilting in either X and Y directions and from lifting from the surface. In figure 6 is shown a detail of the probe and its holder on a specimen.

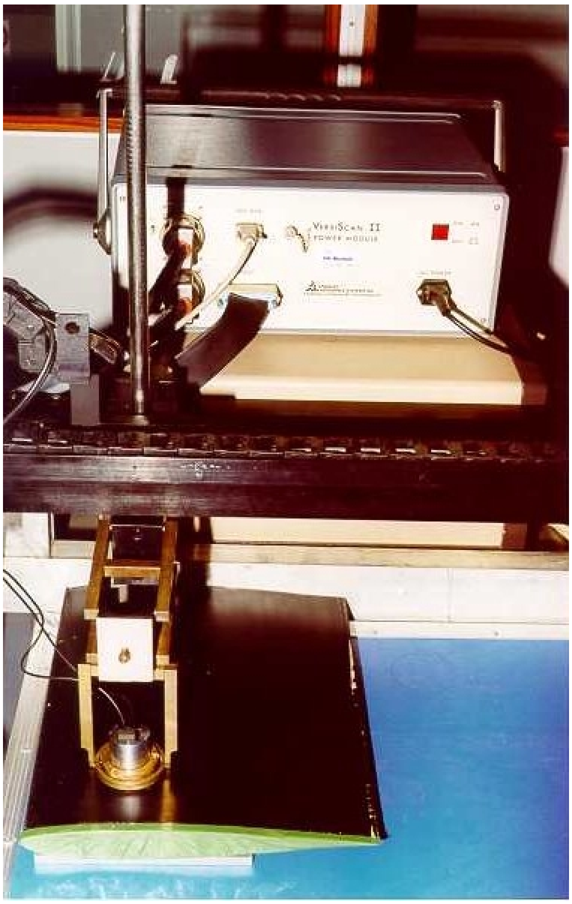

Figure 6: Close image of the probe and Versiscan

Before starting with the scanning, it was appropriate to pour some lubricant on the specimen to allow a better sliding of the probe in order to avoid its tossing that would cause the generation of false indications.
The last things to set were the values of k_1 and k_2 in order to normalize and combine the diagnostic signals to obtain output tension values to be displayed in a graph. To do that, it was followed a step-by-step procedure, beginning with the setting of the max input current values in order not to damage the probe, that were found to be of 200 mA. Next was the minimization of lift-off, that was obtained, using the standard procedure, varying the internal reference phase of the two lock-in amplifiers; in this way it was possible to reduce the variations of one of the two impedance vector’s components between when the probe was in contact on the specimen and when it was in air. This operation had to be repeated for both frequencies.
At this point, it was necessary to look for the mathematical relationship needed to neutralize the disturbance generated by the thin upper sheet. This was done by taking the lock-in amplifiers’ values both on the single-layer and on the double-layer, subtract those related to the same frequency and calculate the percentage ratio between these two values. In this way it was found that $k_1=5k_2$ with an approximate error of 5%, due to unavoidable environmental electronic noise. Once solved all these issues, it was possible to start with the inspection, being careful that, in trying to get the best resolution, the output voltage wouldn’t be so high to saturate the Versiscan blackening the C-scan. In facts, the machine only sees positive voltage and must be prepared to measure different scales, in which it’s forced to remain in order to have good resolution. For this duty, the oscilloscope was really useful, because it could visualize the tension coming from the SPID and allow the right adjustments in order to have the maximum value included in the chosen scale.
Once everything was set, it was possible to start with the scanning of the specimen; to ensure that the two frequencies would interact in the right way, the outputs related to the two-frequency (figure 10) and to both single-frequency contributions (figures 8 and 9) were acquired simultaneously.
Since lighter colors represent higher signal intensity, from figure 8 it becomes clear that the lower frequency alone was not enough for the inspection, because it well detected the inner defect and structure, but only in the side of the specimen (left) not covered by the external sheet. The higher frequency contribution, instead, discerned the thinner superficial structure (right side), but not the internal. Finally, the Multifrequency plot (figure 10), mixing adequately both contributions, clearly showed the defect (dark) and the lead plate (light), avoiding the disturbing effects due to the multilayered structure. The fact that the edges of the defect were not so well defined must be ascribed to the probe, which, being spatially extended, received and averaged adjacent values of the induced field. The probe’s extension was needed in order to produce an electromagnetic field capable of penetrating for a few millimeters through the specimen, thing that a punctiform coil was unable to do.

For an easy comparison of the results, the sketch of the specimen and its C-scans are placed close to one another in figures from 7 to 10.

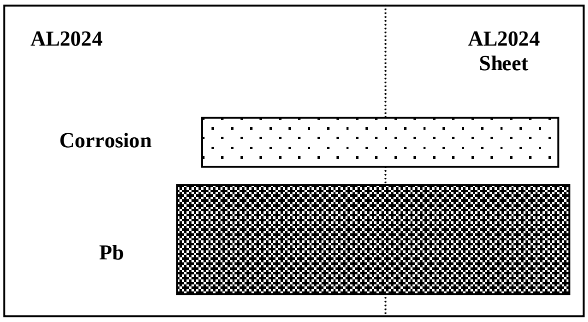

Figure 7: Specimen's sketch

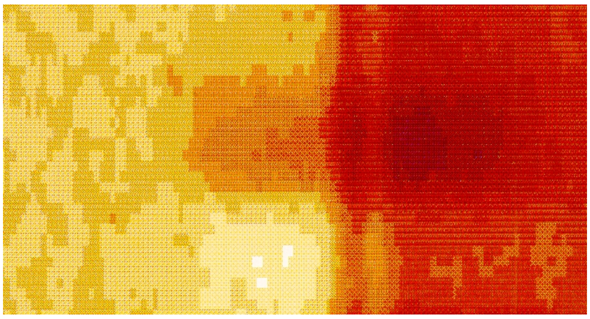

Figure 8: C-scan map of F_1=1 kHz

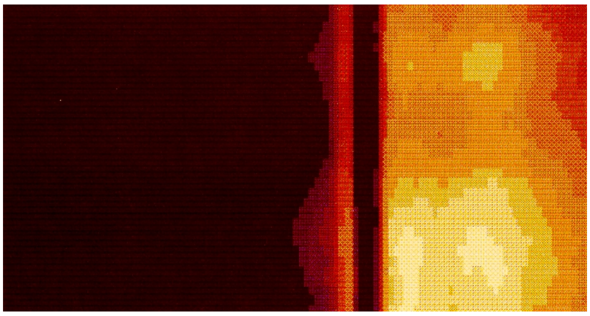

Figure 9: C-scan map of F_2=5 kHz

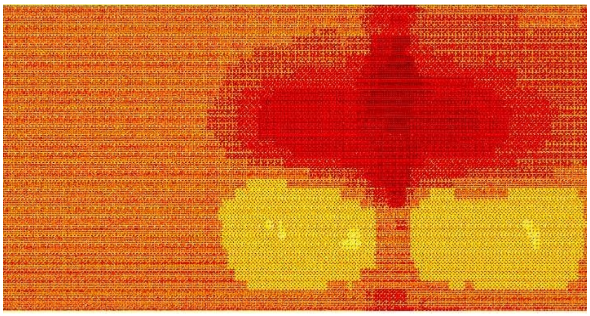

Figure 10: Multifrequency Eddy Current C-scan map.

Conclusions

The observed results confirm the feasibility of the method and the correctness of the approach. The developed system allows the fast nondestructive detection of hidden corrosions in multilayered structures even under particularly difficult conditions, without dismantling sections or removing external layers, with consequent reduction of time and costs for in-service inspections.

The FEM procedure for EC probe design and optimization gave the possibility to increase the knowledge to face and solve this kind of inspection problems with the correct approach and experience. Existing systems and instruments were adapted or assembled to perform multifrequency EC testing and a specific device (SPID) was designed and manufactured to merge the conventional and the modified devices in a Multifrequency Eddy Current laboratory system.

The versatility of this system makes it possible to use it also in other kind of investigations, like, for example, the one concerning the residual stresses state evaluation in metals.

Acknowledgements

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