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DETECTING AND ESTIMATING LOCAL CORROSION DAMAGES IN LONG-SERVICE AIRCRAFT STRUCTURES BY THE EDDY CURRENT METHOD WITH DOUBLE-DIFFERENTIAL PROBES

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ABSTRACT

Monitoring corrosion in aircraft structures through nondestructive testing is crucial for maintaining long-term aircraft serviceability. Corrosion monitoring is particularly challenging when corrosion damage is situated on internal surfaces of multilayer aircraft structures. The eddy current method is one of the most promising techniques for detecting and measuring such subsurface corrosion damage without direct contact or disassembly. However, due to their low sensitivity traditional eddy current probes with coaxial coils are not well suited for detecting corrosion damages of the local type, such as pitting or corrosion pits, in multilayer aircraft structures. This study tested the use of low-frequency eddy current probes of the double-differential type, characterized by 8 and 10 mm operational diameters, in detecting and measuring hidden corrosion damages of this local type. Such corrosion damages were simulated by means of flat-bottomed drilled holes of differing diameters and depths (or different diameters and residual thicknesses of the inspected sheet in the damaged area). The signals from the eddy current probes were evaluated in the complex plane using a universal eddy current flaw detector. The correlations between the amplitude and phase of the eddy current signal and depth of location of the local corrosion damages were analyzed. Results indicate that it is possible to estimate the residual thickness of the skin in locally corroded areas by measuring the eddy current signal phase, independently of the local corrosion damage diameter (size), providing useful information for residual service life determination.

Keywords

multilayer aircraft structure; corrosion damage; pitting; corrosion pit; eddy current method.

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1. INTRODUCTION

Corrosion damages (CDs) due to corrosion-induced metal loss represent one of the most important factors influencing the integrity, safety, and projected service life of aircraft structures (ASs) that have been in service for significant durations. The outer frame of many ASs consists of several aluminum alloy fastened sheets [1–3]. During an aircraft's service life, the infiltration of moisture initiates CDs between these sheets. Most susceptible to CD are aluminum alloy components like double-layer joints and the skins of the fuselage and wings. For example, various types of CD, such as pitting, delamination, intergranular, crevice, contact, and corrosion cracking, have been detected in Antonov airplanes after long-term operation [2]. In aluminum alloy AS, pitting (local point damages, the diameter of which is smaller than their depth) and delamination type CD (swelling and delamination of the metal) are often found. Therefore, the well-timed detection and estimation of hidden CD is very important for ensuring accident-free aircraft operation and projecting the residual service life.

Therefore, monitoring AS corrosion by means of nondestructive testing (NDT) methods is an important part of a maintenance program for aging airplanes, and substantial efforts have been made by NDT researchers and engineers to find reliable ways to detect and quantitatively estimate such hidden corrosion [3-6]. Different types of CDs originating on the external parts of ASs can be detected visually [3]. To detect the external skin thinning concerned with uniform CD presence, the external skin thickness can be measured, for example, by ultrasonic NDT methods [3]. The most complicated situation for corrosion monitoring, however, occurs when internal hidden CD is situated on the internal surfaces of multilayer ASs (the bottom surface of the first/top layer or the top surface of the second layer). The eddy current (EC) method is one of the most promising techniques for detecting and estimating subsurface CD in ASs, as it makes non-contact and productive NDT inspection possible without the need to disassemble multilayer aircraft units [3–7]. This makes further improvement of the EC method based on the development of EC probes particularly sensitive to local CDs as well as advances in quantitative EC signal processing highly desirable.

This study first analyzes the state of the art in detecting CDs in ASs, then investigates the effectiveness of low-frequency double-differential EC probes in detecting hidden local CD detection for inspection carried out from the undamaged surface. It also considers correlations between the EC signal phase and depth of location of the hidden CD, as a potential method for the residual thickness estimation of the skin due to the local CD presence.

2. THE CURRENT STATE OF THE ART IN DETECTING HIDDEN CORROSION DAMAGE IN AIRCRAFT STRUCTURES

The influence of CDs on EC probe signals allows for corrosion damage in ASs to be categorized as either uniform or local. This categorization depends on the ratio of the damaged area's size to the EC probe's area of sensitivity, which determines the locality and the spatial resolution of the EC method [8]. When the corroded area (the area of corrosion-induced metal loss) is larger than the EC probe's sensitivity area, CD can be evaluated as the total corrosion using an EC probe of the absolute type [9]. In this case, CD can be interpreted as the thinning of a metal sheet and evaluated by EC sheet thickness measurements. In study [10], for example, aircraft joints of the stringer-skin type were inspected by low-frequency EC flaw detectors supplied with an absolute-type EC probe. This EC technique was efficient only for the detection of CD more than 1 mm deep, when the damaged area was larger than the diameter of the EC probe. Therefore, the sensitivity of this technique to local CDs was insufficient. Furthermore, absolute-type EC probes have the disadvantage of high sensitivity to interfering factors such as changes in electrical conductivity, thickness of the dielectric coating, and changes in coating or clearance between the tested multilayer sheets, etc. For simulating such CDs, researchers typically use metal sheets of different thicknesses, fabricated from the same structural material as the AS to be investigated (aluminum or titanium alloy).

Local CDs are usually simulated in the form of dead-ended flat-bottom drillings, and usually detected by EC probes of the differential type. These probes are insensitive to changes in thickness, reacting only to local defects like cracks, inclusions, pores, local CD, etc. [7]. The approach of applying hybrid EC probes has also been proposed, with absolute and differential EC probes being combined in a common design. This promising technique has been used to obtain information about uniform and local CD originating in copper ship pipes [11].

The problem is most complicated when CD is hidden, occurring on the inner sides (surfaces) of a multilayer AS and moreover under a layer of dielectric paint coating. Typical examples of double-layer ASs with uniform CDs situated on the bottom surface of the first layer (a) or the top surface of the second layer (b) and local CDs, like pitting, situated on the bottom surface of the first (top) layer (c) are presented in Figure 1. As is evident, even for a relatively simple two-layer AS, the conditions for CD detection are deteriorated due to the weakening of the useful EC probe signal because of the skin effect. The EC probe signal is also distorted by a change in the dielectric coating thickness between the metal layers. Research efforts have focused on reducing the influence of these factors. A general analysis of the influence of the thickness and the clearance between the layers on the signal of absolute-type EC probes in the complex plane was carried out in the study [12].

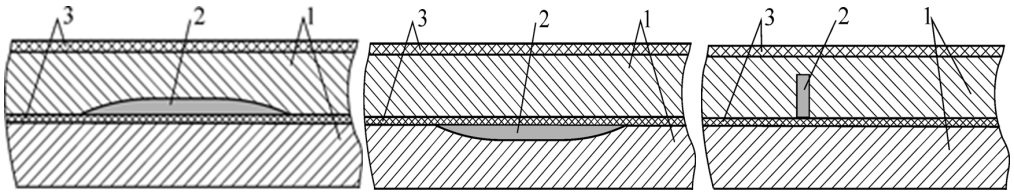


Fig. 1. Hard-to-inspect double-layer ASs with uniform CD situated on the bottom surface of the first (top) layer (a) or top surface of the second layer (b); and local CD (pitting) situated on the bottom surface of the first (top) layer (c): 1 – skin; 2 – CD; 3 – dielectric coatings or sealants.

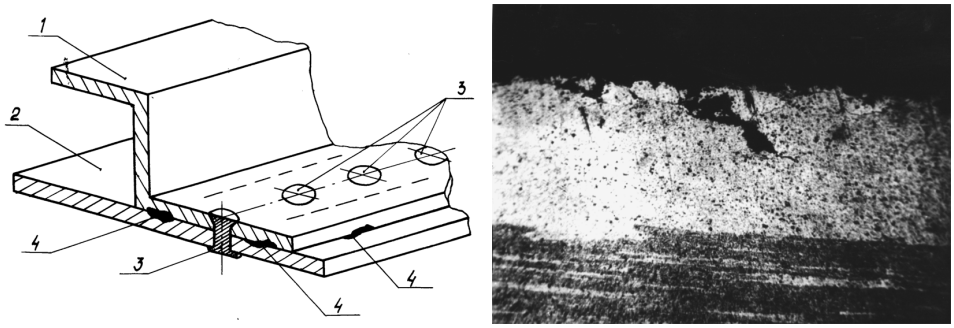
The reliability of various EC techniques for CD detection based on the single-frequency, double-frequency, and impulse excitation modes was analyzed in study [13]. The reliability of determining the thickness of the upper skin by the single-frequency EC technique was found to be low, since a 10% skin thinning can be detected with a probability of less than 90%. The reliability of the double-frequency EC technique, in which the operational frequencies are chosen to obtain sufficient sensitivity to the thickness of the first and second layers and to minimize the influence of the gap, was not much higher than that of the single-frequency one. The prospect of the pulse EC technique was also examined – this approach requires the use of scanners, which slows down the inspection procedure.

Impulse excitation mode and a robotic scanner were used in an EC inspection system of the TRECSCAN type, in which an EC probe was designed with a Hall sensor instead of sensing coils as in conventional EC probes [14, 15]. To isolate a useful signal created by CD against the background of the interfering factors, the EC probe output signal was analyzed over time. In another approach, using an EC probe of the absolute type, the selectivity concerned with CD detection was ensured by analyzing the EC signal in the complex plane [16]. The double-frequency EC technique has been presented as effective tool for detecting CDs in the second layer even with a variable air gap between layers [17]. The pulsed EC technique with giant magneto-resistive sensors in conjunction with proposed signal processing was also presented as a prospective approach to subsurface CDs detection in study [18]. In study [19], in turn, the characteristic features in obtained EC data sensitive to CD and fatigue cracks in ASs and invariant to other noise factors were proposed and investigated. The presented results demonstrate a novel feature for CD characterization using first and second order derivatives of the impedance response.

The above publications all report on EC techniques for determining the level of uniform CDs based on the application of EC probes of the absolute type. The use of a low-frequency EC probe of the double-differential type to detect real local CD situated on the internal surfaces of stringer-skin type joints was investigated for the first time in our previous study [20]. The specimens were selected at a repair plant from among extensively exploited ASs produced by Tupolev Aircraft. A typical

example of a selected specimen is shown in Figure 2a. The selected AS fragments with 1.5 mm thick skin and 3 mm thick stringer fabricated of D16AT aluminum alloy were evaluated at the operational frequency of 3.0 kHz. The depth and area of the detected CD were then determined by subsequent metallographic examination. Inspection was carried out both on the side of the skin and the side of the stringer without removing the coating. During the inspection, the EC probe was scanned along a dashed line (Fig. 2a) at a constant distance from the rivets. The depth of the minimal local CD detected on the bottom side of the stringer was 0.16 mm (5.2% of thickness) (Fig. 2b). The presented results demonstrated the high performance of low-frequency double-differential type EC probes to detect hidden CD originating on the bottom side of an inspected component.

The results so obtained were used to develop a step-by-step procedure for the underfloor part of fuselage inspection. The inspected AS was divided into 4 regions characterized by different probabilities of CD occurrence, estimated following selected statistical data. Initially, it was proposed to examine only the first region, which long-term in-service experience indicates is most often subject to CD. If no CD was detected in this region, EC inspection was not continued. If any CD was detected, the second region was inspected, and so on. This step-by-step procedure provides for improved inspection efficiency and productivity.



a b

Fig. 2. Evaluated stringer-skin type joints with local CDs, where 1 – stringer; 2 – cladding; 3 – rivets; 4 – local CD (a) and detected local CD (b)

At the same time, our previous study did not investigate the detectability of low-frequency double differential EC probes concerned hidden local CD detection for the inspection carried out from an undamaged surface, nor did it propose a method for the residual thickness estimation of the skin due to the local CD presence.

3. INVESTIGATION OF EDDY CURRENT SIGNALS CREATED BY SUBSURFACE LOCAL CORROSION DAMAGES IN MULTILAYER AIRCRAFT STRUCTURES

3.1 Investigated EC probes, specimens, and research methodology

In view of our review of the state of the art and our preliminary study, two low-frequency double differential EC probes – of the MDF 0601 and MDF 0801 type – were selected for the detection of hidden local CDs in ASs [21–23]. Each of these EC probes consists of two excitation coils and two sensing coils, which are arranged according to the double differentiation scheme [22]. The parameters of the probes are presented in Table 1, where D_{ECP} is the diameter of the EC probe, D_f is the diameter of the ferrite cores, W_e and W_s are the number of turns of the excitation and sensing coils, L_e and L_s are the inductances of the excitation and sensing coil, respectively.

Table 1. Parameters of investigated EC probes

EC probe type	D_{ECP}, mm	D_f, mm	W_e	W_s	L_e, μH	L_s, mH
MDF 0601	6.0	1.0	185	360	320	1.2
MDF 0801	8.0	1.85	215	416	940	3.7

Local CDs were simulated by flat-bottomed drillings 2.0, 3.0, and 5.0 mm in diameter, drilled to depths of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm, in a 3.97 mm thick plate made of D16 type aluminum alloy. The EC probe signals were recorded in the complex plane using an Eddycon C type flaw detector. Accordingly, hodographs of the EC probe signals created by subsurface CDs situated at different depths were recorded during the scanning of the specimen with local CD from the undamaged side (reverse to the drillings). This was done to study the signals created by local CD of different diameters and depths (and, accordingly, different residual thickness h_r of the specimen at the CD location) (see the local CD presented in Fig. 1c). Next, the signals for local CDs of different diameters and depths detected through undamaged skins of different thicknesses were investigated. Thus, cases where local CD spreads on the upper surface of the lower skin were simulated – in such cases, it is necessary to detect the damage through the upper, undamaged skin. The effectiveness of identifying various types of CD was determined by an expert assessment of the reliability of distinguishing the signal created by the CD against the background noise during the scanning.

3.2 Eddy current detectability of local subsurface CDs of different sizes and locations

In developing an EC inspection procedure, it is important to determine the ultimate capabilities of the selected EC probe, for which it is necessary to investigate the detectability of local CDs depending on their size and location. Results for the detectability of local CDs during inspection from the bottom undamaged side of the one-layer specimens depending on local CD diameter D_{lc} and residual thickness h_r are presented in Table 2. In this table, the symbols +, - and ± indicate, respectively, reliable detection of the corresponding artificial CD, no such detection, and controversial cases where the signal from the CD is insignificantly distinguishable at the noise level.

Table 2. Detectability of local CDs using MDF 0801 and MDF 0601 EC probes

EC probe type	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601
h_r, mm / D_{lc}, mm	0.5		1.0		1.5		2.0		2.5		3.0	
2.0	+	+	+	+	+	+	+	-	+	-	-	-
3.0	+	+	+	+	+	+	+	-	+	-	-	-
5.0	+	+	+	+	+	+	+	±	+	-	±	-

The results presented in Table 2 show the ability to reliably detect all local CDs situated on the bottom surface of the specimen when the testing was carried out from the undamaged side of the aluminum alloy specimen, at a depth (or residual thickness) h_r of 2.0 mm and 2.5 mm using EC probes of MDF 0601 and MDF 0801 types, respectively. This corresponds to 67% and 59% of the tested specimen's thickness (3.97 mm), respectively. The findings confirm the potential for the practical application of selected EC probes for the detection of hidden CDs on the bottom surface of the AS skin.

The detectability of local CDs of different depths T_{lc} (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 mm) and diameters D_{lc} (2.0, 3.0 and 5.0 mm) situated in the second layer of a two-layer specimen during inspection through the 1.6 mm, 2.2 mm and 2.8 mm thick upper skin are presented, respectively, in Tables 3–5. Importantly, in this case all local CDs were situated on the top surface of the second layer of skin.

Table 3 shows the results for the 1.6 mm thick upper skin. As is evident, both EC probes can detect all local CDs in the second layer when the thickness of the upper skin is less than 1.6 mm.

Table 3. Detectability of local CD situated in the second layer during inspection through the upper 1.6 mm thick skin using MDF 0801 and MDF 0601 type EC probes

EC probe type	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601
T_{lc}, mm / D_{lc}, mm	3.0		2.5		2.0		1.5		1.0		0.5	
2.0	+	+	+	+	+	+	+	+	+	+	+	+
3.0	+	+	+	+	+	+	+	+	+	+	+	+
5.0	+	+	+	+	+	+	+	+	+	+	+	+

The results for the 2.2 and 2.8 mm thick upper skins are presented in Tables 4 and 5, respectively. As is evident, in these cases, the detectability depends significantly on the diameter D_{lc} and the depth T_{lc} of the local CDs.

Table 4. Detectability of local CD situated in the second layer during inspection through the upper 2.2 mm thick skin using MDF 0801 and MDF 0601 type EC probes

EC probe type	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601
T_{lc}, mm / D_{lc}, mm	3.0		2.5		2.0		1.5		1.0		0.5	
2.0	+	±	+	±	+	±	+	±	+	–	+	–
3.0	+	+	+	+	+	+	+	+	+	±	+	–
5.0	+	+	+	+	+	+	+	+	+	±	+	–

Table 5. Detectability of local CD situated in the second layer during inspection through the upper 2.8 mm thick skin using MDF 0801 and MDF 0601 type EC probes

EC probe type	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601	MDF 0801	MDF 0601
T_{lc}, mm / D_{lc}, mm	3.0		2.5		2.0		1.5		1.0		0.5	
2.0	+	–	+	–	+	–	+	–	+	–	–	–
3.0	+	±	+	–	+	–	+	–	+	–	±	–
5.0	+	+	+	±	+	±	+	±	+	–	±	–

The results presented in Tables 4 and 5 show that for the detection of local CDs in the second layer, the MDF 0801 type probe is more promising. This EC probe can reliably detect all the investigated CDs through a 2.2 mm thick skin. Moreover, even through the 2.8 thick skin, it is possible to detect all CDs deeper than 1.0 mm. The MDF 0601 type probe is applicable only for upper skin thickness of less than 1.6 mm.

Overall, the findings show that the investigated EC probes can indeed detect local CDs in the second layer of two-layer ASs.

3.3 Correlations between the EC signal characteristics and depth of local CD location

In the practice of AS maintenance, it is very important not only to detect CD during long-term exploitation. To estimate the technical condition of long-service (aging) ASs, it is also very important to evaluate the residual thickness of the skin at the location of the local CD. In this section of the study, a one-layer specimen with artificial local CD was scanned from the undamaged side and the resulting EC signals were investigated, to evaluate the possibility of estimating the skin residual thickness at the location of the local CD by the parameters of the corresponding EC probe signals in the complex plane. Note that the detectability for this inspection situation for both EC probes is presented in Table 2.

The signals of MDF 0801 type EC probe were investigated in the complex plane of the EC flaw detector display at the operational frequency of 2.5 kHz. The obtained signals (Figure 3) were created by local CDs with a diameter of 2.0 mm during the inspection performed from the reverse (undamaged) side of the skin from a through defect (h_r = 0) (a) and CDs with h_r = 0.5 mm (b); h_r = 1.0 mm (c); h_r = 1.5 mm (d); h_r = 2.0 mm (e), and h_r = 2.5 mm (f). The sensitivities of the flaw detector in Figure 2b, Figure 2c, Figure 2d, Figure 2e, and Figure 2f were increased compared to the signal from the surface (through) CD (Figure 2a) by 3, 6, 16, 18, 20, and 26 dB, respectively.

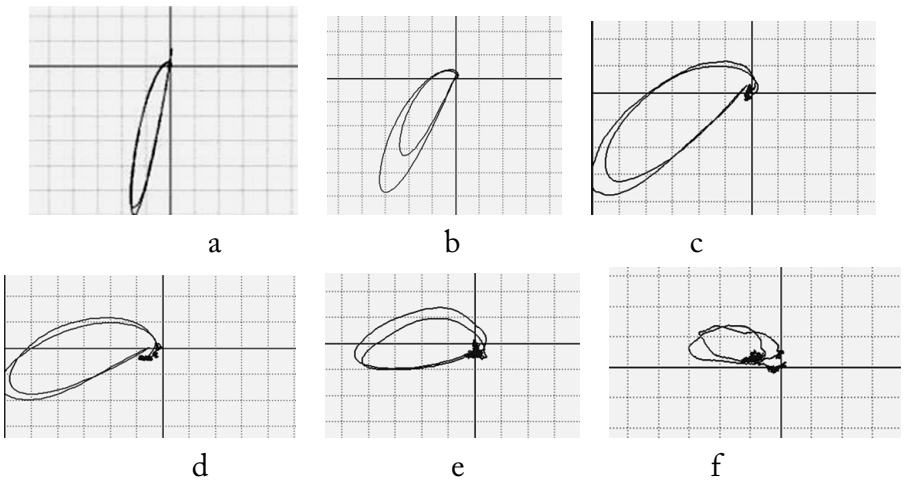


Fig. 3. EC signal in the complex plane (hodographs) created by 2.0 mm diameter local CD for surface location (a), and created by subsurface 2.0 mm diameter local CDs with residual thicknesses 0.5 mm (b); 1.0 mm (c); 1.5 mm (d); 2.0 mm (e); and 2.5 mm (f)

The corresponding changes in the amplitude U estimated in scale intervals (SI) and phase angle φ of the EC probe signals (estimated by obtained hodograph rotational angle) on the residual thickness h_r of the skin at the location of the local CP for both investigated EC probes (MDF 0601 and MDF 0801) are shown in Figure 4.

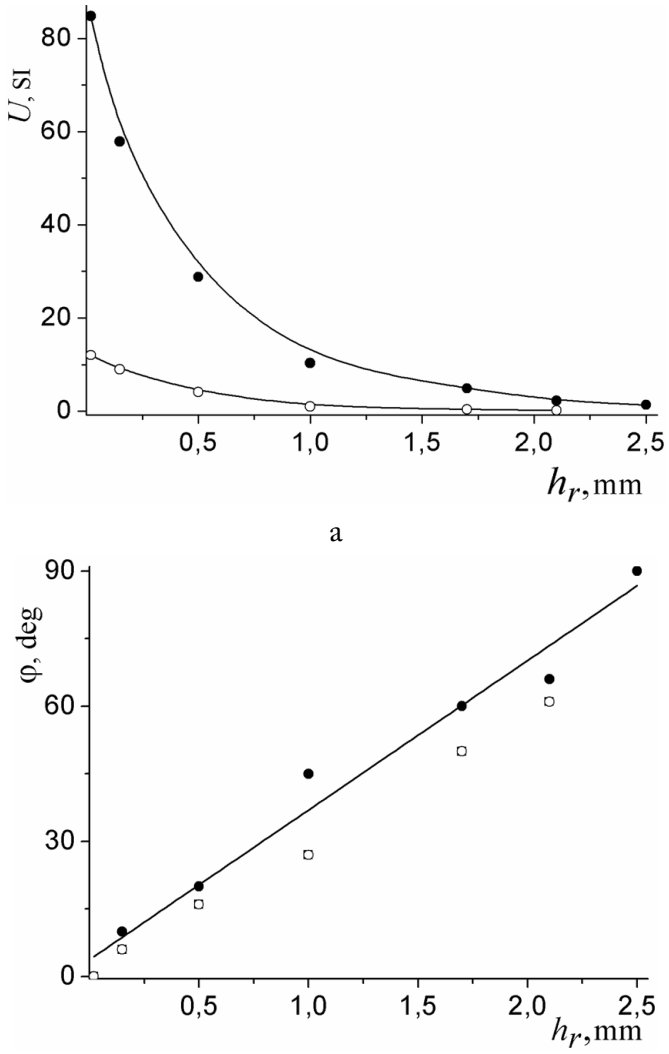


Fig. 4. Dependences of EC signal amplitude U (a) and phase angle φ (b) created by local CD on the residual thickness h_r for EC probes of MDF 0601 (●) and MDF 0801 (○) types

The presented correlations (Figure 3 and Figure 4) between the EC signal characteristics (amplitude and phase) and residual thicknesses h_r related to the depth of location of the subsurface local CDs reveal the significant dependence of

both parameters on the residual thicknesses h_r of the skin at the CD location. The signal amplitude changes most significantly (by 2 orders of magnitude). However, the amplitude is known to depend also on the diameter D of the local CD at the same time, which precludes the amplitude from being applied in the estimation of residual thicknesses h_r [11]. It is more effective to estimate the residual thicknesses h_r by the phase φ characteristic of the EC signal (Figure 4b). As is evident in Figure 4b, the phase angle φ dependence of the EC signal on the residual thicknesses h_r has similar linear characters for both EC probes. This allows us to state that the nature of this dependence is determined mainly by the operational frequency rather than by the EC probe applied.

It has previously been shown [11] that the phase angle of the EC signal correlates with the depths of the local CD location independently of the CD diameters. In other words, the EC signal phase is an invariant measure of the local CD depth of location under CD diameter changes. As such, it is possible to estimate the residual thickness of skin in the area of local CDs (such as corrosion pits or pitting) location by measuring the EC signal phase independently of the local CD diameter (size). This quantitative information is useful for evaluating the condition of the AS, as needed for projecting the remaining accident-free service life of ASs with local CD based on known data and the rate of local CD propagation in in-service conditions [24–25]. Such data can be obtained from statistical data concerned with CD distribution in aging AS or from investigations related to the estimation of the rate of CD distribution in AS material in simulated in-service conditions [26–27].

4.CONCLUSIONS

EC techniques are widely being discussed as highly effective for non-contact detection and measurement of hidden CDs in AS without the need for disassembly. This study investigates and analyzes the advantages and limitations of double-differential EC probes in detecting CDs with different sizes and depths. The findings underscore the potential of the EC method for detecting hidden CDs in double-layer ASs.

Investigations into the relationship between EC signal characteristics (amplitude and phase) and depth of location (or residual thickness) of the subsurface local CDs revealed that the phase angle of the EC signal correlated with the depth of local CD, independently of CD diameter. In other words, the EC signal phase is a measure of local CD depth that is invariant of CD diameter changes. This means it is possible to estimate the residual thickness of the skin in the area of local CD (such as pits or pitting) by measuring the EC signal phase independently of the local CD diameter (size).

These findings pave the way for developing an innovative quantitative approach for the detection and sizing of subsurface local CDs arising in ASs during long-term service life. The demonstrated high detectability of the EC inspection

technique offers useful and critical quantitative information for evaluating AS condition and forecasting its remaining service life. Moreover, quantitative information about CD depth can be used to more precisely define suitable inspection intervals.

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