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EDDY CURRENT TECHNIQUES FOR DETECTING HIDDEN SUBSURFACE DEFECTS IN MULTILAYER AIRCRAFT STRUCTURES

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Abstract

In-service non-destructive inspection (NDI) is a very important part of the aircraft maintenance program that minimizes aircraft breakdowns due to the fracture of critical components. The eddy current (EC) NDI method is one of the most applicable methods for this purpose, due to its high sensitivity to fatigue cracks and corrosion damage in the main structural materials. In this paper, selective double differential type EC probes characterized by the enhanced possibility of detecting subsurface cracks initiated by fatigue or stress corrosion phenomena are presented. For different applications, a family of double differential type EC probes was developed with different sizes (from 5 to 33 mm) and different spatial resolutions. These types of probes are characterized by different operational frequencies in a wide frequency range (from 0.2 kHz to 1.0 MHz), high penetration depth and unique sensitivity to subsurface defects of different types (like elongated fatigue cracks or local corrosive pitting), and a high level of specific noise suppression concerned with the scanning inspection procedures. The EC probes proposed were investigated as effective tools for characteristic aircraft applications concerned with subsurface defect detection in multilayer structures, such as the detection of cracks in the second layer of a riveted two-layer structure or cracks initiated on the side surface of a multilayer structure with the suppression of the reinforcing hoop influence; the detection of subsurface defects in arc welding with a rough surface; the detection of cracks through repair patches fabricated from aluminum alloy or carbon fiber reinforced plastic, etc. These techniques create remarkable possibilities for the well-timed detection of dangerous damage without disassembling the aircraft structure or removing protective coating.

Keywords: aircraft structure, subsurface defect, eddy current, fatigue crack, corrosion, operational frequency, repair patch.
Type of the work: research article

1. INTRODUCTION

Fatigue fracture and corrosive damage to fuselage and wing structures have been one of the factors in aircraft accidents worldwide [1]. To minimize aircraft breakdowns due to the fracture of critical components, in-service non-destructive inspections (NDI) based on different physical phenomena were implemented as an important part of aircraft maintenance programs [2–5].

Since the 1950s, the eddy current (EC) NDI method has been widely applied for in-service evaluation of aircraft structures with the goal of detecting dangerous defects of different types, such as cracks, pores,

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or corrosive pitting [5-10]. At the beginning of development, the EC method was preferentially applied for surface defect detection because of the high operational frequencies used in the first EC flaw detectors and the tendency of a high-frequency alternating current to flow through the outer layer of a conductive material only (the so-called skin-effect). Subsequently, low operational frequencies were considered to be the best choice for hidden subsurface defect detection. Nondestructive EC inspections can be realized without direct contact with the tested object (TO) with high productivity. Therefore, the EC method can detect defects even through the protective anticorrosive coating without removing them before inspection. The TO surface contamination of different types and moisture do not affect the signal of the EC probe, and special procedures for TO surface preparation or cleaning are not needed. For a long time, the high-frequency EC method was mainly applied as one of the most sensitive NDI methods used for shallow surface crack detection in metallic components of aircraft structures through a dielectric coating up to 0.5 mm thick. Recent investigations and developments related to surface crack detection were analyzed in [9]. Different specific EC techniques for detecting cracks in the vicinity of aircraft rivets are analyzed in [10]. It has been recognized before that the EC method based on using a low operational frequency can successfully be applied in the detection of subsurface defects of different origins, such as fatigue cracks or corrosion pitting in internal layers of multilayer aircraft structures (for example, skin-stringer or lap joints of the fuselage or wings) [10–15]. To this day, low-frequency EC techniques cannot be considered routine procedures for aircraft applications, and any aircraft inspection problems concerned with internal defect detection are analyzed individually. To optimize the inspection procedure, the operational frequency must be selected by taking into account the depth of the location h_l for the defects to be detected, the electro-physical characteristics (electrical conductivity for the nonmagnetic alloy) of the tested material, and the thickness of the protective coating.

In this paper, different aspects related to the detection of subsurface defects in aircraft multilayer structures are analyzed. Some significant applications based on low-frequency EC probes of double differential type are presented.

2. SELECTIVE HIGH PENETRATION EDDY CURRENT PROBES FOR SUBSURFACE DEFECT DETECTION

2.1. General considerations on the penetration of eddy currents in the material tested

Let us analyze the most significant factors that influence the penetration of eddy currents. Different definitions of penetration depth inside the tested material (along the Z coordinate) are presented in Fig. 1a, where the eddy current amplitude J_z at depth z was normalized to the eddy current amplitude on the tested surface J_0. The standard penetration depth δ based on the assumption of the plane electromagnetic wave distribution can be presented by the following formula [16]:

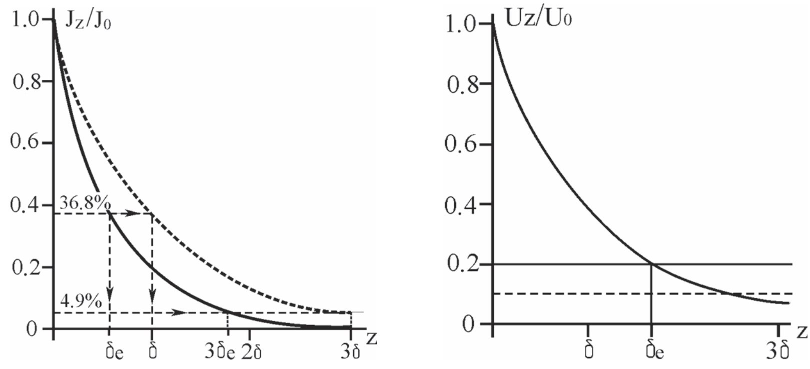
$$\delta = \sqrt{2/\omega\sigma\mu\mu_0},$$

where: $\omega = 2\pi f$ – circular frequency; f – operational frequency; $\mu_0 = 4\pi 10^{-7}$ H/m – permeability of vacuum; μ and σ – relative permeability and electric conductivity of the inspected material, respectively. Therefore, standard penetration depth depends on the electro-physical parameters of the inspected material (such as permeability and electric conductivity) and on the operating frequency. From the equation for the standard penetration depth, it can be seen that the EC penetration increases with lowering frequency. So, low frequencies seem to be best suited for hidden defect detection. The standard penetration depth δ is defined as the depth where the EC density has decreased to 1/e (36.8%) of the surface density. At a depth of 3δ, the EC density decreases to about 4.9% of the surface density (solid line in Fig. 1a). This quantity of EC is sufficiently large to detect a subsurface defect located at a depth of 3δ. So, this depth was defined as the real depth of penetration for the EC method.

In reality, EC probes are sufficiently far from producing a plane electromagnetic field. The decrease in EC density was analyzed analytically [17] with the model developed for a circular air-core EC probe [18]. It was shown that the decrease in eddy current density strongly depends on the EC probe diameter R. When using EC probes with small coil diameters ($R/\delta \approx 1$), the density decreases and the penetration depth is significantly lower when compared to the plane wave (dashed line in Fig. 1a). Only with a significant increase of a coil diameter up to $R/\delta > 10$ did the depth of penetration become similar to δ for a plane electromagnetic wave. But it should be remembered that such EC probes with increased coil diameter can be characterized by low spatial resolution and are unsuitable for a majority of inspection applications.

Both the abovementioned values are theoretical values and do not characterize the achievable inspection depth. To analyze the depth of inspection in real conditions, the effective penetration depth was defined as the depth from which EC signals can be obtained with an appropriate signal-to-noise ratio [15]. It is obvious that this depth cannot be calculated in general but depends on the material and type of defect to be detected, the EC probe type, the EC flaw detector characteristics, and the interfering influences of different types like lift-off, structural inhomogeneity, roughness of the inspected surface, electronic noise, etc. The effective penetration depth for an ultimate signal-to-noise ratio of 6 dB is shown in Fig. 1b. Usually, the effective depth of penetration is much greater than the calculated standard penetration depth.

Very important conclusions related to the EC penetration were drawn from research in which the distribution of eddy currents at different distances from the drive coil winding was investigated. It was shown that the attenuation of eddy currents directly under the coil winding is much more intensive than the attenuation at a distance, and the attenuation at a distance is similar to the attenuation of a plane electromagnetic wave. These results explain the advantages of EC probes in which the sensing (receive) and the drive (transmit) coils are spaced apart. Eddy current probes with spaced coils were named transmit-receive or anaxial EC probes and investigated in detail in a few publications [19–21]. In these studies, the specific useful peculiarities of these probes, such as high penetration and noise tolerance, were shown. In the present paper, these features of anaxial type EC probes are mentioned because they were applied as elements for double differential type EC probe development.

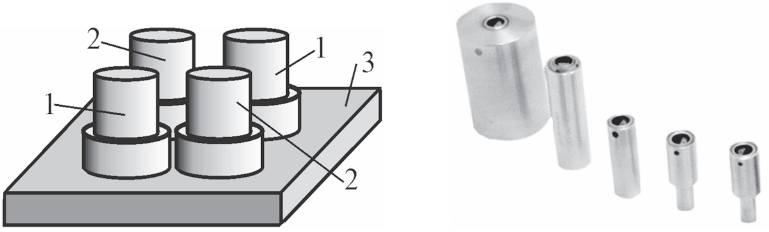


(a) (b)

Figure 1. Definition of standard and effective depth of EC penetration based on the plane wave model and the model of a thin-walled EC probe (a) and based on the signal-to-noise ratio (b).

2.2. EC probes of the double differential type

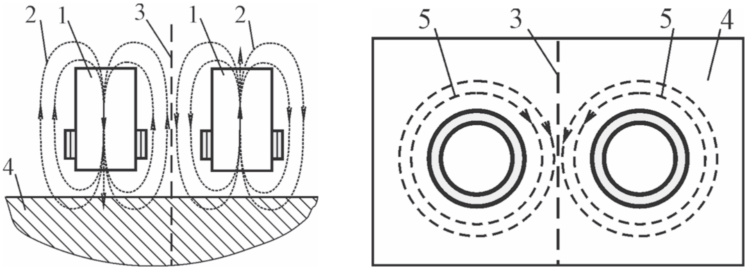
EC probes of the double differential type were developed in the Karpenko Physico-Mechanical Institute of the NAS of Ukraine several decades ago [14, 15]. These probes are composed of two drive coils 1 and two sensing coils 2 mounted on the ferrite core and situated in the tetragon corners (Fig. 2a). Two drive coils 1 are connected in series with each other and oriented to create identical and opposite primary electromagnetic fields. These probes are mounted inside an aluminum alloy case to minimize electronic noise and supplied by a connector of different types for operation with different flaw detectors (Fig. 2b).



(a) (b)

Figure 2. Design of double differential EC probe: 1 – ferrite core drive coils, 2 – ferrite core sensing coils, 3 – the tested object (a) and developed EC probes of different sizes (b).

Due to this design, double differential EC probes have remarkable peculiar properties in the distribution of primary electromagnetic field and secondary field created by the eddy currents induced in the TO, such as the existence of the characteristic neutral plane, in which the vertical component of the summarized electromagnetic field is equal to zero (see Fig. 3a). Sensing coils are oriented to be sensitive to the vertical component of the electromagnetic field and are installed in a neutral plane, where this component for isotropic media is equal to zero but the eddy currents created by the drive coils are summarized as shown in Fig 3b. Due to the opposite connection of sensing coils 2, the double differential type of signal response is realized.



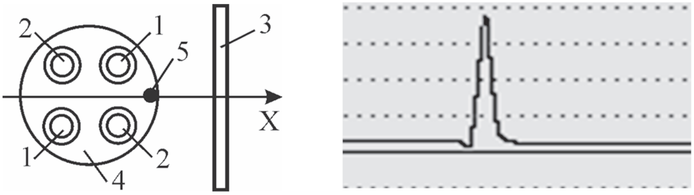
(a) (b)

Figure 3. The primary electromagnetic field created by drive coils (a) and eddy currents (b): 1 – ferrite core; 2 – the primary electromagnetic field; 3 – neutral plane; 4 – tested object, 5 – eddy currents.

Due to the design of these double differential EC probes, high penetration inside the material was achieved. As was mentioned above, the attenuation of ECs can be reduced either by choosing a large diameter for the coaxial type EC probe or by using the small diameter sensing and drive coils situated with some distance from each other (Fig. 2). Due to the small coil diameter, the high spatial resolution required for local defect detection was also obtained.

The main features of such probes can be characterized by high sensitivity to elongated (like cracks) and to local (like short cracks, pitting, or pore) defects; high sensitivity to surface and subsurface defects through a dielectric protective coating or with large clearance between the probe and the surface inspected; high penetration for low-frequency probes; high lift-off suppression and low noise. Today, a set of double differential EC probes of diameters from 4 to 33 mm characterized by coil size, range of operational frequencies, and spatial resolution has been developed (Fig. 2b). Coil diameter and the number of turns relating to spatial resolution and depth of EC penetration were optimized for a specific application. The design of the EC coils mounted on ferrite cores was optimized by a special methodology based on the invariant EC efficiency parameter calculation [24]. Double differential EC probes are adapted to modern universal flaw detectors and provide inspection at different operating frequencies in the range of 50 Hz to 6 MHz. Due to such features, the probes were successfully applied in new NDE techniques developed in aircraft, railway transport, power engineering, chemical industry, etc. [10, 14, 15, 23].

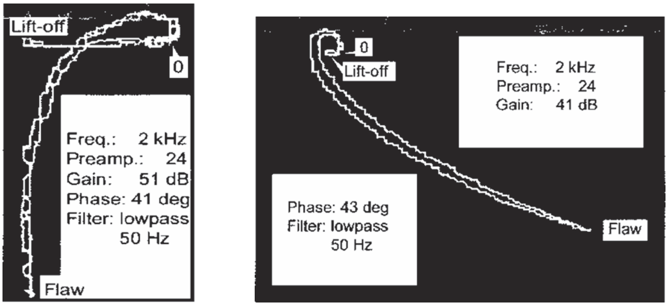
EC probes of double differential type are characterized by different detectability concerned with the crack direction. The optimal probe orientation to crack direction is shown in Fig. 4a. Special marks on the probe case help to select the orientation of maximum sensitivity. During the scanning over the crack, these probes have a quasi-absolute signal response with maximum amplitude for the probe situated directly over the detected crack (Fig. 4b) similar to any conventional EC probe of absolute type.



(a) (b)

Figure 4. Optimal orientation of the double differential probe to crack direction (a): 1 and 2 – drive and sensing coils respectively, 3 – crack, 4 – case, 5 – special mark; and a real quasi-absolute signal response (b).

Real signals from an MDF 1201 type EC probe created by a subsurface defect in the impedance complex plane of the ELOTEST B1 type flaw detector (Rohmann GmbH, Frankenthal, Germany) are presented in Fig. 5. A low operating frequency of 2 kHz was used to detect crack-type subsurface defects lying at depths of 1.0 and 3.0 mm. The sensitivity of the EC flaw detector for the defect located at a depth of $h_l = 3.0$ mm was 10 dB higher than for the defect located at a depth of $h_l = 1.0$ mm. Here, the depth of defect location h_l indicates the distance between the top edge of the subsurface defect and inspected surface. The signals for EC probe lift-off as the main noisemaker are also presented for comparison. In this case, the lift-off signals are oriented horizontally by the complex plane rotating according to the standard inspection procedure.



Freq.: 2 kHz
Preamp.: 24
Gain: 51 dB
Phase: 41 deg
Filter: lowpass 50 Hz

Freq.: 2 kHz
Preamp.: 24
Gain: 41 dB
Phase: 43 deg
Filter: lowpass 50 Hz

(a) (b)

Figure 5. EC probe signal responses for subsurface cracks with different residual depth h_l of location and lift-off signals: $h_l = 1$ mm (a); $h_l = 3$ mm (b).

These results (Fig. 5) show high enough sensitivity to subsurface defects with a high degree of lift-off effect suppression. Even for a defect that lies at a depth of 3.0 mm, the ratio of the amplitude of the signal from the defect to the amplitude of the lift-off signal exceeds 6 dB. In addition, the signals differ in phase (the direction of the signals in the impedance complex plane), which provides additional opportunities for the separation of the useful signals created by defects and lift-off noise.

For local defects like pore or corrosion pitting, double differential EC probes create a specific spatial four-point signal distribution with two positive and two negative peaks as presented in Fig. 6 [14].

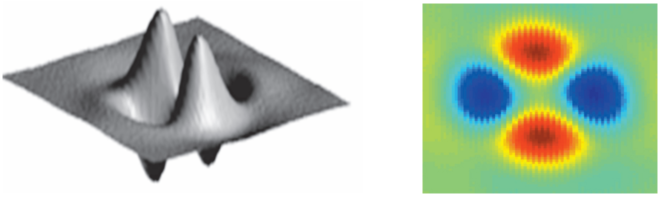


Figure 6. The four-point spatial signal distributions with two positive and two negative peaks for local defects.

3. DOUBLE DIFFERENTIAL PROBES AS AN EFFECTIVE TOOL FOR SUBSURFACE DEFECT DETECTION IN MULTILAYER STRUCTURES

The high sensitivity of double differential EC probes to internal defects, including defects under the skin, allows a number of practical problems with multilayer aircraft structure inspection to be solved.

3.1. Detection of fatigue cracks in the second layer of a riveted two-layer aircraft structure

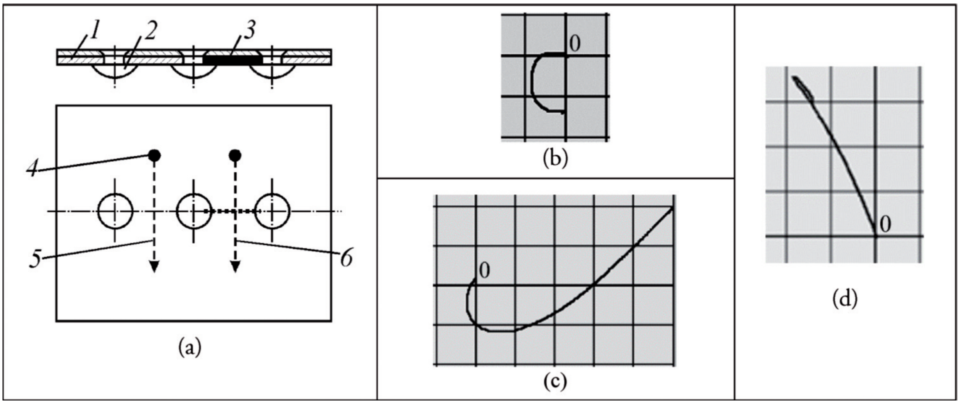


Figure 7. Reference standard for two-layer riveted structure simulation: 1 – two-layer structure; 2 – rivets; 3 – crack; 4 – balance point; 5 and 6 – scan trajectories in defect-free and defect zones, respectively (a), and EC probe signals in the impedance complex plane created by the influence of the defect-free rivets for symmetrical (b) and offset (c) scan trajectories, and signal from a crack in the second layer (d).

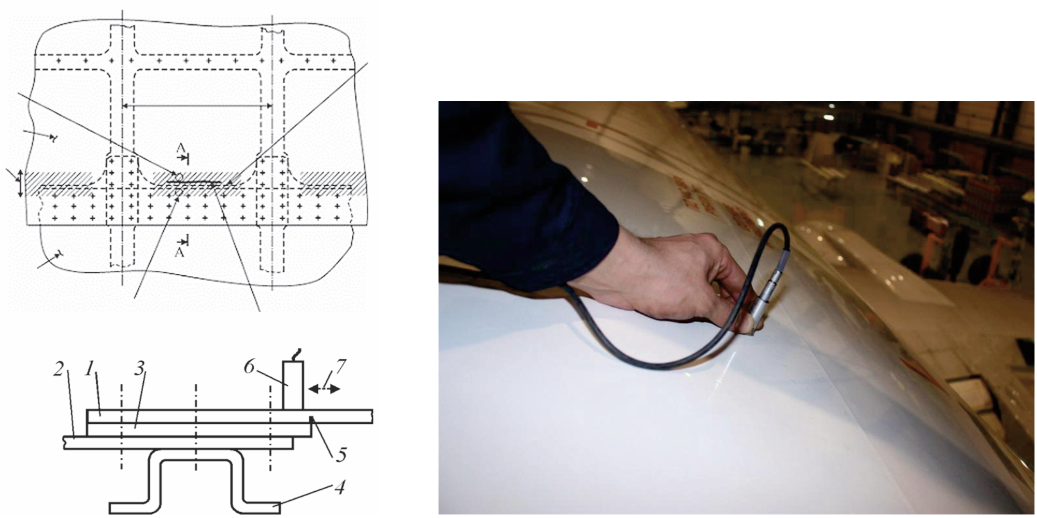
As a typical example, let us consider the detection of fatigue cracks initiated during service life between rivets in the second layer of a two-layer stringer-skin joint. Such joints are typical of the majority of aircraft structures. In the specimen investigated, it was necessary to detect cracks between rivets through the top 1.4 mm thick skin. There was only an 8 mm distance between the edges of the countersunk head rivets. Therefore, some signal disturbances related to the influence of the rivet were observed.

The reference standard for flaw detector adjustment is presented in Fig. 7. There are two scan trajectories used: trajectory 5 corresponds to about defect-free structure, and trajectory 6 simulates a scan through a crack situated in the second layer.

So, the main problem for EC inspection of such structures is the high interference concerned with the rivet`s influence. Therefore, the inspection technique has to separate the signals from the defect in the second layer from the interference signal created by the rivets. Selective interpretation of signals can be provided by analyzing their features in the complex plane on the flaw detector screen. The technique developed involves the use of a 6 mm diameter double differential EC probe by scanning the area between the rivets perpendicular to the direction of the rivet row (dashed lines in Fig. 7a). Before the inspection, it is necessary to compensate the unbalanced signal when installing the EC probe at the balance point 4, which is located at a distance of 10… 12 mm from the line connecting the rivets 2. The proposed technique was investigated using an EDDYMAX type EC board with an operational frequency of 6 kHz during scanning of the area between the rivets symmetrically at an equal distance to the rivets (Fig. 7b) and closer to one of the rivets (Fig. 7b) for defect-free trajectory 5, as well as for the crack presence during the scanning along with the trajectory 6 (Fig. 7d).

From the results obtained it can be observed that the EC probe signals from defect-free rivets (Fig. 5b and 5c) move from the balance point (0) in the direction of the lower part of the complex plane. And vice versa, the signal from the defect has a different upward direction in the second quadrant of the complex plane (Fig. 7d). These results indicate the remarkable possibility of full separation of useful signals created by the defect and false signals created by the rivets, even when scanning of the inspection area was realized along the offset scan trajectory.

3.2. Detection of the fatigue crack initiated on the side surface of a multilayer aircraft structure in the zone of the reinforcing hoop end



(a) (b)

Figure 8. The multilayer aircraft structure (Boeing 737) with the reinforcing hoop: 1, 2 – skins; 3 – reinforcing hoop; 4 – stringer; 5 – crack; 6 – EC probe; 7 – scan trajectory (a); and an EC inspection realized by a double differential EC probe (b).

Another typical example concerns the problem of internal fatigue crack detection in the fuselage skin of Boeing 737 aircraft at the lap joints reinforced by the hoop. The 0.9 mm thick reinforcing hoop 3 is located between 0.9 mm thick aluminum alloy skins 1 and 2 (Fig. 8a). The method is intended to detect 0.45 mm deep fatigue cracks (50% of the skin thickness) initiated from the side surface of the upper sheet 1 along the edge of the reinforcing hoop 3 with access only from the outside of the fuselage (Fig. 8b). An additional inspection problem was concerned with the separation of the signals related to the cracks situated on the side surface of the upper skin from the false signals due to the hoop edge influence.

The proposed inspection technique is based on the MDF 1201 type EC probe at an operating frequency of 26 kHz. The EC signal selection was realized by applying the impedance complex plane (Fig. 9). In this case, by rotating the complex plane, the signal from the hoop edge was oriented in the horizontal direction. With the same vertical *Y* and horizontal *X* gain ($K_Y = K_X$), it is difficult to separate signals from defects and hoop edges (Fig. 9a), because the difference between their signals in the direction is not high enough. The signal selection can be improved by a 12 dB increase ($K_Y = 4K_X$) of the gain along the vertical *Y*-axis compared to the gain along the horizontal axis as seen in Fig. 9b.

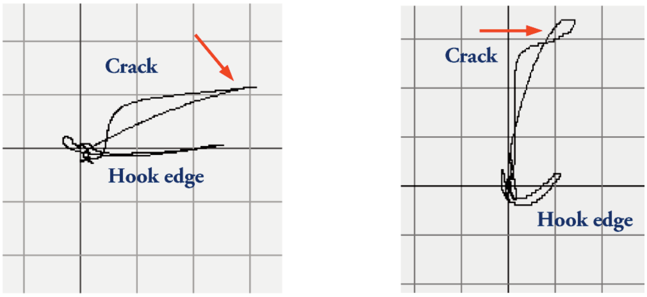


Figure 9. Selective interpretation of EC probe signals obtained from the crack and the reinforcing hoop edge: $K_Y = K_X$ (a); $K_Y > K_X$ (b).

This technique was implemented into the inspection practice for in-service maintenance of the Boeing 737 aircraft operated by "Ukraine International Airlines" (Fig. 8b).

3.3. Detection of subsurface defects in arc welding with a rough surface

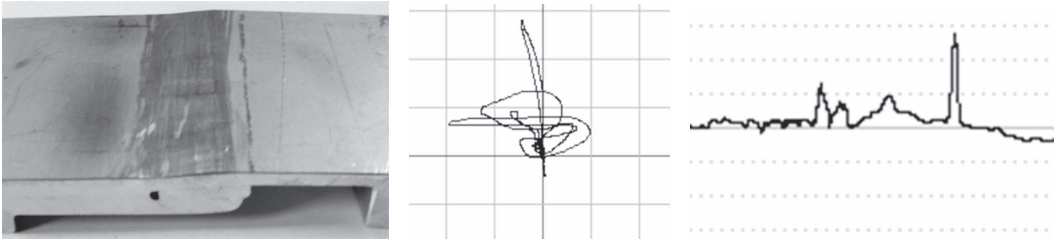
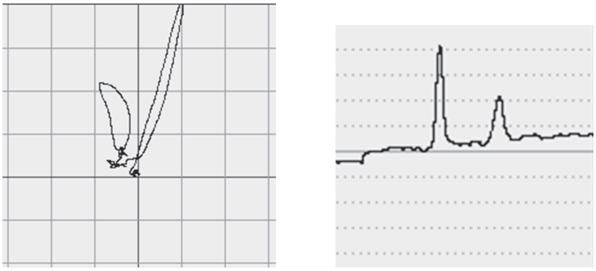


Figure 10. Arc welded specimen with a rough surface and welded plates displacement (a) and EC signals created by subsurface lack of fusion (h_l = 3 mm) and noise in the impedance complex plane (b) and in time base mode (c).

The next study concerns the inspection of the fuel tank welding of airspace structures, which due to two-side access absence cannot be tested by X-ray. It was necessary to detect the subsurface defects (pores, lack of fusion, cracks, etc.) at a depth of 2…3 mm. To investigate the subsurface defect detectability in real conditions, a special welded specimen with a very rough surface after removing the weld face reinforcement and displacing the welded plates (deplanation) in which the lack of fusion was created at a depth of location h_l = 3 mm (Fig. 10b). Signals for the double differential of MDF 0801 type (8 mm in diameter) were analyzed by the EDDYMAX type EC board produced by Test Maschinen Technik Gmbh (Schwarmstedt, Germany). The amplitude of the EC signal from the defect with a depth of location h_l = 3 mm was higher than the level of the noise created by the surface roughness and of the geometry of the weld as shown in Fig. 10b and Fig. 10c. So, the vertical component of the signal from the subsurface defect is approximately 6 dB higher than the noise. This signal-to-noise ratio is considered sufficient for reliable defect detection. These results also indicate the possibility of separating the useful signals from the subsurface defect with a depth of location h_l = 3 mm from noise by looking at the phase difference of these signals.

3.4. Detection of fatigue cracks through bonded repair patches

The repair patches bonded on damaged aircraft structures are widely applied as a cost-effective method of increasing service life [24–27]. Different repair techniques for reinforcing damaged structures suggest using different materials such as aluminum alloy or carbon fiber reinforced plastic (CFRP), etc. Advantageously, the repaired structures are the subject of additional NDI needed for detection of fatigue cracks that may originate in the structure. The double differential EC probes developed were successfully used for the detection of cracks through the aluminum alloy patch bonded on the damaged wing of a Tu-154 aircraft [5]. After the damage removal, the rounded indentation was formed to reduce the stress level. The crack was expected to have originated on the bottom of the indention due to skin weakening. The EC technique based on double differential EC probes enables the detection of cracks in the wing skin through the 2 mm thick aluminum alloy patch without disassembling.



(a) (b)

Figure 11. EC signals created by 0.5 mm and 1.0 mm deep cracks detected through a 4.5 mm thick CFRP patch in the impedance complex plane (a) and in time-base mode (b).

Currently, CFRP composite materials are replacing the high-strength aluminum alloys in many aircraft applications [24, 27]. The repair techniques are very often based on CFRP patches bonded on the damaged aluminum alloy component. The aluminum alloy specimen with two 0.5 mm and 1.0 mm deep slots covered by a 4.5 mm thick CFRP sheet was used to investigate the sensitivity of the double differential EC probe of the MDF 1201 type. No conventional EC probes have good enough sensitivity to these defects tested through the CFRP patch. The signals created by the slots at an operational frequency of 30 kHz were analyzed by the EDDYMAX type EC board in impedance complex plane and in time base mode (Fig. 11).

The results presented in Fig. 11 show the high level of EC signals created by cracks as small as 0.5 mm deep detected through the 4.5 mm thick CFRP patch. The sizing of defects detected is also possible because the amplitude of the EC signal correlates with the crack depth.

4. CONCLUSIONS

In-service non-destructive evaluation (NDE) is a very important area in aircraft maintenance in order to minimize aircraft breakdowns concerned with fracturing of critical components. The eddy current NDE method based on using low operational frequencies is one of the most applicable for the detection of hidden subsurface defects originating during in-service life in multilayer aircraft structures.

Low-frequency double differential type EC probes characterized by the enhanced possibility to detect subsurface cracks were presented. The family of double differential type EC probes of different sizes (from 5 to 33 mm) and different spatial resolutions were developed for different applications. These probes are characterized by different operational frequencies in a wide frequency range (from 0.2 kHz to 1.0 MHz), high penetration depth, and unique sensitivity to subsurface defects of different types.

These double differential EC probes were investigated as effective tools for characteristic aircraft applications concerned with subsurface defect detection in the multilayer structures, such as:

1) the detection of fatigue cracks in the second layer of a riveted two-layer structure,
2) the detection of fatigue cracks initiated on the side surface of a multilayer structure with the reinforcing hoop influence suppressed,
3) the detection of subsurface defects in arc welding with a rough surface,
4) the detection of cracks through repair patches fabricated from aluminum alloy or carbon fiber reinforced plastic composite.

The techniques developed create remarkable opportunities for well-timed detection of dangerous damage without disassembling the aircraft or removing protective coatings.

The EC probes and inspection techniques presented based on the EC flaw detectors produced by industry-leading companies (Rohmann GmbH, Olympus, Promprylad, etc.) were implemented for the detection of subsurface defects on different aircraft companies in Ukraine and abroad.

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