DOI: https://doi.org/10.37434/tpwj2023.02.07

SURFACE EDDY CURRENT PROBES OF DOUBLE DIFFERENTIAL TYPE AS AN EFFECTIVE TOOL TO SOLVE NON-DESTRUCTIVE INSPECTION PROBLEMS

V.M. Uchanin

G.V. Karpenko Physico-Mechanical Institute of the NASU
5 Naukova Str., 79060, Lviv, Ukraine

ABSTRACT

A new type of surface eddy current probes of double differential type, which are characterized by increased sensitivity to surface and subsurface defects of various types, is presented. A family of double differential eddy current probes of different diameters with different spatial resolutions has been developed. The paper analyzes the main features of double differential eddy current probes and presents new innovative inspection techniques which allow solving the most complex problems of non-destructive testing. In particular, the developed eddy current probes have been researched and tested as an effective tool of inspection of multilayered aircraft structures, in which it is necessary to detect internal defects. They provide, in particular, the detection of cracks in the second layer of stratified aircraft structures or cracks on the back surface of the aircraft structures skin; detection of subsurface defects in the weld zone with a rough surface; detection of cracks through repair patches made of aluminium alloy or carbon composite; detection of subsurface cracks near rivet holes, etc. These techniques create unique opportunities for timely detection of dangerous damage without disassembling the inspected object or removing the protective coating. The developed eddy current probes are effective for detecting cracks in ferromagnetic steel products such as forgings, gas turbine blades and shafts, rails, wheels or axles of railway rolling stock, rough-surfaced castings, etc. In addition, high sensitivity to defects can be achieved even during the inspection through an air gap or dielectric coating. This allows them to be successfully used in many automated inspection systems.

KEYWORDS: nondestructive testing, eddy current probe of double differential type, stratified aircraft structure, subsurface defect, repair patches, rivet hole

INTRODUCTION

Eddy current (EC) method of non-destructive testing (NDT) is one of the most widespread for detection of surface and subsurface defects and determination of the characteristics of conductive materials [1-9]. At the beginning of its development the EC method was mainly used for detection of surface defects due to high operating frequencies which were used in the first EC flaw detectors. This resulted in the concentration of alternating current in the external layers of the conductive material due to skin-effect [10, 11]. Later on the low operating frequencies started to be used that expanded a sphere of application of the EC method and allowed detecting hidden subsurface defects including in multilayer structures of aircrafts. Eddy current probes (ECP) being commonly used in EC testing practice are divided on two main types, namely absolute and differential [3–5, 8]. Several decades ago a new type of surface ECP named double differential ECP [8, 12, 13] was created at G.V. Karpenko Physico-Mechanical Institute of the NASU (PMI) for the purpose of improvement of EC testing selectivity. The experience of their application showed that these ECP can solve the tasks, which are difficult (and sometimes impossible) to solve using traditional ECP of absolute or differential type. Proposed ECP of double differentiatial type are characterised with increased sensitivity to surface and subsurface defects of different type which appear during manufacture of a product or initiated by fatigue or corrosion phenomena in an operated structures. There was developed a family of double differential ECP of different diameter with various spatial resolution. Its content is constantly expanded [8]. Developed ECP were examined and tested as an effective tool of NDT of typical aircraft multilayer structures (AS), where it is necessary to detect inner defects. They, in particular, provide detection of cracks in a second layer of multilayer AS or cracks on reverse surface of AS skin with decrease of effect of reinforcing band edge; detection of subsurface defects in weld zone with rough surface; detection of cracks through repair patches, made of aluminium alloy or carbon composite; detection of subsurface cracks near rivet holes etc. These technologies create unique possibilities for timely detection of dangerous damages without disassembly of a tested object (TO) or removal of a protective coating [8, 12, 13]. Besides, developed ECP are efficient for detection of cracks in ferromagnetic steel products such as forgings, blades or shafts of gas turbines, rails, wheels or axes of railway rolling stock, castings with rough-finished surface, etc. [8]. The double differential ECP, for example, is used in the mechanized 8-channel unit for crack detection in welds of ferromagnetic alloys through dielectric protective coating of 4 mm thick-

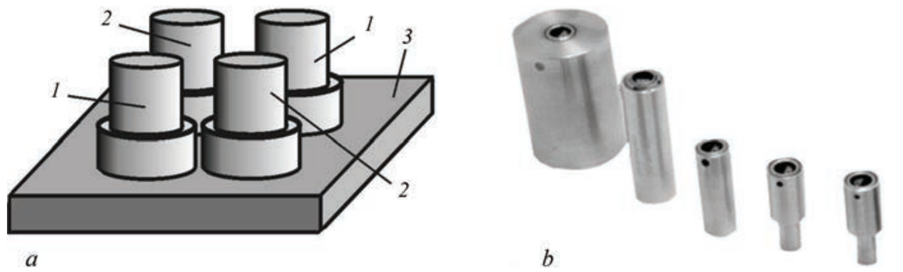


Figure 1. Design of double differential ECP (*a*): *1* — drive coils; *2* —sensing coils; *3* — TO; double differential ECP of different size and spatial resolution (*b*)

ness developed by German Company Test Maschinen Technik GmbH. At that high sensitivity to defects can be reached even at testing through air gap or dielectric coating of up to 10 mm thickness. Thanks to this peculiarity double differential ECP are successfully used in many automated NDT systems, for example, in the 64-channel EC testing system for detection of defects of aluminium bands developed at Fraunhofer Institute for Non-destructive Testing (Saarbrücken, Germany), multichannel NDT systems for wheel pairs and railway axes, developed at the Ukrainian Institute for Non-Destructive Testing (Kyiv) etc. [8].

This paper analyses the main peculiarities of the double differential ECP and provides new innovative technologies of EC NDT which allow solving the most complex NDT problems.

DESIGN OF DOUBLE DIFFERENTIAL ECP AND MAIN PECULIARITIES OF FORMATION OF SIGNALS FROM DEFECTS

Double differential ECP consist of two drive coils *1* and two sensing coils *2*, installed on the ferrite cores and located in the corners of a square (Figure 1, *a*) [8]. Two drive coils *1* have a series connection and oriented for generation of the similar and opposite primary electromagnetic fields. Developed ECP were mounted in a casing from aluminium alloy in order to reduce electronic interferences and provided with the connectors of different type for work with the flaw detectors of the leading manufacturers of devices for EC testing (Figure 1, *b*).

Design of the double differential ECP (Figure 1, *a*) creates the important peculiarities for distribution of a primary and secondary electromagnetic field, created by eddy currents induced in TO (Figure 2). In particular, a typical neutral plane is created in a zone between the drive coils. In it a vertical component of a total electromagnetic field equals zero (shown in Figure 2, *a* by dotted line) [8]. The sensing ECP coils are installed in the neutral plane and they have sensitivity orientation to a vertical component of the electromagnetic field which equals zero for isotropic and defect-free TO materials. It is important that eddy currents generated by both drive coils have similar direction and thus being added in the neutral plane (Figure 2, *b*) that promotes increase of sensitivity of EC testing. A double differential response of output ECP signal is realised due to counter connection of the sensing coils.

The design of double differential ECP provides deep penetration of eddy currents inside TO material since attenuation of eddy currents can be reduced by means of selection of large diameter of ECP coils of co-axial type or by using the drive and sensing coils of small diameter located at some distance from one another (Figure 1). Thanks to relatively small diameters of the coils it was also obtained a high spatial resolution that is important for detection of local defects. A typical peculiarity of such ECP in comparison with regular ones is a high sensitivity to elongated (crack type) as well as local (such as short crack, corrosion pitting or pore) defects; high sensitivity to surface and subsurface defects including at testing through a non-magnetic skin,

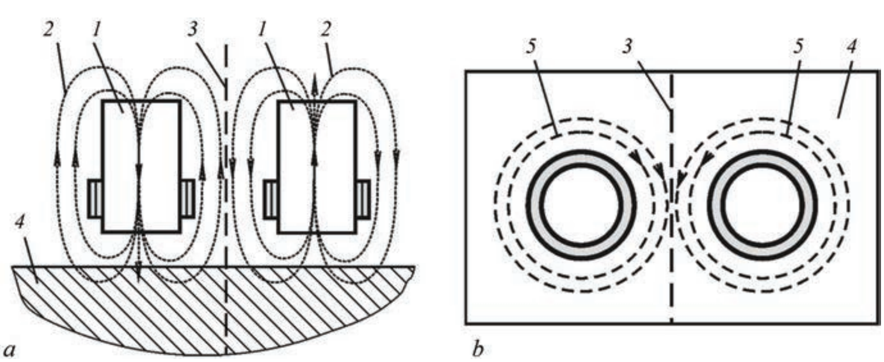


Figure 2. Primary electromagnetic field generated by drive coils (*a*) and corresponding eddy currents (*b*): *1* — ferrite cores; *2* — primary electromagnetic field; *3* — neutral plane; *4* — TO; *5* — eddy currents

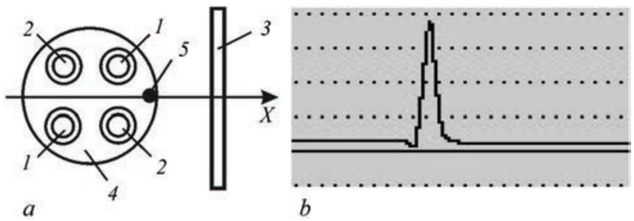


Figure 3. Optimum orientation of double differential ECP relatively to crack direction (*a*): *1*, *2* — drive and sensing coils, respectively; *3* — crack; *4* — casing; *5* — special mark; "quasi-absolute" signal from crack (*b*)

layer of a protective coating or a gap between ECP and TO surface; high testing depth for low-frequency ECP; low level of interferences including caused by effect of lift-off change. There was developed a series of double differential ECP of 4–33 mm diameter that are characterized by different size of the coils, range of operating frequencies and spatial resolution (Figure 1, *b*). Double differential ECP are adapted to modern versatile EC flaw detectors. They provide testing on different operating frequencies in 50 Hz–12 MHz range.

The peculiarity of double differential ECP is a dependence of their sensitivity on crack orientation. The optimum orientation of these ECP relatively to crack direction is shown on Figure 3, *a*, where a line connecting a centre of drive coils is oriented under 45° angle relatively to a crack direction. Special mark on ECP casing helps selecting the optimum orientation. At that a signal from the crack has "quasi-absolute" nature (Figure 3, *b*) similar to an ECP absolute signal which is characterized with the maximum amplitude at a time of ECP location directly over the crack.

Real signals of low-frequency double differential ECP of MDF 1201 type being generated by a subsurface defect in a complex plane of EC impedance of ELOTEST B1 type flaw detector of German Company Rohmann GmbH are presented on Figure 4. A low operating frequency 2 kHz was used for detection of the subsurface defects of crack type located at 1 and 3 mm depth. Sensitivity of EC flaw detector as for a defect lying at 3 mm depth was taken by 10 dB more than for a defect with lying depth 1 mm. In this case the depth of defect lying corresponds the distance between the upper edge of subsurface defect and TO surface. Also for comparison there was given a signal from a gap ("lift-off" on Figure 4) as the main source of the interferences. The lift-off signals are oriented in a complex plane horizontally corresponding to a standard EC testing procedure.

Provided results show a relatively high sensitivity to subsurface defects with high level of suppression of effect of lift-off change. Even for a defect located at 3 mm depth a relationship of the amplitude of signal from defect to the amplitude of lift-off signal significantly exceeds 6 dB. Besides, the signals differ by phase (direction of signals in a complex plane) that provides additional possibilities for separation of the useful signals created by the defect and lift-off effect.

For local defects, such as pores or corrosion pitting, the double differential ECP create a specific spatial four-point distribution of the signal with two positive and two negative peaks. Figure 5 provides typical experimental distributions of sensitivity obtained using double differential ECP of MDF 1201 type during serial scanning of a zone of local defect simulated by 1 mm diameter hole drilling [8].

DETECTION OF FATIGUE CRACKS IN A SECOND LAYER OF RIVETED AIRCRAFT STRUCTURES

Let us consider a problem of detection of fatigue cracks between the rivets in a second layer of double-layer joints stringer-skin that appeared during AS operation. Such joints are typical for most AS.

The task was to detect in the investigated specimen the cracks between the rivets through 1.4 mm thick upper skin. The distance between the edges of the flush rivets made only 8 mm. Thus, scanning of the zone between the rivets revealed a false signal at defect absence related with rivet hole influence. Figure 6 presents a specimen for adjustment of EC flaw detector. Two trajectories of scanning were used during testing, namely trajectory *5* allows observing the signals at defect absence and trajectory *6* simulates scanning through a crack located in the AS second layer [12].

The main problem at EC testing of such structures is a high level of interferences related to the defect-free rivet influence. Therefore, the testing

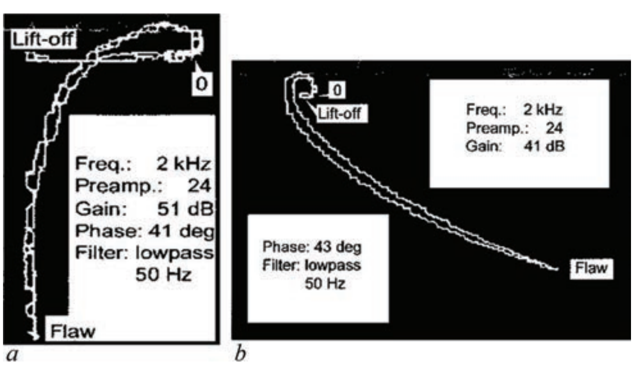


Figure 4. Signal of double differential ECP from subsurface cracks with lying depths 1 (*a*) and 3 mm (*b*)

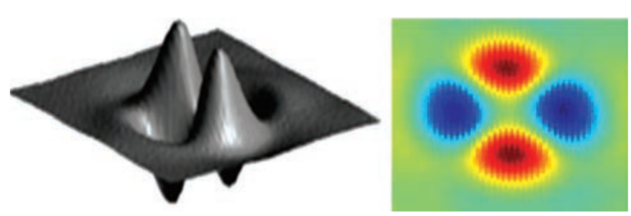


Figure 5. Four-point spatial distribution of signal with two positive and two negative peaks for local defects

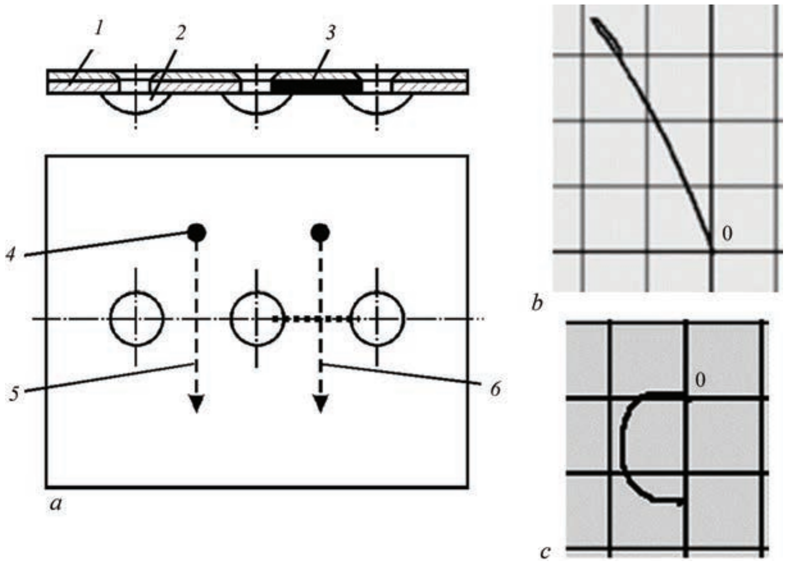


Figure 6. Specimen for simulation of double-layer AS with rivets (*a*): *1* — double-layer structure; *2* — rivets; *3* — crack; *4* — balancing point; *5*, *6* — trajectories of scanning in defect-free and defective zones, respectively; ECP signal in complex plane from crack in second layer (*b*); signal caused by influence of holes of defect-free rivets (*c*)

procedure should separate the defect signals in the second layer from the interference signal created by the rivets. Selective interpreting of the signals can be provided by means of analysis of the features typical for the defect in a complex plane on a flaw detector screen. Developed procedure provides application of ECP of MDF 0602 type of 6 mm diameter, which scans the zone between the rivets (dashed line on Figure 6, *a*). Preliminary an imbalance signal was compensated after ECP installation in point *4* which is located at 10–12 mm distance from a line joining the rivets *2*. The signals were registered using EC board of EDDYMAX type on operating frequency 6 kHz. Figure 6, *b* shows the signals from crack in the second layer and Figure 6, *c* the signals during scanning of defect-free zone between the rivets.

The obtained results indicate that the ECP signals during scanning of a defect-free zone (Figure 6, *c*) move from a balance point (“0” on Figure 6) in a direction of lower part of a complex plane. And vice versa, a signal from the defect has another upward direction into another quadrant of the complex plane (Figure 6, *b*). These results show the possibility of selective EC testing at which useful signals from the defects are easily separated from the signals generated by the rivet holes at defect absence.

DETECTION OF FATIGUE CRACKS CREATED ON AS REVERSE SIDE IN A ZONE OF EDGE OF REINFORCING BAND

Another typical example of effective EC testing of AS concerns the problem of detection of internal fatigue cracks in fuselage skin of Boeing 737 airplane in the places of juncture joints with additional reinforcing band (RB) (Figure 7, *a*). RB 3 of 0.9 mm thickness is located between the skins 1 and 2 from aluminium alloy of 0.9 mm thickness (Figure 7, *a*). The proposed EC testing procedure is oriented on detection of fatigue cracks of 0.45 mm depth (50 % of skin thickness) being initiated on the inner surface of upper skin 1 along the edge of RB 3 with access only from fuselage side (Figure 7, *c*). The problem is in the necessity of separation of the signals from cracks located on the inner surface of upper skin from sufficiently strong false signals caused by effect of RB edge being generated due to the application of low operating frequencies.

The proposed NDT procedure is based on application of low-frequency ECP of MDF 1201 type with operating frequency 26 kHz. The ECP signals were registered in a complex plane which was rotated in such a way that a signal from the RB edge being directed horizontally (Figure 7, *b*) [12]. It can be seen (Figure 7, *b*) that the signal from a crack that occurs at 0.45 mm depth deflects from a horizontal line for ~30° angle. This difference is enough for complete separation of the signals from the crack and RB edge. Moreover, an angle between these signals can be easily increased by selection larger (for example by 12 dB) amplification on a vertical axis in comparison with amplification on a horizontal line. This procedure was implemented for maintenance NDT of Boeing 737 airplane at “Ukraine International Airlines” Company (Figure 7, *c*).

DETECTION OF AS FATIGUE CRACKS THROUGH REPAIR PATCHES

Repair patches glued on airplane damaged structures are widely used as economic effective method of service life increase. The methods of repair with the purpose of reinforcement of damaged AS provide application of different materials such as aluminium alloy

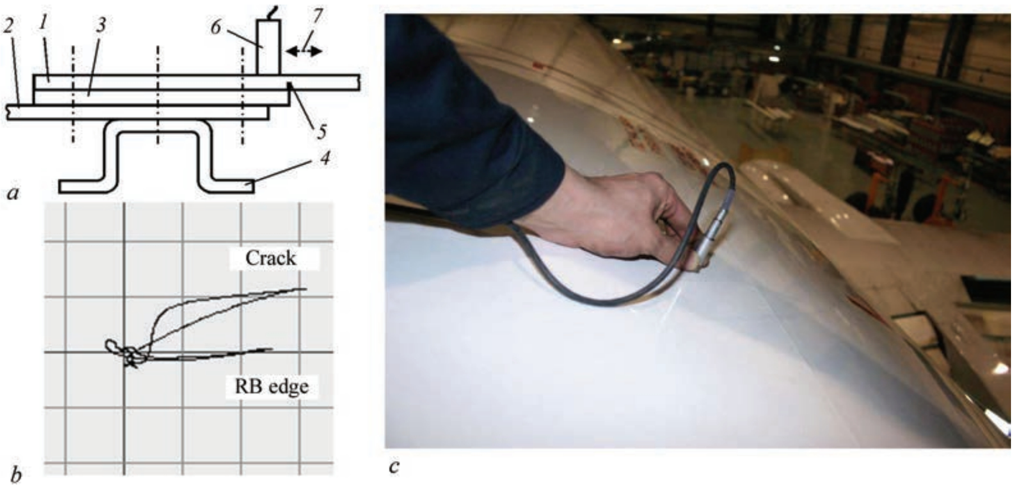


Figure 7. Multilayer structure of Boeing 737 airplane with reinforcing band (*a*): *1*, *2* — skins; *3* — RB; *4* — stringer; *5* — crack; *6* — ECP; *7* — scanning trajectory; signal from crack (*b*); testing of Boeing 737 airplane skin using ECP of MDF 1201 type (*c*)

or carbon fiber-reinforced plastic etc. Such structures are subjected to additional NDT for the purpose of detection of fatigue cracks which can appear in repaired AS under a patch. The double differential ECP were successfully used for detection of cracks through a patch from aluminium alloy glued on a damaged wing of Tu-154 airplane. After crack removal a rounded cavity was formed for reduction of mechanical stress concentration. It was expected that a crack can appear in a lower part of the cavity due to skin weakening. Because of such expectations it was planned to demount the patch every 300 landings of airplane for detection of possible cracks at the bottom of cavity using traditional EC testing methods. The procedure of EC testing built on application of low-frequency double differential ECP provided detection of cracks in a wing skin through the patch from aluminium alloy of 2 mm thickness without its dismounting.

Current AS repair technologies use the patches from composite carbon materials [14, 15]. Most often the repair patches from carbon fiber-reinforced plastic are glued on a damaged AS element from aluminium alloy. To investigate sensitivity of double differential ECP of MFD 1201 type there was produced a specimen of aluminium alloy with two electrodischarge cuts of 0.5 and 1 mm depth which was covered with a carbon fiber-reinforced plastic 4.5 mm thick sheet. Any common ECP do not have sufficient sensitivity for detection of such defects through a carbon fiber-reinforced plastic layer. The signals generated by defects under the patches were registered on operating frequency 30 kHz using EC board of EDDYMAX type in a complex plane and in a mode of time-base sweep (Figure 8) [12].

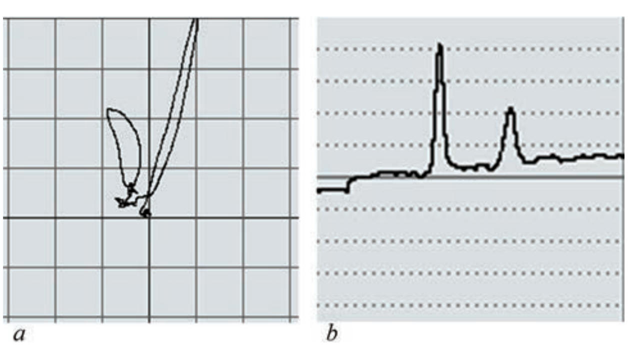


Figure 8. Signals from crack of 0.5 and 1 mm depth during testing through 4.5 mm patch from carbon fiber-reinforced plastic in complex plane (*a*) and in mode of time-base sweep (*b*)

The results given on Figure 8 demonstrate sufficiently high level of signals from a 0.5 mm deep crack during testing through a carbon fiber-reinforced plastic 4.5 mm thick patch that is enough for effective maintenance NDT. At that an amplitude of a signal correlates with a depth of detected defect that can be used for their quantitative evaluation.

ROTATION PROCEDURE OF DETECTION OF FATIGUE CRACKS IN MULTILAYER AS UNDER RIVET HEAD

Earlier it was shown that the highest sensitivity to cracks starting from rivet holes has a rotation method at which ECP is installed on a rivet head and rotated around its axis [8]. Figure 9 presents a scheme of realizing of such a procedure using double differential ECP. A special hole was made for ECP installation and centering in its body. A dielectric plate is used for centering of countersunk rivets. Accuracy of centering of ECP relatively to rivet during its rotation is important since effects the level of interferences.

Rotation ECP was tested on operating frequency 2 kHz. The specimens with a hole of 6 mm diameter were used for the investigation. On hole side surface electro-discharge cuts of 0.1 mm width and the lengths in the range from 1 to 6 mm were produced. The specimen was covered with defect-free 2 mm thick skin with a hole of 6 mm diameter and joined with a rivet for simulation of real AS (Figure 9, *a*, *b*). The ECP signals from the defects were investigated

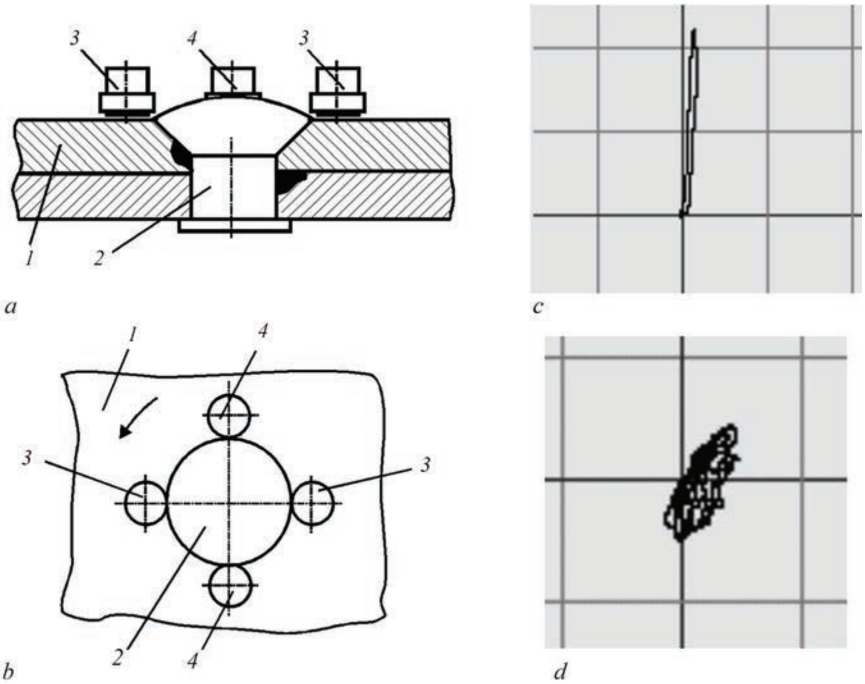


Figure 9. Rotation double differential ECP installed on rivet of double layer AS: cross section (*a*) and upper view (*b*): *1* — TO; *2* — rivet; *3*, *4* — drive and sensing coils, respectively; ECP signals in complex plane from 1 mm long crack located under rivet head and 2 mm thick skin (*c*); interference signals during ECP rotation around defect-free rivet (*d*)

in a complex plane of EC board of EDDYMAX type. Firstly, the ECP were installed on the defect-free specimen that simulates AS without defect and performed compensation of unbalance [13]. After that registration of the signals from the defects was performed by means of ECP rotation. All the defects were detected with a high signal-to-noise ratio. Figure 9, *c* as an example provides a signal in the complex plane obtained from the smallest 1 mm long defect. Figure 9, *d* shows the interference signals generated during rotation of ECP around the rivet in the defect-free specimen. These results show that a signal from the shortest 1 mm long crack for more than 6 dB exceeds the level of signal from possible interferences. It convincingly demonstrates that the proposed rotational ECP is able to detect at least the 1 mm long cracks under rivet and upper 2 mm thick skin. For many AS it means that fatigue cracks will be detected before they developed beyond the edges of a rivet head when fatigue crack reaches the critical size and avalanche-like failure of AS takes place.

PROCEDURE OF SLIDING TESTING FOR DETECTION OF FATIGUE CRACKS IN MULTILAYER AS

New highly productive procedure of detection of transverse (relatively to a row of rivets) cracks occurring in a riveted zone of AS during operation is also based on application of the double differential ECP (Uchanin V. Eddy current method of detection of defects in a rivet zone in the inner layers of one-piece aircraft structures (Pat. of Ukraine 122624, Publ. 10.12.20, Bul. No. 23).

For procedure realizing there was developed a low-frequency ECP of MDF 1502 type of 15 mm diameter. Following the proposed procedure, ECP scans AS along the rivet row line parallel to a row of rivets at some distance as shown on Figure 10.

Possibility of application of the double differential ECP for detection of transverse cracks located in a second layer of 3 mm thickness close to rivets (Figure 10) was investigated using EC board EDDYMAX. The double differential ECP provide the possibility to increase the testing reliability related with complete separation of EC signals from transverse cracks and defect-free rivets by different directions of a signal in a complex plane. This peculiarity is illustrated on Figure 10, which shows the signals for a crack of 6 mm length in a second layer in the complex plane (Figure 10, *b*) and in a mode of time-base sweep (Figure 10, *c*). For comparison Figure 10, *d* and Figure 10, *e* present the signals obtained from the defect-free rivet holes in the complex plane and in the mode of time-base sweep, respectively. It can be seen that the signals from the defect-free holes have sufficiently large amplitude since they are located in upper skin. However, these results show possibility of reliable differentiation of the signals generated by the cracks in the second layer of AS and defect-free holes, by direction in the complex plane or by sign of the signals in the time-base sweep mode. This pro-

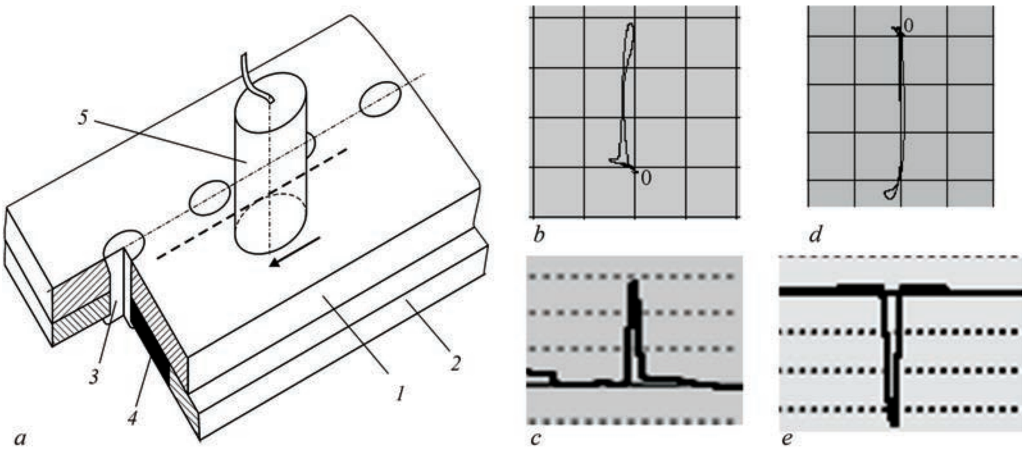


Figure 10. Scheme of realization of sliding procedure for detection of transverse cracks in rivet zone in AS second layer (*a*): *1*, *2* — first and second TO layers, respectively; *3* — rivet; *4* — transverse crack; *5* — ECP; EC testing signals in complex plane (*b*, *d*); time-base sweep (*c*, *e*) from crack in second layer (*b*, *c*) and from defect-free rivet holes (*d*, *e*)

cedure has lower sensitivity to cracks in comparison with the rotation method. Thanks to this it can be used in the cases with lower requirements as for threshold sensitivity. Nevertheless, significantly higher productivity of the sliding EC testing in comparison with the rotation method provides some advantages for on-line testing under AS operation conditions.

DETECTION OF CRACKS IN FILLET ZONE OF GAS TURBINE BLADES

To master a new NDT technology in a fillet zone of a blade there was made a 4 mm long and 0.2 mm deep cut (opening 0.2 mm) using electro-discharge method.

There is always a gap of ~1 mm between ECP operational surface and blade surface due to its curvature (Figure 11, *a*) which limits EC testing possibilities using conventional ECP. Besides, zigzag scanning of this zone provokes change of ECP position relatively to a testing surface that results in generation of high level of interferences by traditional ECP which makes impossible performance of EC testing. These limitations can be eliminated using the double differential ECP of MDF 0501 type on operating frequency 800 kHz. ECP signals were registered using EC flaw detector of ELOTEST 300 type (Rohmann GmbH Company, Germany). The results given on Figure 11, *b* also demonstrate sufficiently high level of signal of double differential ECP of MDF 0501 type in comparison with interference signals. The special double differential ECP with operational diameter 5 mm and long handle was developed for detection of cracks in a fillet zone of gas turbine blades during periodic maintenance EC testing (Figure 12).

DETECTION OF CRACKS IN HOLES OF GAS TURBINES

For detection of the defects on a side wall of gas turbine holes there was developed a special rotation head with double differential ECP based on ELOTEST SR-1 rotor of Rohmann GmbH (Figure 13, *a*). A standard specimen with a hole of 39 mm diameter was produced for testing procedure mastering. Four artificial defects of crack type of 0.2; 0.3; 0.5 and 1.0 mm depth were made on the specimen side wall.

Figure 13 *b*, *c* demonstrates the results obtained in a rotational mode at operating frequency 400 kHz with application of a standard specimen with defects without signal processing and using a filter of upper frequencies with cut-off frequency 20 Hz. In both cases there was achieved a high sensitivity with suppression of typical interferences related to non-uniformity

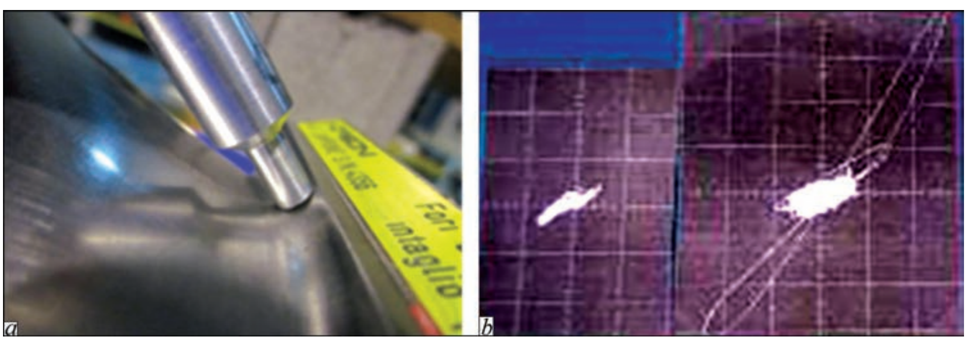


Figure 11. ECP located in blade fillet zone (*a*) and signals (*b*) of gap change during scanning of defect-free zone for different ECP orienting (left) and signal from defect (right)

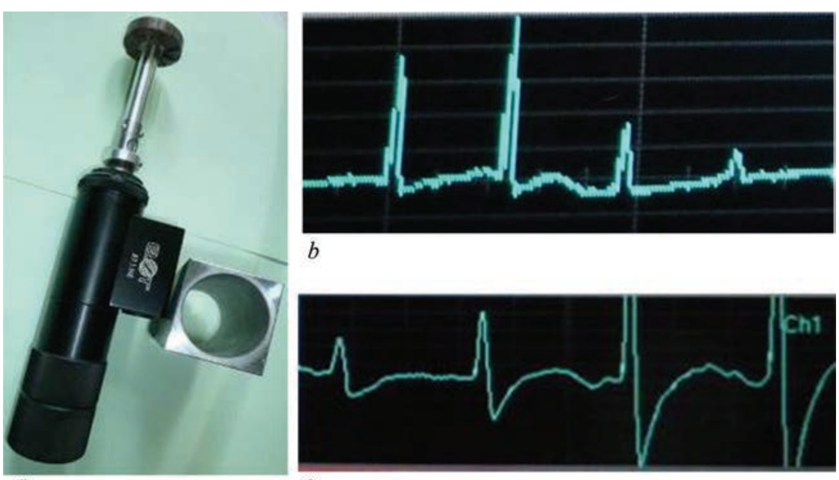
Figure 12. Maintenance testing of gas turbine blades using ECP of MDF 0501 type

of magnetic properties of TO material and change of ECP position relatively to the surface during scanning.

MULTIELEMENT ECP FOR TESTING PRODUCTIVITY INCREASE

Testing of large-sized structures takes a lot of time necessary for sensitive and reliable inspection due to small dimensions of ECP. ECP with elongated sensitivity zones are used in some cases in order to increase testing efficiency. But such ECP do not correspond to the sensitivity requirements that limit their application. The best efficiency can be achieved with application of multiplex testing systems based on array ECP [16, 17]. However, such systems have high cost and necessity of adjustment to assemblies of different sizes and shapes. Our main aim was development of a new ECP characterized with high sensitivity and spatial resolution in combination with expanded testing zone and possibility of work with comparatively cheap one-channel EC flaw detectors. In order to increase testing productivity there was developed the five-element ECP of EDDYLINE 5/12 type (Uchanin V., Ivashchenko K. Multielement eddy current probe of transformer type for single-channel flaw detectors. Positive decision on invention application Ukraine No. 202101949 dated 13.04.21). The multielement ECP consists of five separate located in series ECP connected using a special switching unit for summation of signals from separate ECP (Figure 14). All separate ECP are realized by double differential scheme for better interference suppression. Thanks to such connection it was possible to get a high sensitivity zone of ~60 mm. At the same time high locality of testing was provided since each separate ECP works with the same sensitivity as before their connection by the proposed scheme.

Sensitivity of the developed ECP of EDDYLINE 5/12 type was studied on a specimen made of ferromagnetic steel St 45 with artificial defects of crack type of 0.1 mm width and 30 mm length made by electric erosion method. Produced defects have different depth in the range from 0.1 to 2 mm. Figure 15 shows the signals of EDDYLINE 5/12 type ECP from the smallest 0.1 and 0.2 mm deep notches of when a defect zone was scanned only with one separate ECP on operating frequency 200 kHz. At this moment other four ECP were located outside the specimen (in "air"). Figure 15, *a* demonstrates the signals for the same defects when the defect zone was scanned with two separate ECP. Figure 15, *c* shows the defect signals when three separate ECP simultaneously scanned a zone of elongated defect. It can be seen (Figure 15,



a c

Figure 13. ELOTEST SR-1 rotor with double the differential ECP and standard specimen (*a*) and four signals from defects on side wall of hole without signal processing (*b*) and with application of filter of low frequencies with cut-off frequency 20 Hz (*c*)

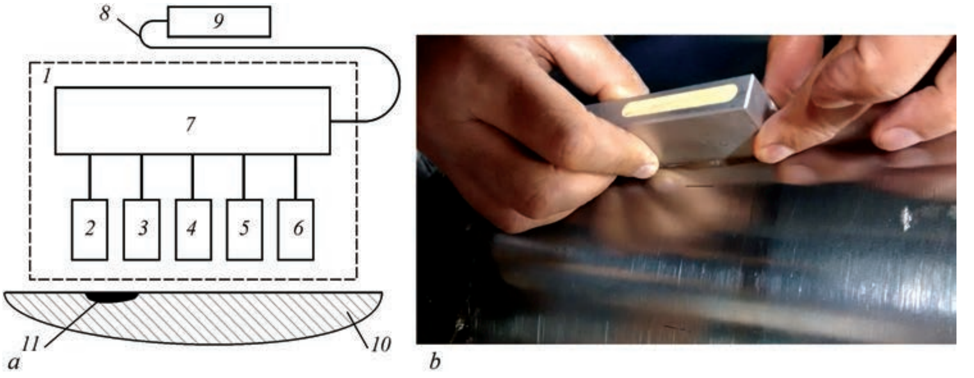


Figure 14. Construction scheme of multielement ECP for work with single channel flaw detectors: *1* — EDDYLINE type ECP; *2–6* — set of separate ECP; *7* — switching unit; *8* — connection cable; *9* — flaw detector; *10* — TO; *11* — crack; five-element ECP of EDDYLINE 5/12 type during testing of steel forgings (*b*)

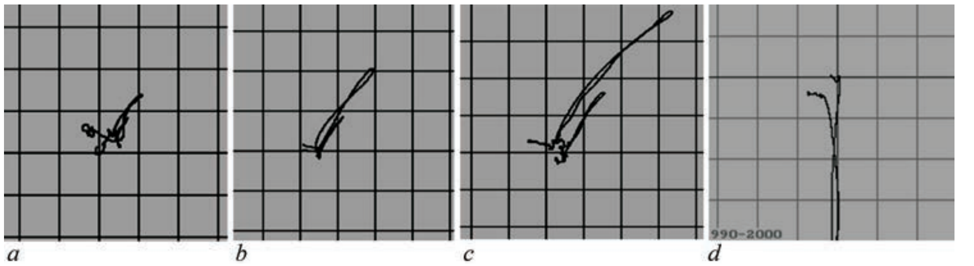


Figure 15. Signals of EDDYLINE type ECP in complex plane for one (*a*), two (*b*) and three separate ECP from 0.1 and 0.2 mm deep crack-like defects; signals from lift-off change (*d*)

a–c) that the signals of each of additional separate ECP passing over the elongated crack are summed increasing an amplitude of signal respectively to number of such ECP, i.e. an effect of possible mutual compensation of their signals is absent. Figure 15, *d* for comparison shows a lift-off signal in a complex plane, from which it can be seen that the lift-off signal and the signals from defects have opposite direction. This demonstrates possibility of reliable separation of useful signals generated by the defects, and interferences, generated by lift-off change of ECP during scanning of TO surface.

Multielement ECP of EDDYLINE 5/12 type is successfully used in a connection with a single-channel flaw detector of ELOTEST B300 type for testing of forgings from ferromagnetic and austenite steels under their production conditions (Figure 14, *b*). There were also carried out the successful trials of multielement ECP for manual testing of shafts of gas turbines and airplane shock strut pistons.

CONCLUSIONS

There was presented a design of the proposed at PMI surface eddy current probes of double differential type and analysed the peculiarities of their signals generated by the different type defects. There were given the typical examples of innovative procedures for EC testing based on application of double differential ECP. Result obtained demonstrates high sensitivity and selectivity of double differential ECP to the surface and subsurface defects of different type and large testing depth that is of particular importance for detection of hidden defects in the inner layers of the multilayer aircraft structures. Presented ECP can be used in industry for effective solution of the most difficult NDT tasks.

REFERENCES

1. Libby, H.L. (1971) *Introduction to electromagnetic non-destructive test methods*. New-York, etc. Wiley-Interscience.
2. McMaster R.C., VcIntire P. (1986) *Nondestructive testing handbook.* Vol. 4: Electromagnetic Testing (Eddy current, Flux leakage and Microwave Nondestructive Testing). Second edition. USA, American Society for NDT.
3. Dorofeev, A.L., Kazamanov, Yu.G. (1980) *Electromagnetic flaw detection.* Moscow, Mashinostroenie [in Russian].
4. Sobolev, V.S., Shkarlet, Yu.M. (1967) S*urface and screen sensors.* Novosibirsk, Nauka [in Russian].
5. Dyakin, V.V., Sandovsky, V.A. (1981) *Theory and calculation of surface eddy-current transducers.* Moscow, Nauka [in Russian].
6. Sophian, A., Tian, G., Taylor, D., Rudlin, J. (2001) Electromagnetic and eddy current NDT: A review. *Insight*, 43(**5**), 1–5.
7. Kriezis, E.E., Tsiboukis, T.D., Panas, S.M., Tegopoulos, J. (1992) Eddy Currents: Theory and Applications. In: *Proc. of the IEEE*, 80(**10**), 1559–1589.
8. Uchanin, V.M. (2013) *Eddy-current surface double differentiation probes*. Lviv, Spolom [in Ukrainian].
9. García-Martín, J., Gómez-Gil, J., Vázquez-Sánchez, E. (2011) Non-destructive techniques based on eddy current testing. *Sensors*, **11**, 2525–2565. DOI: https://doi.org/10.3390/s110302525
10. Hagemaier, D.K. (1985) Eddy-current standard depth of penetration. *Materials Evaluation*, 43(**10**), 1438–1454.
11. Mottl, Z. (1990) The quantitative relations between true and standard depth of penetration for air-cored probe coils in eddy-current testing. *NDT Inter.*, 23(**1**), 11–18.

12. Uchanin, V. (2022) Eddy current techniques for detecting hidden subsurface defects in multilayer aircraft structures. *Transact. on Aerospace Research*, 267(**2**), 69–79. DOI: https://doi.org/10.2478/tar-2022-0011
13. Uchanin, V. (2020) Detection of the fatigue cracks initiated near the rivet holes by eddy current inspection techniques. *Transact. on Aerospace Research*, 258(**1**), 47–58. DOI: https://doi.org/10.2478/tar-2020-0010.
14. *Bachir* Bouiadjra, B., Benyahia, F., Albedah, A. et al. (2015) Comparison between composite and metallic patches for repairing aircraft structures of aluminium alloy 7075 T6. *Inter. J. of Fatigue*, **80**, 128–135.
15. Bona, A. (2019) Theoretical and experimental review of applied mechanical tests for carbon composites with thermoplastic polymer matrix. *Transact. on Aerospace Research*, **4**(257), 55–65. DOI: https://doi.org/10.2478/tar-2019-0023
16. Mook, G., Michel, F., Simonin, J. (2008) Electromagnetic imaging using probe arrays. In: *Proc. of 17th World Conf. on Nondestructive Testing, Shanghai.* www.ndt.net. DOI: https://doi.org/10.5545/sv-jme.2010.173
17. Bureau, J.-F., Ward, R.C., Julien, A. (2012) Application of eddy current array technology to surface inspection. In: *Proc. of 18th World Conf. on Nondestructive Testing, Durban, South Africa.* www.ndt.net

ORCID
V.M. Uchanin: 0000-0001-9664-2101

CORRESPONDING AUTHOR
V.M. Uchanin
G.V. Karpenko Physico-Mechanical Institute of the NASU
5 Naukova Str., 79060, Lviv, Ukraine.
E-mail: vuchanin@gmail.com

SUGGESTED CITATION
V.M. Uchanin (2023) Surface eddy current probes of double differential type as an effective tool to solve non-destructive inspection problems. *The Paton Welding J.*, **2**, 46–55.

JOURNAL HOME PAGE
https://patonpublishinghouse.com/eng/journals/tpwj

Received: 23.12.2022
Accepted: 30.03.2023

SUBSCRIPTION–2023

«The Paton Welding Journal» is Published Monthly Since 2000 in English, ISSN 0957-798X, doi.org/10.37434/tpwj.

«The Paton Welding Journal» can be also subscribed worldwide from catalogues subscription agency EBSCO.

If You are interested in making subscription directly via Editorial Board, fill, please, the coupon and send application by Fax or E-mail.

12 issues per year, back issues available.

$384, subscriptions for the printed (hard copy) version, air postage and packaging included.

$312, subscriptions for the electronic version (sending issues of Journal in pdf format or providing access to IP addresses).

Institutions with current subscriptions on printed version can purchase online access to the electronic versions of any back issues that they have not subscribed to. Issues of the Journal (more than two years old) are available at a substantially reduced price.

Subscription Coupon			
Address for Journal Delivery			
Term of Subscription Since	**20**	**Till**	**20**
Name, Initials			
Affiliation			
Position			
Tel., Fax, E-mail			

The archives for 2009–2021 are free of charge on www://patonpublishinghouse.com/eng/journals/tpwj

ADVERTISING
in «The Paton Welding Journal»

External cover, fully-colored:
First page of cover
(200×200 mm) — $700
Second page of cover
(200×290 mm) — $550
Third page of cover
(200×290 mm) — $500
Fourth page of cover
(200×290 mm) — $600

Internal cover, fully-colored:
First/second/third/fourth page
(200×290 mm) — $400

Internal insert:
(200×290 mm) — $340
(400×290 mm) — $500

- Article in the form of advertising is 50 % of the cost of advertising area
- When the sum of advertising contracts exceeds $1001, a flexible system of discounts is envisaged
- Size of Journal after cutting is 200Í290 mm

Address
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
Tel./Fax: (38044) 205 23 90
E-mail: journal@paton.kiev.ua
www://patonpublishinghouse.com/eng/journals/tpwj