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FATIGUE CRACKS DETECTION IN THE FILLET ZONE OF STEEL BLADES OF INDUSTRIAL GAS TURBINES USING EDDY CURRENT METHOD

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ABSTRACT

The results of experimental investigations aimed at the development of an effective eddy current technique for detection of fatigue cracks originated in the critical fillet zone of gas turbine blades fabricated of ferromagnetic steels are discussed. The proposed inspection technique is based on the use of selective eddy current probes (ECP) of double-differential type, providing high sensitivity when the clearance between the ECP operational surface and the inspected surface in the fillet zone is changed during the scanning. The experimental investigations signals from ECP of MDF 0501 type (operational surface diameter — 5 mm) allowed minimizing the lift-off effect by selecting the optimal operational frequency and choosing the optimal scanning parameters of the inspected zone. The effectiveness of the proposed inspection technique was confirmed with the application of a real gas turbine blade with the 2 mm long and 0.2 mm deep artificial defect in the fillet zone, which characterizes the sensitivity threshold specified in accordance with the technical assignment. The inspection technique has also been successfully used during its tests at enterprises of power engineering.

KEYWORDS: gas turbine blade, fillet zone, eddy current ECP, operational frequency

INTRODUCTION

Gas turbine is called a blade machine, in which the potential energy of compressed and/or heated gas is converted into mechanical operation on the shaft. Its main elements are rotor with operating blades fixed on the discs, and stator. The design of a blade consists of airfoil, platform and shank. Blade airfoil is a metal profiled blade that directly contacts a working gas. Platform is the end airfoil section designed to reduce the vibration and protect the rim of a disc from the action of a heated gas. Shank serves to attach blades in the slot of a disc. Blades are the most critical parts of turbines operating under the conditions of cyclic and thermal stresses in combination with the corrosion and erosion processes under the action of a heated working gas. Gas turbines and their elements are the subject of constant modernization [1, 2]. The most rigid requirements for the quality, reliability and life are specified to blades of gas turbines, as many serious incidents during the operation of gas turbines are associated with their failure. Due to the critical concentration of stresses, researchers pay a particular attention to a fillet zone, where the coupling of a profiled airfoil with the platform surface of a blade is close to rectangular (Figure 1) [3]. Fractographic examinations showed that the main cause of failure of a gas turbine blade is multicycle fatigue [4, 5]. Primary crack can arise due to large inclusions of another phase [3] or corrosion phenomena [5, 6]. Failure and tearing of rotor blade fragments during operation can be a cause of the most serious accident because of significant damages to other turbine units. The economic aspect is also of great importance, which is associated with a high-cost fabrication of a blade unit, which can reach 35 % of a turbine cost as a whole.

Figure 1. Typical gas turbine compressor blade with an electro-erosion slot of 4 mm long, 0.2 mm deep and opening of 0.1 mm in the fillet zone for adjustment and checking of the inspection technique

The safe operation of gas turbines is guaranteed by a timely detection of operational defects by means of non-destructive inspection (NDI). Therefore, the development of effective methods of NDI of gas turbine blades is an urgent task of modern engineering.

STATE OF THE PROBLEM

Periodic in-service NDI of blades and other gas turbine units is important for safe operation due to timely detection of defects before a complete failure of a structure. It is necessary to carry out NDI quickly and efficiently to minimize the shutdown period of a turbine. There are many NDI methods that can be used to check gas turbine components [6–8]. The method of penetrating liquids (colour method) using dye is a cost-effective NDI technique and simple in implementation, which is often used for NDI of gas turbine components. The drawbacks of this method are high requirements for the quality of surface cleaning and restrictions during NDI of corroded surfaces. Another restriction of this method is its suitability to detect only open cracks. Therefore, this method cannot be used for NDI of blades with protective coatings. The magnetic powder method allows detecting cracks in blades fabricated of ferromagnetic steels and is relatively low-cost. But it has the same restrictions as the method of penetrating liquids. The ultrasonic method can be used for NDI of blades [8]. But it also has disadvantages associated with the need in using contact liquids, which significantly complicates NDI in real industrial conditions of power engineering.

Considering the abovementioned, from our point of view, the most suitable method for in-service NDI of gas turbine blades is eddy-current NDI method [9–12]. But also during attempts to apply eddy-current NDI of blades, challenges arise, in particular related to:

1) a complex shape of a blade;

2) presence of clearances between the ECP during inspection of concave zones;

3) increased lift-off level characteristic of eddy-current NDI of products fabricated of ferromagnetic steels due to magnetic inhomogeneity of the material.

The most important thing when developing the eddy-current NDI technique for blades is to consider the complex shape of a blade (Figure 1) with curved convex and concave surfaces, edge and fillet zones, that are usually allocated as separate inspection zones, flaw detection of which is carried out after appropriate adjustment with taking into account the features of the specified zone.

Eddy-current NDI of zones with a large curvature radius at a remoted distance from the edge is not a cause for great concern and requires only manufacturing of special nozzles to orient the ECP perpendicular to the inspected surface. The problem of eddy-current NDI of the edge zones can be also solved by using appropriate nozzles that allow scanning the edge zone at a constant distance from the edge of a blade. When developing the procedure for blades inspection, the edge zone should be allocated to a separate zone, whose inspection requires balancing of the ECP, installing it at a certain distance from the edge with the appropriate adjustment of the eddy-current flaw detector (ECFD). Significant problems arise during the inspection of fillet zones between the platform and the airfoil of a blade, where fatigue cracks are most often formed during operation, which are mainly oriented along the fillet zone. These circumstances are the reasons for the development of special eddy-current inspection techniques built on using ECP of a complex shape, whose working surface reproduces the profile of an inspected surface in the fillet zone [13]. This approach limits the possibility of inspecting areas of a testing object (TO) with a different radius of surface curvature. ECPs on a flexible lining with a wide inspection zone are more versatile, but they do not meet the requirements for sensitivity to defects. To reduce the lift-off level characteristic of ferromagnetic steels when detecting cracks under the coating, pulsed eddy-current inspection method is promising [14–16]. Summarizing, we should note that this approach eliminates the possibility of using widespread ECFDs with harmonic excitation current, and serial ECFDs with a pulsed excitation are still absent at the market of eddy-current NDI means.

As noted above, the reliable detection of cracks in TO of ferromagnetic steels by the eddy-current method often interfere with the lift-off, induced from the magnetic and structural inhomogeneity of the material under study [12, 17, 18]. Therefore, in many outdated documents and publications, the eddy-current NDI method was determined as completely unsuitable or low-reliable for detecting defects in ferromagnetic steels. Let us note several approaches to reducing the effect of the mentioned specific lift-off. The first one consists in the additional magnetization of the TO area under study. This approach often gives a positive result, especially when introducing special screens in the ECP design (for example, Uchanin V.M. Eddy-current attachable probe for inspection of ferromagnetic materials. Patent of Ukraine No. 99379). However, additional screens increase the size of the ECP, which is not always appropriate. Moreover, additional magnetization limits the sensitivity of the ECP due to the magnetization of the ferrite core.

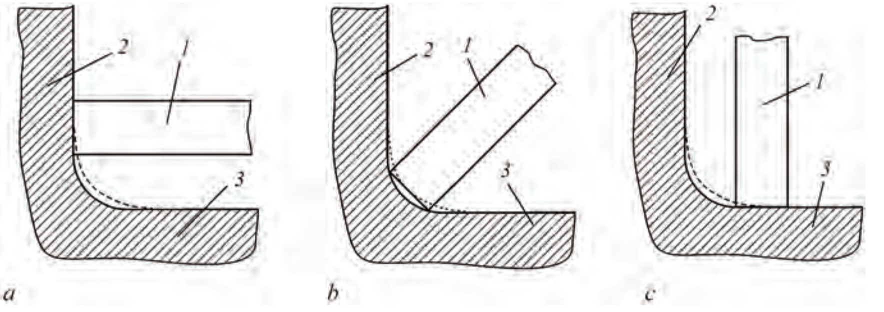

Figure 2. Location of ECP in the extreme position on the blade airfoil (*a*), in the zone of the maximum curvature of the fillet zone (*b*) and in the extreme position on the blade platform (*c*): *1* — ECP; *2* — blade airfoil; *3* — blade platform

Another approach can be implemented by creating selective ECPs, that have a low level of lift-off associated with the magnetic inhomogeneity of the TO material. Our experience shows that many complex problems of eddy-current detection of TO of ferromagnetic steel can be solved by using a double differential ECPs [17–20], which are composed of two generator and two measuring windings located at the square corners. All windings are wound on identical cylindrical ferritic cores. At the same time, both generator windings are connected in series and oriented to generate the same and opposite primary electromagnetic fields. Such a ECP design allows placing windings in a metal cylindrical case (usually from aluminium alloy), which significantly reduces the level of electronic lift-off. During wiring, the windings are thoroughly balanced, focusing on the minimum level of lift-off, which are formed as the ECP distance to a metal specimen in the form of a plane plate grows. When installing the windings in the metal case, it is necessary to provide an equal distance of the windings to the inner wall, so as not to violate the balance obtained during adjustment of the ECP.

Figure 3. Experimental mock-up of ECP of MDF 0501 type

STUDYING THE ECP SIGNALS AND OPTIMIZATION OF INSPECTION MODES FOR FILLET ZONES OF BLADES

During transverse scanning of the fillet zone of a blade when using ECP of a cylindrical shape with a plane working surface, changes in the ECP distance from the TO surface occur, as it is schematically shown in Figure 2. Therefore, when choosing ECP, the preference should be given to ECPs of smaller diameter that are best adhere to the fillet surface. Previous studies have shown that to inspect fillet zones of a blade, ECPs of MDF 0501 type with an outer working diameter of 5 mm are best suited (Figure 3). In our case, such a small size of ECP allows scanning the fillet zone of a blade without creating clearances of more than 0.5 mm.

Signals from the ECP of MDF 0501 type were studied with the use of a standard specimen (SS) of SOP 2353.08 type (manufacturer — Promprylad, Kyiv) made of ferromagnetic 45 steel with electro-erosion defects of the type of a crack of different depth. Only defects of 0.2 and 0.5 mm deep were used for our research. The width (opening) of artificial defects is about 0.1 mm. The studies of sensitivity and registration of signals of the ECP were conducted by means of the eddy-current plate of EDDYMAX type of the Test Maschinen Technik Company, Germany. The scanning of the defective zone of the SS was performed at the optimal ECP orientation, when the line joining the excitation winding centers is oriented at an angle of 45° relative to the crack direction [20]. The signal from a crack has a “quasi-absolute” nature, when the maximum amplitude corresponds to the ECP position directly above the crack similarly to the ECP signal of an absolute type [20]. To choose the optimal orientation, on the ECP case, a special mark is applied (Figure 3).

The practical purpose of the experimental research is to choose the optimal frequency that will provide the best conditions for detecting defects in a convex fillet zone of a blade. The complex concept of such optimization involves the choice of opera-

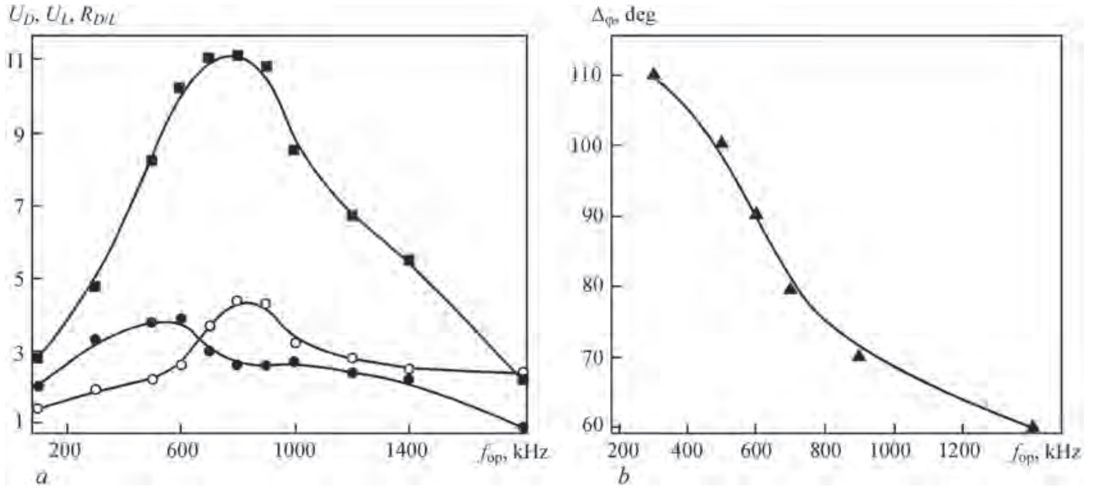

Figure 4. Dependences of the signal amplitude from a defect U_D (■), change in clearance U_L (●), and ratio $R_{D/L}$ (o) of the signal amplitude from a defect to the signal amplitude from the change in clearance on the operational frequency f_{op} (*a*), as well as dependence of difference in Δφ (▲) of phase signal angles from a defect and change in clearance on the operational frequency f_{op} (*b*)

tional frequency f_{op}, at which not only a sufficiently high level of signal amplitude from a defect U_D can be achieved, but also the best ratio $R_{D/L}$ of the signal amplitude from a defect to the signal amplitude from the lift-off, which in our case is the amplitude of U_L signal, caused by the change in clearance between the working surface of the ECP and TO surface during scanning. In addition, we have an additional opportunity to separate useful signals from defects and the change in the clearance by using a complex plane at different directions (different angles) of signals from a defect and signals from the change in clearance. The best conditions for distinguishing signals from defects against the background of signals from the lift-off are in general performed when we have a right angle (Δφ = 90°) between them. But from the practical experience, the lesser difference of directions (but higher than 60°) can also be effectively used, because in this case the angle can be increased by the choice of different sensitivity on the orthogonal ECFD channels. The factor of signals direction in the complex plane sometimes allows making compromise decisions and be crucial to choose the optimal operational frequency in difficult situations, when the amplitudes of signals from defects and lift-off are close.

Figure 4, *a* shows the dependences of the signal amplitude from a defect U_D, signal amplitude from the change in clearance U_L and the ratio $R_{D/L}$ of the signal amplitude from a defect to the signal amplitude from the change in clearance on the operational frequency f_{op} in the range of 100–1800 kHz. The signals from a defect were received by scanning the specimen in the zone of an artificial defect of 0.2 mm deep, which corresponds to the minimum crack size to be detected in blades in accordance with technical requirements. The amplitude of the signal caused by the change in clearance was evaluated by removing the ECP from the SS surface at a distance significantly larger than 10 mm. Amplitudes of signals from a defect and clearance are given in conditional values by divisions of the display scale of the eddy-current system, because the ratio of divisions and physical units of the signal amplitude is unknown due to lack of appropriate calibration.

Figure 4, *b* shows the dependence of the difference between the phase angles of signals from a defect and the change in clearance Δφ, which were evaluated according to the direction of hodograph signals in the complex ECFD plane with sufficient accuracy for practice.

It should be noted that the amplitude of signals from defects is high enough to detect them in the whole range of frequencies (100–1800 kHz). The largest amplitudes of signals from a defect of 0.2 mm deep are observed at the operational frequencies of 600–800 kHz (Figure 4, *a*), which can be considered as optimal by this criterion. But the best ratio of the signal from a defect to the signal from the lift-off is observed at the operational frequency of 800 kHz. Analysis of the change in the difference between the phase angles Δφ of signals (Figure 3, *b*) shows that according to this criterion, the operational frequency of 600 kHz is optimal, at which the angle between the useful signal from a defect and the signal from the change in clearance is close to the right one (90°). Taking into account the results analyzed above, the operational frequency of 700 kHz was determined as optimal. Subsequently, signals from defects were registered at this operational frequency.

To analyse the ECP sensitivity at different distance of the ECP from the TO surface, the registration of ECP signals from defects of 0.2 and 0.5 mm deep was performed at direct contact of the ECP with the TO

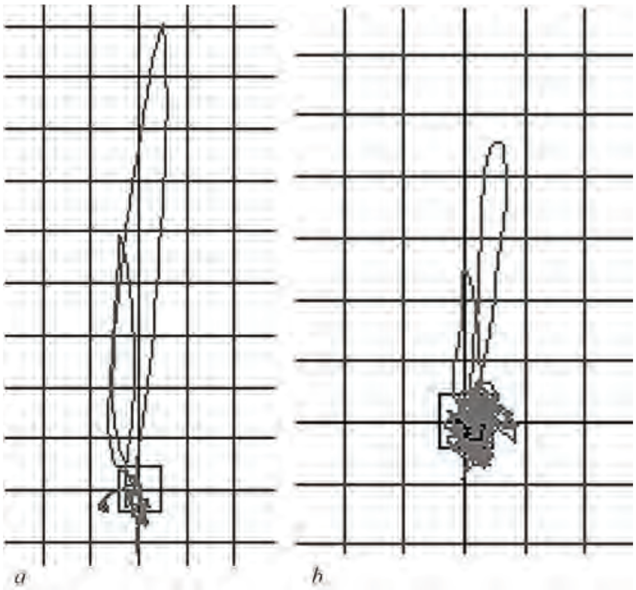

Figure 5. Signals caused by defects of 0.5 mm and 0.2 mm deep, at a direct contact of ECP with the specimen surface (*a*) and with the clearance of 0.5 mm in the complex plane (*b*)

surface and at a distance of 0.5 mm, provided by a dielectric plate of corresponding thickness.

Figure 5 shows signals caused by defects of 0.2 and 0.5 mm deep, in the complex ECFD plane at the operational frequency of 700 MHz, which were obtained at a zero distance of the ECP from the SS surface (*a*) and through a dielectric plate of 0.5 mm thick (*b*). In Figure 5, b signal registration sensitivity during scanning through a dielectric plate was increased by 12 dB to compensate for a significant decrease in amplitude.

Signals given in Figure 5 show the ability to detect a defect that characterizes the sensitivity threshold in depth (0.2 mm) with a sufficiently high signal/lift-off ratio even during inspection through a dielectric plate of 0.5 mm thick. We shoud note that for the ECP remoted from the TO surface at a distance of 0.5 mm (without a dielectric plate), the results will be similar. It is seen that the signal amplitude from a defect of 0.5 mm deep is approximately by 80 % higher than the amplitude of the signal induced by a defect of 0.2 mm deep, both for the case of direct contact of the ECP with the SS surface, as well as for inspection through

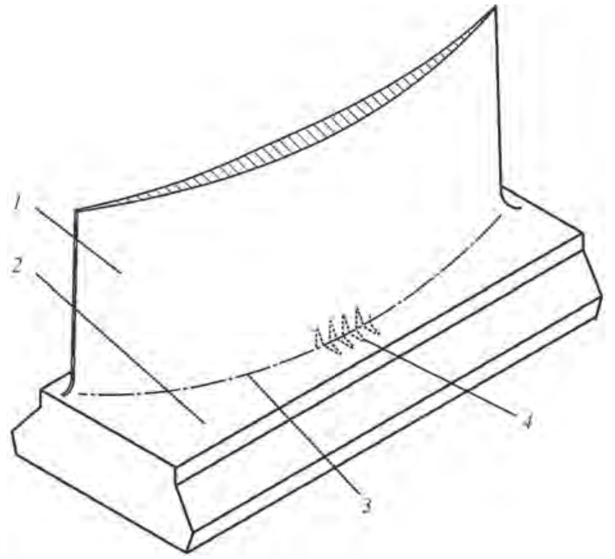

Figure 7. Zigzag trajectory of scanning fillet zone: *1* — blade airfoil; *2* — blade platform; *3* — fillet coupling line; *4* — scanning trajectory

a dielectric plate of 0.5 mm thick. Moreover, on the ECFD screen, electron noise can be observed, which at amplified sensitivity (Figure 5, *b*) is respectively more intensive by approximately 12 dB. In Figure 5, *a* signal from the change in clearance in the form of a small "shank" is observed, which is shifted to the left from the zero point, which corresponds to the compensation of the ECP imbalance during its installation on a defect-free area of the SS. In Figure 5, *b* signal from the change in clearance is already not observed, as far as the ECP was already remoted by 0.5 mm from the SS surface and sensitivity to the changes in clearance is significantly lower.

TESTING OF THE PROPOSED IN-SERVICE EDDY-CURRENT FLAW-DETECTION TECHNIQUE FOR FILLET ZONES OF TURBINE BLADES

To inspect gas turbine blades without their disassembly (during inspection shutdown of turbine), a special ECP was produced, whose sensitive element by means of a thin pipe of austenitic steel of 3.5 mm diameter is remoted at a distance of 20 mm from the handle operated by the flaw detection operator. In this

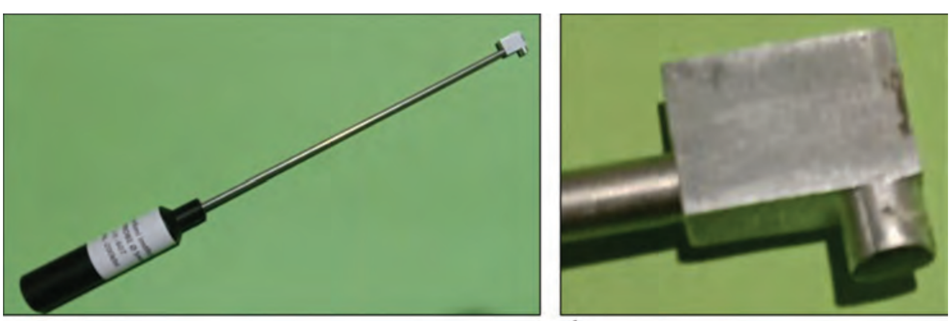

Figure 6. Eddy-current probe of MDF 0501 type with a remoted sensitive element: general appearance (*a*), sensitive ECP element (*b*)

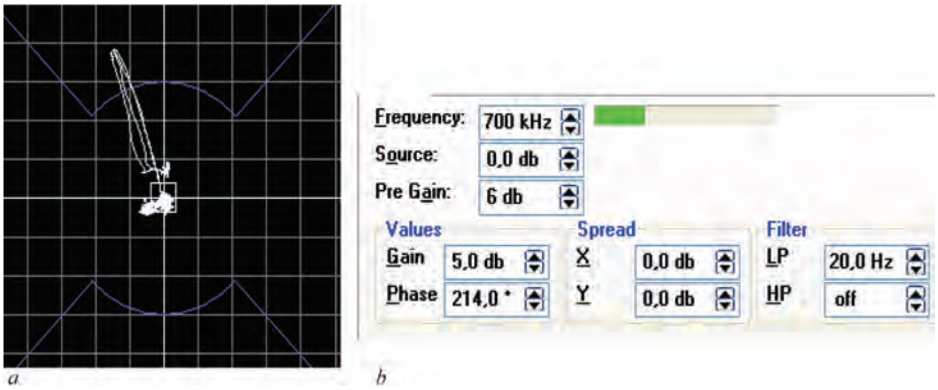

Figure 8. Signals from a short slot type defect (see Figure 1) in real blade (*a*) and displaying inspection parameters on the display (*b*)

Figure 9. In-service tests of the proposed eddy-current inspection technique of gas turbine blades

case, the sensitive element is oriented perpendicular to the handle axis (Figure 6).

Figure 7 schematically shows a blade fragment with a zigzag trajectory of manual scanning *4* of the fillet zone between the airfoil *1* and the platform *2* of a blade. In practice, this is performed by turning the ECP around the handle axis with its gradual advancement along the fillet. The step between the scanning lines is approximately 0.5 mm, that ensures a reliable detection of defects of more than 2 mm long. During scanning, the flaw detection operator should maintain the perpendicular position of the sensitive ECP element relative to the convex fillet surface. This operation requires some experience. Therefore, the flaw detection operator preliminary practices it on a real blade with an artificial defect (Figure 1).

The ECP of MDF 0501 type shown in Figure 6 with an elongated pipe was tested on a gas turbine compressor blade with an electro-erosion slot of 4 mm long, 0.2 mm deep and opening of 0.1 mm in the fillet zone, which is designed to adjust the equipment and check the inspection technique. The obtained results are shown in Figure 8, where the ECFD display in the mode of reproduction of a complex signal plane is depicted. The flaw detection pattern shows two signals from a defect close by amplitude, since the ECP crossed the defect zone twice. This made it possible to highly evaluate the repetition rate when receiving signals from defects. The signals from a defect are oriented and clearly fall into the sector frame of the automatic alarm. The signals caused by changes in clearance during zigzag scanning of the fillet zone at a distance from a defect, first, are significantly smaller relative to the signal from a defect, and secondly, are oriented to the left from the starting point (ECP balancing point), i.e. different in direction.

The tests showed that ECP of MDF 0501 type at selected optimal inspection parameters is characterized by high sensitivity and selectivity of inspection even under the conditions of manual scanning. The set sensitivity parameters of the ECFD use only a small part of capabilities for amplification of ECP signals (Figure 8, *b*).

The developed in-service eddy-current flaw detection technique for blades was successfully tested at gas turbines of the Nuovo Pignone SPA Company (Florence, Italy), which is a regional representative of an American multisectoral corporation General Electric (https://ge-nuovopignone.com) (Figure 9).

CONCLUSIONS

The results of experimental studies aimed at creating effective eddy-current flaw detection technique of a critical fillet zone of gas turbine blades fabricated of ferromagnetic steels were considered. The proposed inspection technique was implemented by using selective double differentiation ECP, which provide high sensitivity during inspection in the conditions of changes in clearance between the working surface of the ECP and blade surface in the fillet zone. A comprehensive approach to the optimal choice of the operational frequency was proposed. The carried out studies of signals of the ECP of MDF 0501 type (working surface diameter is 5 mm) allowed minimizing the lift-off effect by selecting the operational frequency and choosing the scanning parameters of the inspected zone, which is confirmed on a real blade with an artificial defect of 2 mm long and 0.2 mm deep, which characterizes the sensitivity threshold set by the technical assignment. The effectiveness of the proposed technique is confirmed during its tests at entrprises of the power engineering, in particular in gas turbines of the Nuovo Pignone SPA Company (Florence, Italy).

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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