Detection of Surface and Subsurface Defects in Ferrous Steel Components and New Inspection Technologies Development

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Abstract
Our investigations show the possibility to detect the surface and subsurface like crack defects in ferrous steel by eddy current (EC) method with new low frequency double differential probes. By this probes application complicated gas turbine inspection problems connected with possibility to detect defects (1) with large clearance between probe and inspected surface; (2) through nonmagnetic conductive coating and (3) to detect subsurface defects in ferrous steel without magnetic saturation were investigated and solved. High sensitivity to subsurface defects can be explained by remote field effect when transmit and receive coils in surface EC probe are separated. Additional advantages of developed probes are high lift-off effect and structural noise suppression due double differential coils connection.

For blade inspection special double differential probes with 5mm and 6 mm operational diameters and long handle were produced. The developed double differential probes were applied for detection of defects situated on sidewall of gas turbine holes. For this purpose special rotating head with double differential EC probe based on ELOTEST SR-1 rotor was developed for productive gas turbine holes inspection. Presented technologies were applied for gas turbine maintenance in different countries.

Keywords: Eddy current (EC), EC probe, operational frequency, complex plane, defect, gas turbine blade, coating.

1. Introduction

Gas turbine components over the operation life are influenced by cyclic and thermal stresses in combination with corrosion and erosion processes [1-3]. Due to the fractographic investigations the primary cause of gas turbine blade failure was established as high cycle fatigue [1]. Meanwhile, the primary crack can be originated from the large second phase particles [1] or from the corrosive pits [4]. Fracture of rotating blade can be a cause of accident attended with extensive damages of other turbine components. So, periodic inspection by nondestructive (NDT) methods is vital for the safe operation of gas turbine because of timely defect detection with subsequent cracked component replacement before full fracture. In order to minimize the turbine downtime the NDT inspection is needed to be carried out quickly and efficiently.

There are many NDT methods possible to be applied for gas turbine inspection [2-7]. Dye penetrant method is low-cost and easy-to-use technique frequently used for gas turbine component inspection. Disadvantage of this technique are high demands to surface cleaning. This method has also limitations when inspected surface is corroded. Another limitation of dye penetrant inspection is its suitability to detect only opened cracks [3]. Beside this, the dye penetrant method is not possible to be applied for coated blade inspection. Magnetic particle inspection is a relatively low-cost technique that allows the detection of cracks in ferrous materials. But this method has the same limitations as dye penetrant inspection. The EC and ultrasonic techniques can be selected as most applicable for practical blade inspection on site [3]. But from our point of view only EC method looks to be most convenient for in-service inspection [3, 6-9].

There are some blade specific feathers needed to be appreciated when EC technology will be developed. It is first of all the complicated form with curved convex and concave surfaces,
edge and fillet zones. The second important feature is the different types of coating (ceramic or aluminium) for special blades. These coatings can sufficiently influence the defect detectability. These circumstances are the reasons of specific EC technologies developed such as complex shape EC probes for curved zone inspection or pulsed EC method for detection of cracks under coating [6,7]. But the disadvantages of these approaches are the low sensitivity when complex form EC probes with wide inspection zone are applied and impossibility to utilize conventional commercial EC flaw detectors with harmonic EC excitation.

Double differential (also called multi-differential) EC probes were developed some decades ago [8,9]. In these probes the coil were connected to obtain the second order differential signal response. Due such design this probes are characterized by specific quasi-absolute signal response with maximum signal amplitude when EC probe is situated directly under elongated like crack defect. Such feature is easy to be explained by analyzing the second derivative of absolute type signal response distribution. For local like pitting defect all coils sense the flaw separately without signal summation. Thereof for local defects this type probes are characterized by specific four point spatial signal response distribution with two positive and two negative peaks [8]. In presented double differential probes small size separated coils are used to obtain high sensitivity and penetration features in combination with high spatial resolution. Different investigations show that the main features of such probes can be characterized with [9]:

- High sensitivity to elongate like crack and to local like pitting defects due small size coil application;
- High sensitivity to surface and subsurface defects under coating and the possibility to detect defects with large clearance or dielectric layer between probe and inspected surface;
- High penetration for low frequency probes;
- High lift-off and probe inclination suppression;
- Wide inspected path with high spatial resolution.

Last years new double differential type EC probes with different operational frequencies and operational surface diameters from 5 to 33 mm were designed [9]. Coil size, number of turns, penetration and spatial resolution can be optimized for specific application. Special methodology was developed for EC coil efficiency estimation needed for coil design optimization [10].

Comparatively new range of application is the detection of cracks in ferrous steel components. In this case the main advantage of these probes is high sensitivity through large clearance between probe and inspected surface, possibility to detect cracks through conductive (for example, aluminium coating) and subsurface defect detection.

In this paper new EC inspection technologies developed on the base of double differential type EC probes are presented.

2. Investigation of the possibility to detect defects with large clearance between EC probes and inspected surface

The possibility to detect defects with some clearance with high sensitivity is very important for gas turbine blade inspection due curved surfaces and fillet zones presence. It is also essential to investigate the possibility to detect the defects in ferrous steel through dielectric coating for blades covered by ceramic coating [11].

For our investigations small size MDF 0602 EC probe was selected as perspective for blade inspection due small operational diameter (6 mm). This probe has high enough spatial resolution due small EC coil diameters. The investigations were conducted with application of the special specimen fabricated from ferrous steel 45 with smooth A (Ra 1.25 µm) and rough
B (Rz 160 µm) surfaces (fig. 1). The surface roughness on the surface B was simulated in the form of the sawcut grid. In specimen the artificial electrical-discharge-machined 0.1 mm wide slots with depth 0.1; 0.2; 0.5; 1.0 and 2.0 mm on the smooth surface A and 0.6; 1.5 and 3.0 mm on the rough surface B were fabricated.

The EC probe signals were investigated by the EDDYMAX flaw detector card produced by Test Maschinen Tecknik in the hand scanning mode. Obtained signals were stored in PC memory in TIFF format. All slots in specimen were detected with high signal-to-noise ratio. As example, fig. 2 presents the signals in complex plane and in time-base mode obtained from shallowest 0.1 mm depth defect at operational frequencies 40 and 400 kHz.

To estimate sensitivity changes, when defect is detected through different thickness dielectric coatings, signals were registered for specimen covered by dielectric plates with thickness \( t \) changed from 0.5 to 5.0 mm. For every defect depth \( a \) in the range from 0.1 to 2.0 mm there was estimated the limiting thicknesses \( t_{lim} \) of coating through which the defect was surely detected with sufficient signal-to-noise ratio. For example, on fig. 3 the signals in complex plane and in time-base mode obtained from shallowest flaw through dielectric plates with 2.5 mm and 1.5 mm thicknesses (estimated as limiting thicknesses \( t_{lim} \)) at operational frequencies 40 and 400 kHz are presented. Amplification in fig. 3 is 24 dB and 18 dB higher than the amplifications in fig. 2 for 40 kHz and 400 kHz relatively.
It is natural that the limiting thickness $t_{lim}$ of dielectric coating depends on the defect depth and operational frequency. The dependences of limiting thickness $t_{lim}$ on the defect depth at operational frequencies 40 and 400 kHz for MDF 0601 EC probe are presented in fig. 4.

![Graph showing the dependence of limiting thickness on defect depth at 40 and 400 kHz.](image)

**Figure 4.** The dependences of limiting thicknesses $t_{lim}$ on the defect depths at operational frequencies 40 (V) and 400 kHz (Δ).

The best possibility to detect the defects through the dielectric coating is obtained at low operational frequency 40 kHz. For this frequency the shallowest 0.1 mm defect is estimated to be detectable through the 2.5 mm thick dielectric coating (see fig. 3.a) and deepest 2.0 mm defect is detectable through the 5.0 mm thick coating. Results presented on fig. 2-4 show the excellent sensitivity of MDF 0602 EC probe. These results are useful to estimate the possibility to detect the defects in fillet zone where some clearance between the probe and inspected surfaces is created due surface curvature in this zone.

![Graph showing EC probe signals.](image)

**Figure 5.** EC probe signals obtained through 0.5 mm (a); 1.0 mm (b) and 1.5 mm (c) thicknesses of aluminum plates.
3. Investigation of the possibility to detect defects through conductive nonmagnetic coating

In this section the possibility to detect the defects in ferrous steel components through aluminium coating with selected EC probe was investigated. Investigations were executed by few 0.5 mm thick aluminum plate applications. For better penetration low 40 kHz operational frequency was selected. In fig. 5 the signals in impedance and time-base modes obtained from different depth defects through aluminium plates with 0.5 mm (a), 1.0 mm (b) and 1.5 mm (c) thicknesses are presented. Amplifications in fig. 5,b and 5,c are relatively 6 dB and 12 dB more than the amplifications on fig. 5,a. These results are useful to estimate the possibility to detect the defects in blades coved by ceramic.

4. Investigation of the possibility to detect subsurface flaws in ferrous steel

The investigations were conducted with application of the special 5.0 mm thick specimen fabricated from ferromagnetic steel (fig. 6). In specimen 4 artificial electrical-discharge-machined slots with the same 0.1 mm width and 10 mm length and different 4.5; 4.5; 4.0 and 3.5 mm depths were performed. So, two adjacent defects were produced with the same maximal depth – 4.5 mm. In this case the flaw laying depths (or residual thicknesses) of flaws when specimen was inspected from undamaged side were 0.5; 0.5; 1.0 and 1.5 mm (see fig. 6). The initial point for probe balance and beginning of scanning is presented in fig. 1 also. For preliminary investigations 4 small size MDF 0601, MDF 0801 and MDF 1201 type low frequency double differential type EC probes with diameters 6.0, 8.0 and 12.5 mm were applied. The inspection results obtained with these probes are very similar. Best results were obtained with MDF 0801 EC probe which combines high penetration and spatial resolution with small operational size.

**EC inspection signal acquisition.** The EC probe signals were investigated in the hand scanning mode by computerized EC system based on the EDDYMAX card produced by Test Maschinen Tecknik. Signals were registered in complex plane and time-base modes at operational frequency 200 kHz.

**Surface braking defects.** As example, fig. 7 presents EC probe signals for 4 surface braking defects with depths 4.5; 4.5; 4.0 and 3.5 mm obtained were presented for next comparison. In this case the specimen was scanned from the damaged side.

![Figure 6. Ferromagnetic steel specimen with 4 artificial defects with 0.5; 1.0 and 1.5 mm laying depths](image-url)
The signals for different depth defects are differed by amplitude. One can indicate low frequency noise (trend) which becomes evident in changes of background signal amplitude between flaw indications. The main reason of these background amplitude changes is the material magnetic properties inhomogeneity.

**Subsurface defect signals analyses.** Fig. 8 represents EC probe signals obtained by scanning along 4 subsurface defects with 0.5; 0.5; 1.0 and 1.5 mm laying depths at operational frequency 200 kHz in time base mode without signal processing (left) and with HP filtering (right). High pass (HP) filtering with 0.5 Hz filter cutoff frequency was applied for low frequency noise suppression. The EC flaw detector input channel amplification (sensitivity) in fig. 8 was adjusted 18 dB (8 times) greater than in fig. 7 for surface defects.

Presented results (fig. 8) show that signals from defects with different laying depths are differed by amplitude. High low frequency noise (trend) is indicated. This noise is greater than presented before in fig. 7 because of greater flaw detector input channel sensitivity. Presented results show the possibility to detect subsurface defects in ferromagnetic steel without magnetic saturation when defect laying depth isn’t more than 1.5 mm. The signal amplitude for defects with maximal laying depth 1.5 mm is comparable with noise amplitude. So this small signal can be selected only by high speed signal changes observation. Better results were obtained when HP filtering with 0.5 Hz filter cutoff frequency was applied (see fig. 8, right). In this case the background line is not changed. So such mode is better for automatic threshold alarm application.

Next investigations represent the possibility to detect subsurface defects in ferromagnetic steel with additional clearance or dielectric coating between EC probes and inspected surface. Signals for 4 subsurface defects with 0.5 (twice); 1.0 and 1.5 mm laying depths through 2 mm thick dielectric plate obtained at 200 kHz operational frequency are presented in fig. 9. HP filtering for low frequency noise suppression also was applied for comparison.
Results obtained show the possibility to detect the subsurface flaw in ferromagnetic steel even through additional 2 mm thick dielectric coating or air clearance. It is very importance for hand inspection of components covered by coating or in automatic mode when some air clearance it is needed.

5. EC inspection of compressor blades by double differential probes

In this section some promising results obtained during compressor blades in-service inspection are presented [11]. Special double differential type EC probe with 5 mm operational diameter and long handle was developed for blade inspection. The most difficult for inspection and one of the most critical from the fracture mechanic point of view are the blade fillet zones. To validate new technology based on new probes application special reference blade with two 0,2x0,2x4 mm size slits were produced (fig. 10, left).

![Figure 10](image1.png)

**Figure 10.** Typical compressor blade for validation of EC testing with slits of 0,2x0,2x4 mm size (right); EC probes during fillet zone inspection (left)

![Figure 11](image2.png)

**Figure 11.** Signals obtained during compressor blade (fig. 10) inspection: lift-off signal for different probe orientation (a); signal of the slit (b) and slit repetition test for POD estimation (c)

Due high sensitivity with large clearance the fillet zones of blades can be inspected with double differential EC probes without shaping the head of the probe following the radius of
the fillet (fig. 10, right). Due high lift-of suppression the noise produced by changing of the radius along the scanning path also can be suppressed and don’t confuse the real indications (fig. 11). Presented results (fig. 11,c) also show the possibility to obtain not less than 95% POD for surface breaking slits. Presented technologies were applied for on-site gas turbine blade inspection in different countries (fig. 12).

Figure 12. The procedure of on-site inspection of gas turbine blades with long handle EC probe in Algeria

6. EC inspection technologies for detection of defects in gas turbine holes

For detection of defects on the lateral wall of gas turbine holes the special rotating head with double differential EC probes for application with ELOTEST SR-1 rotor was developed (fig. 13, left). Developed technology was based on ELOTEST 300 flaw detector application. For EC flaw detector calibration spatial reference standard with 39 mm hole and 4 artificial 0.2; 0.3; 0.5 and 1.0 mm depth like crack defects situated on hole sidewall was developed and produced.

Figure 13. ELOTEST SR-1 rotor with developed EC head and calibration reference standard

Figure 14 represents the results of reference standard inspection in rotating mode at operational frequency 400 kHz without any signal processing and for HP filtering with 20 Hz cutoff frequency.
7. Conclusions

1) Three EC inspection problems very important for gas turbine maintenance were investigated:
   - the possibility to detect defects with large clearance between probe and inspected surface;
   - the possibility to detect defects through nonmagnetic aluminum (conductive) coating;
   - the possibility to detect the subsurface defects in ferrous steel.
2) Investigations show a promising possibility to solve presented above problems with new double differential type EC probes application.
3) Double differential type EC probes demonstrate high sensitivity to surface and subsurface defects needed to be detected during gas turbine inspection. Even subsurface defects in ferrous steel can be detected without any magnetic saturation. Additional advantages of developed probes are high lift-off effect and structural noise suppression.
4) The developed double differential type EC probes were applied for detection of defects in blades and situated on sidewall of gas turbine holes. For this purpose special long handle EC probes and rotating head with double differential EC probe based on ELOTTEST SR-1 rotor are developed.
5) Presented technologies were successfully applied for gas turbine maintenance in different countries.

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