ANALYSIS OF THE FEASIBILITY TO INVESTIGATE CONDITION OF GAS TURBINE VANES BY MEANS OF THE RADIOGRAPHIC METHOD

ANALIZA MOŻLIWOŚCI BADANIA STANU ŁOPATEK TURBINY GAZOWEJ METODĄ RADIOGRAFICZNĄ

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Abstract: Operation of avionic turbine engines is always associated with possibility of various defects that may happen to turbine components, in particular to its vanes. The basic examination method intended to assess condition of the turbine vanes is the metallography, a destructive testing technology. The paper deals with the non-destructive test method of X-ray computer tomography (CT) that is chiefly used in medicine but is also suitable to diagnose how far the process of turbine vanes wear and tear is advanced. The computer tomography (CT) is the transmission diagnostic technique that makes it possible to obtain images of various layers within the investigated object. Application areas of this technique include also the quality control in manufacturing of technical facilities. The study presents results of assessments for gas turbine vanes with the use of the X-ray computer tomography after a specific period of the turbine operation. It was found out that the radiographic method, owing to availability of 3D images (including also internal defects) makes it possible to detect types of defects, their sizes and locations.

Keywords: X-ray computer tomography, turbine vane, status, diagnostics

Streszczenie: W procesie eksploatacji lotniczych silników turbinowych występują różnego rodzaju uszkodzenia elementów turbin, a zwłaszcza ich łopatek. Podstawową metodą oceny stanu łopatek są badania metalograficzne – metoda niszcząca. W artykule omówiono stosowaną obecnie, głównie w medycynie, rentgenowską tomografię komputerową (angielski skrót: CT) oraz możliwości jej wykorzystania do diagnozowania zmian stanu łopatek turbin, jako metodę badań nieniszczących. CT jest transmisyjną techniką diagnostyczną umożliwiającą uzyskiwanie warstwowych obrazów obiektów badań. Wykorzystywana jest między innymi w procesie kontroli jakości produkcji obiektów technicznych. Przedstawiono wyniki oceny stanu eksploatowanych łopatek turbiny gazowej rentgenowską tomografią komputerową. Stwierdzono, że metoda radiologiczna wygenerowując przestrzenny obraz stanu (wad wewnętrznych) łopatek umożliwia rozpoznanie ich rodzaju, wielkości i umiejscowienia.

Słowa kluczowe: rentgenowska tomografia komputerowa, łopaska turbiny, stan, diagnozowanie

1. Introduction

Operation of avionic turbine engines always entails various damages to their components, in particular their vanes. The analysis of failures that have occurred in the past indicates that all possible defects can be classified to one or several causal groups that are frequently mutually interconnected. As a result one can distinguish failures that may result from manufacturing imperfections, improper repairs or negligence in maintenance or operation.

The most frequent defects of turbines are associated with adverse structural alterations of the vane material caused by excessive temperature and prolonged duration of its effect as well as aggressive composition of exhaust gases (overheating of the material, thermal fatigue of vanes). Small and dot impairments or insignificant rubs on the vane surface are frequently not visible during first hours of the engine operation after the damage has occurred and cannot be detected by the diagnostic staff during investigations. Due to damage of protective coatings that cover the turbine vanes with simultaneous effect of high temperatures and aggressive environment of exhaust gases the vanes are subjected to the overheating process with burning of the parent material of vanes. The original reason for such a deterioration of vanes that finally lead to material defects (Fig. 1) are just below the vane surfaces [1, 2].

Deficiencies in quality of the manufacturing process and incompetent repairs present the next group of reasons for defects that are detected within the 'hot' part of the engine during prophylactic diagnostic examinations. These are defects that remain beyond control of users and that may be disclosed during the entire lifetime of engines.

The repair and overhaul processes enable easier access to turbine vanes, hence their technical condition can be assessed more precisely in a direct manner.

- visual assessment,
- fluid penetration,
- ultrasonic tests,
- X-ray examination (conventional, 2D)

As yet, the conventional methods fail to guarantee sufficient reliability and trustworthiness of assessment dedicated to structural alterations within vanes, internal defects, initiation of subsurface cracks. Condition of vanes can be preliminary estimated by the diagnostic staff after a visual inspection and their decision is verified by means of the destructive method by completion of metallographic investigations.

*Fig. 1 Examples of thermal defects on edges of attack
on vanes of the turbine rotor [2]*

Therefore, the method of computer tomography can be really suitable for the verification process as CT is a non-destructive method of investigation.

2. Essence of the tomography method

Tomography is a collective name for a set of diagnostic techniques intended to obtain a 3D image that present cross-sections of the test piece. Several different tomography techniques are distinguished:

- ‘Conventional’ tomographic X-ray imaging,
- 2D ultrasonography (USG 2D),
- Computer tomography (CT),
- Magnetic resonance tomography/imaging (MRT /MRI),
- Positron emission tomography (PET),
- Single photon emission computed tomography (SPECT),
- Optical coherence tomography (OCT)

Many fields of technical diagnostic systems widely use the method of computer tomography (CT). It is the variation of X-ray tomography that makes it possible to obtain 3D images owing to X-raying of the object from various directions. A tomograph (X-ray scanner) along with an implemented computer software is used to enable processing of tomographic images (Fig. 2). Nowadays, the CT technique is widely used in many industries for the process of quality control as a NDT method.

Fig. 2 Example of a tomographic image for a test piece with sophisticated geometry [5]

The first tomograph was constructed by EMI Ltd. from the United Kingdom in 1968 whilst the mathematical foundations were developed by Johan Radon in 1917 [3]. The appliances use an X-ray tube as a source of irradiation (Fig. 3).

Fig. 3 Schematic diagram of an X-ray tube [3]

Detectors of X-rays that are applicable to the computer tomography chiefly include ionization chambers and scintillators. In case of a scintillating detector the ionizing radiation causes excitation of atoms or molecules of the scintillating material. These, in turn, transmit the received energy by emission of radiation quanta (photons) within the visible spectrum. The light signal must be then converted to an electric current or voltage by means of a photomultiplier tube or a semiconductor photodiode.

The photomultiplier tube is a photoelectric tube that incorporates a photocathode intended to emit electrons in reverse to the received light illumination as well as a system of dynodes (electrodes) that multiply number of electrons, and an anode. Owing to the differential voltage between subsequent dynodes, the primary photoelectric current is amplified by several magnitudes of the initial value.

The photodiode is a semiconductor diode and its operation principles bases on the photoelectric effect that takes place within the area of a *p-n* junction. The voltage is applied to the photodiode in the reverse direction and the electric current flowing through the diode is directly proportional to the flux intensity of the falling light. The photodiode presents some advantages as compared to the photomultiplier, such as low value of the supply voltage as well as small dimensions and low weight.

The source of X-ray irradiation is used to take a series of X-ray images. Data stream from X-ray detectors convey information on absorbed or scattered irradiation by individual components of the examined test piece. That information is stored in the computer memory and is subject to the digital analysis in order to produce grey scale images. Each cross-section of the test piece images by means of X-rays is then decomposed to small components – voxels. Each voxel is associated with a numerical value that is proportional to the degree of X-rays absorption by a specific part of the test piece. To define these values for *n* voxels it is necessary to formulate at least *n* equations that describe absorption of radiation within a specific layer (cross-section). Therefore, one has to perform *n* various exposures for each cross-section of the examined layer. The more exposures is performed, the better image quality can be achieved. The first tomograph (X-ray scanner) was able to perform 28,800 exposures to formulate 6,400 equations (80 x 80 pixels). Modern instruments make it possible to carry out even up to 2 millions of exposures.

Nowadays, the analytic methods are mostly used to reproduce the images. They offer the best results but they require really high computation performance. The method of 2D Fourier analysis uses the Fast Fourier Transformation (FFT) method to interpret the obtained absorption profiles. The FFT method is applied to each exposure and therefore the absorption coefficient can be determined for each voxel. The absorption coefficients are then converted to CT numbers, which are also referred to as Hounsfield Units (HU).

$$IHU = K \frac{\mu_p - \mu_w}{\mu_w} \quad (1)$$

where:

K - amplification coefficient for images (a characteristic parameter for each individual tomography);

μ_p - absorption coefficient for each pixel,

μ_w - absorption coefficient for water (the reference value).

The CT numbers range from -1000 to +4000.

The assumed conversion method makes it possible to present grey scale images. As human eyes are not capable to differentiate 5,000 grey scale thresholds, only 256 levels of the dimming intensity are used. It presents a selected interval for the CT values. Finally, the computer display is used to present highly contrastive images that are easy for further interpretation. The predominant effect related to interaction between any part of the test piece and the falling radiation that is used for the power range typical for the CT method is the Compton's effect. The essence of that effect consists in scattering of electromagnetic radiation on a free or a valence (outer-shell) electron (Fig. 4).

Fig. 4 The effect of electromagnetic radiation scattering [3, 4]

That process can be described by means of the equation that defines intensity I of the radiation after passing through the examined material:

$$I = I_o \exp(-\mu \cdot dl) \quad (2)$$

where:

- μ - linear coefficient of radiation attenuation for the specific material and the radiation spectrum,
- dl - thickness of the homogenous material layer that is penetrated by the X-ray beam,
- I_0 - primary intensity of the radiation.

To diagnose condition of gas turbine vanes it is necessary to reproduce internal structure of the test piece with very high accuracy e.g. in order to determine dimensions of walls or to detect defects (failures). It is why the best results can be obtained with the use of the method with a linear detector (Fig. 5). That method assumes that the radiation beam is confined by means of a slit diaphragm (beam stop) to a flat beam in order to use a digital linear detector (only one row of sensors). After rotation of the test piece by 360° a flat X-ray image is obtained for the slice. In order to obtain a 3D image for the entire test piece the detail must be additionally moved along a horizontal plane with a full revolution after each step. The full 3D image is obtained after processing of all the collected information.

Fig. 5 Example of a tomographic examination with the use of a linear detector [5]

The CT examination can be carried out during the manufacturing process of turbine vanes for avionic engines, for instance to measure thickness of their internal walls with cooling channels or to examine structures of materials, detect defects or to support the diagnostic process during repairs or overhauls (thermal defects, alterations of the structure, contamination or clogging of cooling channels, etc.).

3. Application of the X-ray method to examine technical condition of gas turbine vanes

The computer X-ray scanning can be applied to examine turbine vanes, e.g. to measure actual thickness of internal, invisible walls. The scanned image of the examined test piece can be presented with colours to present shapes of internal walls with appropriate scale, size and location of possible defects. It is also possible to measure geometrical parameters of internal components and evaluate tolerances of their actual dimensions. Therefore, tomographic examinations enable to verify correctness of the part manufacturing with very high accuracy and to diagnose possible internal defects (cracks, clogging of cooling channels, etc.) in vanes that may directly result in thermal defects during operation of engines.

Fig. 6 The image of the gas turbine vane with determined thickness of its profile measured by means of the tomography from YXLON [6]

Fig. 7 The image obtained from examination of the gas turbine vane performed by means of the tomography from YXLON with the example for dimensioning of internal walls [6]

Fig. 8 The image of the gas turbine vane with determined thickness of its profile measured by means of the tomography from YXLON [6]

4. Conclusions

Verification of the technical condition demonstrated by gas turbine vanes that must be carried out both during manufacturing and repairs or overhauls is a very important but also a very expensive procedure. It is why application of the Computer Tomography (CT) method makes it possible to diagnose condition of the vanes (defects, failures) with fast rates, high accuracy and by means of non-destructive method. The method can be applied to on-line tests of all vanes from a manufacturing batch instead of

already performed random tests of representative samples taken from each batch.

The NDT method of computer tomography makes it possible to obtain 3D images that present actual condition of test pieces in extremely short times and with high reliability. It is a really promising method that can be possibly applied to large variety of test pieces, both to components of gas turbines and other parts of avionic engines or airframes, e.g. to perform diagnostics of parts that are made of composite materials.

Application of the CT method combined with other NDT techniques may substantially increase the probability that even POD defects are detected. It is the opportunity that shall significantly contribute to the improvement of operation safety, not only of engines but also of entire aircraft or helicopters.

References

1. Kułaszka A., Chalimoniuk M., Błachnio J.: *Types of damages to turbines of aircraft turbine engines and possibility of diagnosing them*. Journal of Polish CIMAC 2009 Vol. 4 No. 2 pp. 153-160.
2. Kułaszka, A., Chalimoniuk, M., *Report on research developments*, ITWL, Warsaw 2000 – 2010, unpublished (in Polish)
3. Cierniak R. *Computer Tomography. Design principles of CT equipment. Algorithms for recovering of images*. Warsaw 2005. (in Polish)
4. The research report from the X-ray Division of the Oncology Centre in Bydgoszcz: *'X-ray Computer Tomography'* (in Polish)
5. The research report from Electronic Instrument Service: *'CT – X-ray Computer Tomography for industrial applications'* (in Polish)
6. Data sheets from YXLON International GmbH.

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