ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1136990

THE COMPUTER-AIDED ANALYSIS OF IMAGES TO ASSESS CONDITION OF GAS TURBINE BLADES

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Abstract

In order to guarantee reliable and safe operation of avionic turbo engine their components and subassemblies are subjected to regular inspections and maintenance. The most frequent reasons for failures of the engines include overheating of materials, thermal fatigue of blades and vanes in the jet subassembly as well as the gas turbine rotor. Failures of that type lead to faulty operation of the engine and sometimes to accidents with disastrous consequences. The decision to have the engine repaired is taken by maintenance personnel that chiefly employ the method of visual inspection with use of a videoscope. However, such examination of turbine components is burdened by a subjective approach. To improve reliability and trustworthiness of the examinations results it is necessary to enable objective and unbiased evaluation of examination results. This paper outlines a non-destructive method that is suitable for evaluation of condition demonstrated by gas turbine blades and is based on digital processing of images acquired from the blade surface in visible light. To enable high clearness of these images the particular attention is paid to the problem of how to provide optimum conditions for investigations and mitigate geometrical distortions of images acquired from maintenance operations. The paper demonstrates that there are relationships between operation lifetime of blades and discoloration of their surfaces due to overheating of the blade material. These relationships are revealed by digital analysis of images acquired for the blade surfaces and expressed as statistical parameter of the first and second order. To improve unambiguity of the analysis results a low-pass filter was applied. It was demonstrated that these relationships are suitable for evaluation how much the status of the blade material microstructure is altered. Results from this study enable formulation of the conclusion that diagnostics of gas turbine blades through computer-aided analysis of images acquired from the blade surfaces may even be possible under field conditions with no downtime of the equipment under tests.

Keywords: *gas turbine, blades, discoloration, deterioration of microstructure*

1. Introduction

The key task for diagnostic technologies is to investigate condition of machine components and to answer the question whether the examined parts or subassemblies are suitable for further operation. In case of examinations by visual inspection the diagnostic personnel evaluates technical condition of the machine part predominantly on the basis of their subjective feelings and experiences. It is a really responsible job due to the need to take a decision whether the certain component is good enough for further use. On one hand, a part in sound technical condition can be replaced by mistake although it would be in use for a long time onwards, on the other hand, the omission to replace a faulty component may lead to a disastrous accident due to excessive wear of that part.

The ability of a human being to assess technical condition of machinery components depends on many external factors, thus the efforts have been undertaken to develop unbiased and objective techniques that make it possible to evaluate technical condition of a certain machine part or subassembly in a reliable and trustworthy way [2, 5, 12]. Continuous development of IT technologies is conducive to computerization of maintenance processes, including also formulation of diagnostic conclusions. Drawing up of a relevant algorithm for computer-aided decision making with regard to suitability of a component for further operation or not needs selection of input signals and parameters that shall be subjected to the analysis [1, 10, 11].

Images that present surfaces of gas turbine blades are usually acquired with use of optoelectronic devices, i.e. videoscopes or video analysers [3]. Such devices make it possible to take snapshots of hard accessible machine parts. Such devices (Fig. 1) are made up of a central unit that performs as a portable workstation capable of managing the acquired data as well as of an inspection probe provided with a powerful illumination source that provides a focused light beam, although such a light source makes it difficult to illuminate the investigated surface in a uniform manner.

Fig. 1. An optoelectronic device – a videoscope [3]

2. Investigation Methodology

Acquisition of information by means of a visual method with support of an optoelectronic device with further processing of gathered information and selection of the one that can be suitable for diagnostics of machinery components is a sophisticated process that needs an appropriate scheme of operations. In general, that process can be sequenced in the following way [2, 4, 5]:

- illumination, preferably with white light, of the investigation object located in the background,
- acquisition of images for the object of investigations,
- digital analysis of images,
- presentation of information about the image,
- taking a diagnostic decision.

Images for surfaces of gas turbine blades are recorded in the digital form with use of the RGB model of colours and the 24-bit format. It is the format that is predominantly used for colour images and enables digitalization of 16,777,216 different colours since each of three basic colours (Red, Green, Blue) may adopt 256 various grades of saturation [1, 11]. Each colour can be defined by three numbers within the range from 0 to 255. The white colour can be encoded as the three numbers [255, 255, 255] whilst the black one is represented by [0, 0, 0].

However, the RGB model substantially differs from the way how colours are identified by a human eye, since the identification process is based on evaluation of the colour attributes. The colour attributes should be understood as its typical, inseparable properties that are used to describe each of the three parameters: colour hue (tint, shade) – the quality identification of the colour wavelength, saturation – the deviation of the specific colour from whiteness and brightness that indicates whether the specific colour is more white or black.

The images of already operated gas turbine blades that are acquired with use of a videoscope are shown in Fig. 2. These snapshots were taken during subsequent inspections of the turbine interior. The first inspection of the turbine was carried out when the machine was new, i.e. after 0% of hours of its operation and the subsequent ones after specific operation time, until 100% of supervised operation expired. During the subsequent test phases some interesting fragments of blades were selected with symptoms of blade defects and these fragments were subjected to detailed analysis (Fig. 3). Due to irregular shape of the interesting fragments of defects, these images were trimmed to regular forms on the black background in order to get rectangular images with the size of *MxN* pixels.

Digital images have a specific property, namely it is possible to plot their histograms, i.e. a bar graph that represents frequency of pixels with a specific colour. It is one of possible methods that make it possible to present empirical distribution of a specific feature. In case of digital images, the histogram depicts frequency of shades that are assigned to individual pixels. The OX axis presents subsequent values of brightness level from 0 that stands for black to 255 that corresponds to white. In turn, the numbers of pixels with specific brightness are marked down the OY axis.

a) *b)* *c)* *d)*

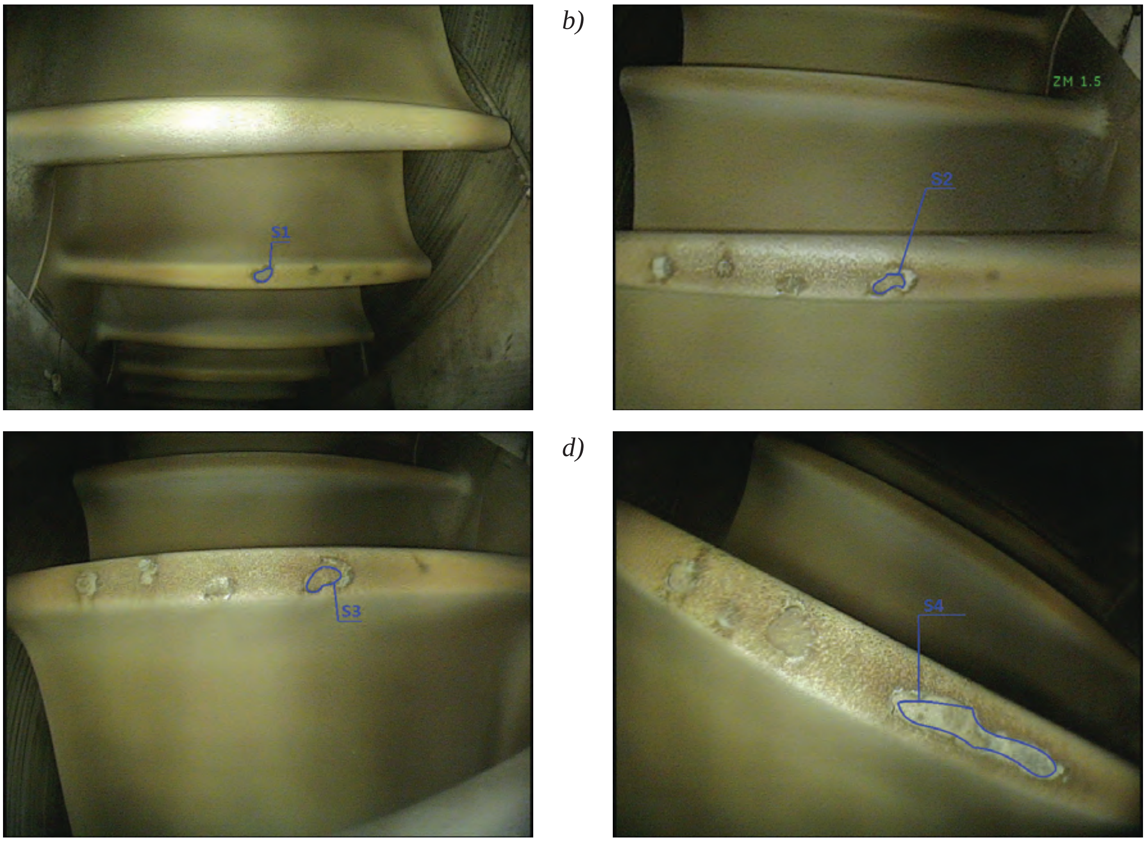

Fig. 2. Forms of defects exhibited by an example of a gas turbine damaged by overheating with indicated areas of interests. The sequence of inspections: a) No. 1; b) No. 2; c) No. 3; d) No. 4 [8, 9]

The analysis of each single image was started with loading of the image file to the operating memory of the Matlab software environment and then the commands of the Image Processing Toolbox package were used to extract basic layers of the RGB model and to convert a colour image into a monochromatic one. Consequently, four matrices were obtained as results of these operations and the values of histograms were determined for each matrix and then stored in the form of vectors.

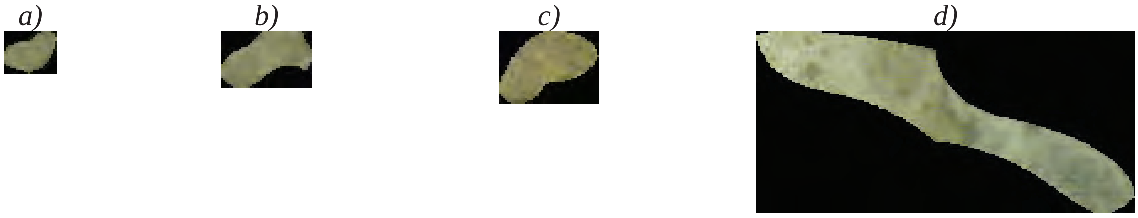

Fig. 3. Images from subsequent areas of interest subjected to the analysis: a) S1, b) S2, c) S3, d) S4

The version of the Matlab-Simulink software available to authors [6] is deprived of bandwidth filters. Therefore, an own circuit (workflow) was developed [7] with use of other available tools within the package with the aim to smooth histograms as is shown in Fig. 4. It is based on a purposefully developed low-pass Butterworth filter of the 4th order [9] that has been used both for smoothing the histograms (FiltrBut4ord3) and for compensation of a phase lag (FiltrBut4ord2).

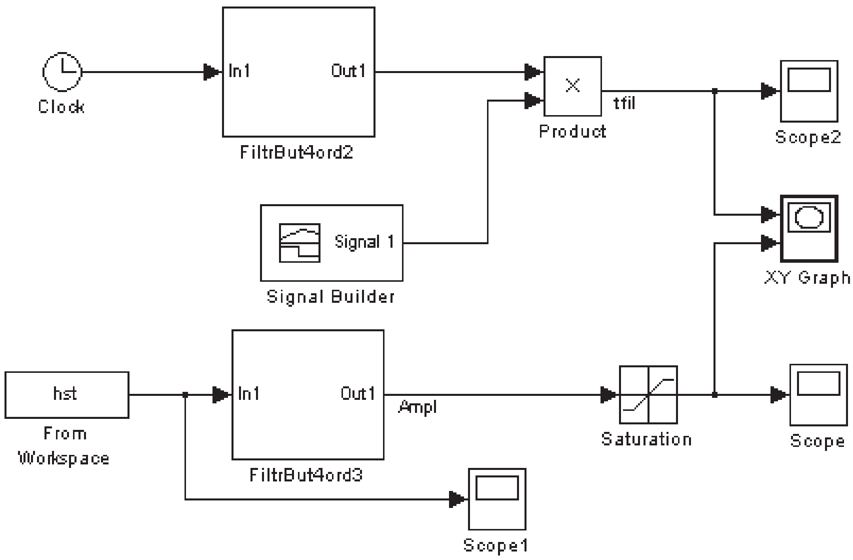

Fig. 4. The circuit for smoothing histograms by means of low-pass filtration along with compensation of phase lag

The histogram in Fig. 5 shows how many points with specific values of colour saturation belong to the image under analysis.

$$H_g = \sum_{n=1}^{L_w} \sum_{k=1}^{L_k} p(g, x_{w,k}), \quad p(g, x_{w,k}) = \begin{cases} 1 \text{ when } x_{w,k} = g, \\ 0 \quad \text{otherwise,} \end{cases} \tag{1}$$

L_w – number of rows in the image matrix,
L_k – number of columns in the image matrix,
g – number of pixels with the specific colour saturation.

The next step consisted in determination of the saturation peak and the brightness that corresponded to that peak as well as the method of acquiring these parameters. The last operations comprised by that cycle included storage of brightness and saturation parameter into a file and plotting envelopes for all histograms.

A separate software was used to calculate statistical parameters of the second order, i.e. the arithmetical mean, variance, skewness and kurtosis. The method for determination of these parameters was modified to avoid calculation errors due to superposed background. The introduced correction consisted in making the following substitutions in the foregoing formulas:

– the number of pixels with the values different from 0 counted up by the software was substituted with *MxN*,

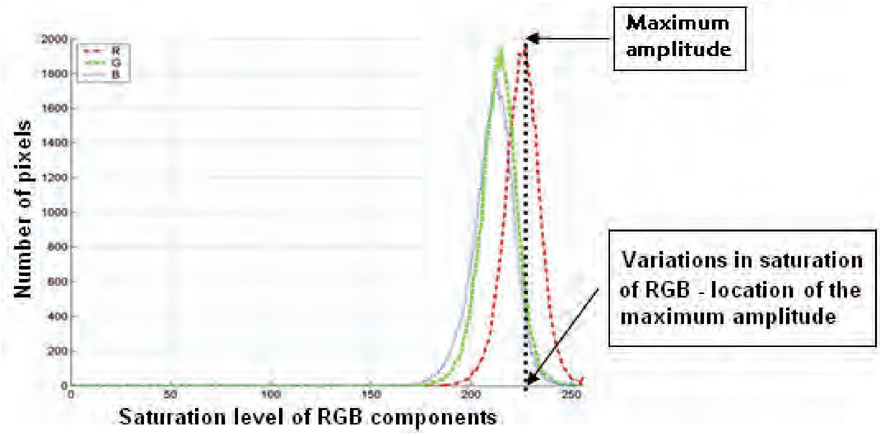

Fig. 5. Examples of smoothed histograms for RGB images of the blade surface

– *H(1)=0* – it is the reset of the sum for black pixels of the background,
– $(i-1)-\mu$ – the Matlab software starts indexation from 1, therefore the values corresponding to the specific levels of brightness are shifted up by 1.

These measures resulted in the benefit that statistical parameters were calculated exclusively for pixels that conveyed valuable information, suitable for further analysis.

The own workflows developed in the environment of Matlab software and the parameters obtained from analysis of image made it possible to carry out objective analysis of blade leaves with consideration to their defects due to overheating of the blade material.

3. Investigation results

The data obtained from processing of monochromatic images for blade surfaces depict variation of the parameters subjected to the analysis as functions of the overall operational lifetime. Filtration of results of the first order statistics was the initial stage of image analysis (Fig. 6).

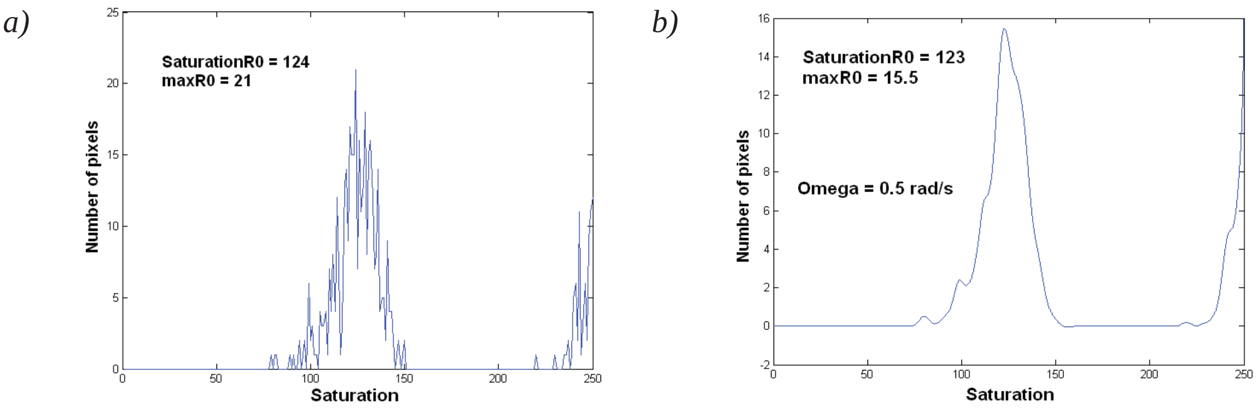

Fig. 6. The first order statistics for a sample cut-out of an equivalent monochromatic image acquired for overheated blade edge a) – without filtration of results, b) – after low-pass filtration

As the time of blade operation goes by, its edge of attack exhibits increased areas of defects on the protective coating (Fig. 2). In addition, the analysis of images acquired for the blade surface made it possible to reveal dislocation of the saturation peak (Fig. 7). The brightness of monochromatic images for overheated areas is getting more and more intense. It is possible to assume that the variation of the average image brightness (RO saturation) in time represent a linear function whilst position of the saturation peak (max. RO) varies as an exponential function (Fig. 8 and 9).

Shapes and sizes of overheated areas on turbine blades clearly indicate that these areas tend to expand in pace with the operation time. Processing of images for these areas made it possible to achieve results that confirm progress of the destructive effect associated with the material overheating. The values of calculated statistical parameters for pieces of images acquired from inspections on the early stage of the turbine operation are pretty comparable but substantial growth of these values is observed for further areas of interest.

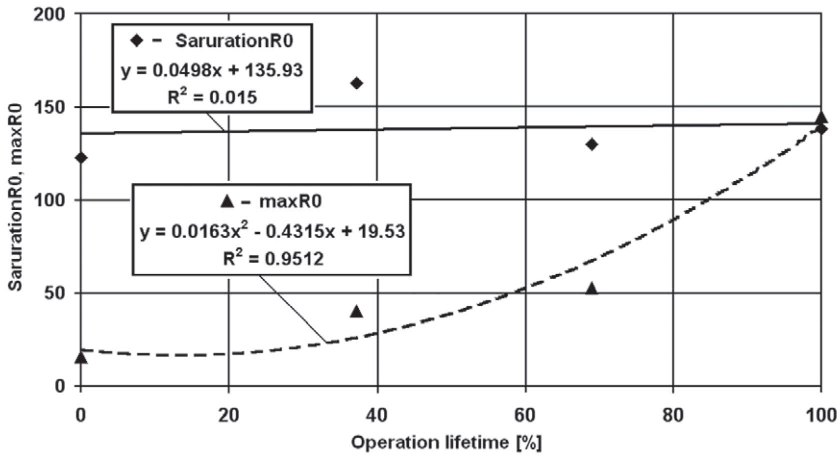

Fig. 7. Variations of the first order statistical parameters – saturation RO and max RO

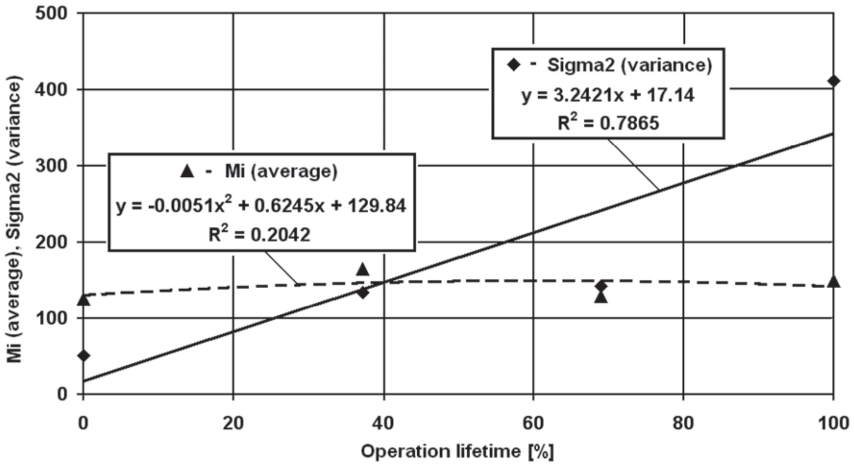

Fig. 8. Variations of the second order statistical parameters – Mi – average and Sigma^2 – variance

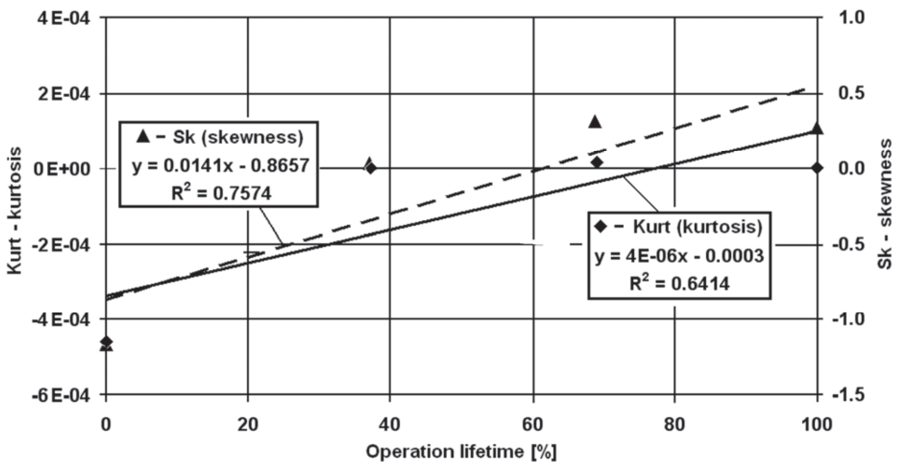

Fig. 9. Values of the second order statistical parameters – Sk – skewness and Kurt – kurtosis

4. Recapitulations and Conclusions

Operation of gas turbines, similarly to other machinery, is associated with defects of various size and severity. Due to operating conditions of turbines, the most frequent defects include overheating of the blade material and thermal fatigue. These defects are caused by exceeding the maximum permissible temperature of the exhaust gas and uneven distribution of temperatures on the turbine rim and they lead to deterioration of the material strength. In addition, such defects entail extremely substantial difficulties in objective assessment of whether or not the turbine components are suitable for further operation. Since provision of high level of reliability and operational safety of turbines is the unconditional requirement, the turbines are subjected to periodical inspections of their technical condition.

Until recent times the evaluation of technical status demonstrated by the turbine the maintenance staff by means of visual inspection have carried out blade. Reliability and trustworthiness of such inspections can be improved when the acquired images are subjected to computer-aided analysis. Under such circumstances, the servicemen may take advantage of a multi-criteria evaluation with consideration to statistical parameters of the first and second order. The decision whether or not operation of the machine can be carried on should be based on the fact that not every defect is critical and prevents the machine subassembly or part from further operation. Therefore, the objective and reliable evaluation of the overheating severity supported by software tools may be suitable for optimization of the overall lifetime for gas turbines.

The investigation methodology outlined in this paper should be validated for each type of gas turbines since nature of defects in the form of the blade material overheating is specific for each turbine type. The analysis of overheated areas for various types of gas turbines has revealed that for some turbines the blades demonstrate overheating defects on the leaf surfaces and for other ones on the blade edges of attack. This fact needs adjustment of the investigation methodology to individual case studies, with consideration to various configurations and irregular shapes of overheated areas (areas of interest).

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