IDENTIFICATION OF MACHINE TECHNICAL STATE ON THE BASIS OF FOURIER ANALYSIS OF INFRARED IMAGES

Marek FIDALI

Department of Fundamentals of Machinery Design, Silesian University of Technology
Konarskiego 18a, tel.: 32 237 1063, fax.: 32 237 1360, e-mail: marek.fidali@polsl.pl

Summary

In the article results of analysis of sequence of infrared images with use 1D Fourier transform is presented. Images were analyzed in the same way like this known from branch of active thermography where pulse phase method is applied in order to detect structural defects in the materials. Research was carried out with use of thermovision images recorded during operation of rotating machinery. The amplitude and phase images which described different technical states of observed machines were calculated. In order to generate the most informative images of amplitude and phase a procedure of frequency selection was proposed. Qualitative and quantitative estimation of the amplitude and the phase images shows that presented way of sequence of infrared image analysis provide useful diagnostic data which allow identification changes of machine technical state.

Keywords: diagnostics, thermovision, Fourier analysis, image processing.

IDENTYFIKACJA STANU TECHNICZNEGO MASZYN NA PODSTWIE WYNIKÓW ANALIZY FOURIERA OBRAZÓW TERMOWIZYJNYCH

Streszczenie

W artykule przedstawiono wyniki analizy obrazów termowizyjnych z zastosowaniem jednowymiarowej transformaty Fouriera. Obrazy analizowano w sposób znany z dziedziny termografii aktywnej gdzie dla potrzeb detekcji defektów materiałowych stosowana jest metoda impulsowo fazowa. Badania przeprowadzono na obrazach zarejestrowanych podczas działania maszyny wirnikowej w różnych stanach technicznych. W wyniku analizy zarejestrowanych termogramów wyznaczono amplitudogramy i fazogramy reprezentujące różne stany techniczne maszyny. Jakościowa i ilościowa analiza obrazów amplitudy i fazy wskazują, że prezentowane podejście do analizy sekwencji obrazów termowizyjnych umożliwia identyfikację zmian stanu technicznego maszyny.

Słowa kluczowe: diagnostyka, termowizja, analiza Fouriera, analiza obrazów.

1. INTRODUCTION

Thermographical measurements find a broad application in maintenance and technical state assessment of machinery, apparatus and industrial processes [5]. Continuous thermovision diagnostics of a technical object requires that systematic series of operations consisting in acquiring, processing, analyzing and recognizing infrared images have to be carried out. As a result of image analysis, important diagnostic information coded in thermographic images is extracted.

The research connected with infrared image processing and analyzing for machinery diagnostic has been carried out in Department of Fundamentals of Machinery Design for a few years [2],[3],[4]. During the previous research a formalized method of thermovision data analysis has been proposed. According to the method a sequence of thermograms acquired during a continuous observation of a machine is treated as a multidimensional thermographic signal ST(T(x,y),t) where $T_i(x,y)$ is thermographic image recorded in given moment of time t_i and x, y describe spatial resolution of the image. Thermographic signal could be analyzed under assumption that real time domain could be partitioned into “micro” (dynamic) and “macro” (operational) time domains [1]. Such approach allows treating short sequence of infrared images as thermographic signal in “micro” time. One could assume that analysis of thermographic signal in “micro” time result one relevant feature value which could be treated as value of diagnostic signal in “macro” time (Fig.1).

Due to large thermal inertia of most mechanical objects, “micro” time should be treated in range of minutes or hours and “macro” time in range of days and weeks.

Example of application of assumed methodology is presented in the article. A results of the research concern in “micro” time analysis of thermographic signals recorded during operation of investigated machine in different technical states.

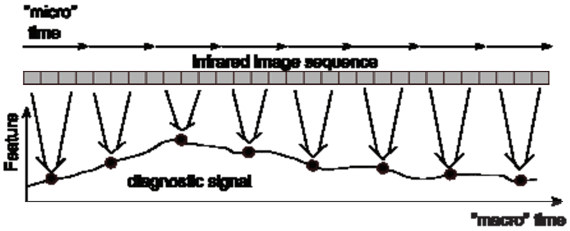


Fig. 1. Idea of analysis of sequence of infrared images in both “micro” and “macro” time

For purposes of analysis of thermovision image sequence approach based on commonly used method in branch of active thermography was applied. The method use 1D Fourier analysis of thermovision image sequence.

2. FOURIER ANALYSIS OF SEQUENCE OF THERMOVISION IMAGES

1D Fourier transform can be applied to the thermographic signal acquired during machine observation in the same way as it is known in the field of active thermography where a pulse phase method is applied in order to detect structural defects in materials [7].

In this method a signal describing temperature evolution over time for a given pixel of each recorded infrared image is transformed to frequency domain with the use of Fourier transform. The results of Fourier transform are represented in a form of real and imaginary parts estimated for given discrete frequency values f_n calculated in the following way [7]:

$$f_n = \frac{n}{Nt_s} \tag{1}$$

where:

N – number of thermal images in the sequence
ts- time interval between thermal images (ts=30s)
n=0,1,…,N/2.

On the basis of the real and imaginary parts of spectrum calculated for all pixels at given frequency new images of magnitude and phase are formed. As shown in the literature [7], phase and amplitude images have selective, frequency-dependent capability in identification of heating uniformity. The amplitude images are less noisy but are sensitive to no uniform heating what can be referred to low-pass filter behavior. The phase images allow us to probe under the surface of observed an object and are less sensitive to degradation coming from optical and infrared surface features. The phase images can be also considered with respect to the band-pass filter behavior [7].

One can expect that discussed method could be useful to estimation of machine technical states whose manifest in no uniform distribution of temperature on observed surface and produce more heat in short time e.g. during machine run-up or during disturbance of machine operation.

Application of 1D Fourier analysis to sequence of thermovision images generates two series of images both magnitude and phase in frequency domain. The images could be called magnitudegrams and phasegrams. Analysis of these images seems to be time consuming because need to examine and interpret each of them in order to choose relevant one. Selecting of relevant images strongly depend on experience and subjective decision of the researcher. Make of the magnitudegrams and phasegrams suitable for automatic evaluation of machine technical state requires procedure of selecting of representative images for further analysis. Such procedure was proposed and is based on assumption that reference sequence of images described proper and nominal machine technical state is available. On the basis of such reference sequence of infrared images one can find coordinates of such image pixel over which temperature evolution in time have the highest variation. Such pixel could be called as reference one. Function described temperature evolution over reference pixel is transformed to frequency domain in order to obtain reference spectrum for further analysis. On the basis of the reference spectrum one can identify *n* meaningful frequency components e.g. components with first few highest values. For the frequencies corresponding to chosen spectrum components one can select magnitudegrams and phasegrams for further analysis.
In order to obtain qualitative or quantitative data both amplitude and phase images could be processed and analyzed with use of suitable fitted methods [6].

2.1. Considered data

Usability of application of Fourier analysis of infrared image sequence for the purposes of machinery diagnostics was verified on experimental data acquired during an active diagnostic experiment The experiment has been performed in the Laboratory of Technical Diagnostics of Department of Fundamentals of Machinery Design. The aim of the experiment has been to acquire thermographic signals during operation in following manually simulated technical (operational) states:

S0 – machine during heating (run-up) – 120 images
S1 – machine without faults – 120 images
S2 – 50% throttling of air pump - 120 images
S3 – 90% throttling of air pump – 120 images
S4 - 90% throttling of air pump + clearance of second bearing mounting – 120 images
S5 – load of disk brake – 120 images
S6 – faulty bearing no 2– 120 images.

Infrared images have been acquired with use of thermovision system every 30 seconds period. The total number of recorded images has been 840. The machine was working with rotation speed equal to 1150 rmp.

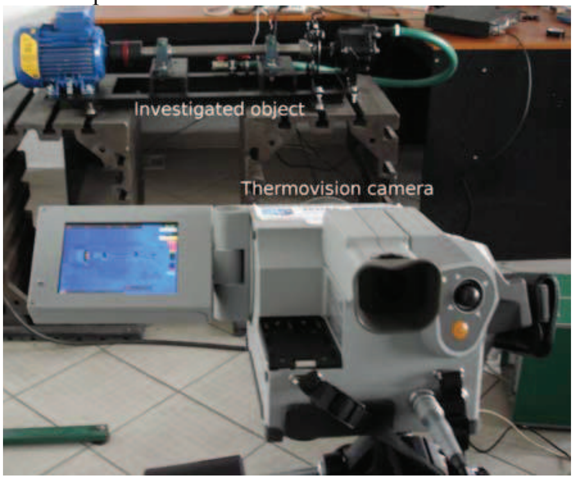


Fig. 2. Investigated object and applied infrared camera

It is necessary to point out that technical state S1, S2 and S3 were very similar and were simulated purposely in order to check whether it was possible to notice a weak change of the technical state on the basis of the considered diagnostic signals. Such a small change in the technical state were also desirable for testing ability of the classifiers recognizing machine technical states difficult to be distinguished.

The thermovision images acquired during the experiment were processed before further analysis. The first operation was selection of interesting areas in the thermograms. One decided to select two Regions Of Interest (ROI3 and ROI4) representing the bearing housings (Fig. 3).

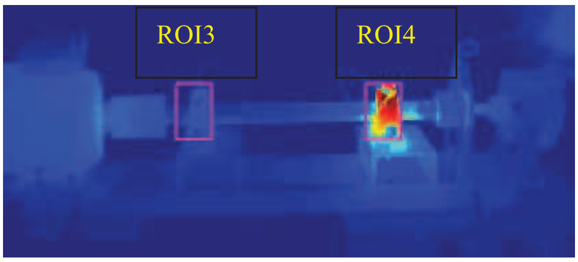


Fig. 3. Thermovision image of the operating laboratory stand, with marked ROIs of the first (left, ROI3) and the second (right, ROI4) bearings

Those ROIs were interesting due to two reasons. Firstly, the most of the machine failures are visible in bearings operation and secondly the construction and shape of both the bearings housing were the same. One expected that changes in the machine technical state affect changes of bearings temperature and should be revealed in the sequence of thermographic images. Taking into account two ROIs presenting a view of the same type of the bearing housing could be beneficial for the verification of different image features.

In Fig. 4. functions of temperature mean value computed for ROI3 and ROI4 is presented. One can observe that for state S0 heating process of bearing housings is clearly visible on the both plots. In case of ROI3 for states S3 and S5 significant temperature changes are noticeable. Within the boundaries of the ROI4 mean value of temperature along time of observation indicates that rapid temperature change occurs for state S6. In state S4 a significant temperature change is also visible.

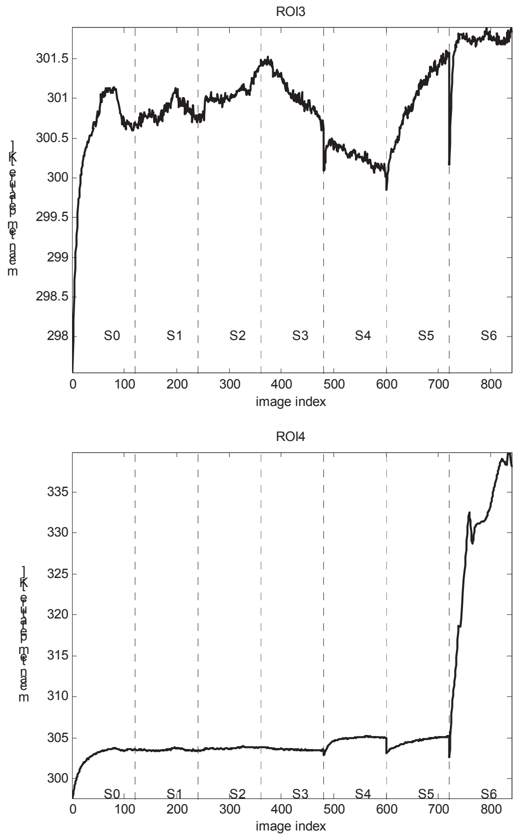


Fig. 4. Course of mean temperature computed over a) ROI3 and b) ROI4

The recorded sequences of thermovision images represented by the selected ROIs was submitted for analysis with use of procedure described earlier.

2.2. Analysis of magnitudegrams and phasegrams

According to proposed procedure of analysis in “micro” time the infrared image sequence for state S1 was selected as reference. For this state reference temperature characteristics over observation time, described by the highest variance was estimated. On the basis of a spectrum of reference temperature characteristics n=4 frequency components were identified (Fig. 5). Constant component of the spectrum wasn’t considered. Frequency components were identified for both ROI3 and ROI4 and in Fig. 5 exemplary plots of magnitude and phase spectrum for ROI3 is presented. For frequency values of selected components for each state magnitudegrams an phasegrams were selected for further analysis.

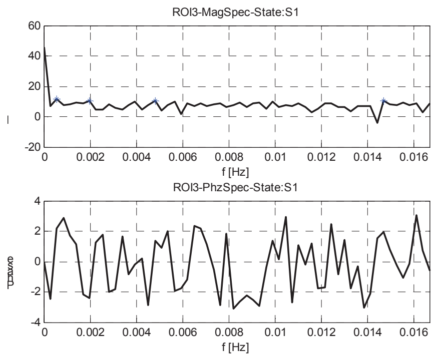


Fig. 5. Exemplary plot of magnitude and phase spectrum with selected 4 highest frequency components

In figure 6a exemplary magnitudegrams and phasegrams of state S4 are showed. Qualitative analysis of presented images is rather difficult due to high level of noise especially for images corresponding to higher frequency components. Image of magnitude corresponding to first frequency component allow identifying shape of the bearings housing. Images of phase are characterized of high level of noise. Visual analysis of the magnitudegrams and phasegrams allowed us to assumed that the most informative for further analysis are images corresponding to the first significant frequency component.

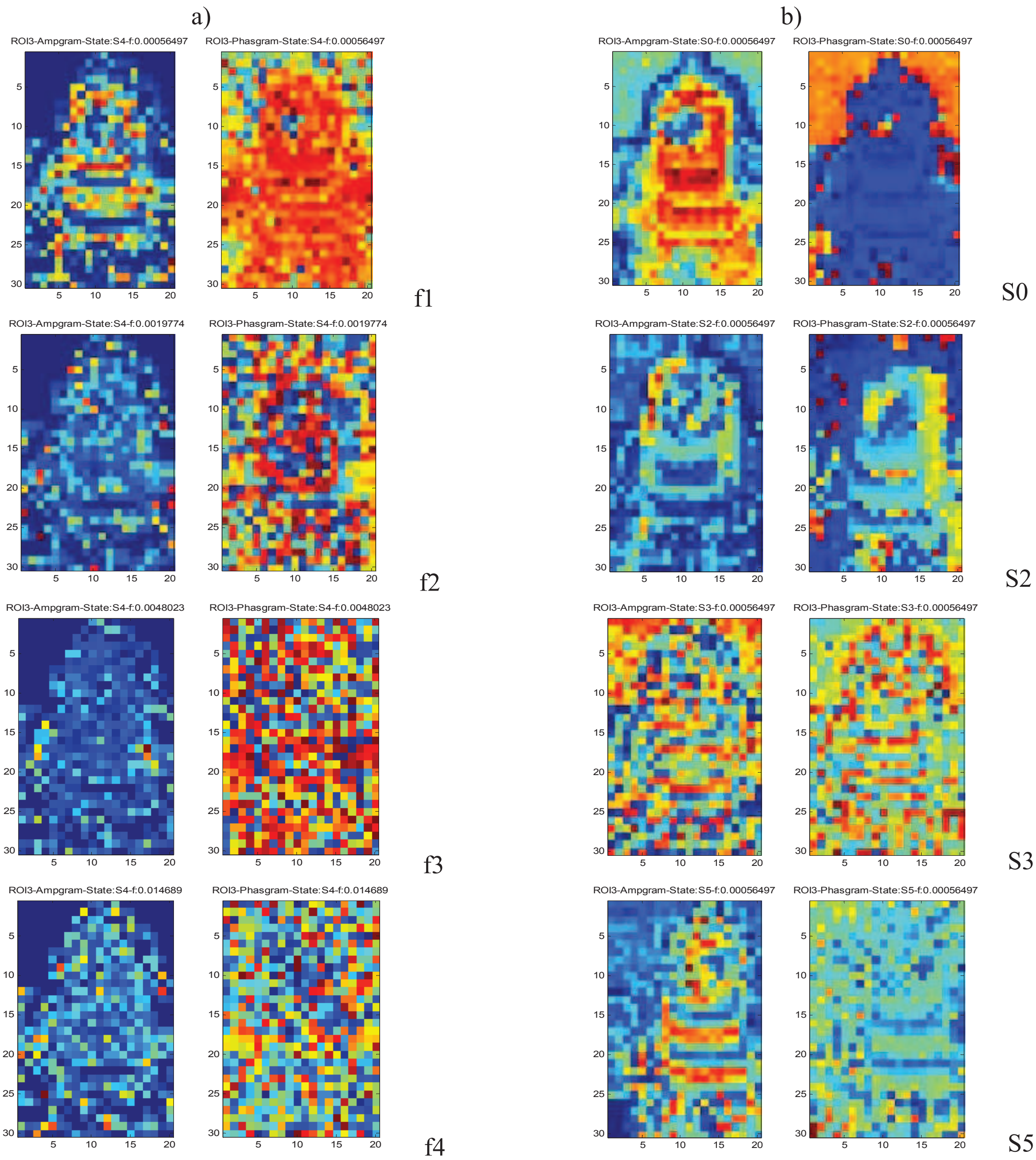


Fig. 6. Magnitudegrams and phasegrams calculated over ROI3 for a) different frequencies and b) different technical states

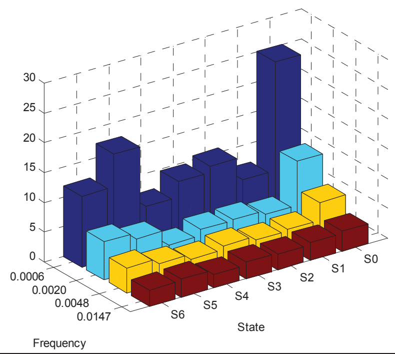
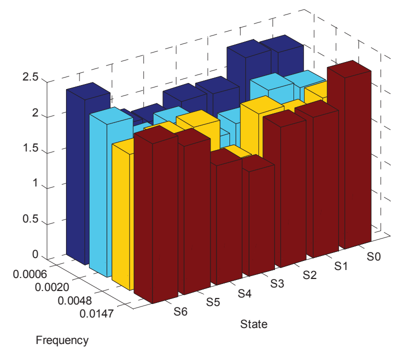
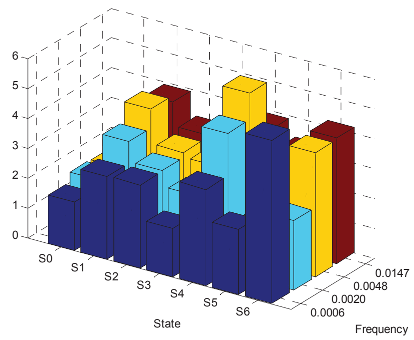
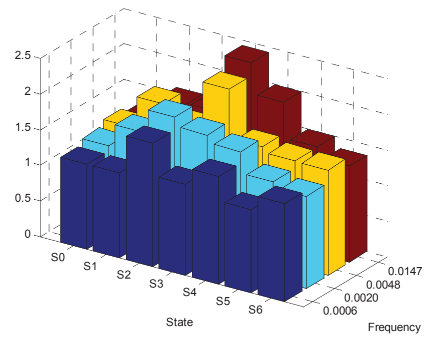
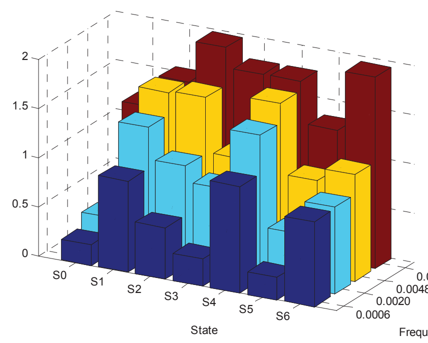
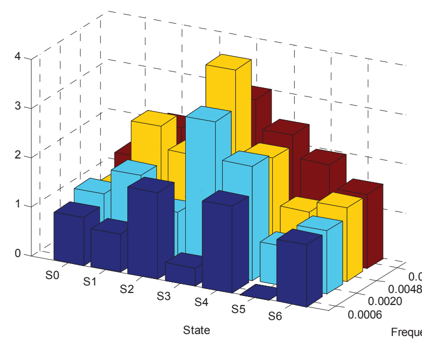
	Estimated for Magnitude Images	Estimated for Phase Images
RMS		
Kurtosis		
Entropy		

Fig. 7. Exemplary plots of different feature values for magnitudograms and phasegrams represented by ROI3

3. CONCLUSIONS

On the basis of the conducted research it was found that application of Fourier analysis to sequence of infrared images in “micro” time allow us identify changes in the machine technical state. One can state that images of magnitude and phase corresponding to first frequency component are significant and their analysis with use of commonly know statistics allow us to recognize change of technical state manifested by rapid increase or decrease of temperature on observed area of the machine. One can assume that features of magnitudegrams and phasegrams could classify machine technical state. In order to confirm this assumption further research are necessary to perform.

REFERENCES

[1] Cholewa W., Kaźmierczak J.: *Data Processing and Reasoning in Technical Diagnostics*, Wydawnictwo Naukowo_Techniczne, Warszawa, Poland, 1995.

[2] Fidali M., Jamrozik W.: *Search for optimal estimators of thermogram Fourier images*. In “*Recent Developments In Artificial Intelligence Methods*”. Edt. Burczyński T., Cholewa W., Moczulski W. AI-METH Series, Gliwice 2009, p. 103-112.

[3] Fidali M.: *An idea of continuous thermographic monitoring of machinery*. Proceedings of 9th International Conference on Qualitative InfraRed Thermography QIRT 2008, July 2-5, Kraków, Poland, 2008.

[4] Fidali M.: *Zastosowanie transformaty Fouriera obrazów termograficznych do oceny zmian stanu technicznego maszyny*. Diagnostyka procesów i systemów, Korbicz J., Patan K.,

Kowal M. (ed.). Akademicka Oficyna Wydawnicza EXIT, Warszawa 2007, 181-188.

[5] R. A. Thomas, *The thermography monitoring handbook*. Machine & systems condition monitoring series, Oxford, UK: Coxmoor Pub., 1999.

[6] S. M. Nixon and S. Aguado, *Feature Extraction and Image Processing*. Newnes, 2002.

[7] X. P. V. Maldague, *Theory and Practice of Infrared Technology for Nondestructive Testing*. Wiley, 2001.

Marek FIDALI, PhD, assistant professor at Department of Fundamentals of Machinery Design. Main area of research: technical diagnostics, thermovision, modal analysis, signal and image processing.