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THERMAL ANALYSIS OF THE FRICTION PROCESS OF SLIDING BEARINGS USING A STATISTICAL APPROACH

TERMICZNA ANALIZA PROCESU TARCIA ŁOŻYSK ŚLIZGOWYCH W UJĘCIU STATYSTYCZNYM

Key words:

sliding bearing, thermal imaging, statistical analysis, operating temperature

Słowa kluczowe:

łożysko ślizgowe, termowizja, statystyczna analiza, temperatura pracy

Abstract

During the friction processes in a sliding bearing complex, phenomena occur that are included amongst the most difficult and complex problems in tribological studies. Therefore, there is a need for a systematic application of modern diagnostic methods and statistical tools to correctly interpret the operating status of the sliding bearing. The use of these tools is designed to ensure proper operational functioning of the tribological system. The paper

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presents the test results in the form of thermograms and their subsequent processing with the use of statistical tools. The tests were performed on a laboratory stand with the bearing operating in the presence of a lubricant and with the bearing operating in conditions of technical dry friction. FLIR ResearchIR and STATISTICA software were used for the analysis of the temperature distribution. Final remarks contain the conclusions of the research and recommendations for further study.

INTRODUCTION

Thermal diagnostics is a simple and very effective method for detecting irregularities in many technical facilities **[L. 1]**. The thermal diagnostics methods include, on one hand, the observation of thermal phenomena, and, on the other hand, diagnostic inference based on recorded temperature values **[L. 2]**. The basic factor that determines the methodology of diagnostic inference based on temperature data is the way the data are gathered and interpreted. Among many methods, particularly interesting is the observation of thermal phenomena occurring in technical facilities using infrared thermal imaging **[L. 3]**. Application of thermal imaging is especially justified in tribological systems, e.g., a sliding bearing. Friction work takes place during the operation of the sliding bearing on the contact surface between the shaft journal and the bushing, and, as a result, dissipated heat is generated and mechanical work occurs which is related to tribological wear of the sliding bearing **[L. 4]**. The dissipated heat and related changes of temperature have a significant impact on determining the correct operating status of a tribological system. In particular, this refers to the impact of temperature on the thermal expansion of the bearing materials, bearing seizure, the change of lubricant properties at a given temperature, and grease aging, which is accelerated at high temperatures. The aim of this paper is to present the thermal diagnostic method of bearing operating status that occurs when the bearing is and is not lubricated. The temperature is measured with contact and contactless methods using a pyrometer and a thermographic camera. The paper also presents the methods of statistical analysis and an interpretation of the results of thermographic measurements obtained during the operation of the sliding bearing on the laboratory stand.

STATISTICAL ANALYSIS OF THE FRICTION PROCESS

Statistical methods are now widely used in the analysis and optimization of complex industrial systems **[L. 5, 6]**. Statistical analysis is applied in order to evaluate the operation of a sliding bearing based on the bearing housing temperature. The presented solution is based on the assumption that friction occurs on the contact surface between the shaft journal and the bushing and, as a result, dissipated heat is generated that then changes the bearing housing temperature.

The analysis will allow one to forecast incorrect friction processes occurring in the bearing that can lead to its damage. The starting point in the proposed solution is a stable operation of the bearing in a tribological system that corresponds to the specific bearing housing temperature, and the determination of factors that indicate significant irregularities in the operation. Stable operation is understood as the operation of a properly lubricated bearing during which unfavourable friction processes causing bearing seizure do not occur, and the temperature during the bearing operation is kept constant. This can be written as follows:

$$Y(t) = X_0 + \sum_{i=1}^{k} I_i(t) X_i \quad (1)$$

where $Y(t)$ – random variable corresponding to the observed friction operation in the sliding bearing at time t, X_0 – random variable corresponding to the stable friction process in the sliding bearing, X_i – random variables disturbing the stable friction process, k – possible causes of disturbed friction process, $I_i(t)$ – indicator function which takes the form: $I_i(t) = 1$ for all $i = 1, .., k$ of occurrence of causes of disturbed friction process with probability p_i, $I_i(t) = 0$ for all $i = 1, .., k$ of non-occurrence of causes of disturbed friction process with probability $1 - p_i$.

Assuming that the reason for unstable bearing operation is the absence of lubrication causing the increase in the bearing temperature and its seizure, the relationship (1) can be written as follows:

$$Y(t) = X_0 + X_i \quad (2)$$

where $Y(t)$ – random variable corresponding to the observed friction operation in the sliding bearing at time t, X_0 – random variable corresponding to the stable friction process in the sliding bearing, X_i – random variable disturbing the stable bearing operation.

Assuming that random variables $Y(t)$, X_o, X_i are independent and come from the same distribution with expected value μ, μ_o, μ_i and variance σ^2, σ_0^2 and σ_i^2, the relationship (2) describing the friction process in a sliding bearing can be written as follows **[L. 7]**:

$$Y(t) = N(\mu, \sigma^2) = N(\mu_0, \sigma_0^2) + N(\mu_1, \sigma_1^2) \quad (3)$$

where N – distribution of random variable corresponding to the observed friction process in the sliding bearing, μ_0, σ_0^2 – expected value and variance of temperature corresponding to friction during the correct operation of the bearing, μ_i, σ_i^2 – expected value and variance or temperature corresponding to friction during the incorrect lubrication or absence of it.

In our case, the determination of the statistical characteristics of the operation of the tested bearing involves the calculation of average temperature as an estimator of expected value, and of the variance for successive $i = 1, ..., n$ of temperature measurements from the marked areas of thermograms according to the following relationships **[L. 8]**:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{4}$$

$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \tag{5}$$

where $\bar{x}$ – average temperature value calculated from the marked area of the thermogram, σ^2– variance calculated from the marked area of the thermogram, x_i – i th thermogram recorded by the thermographic camera, n – number of temperature measurements made during the experiments.

In statistical analysis, the variance (5) is often substituted by standard deviation σ*,* which is calculated according to the following relationship **[L .9]**:

$$\sigma = \sqrt{\sigma^2} \tag{6}$$

The estimators determined according to (4) and (6) are indicators of the bearing operation. Observing their values allows one to forecast the friction conditions at which a given sliding bearing operates. It is also possible to determine the statistical limits (lower and upper) between which the average temperature values and standard deviation should lie for a correct bearing operation. The determination of these limits will be a subject of successive papers.

LABORATORY STAND

The stand design allows testing a sliding bearing using a thermal method **[L. 10]**. The schematic drawing of the stand is presented in **Figure 1**. The stand consists of the frame (1) on which the shaft (2) is supported on two ball bearings (3). The shaft is driven by the MS80 1.1 kW electric motor (4) with the speed controlled by the E1000 1.5 kW frequency converter (5).

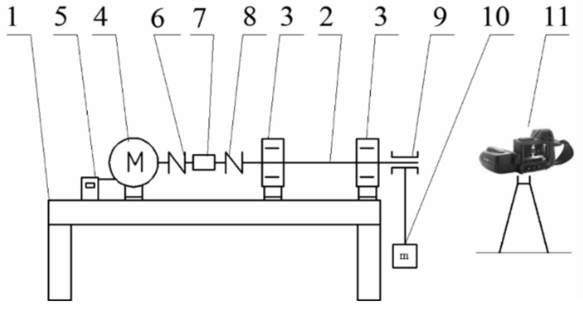

Fig. 1. Schematic drawing of the test stand
Rys. 1. Schemat stanowiska badawczego

The drive from the motor is transmitted via the metal bellows coupling (6) to the torque meter T20WN/10 Nm (7) and then via the metal bellows coupling (8) to the shaft (2). On the end journal of the shaft there is the tested sliding bearing (9) loaded with its own weight and the weight (10). Friction in the sliding bearing occurs on the contact surface between the shaft journal (2) made of C45 steel (hardness 220 HB and roughness of slide surface R_a = 0.063 μm and the bronze bearing bushing). The bearing operating temperature was recorded with a Flir T335 thermographic camera (11). The measuring system was built based on the amplifier and Catman software from HBM. The amplifier accuracy declared by the manufacturer is 0.1 %. The torque was measured on the T20WN/10Nm torque meter (7), which measures torque up to 10 Nm with a 0.2% accuracy at 10000 rpm maximum. This sensor additionally features an optical rotational speed transducer allowing the speed measurement up to 3000 rpm **[L. 11, 12]**.

The temperature distribution analysis was performed with FLIR ResearchIR software cooperating with a Flir T335 camera. Proprietary software was used to process the thermograms taken by the camera and to export them to other formats in the form of digital data. The obtained data were then used to calculate the average temperature and standard deviation using the STATISTICA package **[L. 13]**.

RESULTS

Selected results of the thermographic examination of sliding bearing operating in the conditions of mixed and technical dry friction conducted on the laboratory stand are presented in **Figure 2**.

Table 1 includes the measurement results of the mean and standard deviation of the bearing housing temperature during operation. The values were calculated using the STATISTICA software **[L. 13]**. The results included in **Table 1** refer to the bearing operation states a, b, and c presented in **Figure 2** and, in addition, the results of three measurements made at equal time intervals between the states a, b, and c. The first measurement was made in the initial phase of bearing operation, and the last one was made during the stabilized operation of the lubricated bearing or during the overheating of the non-lubricated bearing.

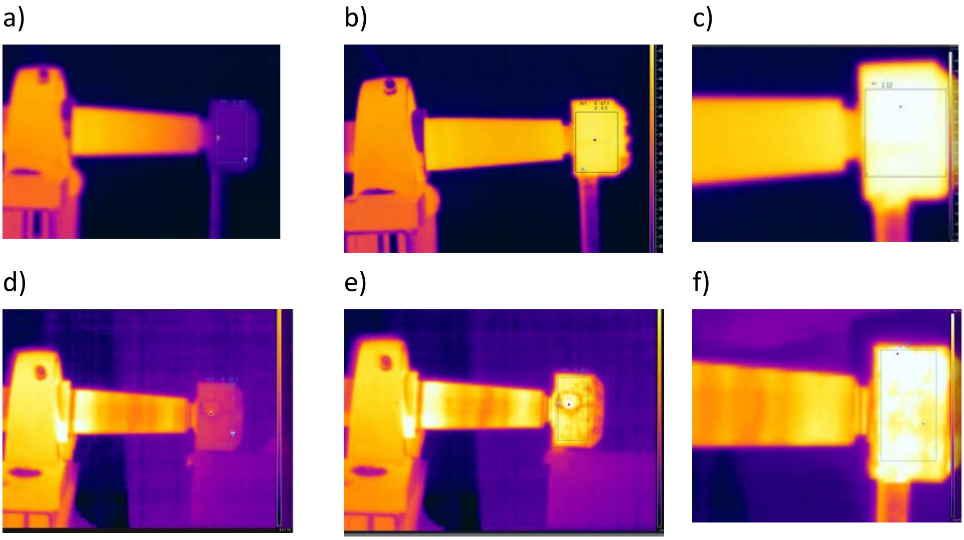

Fig. 2. Thermograms of the tested sliding bearing with the selected measurement areas: (a b, c) thermogram for the lubricated and loaded bearing, (d, e, f) thermogram for loaded bearing without lubrication

Rys.2. Termogramy badanego łożyska ślizgowego z zaznaczonymi obszarami pomiarowymi: (a b, c) termogramy dla łożyska obciążonego smarowanego, (d, e, f) termogram dla łożyska obciążonego niesmarowanego

Table 1. Results of measurements of the tested sliding bearing.

Tabela 1. Wyniki eksperymentów pomiarowych łożyska ślizgowego

Meas-urement No. i	Loaded bearing lubricated with VG46 oil		Loaded and non-lubricated bearing	
	Temperature mean $\bar{x}$, °C	Standard deviation σ, °C	Temperature mean $\bar{x}$, °C	Standard deviation σ, °C
1	26.8	0.3	26.3	0.6
2	28.1	0.2	30.4	0.9
3	36.8	0.2	39.6	1.6
4	59.6	0.5	68.7	2.8
5	60.2	0.5	75.8	2.9
6	61.3	0.5	78.6	3.8

Figures 2 a, b, and **c** present the results in the form of thermograms with marked areas for which the mean temperature and standard deviation were determined. The bearing was lubricated with hydraulic oil with a kinematic viscosity of $\mu = 47\ mm^2/s$ at 40°C. The individual thermograms present the bearing's initial phase of operation (**Figure 2a**), after half of the operation time (**Figure 2b**), and during the stabilized operation (**Figure 2c**) when the bearing reached the maximum operating temperature. The average bearing operating temperature read from the thermograms was between 26.8°C and 61.3°C. The individual values of average temperature for selected characteristic points are also included in **Table 1**.

Figures 2 d, e, and **f** present the results obtained with a thermographic camera for technical dry friction, i.e. a bearing without lubrication. Similarly to the first case with a lubricated bearing, the thermograms show the bearing in successive stages of its operation. However, in this case, after the bearing reached the maximum temperature, it quickly overheated with symptoms of shaft journal discoloration, and it was necessary to stop the operation. The average temperature read from the thermograms was between 26.3°C and 78.6°C. The individual values of average temperature for selected characteristic points are also included in **Table 1**.

The analysis of obtained results indicates that the average bearing operating temperature in conditions of technical dry friction is higher than the average bearing operating temperature in the presence of a lubricant. **Table 1** also includes also the standard deviation values calculated using the STATISTICA package for the two cases already described. The calculations were made based on thermograms obtained during the experiments. The analysis of results indicates that the average value of the standard deviation for the bearing operating in the presence of oil as a lubricant was 0.4°C, and for the bearing operating in the conditions of technical dry friction, it was 2.1°C. The significant difference between these two values can also be an indication of incorrect friction processes taking place in the bearing.

CONCLUSIONS

The statistical analysis presented in the paper and the results of the experiments confirm that two statistical estimators – mean bearing housing temperature and standard deviation of the bearing housing temperature – can be used as a basis for inferring the status of bearing operation. This is particularly true for the standard deviation. A significant difference was recorded between the two values of standard deviation for two states of bearing operation: first for the loaded bearing lubricated with the VG46 oil, and second for loaded and non-lubricated bearing. This difference in standard deviation between the two states of operation is an indicator of thermal processes occurring in the bearing. In the final phase of the operation of the non-lubricated bearing, which overheated, the difference of standard deviation values was 3.3°C.

The proposed solution with statistical analysis of thermograms allows one to determine the correct state of bearing operation based on contactless thermal imaging measurement of the bearing housing.

The obtained results and calculated estimators of the mean and standard deviation can be used to determine the following:

– The correct state of bearing operation, and
– The statistical limits of measured temperature for a correctly operating bearing.

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Streszczenie

W procesie tarcia w łożysku ślizgowym zachodzą złożone zjawiska, które zalicza się do najbardziej trudnych i skomplikowanych w badaniach tribologicznych. Dlatego też istnieje potrzeba systematycznego stosowania nowoczesnych metod diagnostycznych i narzędzi statystycznych w interpretacji poprawnego stanu pracy łożyska ślizgowego. Wykorzystanie tych narzędzi ma na celu zapewnienie poprawnej pracy układu tribologicznego w warunkach eksploatacyjnych. W artykule przedstawiono wyniki badań w postaci termogramów oraz ich opracowanie z wykorzystaniem narzędzi statystycznych. Badania wykonano na stanowisku laboratoryjnym dla łożyska pracującego w obecności środka smarnego oraz dla łożyska pracującego w warunkach tarcia technicznie suchego. Do analizy rozkładu temperatur wykorzystano program komputerowy FLIR ResearchIR i STATISTICA. W opracowaniu sprecyzowano również wnioski i wyznaczono dalszy obszar prac.