Journal of KONBiN 4 (16) 2010
ISSN 1895-8281

THE COMPREHENSIVE METHOD FOR AVAILABILITY MONITORING OF ANTIFRICTION BEARINGS DURING THE LIFETIME PERIOD

KOMPLEKSOWA METODA MONITOROWANIA STANU ZDATNOŚCI ŁOŻYSK TOCZNYCH W PROCESIE UŻYTKOWANIA

Paweł Lindstedt, Paweł Majewski

Air Force Institute of Technology

Abstract: *This paper presents the new and innovative method for assessment of the availability status demonstrated by antifriction bearings. The availability status is understood as the comprehensive assessment of the operational integrity (control functions) incorporating the technical status (diagnostic features) and the reliability status of the technical object. The assessment is based on two convoluted status equations with the specific feature that the technical status is considered as the environment for the operational status whilst the operational status serves as the environment for the technical status. The paper presents also converters designed to measure parameters of the technical status as well as the operational status where waveforms for the status variations can be used for identification of parametrical faults (resulting from variations of the technical status) and instantaneous faults (resulting from variations of the operational status). Finally, it is possible to derive reliability characteristics even before occurrence of catastrophic failures that always pose the most threatening hazards for technical facilities*
.

Streszczenie: *W artykule przedstawiono nową i oryginalną metodę oceny stanu zdatności łożysk tocznych. Stan zdatności rozumiany jest tu jako kompleksowa ocena stanu działania (regulacji) stanu technicznego (diagnostyki) i stanu niezawodnościowego. Podstawą do oceny stanu zdatności są dwa sprzężone równania stanu o tej znamiennej właściwości, że stan techniczny jest otoczeniem dla stanu działania a stan działania dla stanu technicznego. Zaproponowano przetworniki do pomiaru parametrów stanu technicznego i stanu działania. Ich przebiegi mogą być wykorzystane do identyfikacji uszkodzeń parametrycznych (wynikających ze zmian parametru stanu technicznego) i uszkodzeń chwilowych (wynikające ze zmian parametru stanu działania) a stąd charakterystyk niezawodnościowych przed wystąpieniem uszkodzeń katastroficznych, zawsze niebezpiecznych dla obiektu.*

1. INTRODUCTION

Antifriction bearings represent very popular components that are commonly used for construction of vast variety of machinery. Such bearings are designed and manufactured by highly specialized companies that have majored in that business. Consequently, that really sophisticated design process leads to development of desired products, i.e. bearings with strictly defined design parameters (dimensions, fit) and directly associated and corresponding strength and durability parameters (bearing capacity, lifetime period). Such bearings are appropriately suitable to the unambiguously defined operational environment (rpm, temperature, lubrication) where the bearing with specific design dimensions as well as strength and durability characteristics is to be operated. For instance, an ordinary ball bearing (PN-6200) features specific parameters, i.e. inner diameter d, outer diameter D, width B, roundness r and weight G as well with its fit at the journal and the bearing seating unambiguously defined by Polish Standards (PN) and the play between the basic components of the bearing demonstrates precisely defined bearing capacity C in running conditions and C_0 in standstill conditions, the relative bearing capacity c_n and the lifetime L_h that is defined by means of the f_h coefficient. Such a bearing can be correctly operated in the working environment with the specific rotation speed (rpm) of n, where the interrelationship between the environment parameter and the bearing status is expressed by the impact factor f_n. Moreover, the working environment status is also determined by other ambient factors, such as operational temperature associated with the f_t factor that stands for the temperature effect onto the bearing capacity C, as well as friction, lubrication technique and type of the bearing cage [3, 23, 24]. The interrelationships between such parameters, effects and manufacturing technologies are non-linear and cross-linked, thus really sophisticated and very difficult for accurate description.

Even if such a multi-parametrical description for a specific bearing of series production installed in a newly designed machine is available, it is again a challenge to efficiently benefit from such a description. The way, how that challenge is resolved, substantially affects operational quality of the device, its safety and reliability. The accuracy of the bearing installation in a machine, variable operating conditions of the bearing and other important signals that are produced by the machine may be the reason that actual bearing capacity and its durability after installation of it in the machine may differ from the reciprocal design parameters prescribed by the bearing manufacturer. Appropriate operation of bearings presents also a sophisticated problem related to assurance of safety and reliability of bearing during the required time period and under specific operating conditions of the machine. All in all one can conclude that variable loads, oscillations of operational temperature, unsteady lubrication, continuous growth of play, misalignment and run-out combined with gradual wear of the bearing components lead to a rapid drop in the bearing capacity and durability, where the actual parameters may significantly differ from the design values assumed by the

bearing manufacturer as well as the values that had been expected by the manufacturer of machinery where the bearing is to be installed.
This is why technical maintenance of the machinery (together with incorporated bearings) has to cope with a very important task, namely the monitoring of the 'availability status' of bearings, which is the task that brings together (synthesizes) all the factors that affect current bearing capacity and its lifetime.

2. METHODS FOR MONITORING OF THE AVAILABILITY STATUS FOR THE BEARING SYSTEM

The typical antifriction ball bearing is shown in Fig. 1. Its design is very simple, but its handling and maintenance are really sophisticated [1.6].
Each method applicable to monitor the availability status of a bearing (or a system of bearings) is based on a specific diagnostic model that is derived on a background mathematical model. The diagnostic model must be capable of bringing together and correlating all the factors (components) that affect technical condition of the bearing in close interrelationship with its operation status and consideration of the variable working environments where the bearing is operated [11, 19]. There is a number of diagnostic models already developed and applicable to bearings and used to derive operation methods intended for assessment of the availability status of bearings.

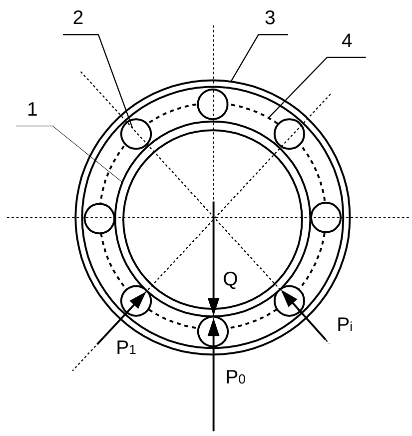

Fig.1. Design diagram of a roller bearing: 1 – inner ring pushed onto a shaft, 2 – balls, 3 – outer ring mounted in an equipment body, 4 – bearing cage, P – reaction forces induced by the Q force

The most common models that are frequently applied include:

a. The amplitude and frequency model of bearings and inner and outer rings, based on the frequency of their own vibrations [1, 2, 12, 13]
b. The model that is based on measurement of the vibration and noise levels as a function of the bearing rotation speed (rpm) [4, 9]

c. The spectral and correlational model for quality assessment of antifriction bearings [10, 14]
d. The $y(t)$ model that represents a convolution of signals of the determined $\rho(t)$, the random $\eta_i(t)$, the transit functions $h(t)$ and the Dirac delta function $\delta(t)$ [16]:

$$y(t)=\sum_{i=0}^{\infty}[(\rho(t)+\eta_i(t)]*h(t)*\delta(t-iT))$$

e. The model that is based on the correlation function and the power spectral density (PSD) function [14, 15]
f. The model that is based on probabilistic parameters of the vibroacoustic process [17]
g. The ferrographic model that is based on identification of all magnetic products from wearing processes [6, 18]
h. The model that is based on spectroscopic identification of fine particles from wearing processes [6, 18]
i. The model with automatic count-up of particles from wearing processes [6, 18]
j. Models involving identification of the surface condition [5, 18]

Each of the foregoing models, or a combination of several ones at a time can be used to develop the method for assessment of the availability status (in terms of technical and operational parameters), suitable both for a single bearing and the entire bearing system. These methods are efficient, which has already been confirmed during the long-term operation, but they need specialized measuring facilities and very accurate application of these measuring facilities supported by advanced methods of signal processing. This is why researchers keep seeking for new operational mathematical models as well as models for assessment of the availability status (understood as the assessment of the operational, technical and reliability status components) of the bearing when the machine is in use.

The next innovative method can be based on the model that involves convoluted interactive status equations [8, 19, 20] that can establish mutual relationships between design, strength and durability (lifetime) of the bearing and then determine its technical, operational and reliability status components. The schematic diagram for that new method is shown in Fig. 2. The method is based on an interactive model of a bearing. This model makes it possible to carry out tests and find out current parameters a_T of the technical status, the a_D parameters of the operational status during the predefined time interval (e.g. 1 hour) and accumulated sums of these A_T and A_D parameters. Next, as a result of the diagnostic inferring process, the waveforms for A_T and A_D parameters are developed and then exceeding moments m_T and m_D when statistic thresholds are exceeded by the A_T and A_D parameters. Subsequently, there is a very simple way to find out the technical status $\sum A_T$, the operational status $\sum A_D$ and the reliability status on the basis of the m_T and m_D moments.

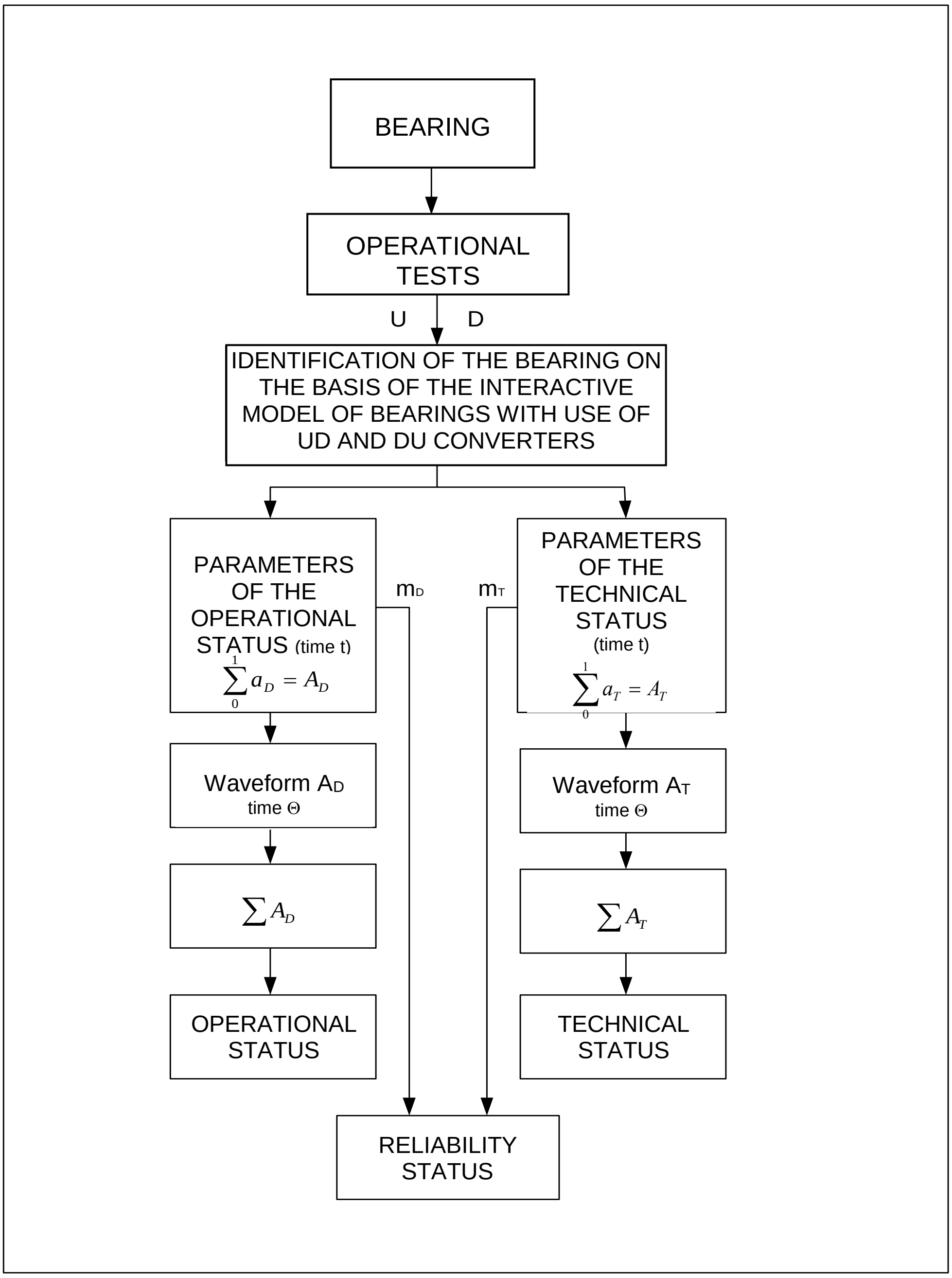

Fig.2. The method for determination of parameters for the technical status, the operational status and the reliability status of a bearing

a_D – instantaneous parameter of the operational status, A_D – current parameter of the operational status, m_D – number of moments when statistical thresholds have been exceeded by the A_D parameter, a_T – instantaneous parameter of the technical status, A_T – current parameter of the technical status, m_T – number of moments when statistical thresholds have been exceeded by the A_T parameter, t – operation time, Newton's time, of tests, Θ – time of the process evolution,

3. THE INTERACTIVE MODEL OF BEARINGS

The interactive model involves two mutually convoluted status equations that are based on the observation that usefulness (operability) of a bearing that results from its functional qualities depends on its technical condition related to its wear, misalignment, fit, play, lubrication, etc., and the technical condition (its rapid alterations) depends on the operation status (intensity of operation). All in all, the technical status is the environment for the operational status whilst the operational status itself serves, in reverse, as the environment for the technical status. It is the interrelationship that can be expressed by two mutually convoluted status equations: [8, 19, 20].

$$\frac{dU}{dt} = a_D U + b_D D \tag{1}$$

$$\frac{dD}{dt} = a_T D + b_T U \tag{2}$$

where:

- U – combined useful signal associated with the operational status,
- D – combined useful signal associated with the technical status,
- aD – parameter of the operational status,
- b_D – parameter that reflects how much the technical status of a bearing determines its operational features
- aT – parameter of the technical status of a bearing,
- bT – parameter that reflects how much the operational status of a bearing determines its wear (deterioration)

The equation that defines the operational status (1) is used to determine the parameter for the operational status a_D. The equation (1) can be then rewritten in the following form:

$$\dot{U} = a_D U + b_D D \tag{3}$$

According to the identification rules [7, 21, 22] it is possible to rewrite the equation above:

$$\ddot{U} = a_D \dot{U} + b_D \dot{D} \tag{4}$$

The equation (4) can be used to calculate:

$$b_D = \frac{\ddot{U} - a_D \dot{U}}{\dot{D}} \tag{5}$$

After substitution of (5) to (3) the following formula is obtained:

$$\dot{U} = a_D U + \frac{\ddot{U} - a_D \dot{U}}{\dot{D}} D \tag{6}$$

After simple transformations the parameter of the operational status can be determined from the equation (6):

$$a_D = \frac{\dot{U}\dot{D} - \ddot{U} D}{U \dot{D} - \dot{U} D} \tag{7}$$

In a similar way the parameter a_T for technical status of the bearing can be calculated from the equation (2).

$$a_T = \frac{\dot{U}\dot{D} - \ddot{D} U}{D \dot{U} - \dot{D} U} \tag{8}$$

Therefore, the current value of the parameter a_D for the operation status as well as the parameter a_T for the technical status can be determined by continuous measurement of the U and D signals together with their first and seconds derivatives $\dot{U}, \ddot{U}, \dot{D}, \ddot{D}$ that can be easily found out with the use of specific electronic filtering (differentiating) circuits.

The a_D and a_T parameters determined in such a manner represent instantaneous values that are measured at each moment of sampling over the presumed observation time (e.g. Δt=1h). The accumulated sum of these instantaneous values over the considered time period makes up the current value of A_D and A_T parameters (Fig. 2, 3 and 4). The process of diagnostic inferring consists in monitoring of the accumulated parameters ΣA_D and ΣA_T that, in turn, serve as a basis for the full assessment of the operational and technical statuses of the facilities in use. Waveforms of the A_D and A_T parameters over the operation time Θ (Fig. 2) may serve as the basis for finding out moments of instantaneous defects m_c (the A_D waveform) as well as parametric defects m_b (the A_T waveform). Consequently, the desired point estimators $R^*(m_b, m_c)$ for reliability characteristics are determined and then the reliability function R(t) [20, 25]. Finally, the availability assessment for the examined facilities (bearing) is obtained, incorporating its operational, technical and reliability statuses.

4. CONVERTERS FOR MEASUREMENTS OF THE TECHNICAL AND OPERATIONAL STATUSES

The examination process of the object under tests includes the measurement of signals related both to the object under tests and to its environment as well as to derivatives of these signals. Therefore, it is possible to design electronic circuits designed to determine current (instantaneous) values of a_D and a_T (Fig. 3, Fig. 4), accumulated sums A_D and A_T of these values over the presumed time intervals (e.g. 1h).

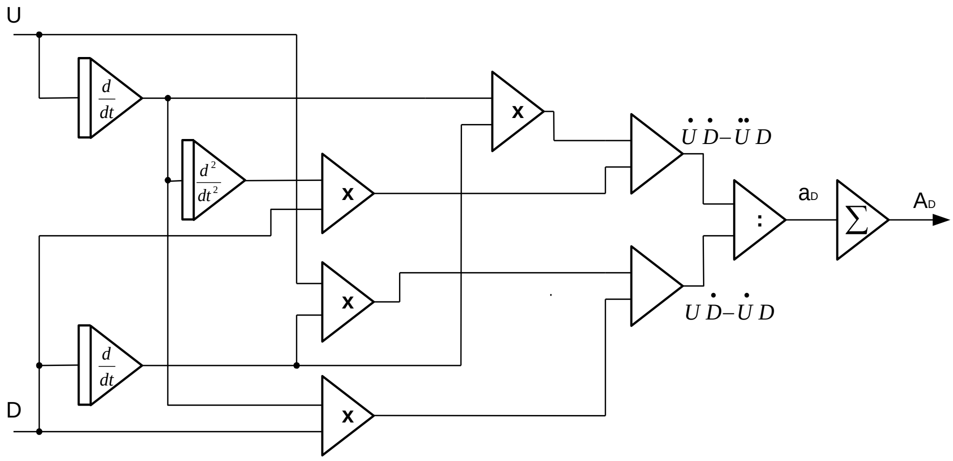

Fig. 3. The schematic diagram of the converter of the object operation status (technical implementation of the formula 7).

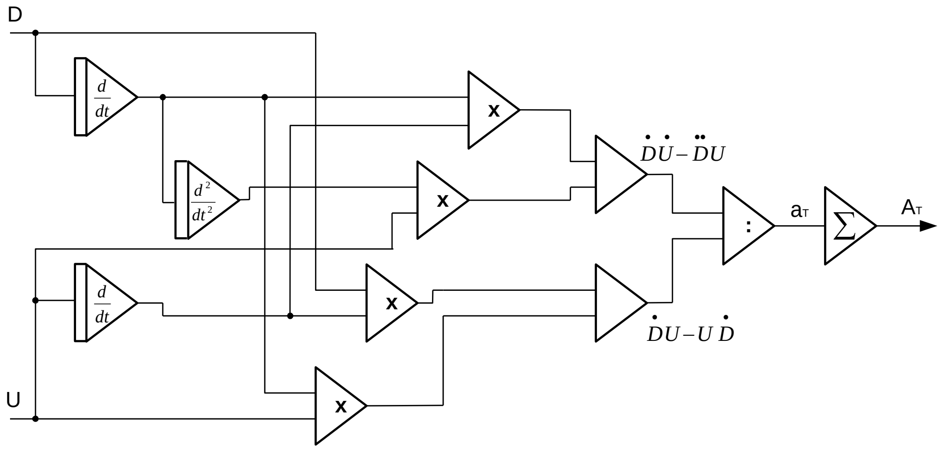

Fig. 4.. The schematic diagram of the converter of the object technical status (technical implementation of the formula 8).

The waveforms for the A_D and A_T parameters determined during operational tests make it possible to assess the operational, technical and reliability statuses of the object (the bearing) it terms of both quantitative and qualitative characteristics.

The fundamental feature of physical phenomena is the fact that the effect D is always less in power and shifted in the phase (delayed) as compared to the stimulus U. It makes it possible to assume that in formulas (7) and (8) the following relationship shall be always true:

$$U\dot{D} \neq \dot{U}D$$

It is the paradigm that enables the division operation with use of the relevant electronic circuit. Obviously, this problem can be also resolved by means of other mathematical operations. Anyway, the foregoing preliminary assumptions to measurements need experimental verification whether the proposed converters for the operational status and the technical status of bearings are suitable and relevant for real components.

5. EXPERIMENTAL EXAMINATIONS OF BEARINGS

In order to investigate interrelationships between signals from the environment (the operational status) and the diagnostic signals (the technical status) the following workbench for experimental examinations was constructed. (Fig. 5).

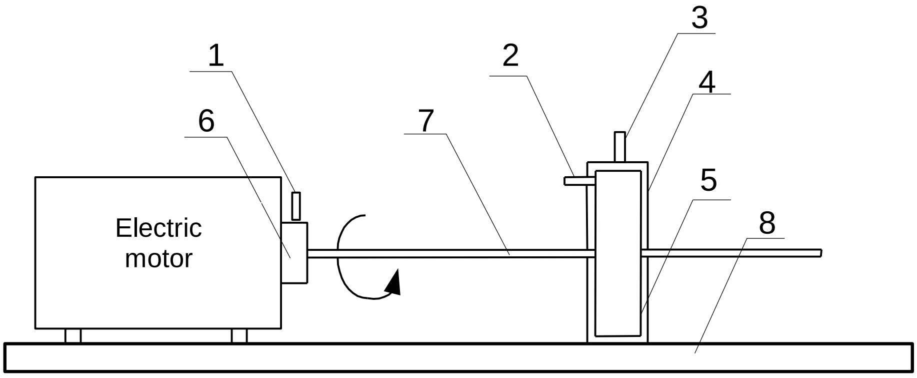

Fig.5. The workbench for experimental examinations of bearings (1 – rpm gauge, 2 – gauge for measurements of the external bearing track temperature and gauge for measurements of the bearing cage rpm, 3 – vibration gauge, 4 – bearing seating, 5 – bearing, 6 – coupling, 7 – driving shaft, 8 – base).

The workbench comprises an electric motor designed to drive the external bearing track of the bearing under test. The motor is connected to the bearing (5) via a flexible coupling (6) and the driving shaft (7). The bearing is placed inside a specific seating (4). Both the motor and the bearing seating are attached to a robust and heavyweight base (8). The workbench incorporates appropriate sensors and gauges that make it possible to measure rotation speed of the driving shaft (1), temperature of the outer running track of the bearing and rotation speed of the bearing cage (2) as well as vibrations of the bearing cage mounting (3). One can assume that, for instance, the rotation speed (rpm) is the signal that conveys information about the bearing operation, similarly to the bearing temperature, whilst vibrations and velocity of the bearing cage serve as signals associated to technical status amendments of the bearing.

Moreover, the workbench enables simulation of bearing defects that affect operation quality and rates of the bearing wear. These defects include:

- misalignment,
- extentricity,
- unbalancing,
- bearing seizure.

During the further stage of the research studies the already developed scientific output shall be implemented to investigation under real conditions and with use of a reactive engine with appropriate measuring equipment installed and connected.

LITERATURE:

1. Andrzejewski M. Cempel Cz. Kowalak J. „Łożysko jako układ dynamiczny" Praca zbiorowa - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd. Wrocław 1980 (*'Bearing as a dynamic system, Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980)*
2. Andrzejewski M. Cempel Cz. „Diagnostyka eksploatacyjna łożysk tocznych w silnikach elektrycznych za pomocą zjawisk elektrycznych" Praca zbiorowa - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd. Wrocław 1980 (*'Operation diagnostics of antifriction bearings in electric motors by means of electric phenomena, Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980).*
3. Barwell F. T. „Łożyskowanie" WNT Warszawa 1984 (*'Bearing systems', ed. The WNT Publishing House Warsaw, 1984)*
4. Baumgarter K „Ocena stanu łożysk w elektrowni za pomocą metody SPM" Der Machinenschade 11, 51, 1978 (*'Assessment of the bearing status with use of the SPM method at an electric power station',* Der Machinenschade 11, 51, 1978
5. Beksiński R. Błachnio J. Stukonis M. „Badania tribologiczne agregatów systemów paliwowych" Problemy badań i eksploatacji techniki lotniczej t.2 rozdz. 10 Wyd. ITWL Warszawa 1998 (*'Tribologic studies on pumping motors in fuel-supplying systems', Issues of research studies and operation of aviation technical equipment, vol. 2, Chapter 10'. ed. ITWL [Air Force Institute of Technology], Warsaw 1998*).
6. Bieńczak K. Lewitowicz J. „Ocena stanu technicznego systemów tribologicznych silników lotniczych i przekładni na podstawie produktów zużywania" Problemy badań i eksploatacji techniki lotniczej t.4 rozdz. 1 Wyd. ITWL Warszawa 1998 (*'Technical status assessment of tribologic systems and transmission gears on the basis of wear rates", Issues of research studies and operation of aviation technical equipment, vol. 4, Chapter 1'), ed. ITWL [Air Force Institute of Technology], Warsaw 1998).*
7. Bubnicki Z. „Identyfikacja obiektów sterowania" PWN Warszawa 1974. (*'Identification of control facilities', ed. PWN, Warsaw, 1974*).

8. Cempel Cz. „Teoria i inżyniera systemów" (*'Theory and engineering of systems'*) ITE-PIB Radom 2006
9. Cempel Cz. Stepaniak Z „Hałas i drgania nowych łożysk tocznych" Praca zbiorowa
   - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd. Wrocław 1980 (*'Noise and vibrations of new antifriction bearings', Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980).*
10. Dekert J. Kurowski W. Rysiński B. „Analiza diagnostyczna sygnału wibroakustycznego łożysk tocznych zabudowanych" Praca zbiorowa - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd. Wrocław 1980 (*'The diagnostic analysis of the vibroacoustic signal from embedded antifriction bearings', Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980).*
11. Furmanek S. Kraszewski Z. „Niezawodność łożysk tocznych" Wydawnictwo Przemysłowe WEMA Warszawa 1989 *('Reliability of antifriction bearings' The Industrial Publishing House WEMA, Warsaw, 1989*).
12. Gębura A. Tokarski T. „Metody FDM-A i FAM-C w wykrywaniu i monitorowaniu silnie zaciśniętych łożysk tocznych" Prace naukowe ITWL 2008 z. 23 (*'The FDM-A and FAM-C methods as a tool for detection and monitoring of tightly seized antifriction bearings', Scientific Journals of the ITWL [Air Force Institute of Technology], 2008, vol. 23).*
13. Gębura A. Tokarski T. „Zastosowanie metody FDM-A do oceny poślizgu łożysk tocznych i niewspółosiowości podpór łożyskowych" Prace Naukowe ITWL 2007 z.22 (*'Application of the FDM-A method for evaluation of the bearing spin as well as non-alignment of bearing supports', Scientific Journals of the ITWL [Air Force Institute of Technology], 2007 vol. 22).*
14. Golec M. Cempel Cz. Widmowo-korelacyjna metoda oceny jakości łożysk tocznych Praca zbiorowa (*The spectral and correlational model for quality assessment of antifriction bearings, Collective study*).
15. Kowalak J. Cempel Cz. „Metody i przyrządy do oceny jakości łożysk na podstawie sygnału drganiowego" Praca zbiorowa - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd. Wrocław 1980 (*'Methods and tools for quality assessment of bearings on the basis of the vibration signal', Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980).*
16. Kowalski K. Cempel Cz. „Zastosowanie sumowania synchronicznego sygnału drganiowego do diagnostyki kontrolnej łożysk tocznych" Praca zbiorowa - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd. Wrocław 1980 (*'Application of accumulative summation to the synchronous vibration signals for scheduled inspection of antifriction bearings, Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980).*
17. Kowalski K. „Niezależne parametry wymiarowe i probabilistyczne sygnału wibroakustycznego na przykładzie badan tocznych" Praca zbiorowa - Diagnostyka Łożysk Tocznych Zakład Narodowy im. Ossolińskich Wyd.

Wrocław 1980 (*'Independent size-related and probabilistic parameters of vibroacoustic signals on the example of antifriction bearings', Collective study – The Diagnostic of Antifriction Bearings, ed. The Ossoliński National Institute, Wrocław, 1980).*
18. Lewitowicz J. „Badania nieniszczące w diagnostyce maszyn" V Kongres Eksploatacyjny Sekcja III – Diagnostyka techniczna. Warszawa 1983 (*'Non-destructive tests for the diagnostics of machinery', The 5th Operational Congress, Section III – Technical diagnostics, Warsaw, 1983.)*
19. Lindstedt P. „The Method of Complex Worthiness Assessment of an Engineering Object in the Process of its use and service" Solid State Phenomena vol. 144/2009 Trans Tech Publications, Switzerland 2009
20. Lindstedt P. Sudakowski T. „Possibilities of assessment of reliability of anthrophotechnical system" Journal of Vibroengineering vol.9, Issue 4, Vilnius Lithuania 2007
21. Manerowski J. „Identyfikacja modeli dynamicznych ruchu sterowanych obiektów latających" Wyd. Nauk ASKON Warszawa 1999 (*'Identification of dynamic models for motion of steerable aircraft facilities', The Scientific Publishing House ASKON, Warsaw, 1999).*
22. Mańczak K. „Metody identyfikacji wielowymiarowych obiektów sterowania" WNT Warszawa 1971 (*'Methods for identification of multidimensional controllable objects, The WNT Publishing House, Warsaw, 1999)*
23. Osiński J i zespół „Wspomagane komputerowo projektowanie typowych zespołów i elementów maszyn" Wyd. Nauk. PWN Warszawa 1994, (*Osinski J., et. al. 'Computer-aided designing of typical subassemblies and components of machinery, Polish Scientific Publishers PWN, Warsaw, 1994).*
24. Palmgrem A. „Łożyska toczne" PWN Warszawa 1951 (*'Antifriction bearings' The Polish Scientific Publishers PWN, Warsaw, 1951*).
25. Sotskow B. W. „Niezawodność elementów i urządzeń automatyki" WNT, Warszawa 1973 (*Reliability of components and equipment of automatic control systems, The WNT Publishing House, Warsaw, 1973).*

Prof. Paweł Lindstedt, DSc., Eng. professor of the Technical University in Białystok, associate professor of Air Force Institute of Technology. Research subjects: Design and application of machinery, applied automatics, diagnostics and reliability of equipment. His works concern diagnostics of aircraft engines, hydraulic and bearing systems with application of functional, vibro-acoustic and wear methods.

Major Paweł Majewski Msc. Eng. Air Force Institute of Technology, graduated from Military University of Technology in 1997 Msc. in Mechatronics specialized in Aircraft Diagnostics. He is engaged in development and implementation of modern aircraft engine diagnostic systems.