POLISH
ACADEMY
OF SCIENCES

COMMITTEE
OF MACHINE
ENGINEERING

SCIENTIFIC PROBLEMS OF MACHINES OPERATION AND MAINTENANCE

ZAGADNIENIA EKSPLOATACJI MASZYN

TRIBOLOGY • RELIABILITY • TEROTECHNOLOGY
DIAGNOSTICS • SAFETY • ECO-ENGINEERING

TRIBOLOGIA • NIEZAWODNOŚĆ • EKSPLOATYKA
DIAGNOSTYKA • BEZPIECZEŃSTWO • EKOINŻYNIERIA

2 (158)
Vol. 44
2009

Institute for Sustainable Technologies – National Research Institute, Radom

Mailing address: Scientific Problems of Machines Operation and Maintenance
Institute for Sustainable Technologies – National Research Institute
ul. Pułaskiego 6/10, 26-600 Radom, Poland
Phone (48-48) 364 47 90
E-mail: ewa.szczepanik@itee.radom.pl

The figures have been directly reproduced from the originals submitted by the Authors.

Publishing House of Institute for Sustainable Technologies – National Research Institute
26-600 Radom, K. Pułaskiego 6/10 St., phone (48-48) 364-42-41, fax (048) 364-47-65
www.tribologia.org

2024

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

CONTENTS

SPIS TREŚCI

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

BOGDAN ANTOSZEWSKI*

The formation of antiwear surface layers on elements of machine parts

K e y w o r d s

Thermal spraying, electro-spark deposition, laser treatment, coating.

S ł o w a k l u c z o w e

Natryskiwanie cieplne, powłoki elektroiskrowe, obróbka laserowa.

S u m m a r y

The paper deals with selected technological and research aspects of the formation of surface layers, the aim of which is to prevent wear of machine elements. Three main problem areas will be discussed. The first is the deposition of antiwear coatings with a solid lubricant using the plasma and HVOF spraying methods. Tests were conducted to analyse the changes in the properties of NiCrBSi coatings plasma or HVOF-sprayed with an addition of ferric oxide as a solid lubricant. It has been reported that the method of coating deposition affects the behaviour of the solid lubricant phase and that the addition of ferric oxide reduces the friction resistance. The second area of interest is the electrospark deposition of transition and antiwear layers on the surfaces of sliding bearing bushes. Tests were conducted to analyse the process of the formation of antiwear silver-indium-tin layers electrospark deposited on the B83 bronze bushes. It has been found that such thin (30 μm) and soft layers are effective and suitable for the processes of lapping and the formation of low-friction surface structures. The third problem is the formation of geometrical surface textures able to reduce the friction resistance and improve the load capacity. The test results refer to the technological aspects of texture formation using the laser erosion and electroerosion techniques.

* Kielce, University of Technology, Center for Laser Technology of Metals, Al. 1000-lecia P. P. 7, 25-314 Kielce, Poland, *e-mail: ktrba@tu.kielce.pl.

1. Introduction

Wear prevention activities are essential at each stage of the life of a technical object. Basic assumptions concerning the object durability and reliability are made as early as at the concept stage. It is also necessary that a designer prepare the details of a security standard concerning antiwear prevention and a process engineer make sure it is met at the manufacturing stage. During the service life, antiwear prevention activities focus on the durability assurance by proper usage. A majority of wear processes begin on the product surface, and the surface properties determine the product wear resistance. Of significance are sliding velocity, pressure, surface roughness, operation temperature, hardness, heat removal capacity, moisture, type of motion, and other factors related to the environment. The application of specially formed coatings or outer layers is one of the most rational and effective methods of wear prevention. There is a tendency to combine different properties in one coating, for example, wear resistance and lubricating ability (lubricant function).

2. Thermally sprayed coatings – containing a solid lubricant

The tests were carried out for NiCrBSi coatings known to be exceptionally resistant to various wear processes, including abrasive wear. The coatings can be deposited using various thermal spray techniques, and the most important of which are plasma spraying and HVOF spraying. Various materials can be added as solid lubricants; however, it is important that their properties do not change during the spraying process. An example of such a material is one of the forms of ferric oxide. The tests [3] involved analysing the effects of the spraying process on the destruction of the solid lubricant (FeO). It was significant to determine how the high temperature of the plasma spraying process and the substantial strains occurring during the HVOF spray process influence the lubricating ability of the coating. Figures 1 and 2 show the microphotographs of the input materials and their mixtures, respectively, obtained by means of a Joel scanning microscope.

The powder mixtures were deposited using two methods: plasma and HVOF spraying. The results of the linear analysis of the content and microstructure of the resulting coating are shown in Fig. 3. The structure of the coating obtained by HVOF spray is more uniform with a clearly smaller amount of oxides and pores (dark areas in the microsections). The lamellar structure is typical of the two methods of spraying. However, the lamellas are more deformed after the HVOF process, and in some areas their boundaries are not clear [14–38].

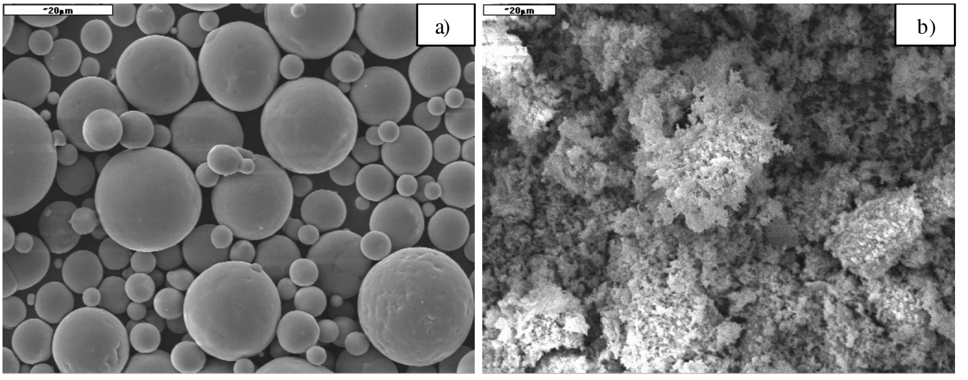


Fig. 1. Microphotographs of the input material (powders) a) NiCrBSi, b) Fe_2O_3
Rys. 1. Mikrofotografie materiałów wyjściowych (proszków) a) NiCrBSi, b) Fe_2O_3

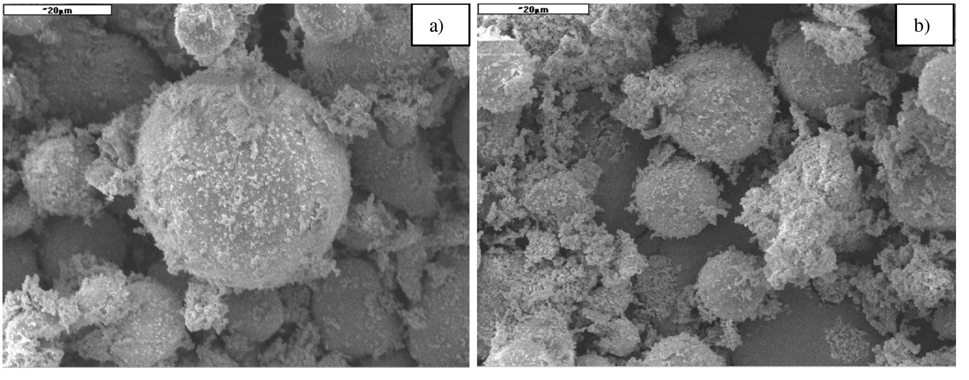


Fig. 2. Powder mixtures a) 90%NiCrBSi/10% Fe_2O_3, b) 60%NiCrBSi/40% Fe_2O_3
Rys. 2. Mieszanina proszków a) 90%NiCrBSi/10% Fe_2O_3, b) 60%NiCrBSi/40% Fe_2O_3

The plasma-sprayed coatings show microsections with iron compounds visible as dark areas. A diffractometric analysis of the phase composition shows that the ferric oxide in the form of hematite is found in the input material and in the HVOF deposited coating. The ferric oxide in the form of maghenite is reported in the plasma-sprayed coating. This confirms the occurrence of destructive transformations during the plasma spraying process.

The lubricating ability (seizure resistance) and wear resistance of the resulting coatings were analysed using a Falex test machine and a roller-block device. As can be seen from Fig. 4, an increase in the amount of ferric oxide causes an improvement in the antiseizure properties and a decline in wear resistance. An optimal content of ferric oxide is about 21% for HVOF-deposited coatings and 27% for the plasma-sprayed coatings. The results confirm the occurrence of an unfavourable transformation of the hematite form of ferric oxide into a form with no lubricating ability.

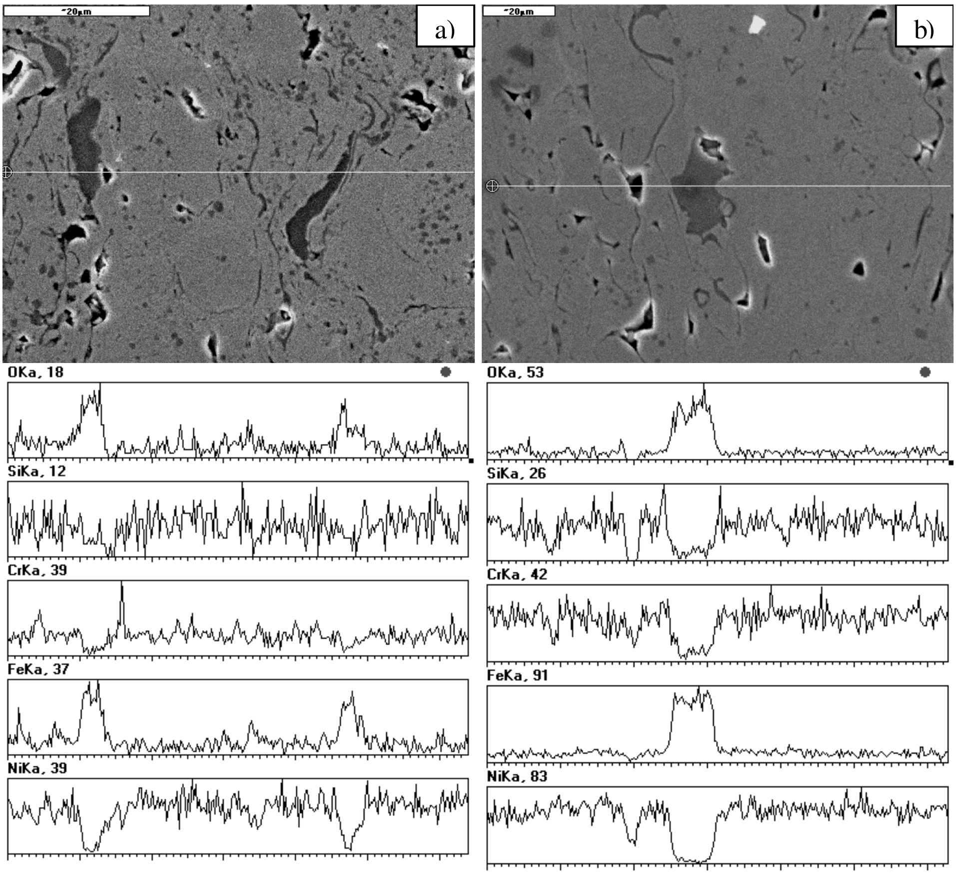
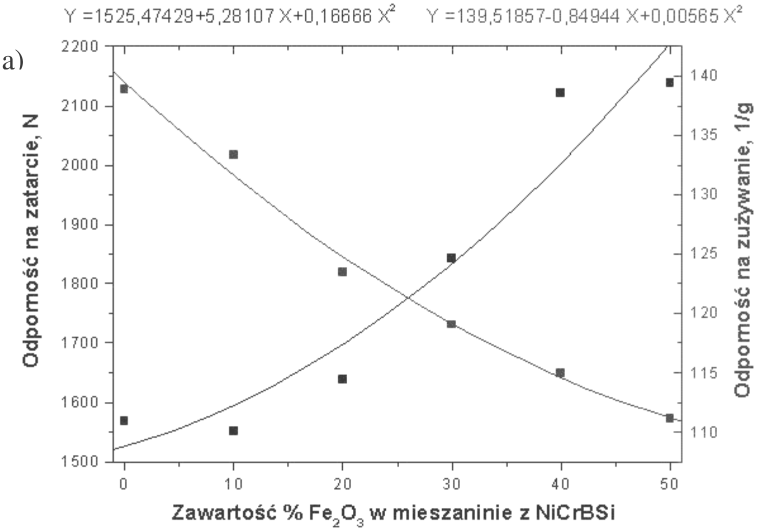


Fig. 3. Microstructure and linear analysis of the 50%NiCrBSi/50% Fe2O3 coating deposited by: a) plasma spraying, b) HVOF spraying

Rys. 3. Mikrostruktura i analiza liniowa powłok 50%NiCrBSi/50% Fe2O3 otrzymanych przez a) natrysk plazmowy, b) natrysk naddźwiękowy



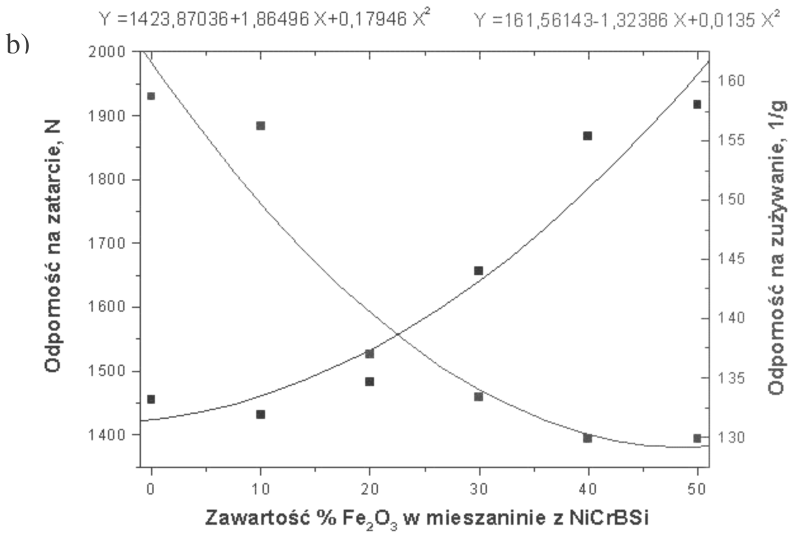


Fig. 4. Wear and seizure resistance of composite coatings with different percentage of Fe_2O_3 in the mixture with after a) plasma spraying, b) HVOF spraying
Rys. 4. Odporność na zużycie i zacieranie powłok z NiCrBSi zawierających różne udziały Fe_2O_3 natryskiwanych a) plazmowo b) naddźwiękowo

3. Antiwear layers obtained by electrodischarge machining

Among the numerous methods of outer-layer modification, the most important are those involving the deposition of metallic coatings with functional properties different from those of the substrate material. An example is the electrodischarge deposition process (EDM), which has been modified a number of times. Using this method, it is possible to apply locally thin (from several μm) or thick (up to several dozen μm) coatings of any metallic materials diffusely connected with the substrate. The tools for coating deposition are easy to use and inexpensive. The processes of coating formation on metallic elements, including the electrospark deposition, are accompanied by the transport of mass and energy as well as chemical, electrochemical, and electrothermal reactions [1–2]. Different varieties of the electrospark deposition method meet the standards of coating and surface microgeometry formation [1–4, 10–14].

Electrospark deposited coatings can be used to do the following:

- To protect new elements, and
- To regenerate worn elements.

The properties of electrospark coatings can be improved. One of the methods for coating improvement is laser treatment. A laser beam is applied to polish a surface, form the surface geometry, seal it or for uniforming the chemical composition of the resulting coatings. The electrospark technologies can be employed for the following:

- To form transition layers of copper, tin and tin bronze, the aim of which is to increase the adhesion to babbitt, tin and bronze bushes; and,
- To form silver-indium and tin layers, which are to facilitate the lapping of bronze and babbitt bushes.

As can be seen from the linear distribution of elements in Fig. 5a, the transition layer increases the adhesion of the tin coating by 35%. This is a result of a diffusive adhesion of the ESD layer with steel and the affinity of tin with the tin bronze of the transition layer. Figure 5b shows the analysis of the antiseizure indium layer electrospark deposited on babbitt bushes. The thin, easy to deform, indium layer adheres to the babbitt substrate. The results of in-service tests show that this solution is suitable for the lapping of elements and prevents the seizure of a bearing during the first hours of operation.

The tests also involved electrospark deposition of multilayer silver and brass coatings on a bronze bush. Three layers of the coating were differentiated as follows:

- The outer, softest layer (600MPa) with a height of 70–80 μm,
- the transition layer with a hardness of 1270–1400 MPa and a height of 50–60 μm,
- the matrix with a microhardness of 1050–1100 Mpa.

By electrospark alloying of a bearing alloy with indium and tin, it is possible to form an outer layer with a height of the order of 100–130 μm, containing the above elements and the substrate components. Its hardness is lower than that of the matrix. Such surface layers facilitate the lapping, because the accompanying plastic deformations are located in the thin, easy to deform, layer. It is, thus, possible to prevent seizure and, accordingly, increase the hardness and reliability of sliding bearings.

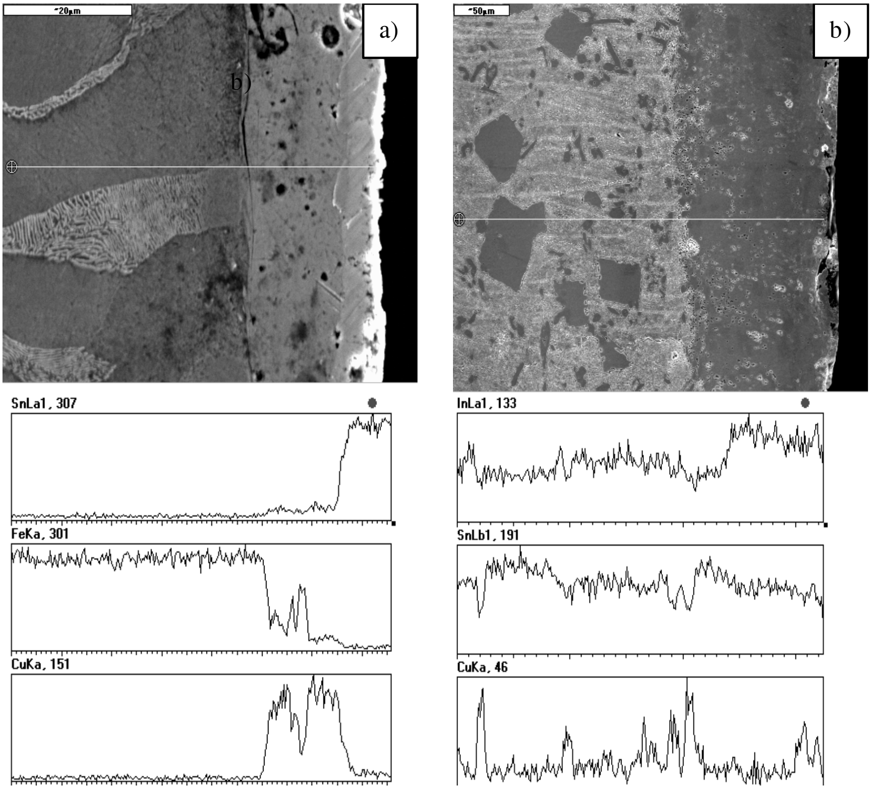


Fig. 5. Microstructure and linear composition analysis of a) a bush with a tin layer deposited on a tin bronze transition layer, b) a babbitt bush with an indium antiseizure layer deposited by EDM

Rys. 5. Mikrostruktura i liniowa analiza składu a) panewki z wylewanej cyny na warstwę przejściową z brązu cynowego, b) panewka babitowa z przeciwzatarciową warstwą indu nakładaną EEL

4. Surface texture formation

The states of the surfaces of the elements in a sliding pair have a substantial influence on the course of the friction and wear processes. In many cases, the surface state is responsible for the losses and indirectly for the general machine operation, i.e. efficiency. Additionally, in the case of combustion engines, the surface state affects the emission of toxic exhaust fume components. The formation of surface topography is becoming an increasingly important problem. Today, it is possible to form the surface micro- and macro-geometry by applying coatings of all shapes and dimensions locally and accurately. The texturing technology involving the formation of non-uniform surfaces using different methods has become very popular when the lubrication conditions of a friction pair need to be improved [5–9].

It should be noticed that the texturing processes used today mainly aim at the formation of surface geometry. The texturing processes responsible for the formation of physical properties, however, such as micro-local tempering and alloying, have not been analysed and applied sufficiently [5]. In certain applications, the texture efficiency is so high that the process can be standardised [1]. The most common technologies include the laser beam, electron, ion, as well as microelectroerosion and lithographic methods (Fig. 6).

One of the methods used for surface texturing is laser erosion, classified as a metal removal machining process usually performed at a power density of $10^6 \div 10^9$ W/cm^2. Today, it constitutes 2% of all the laser-based methods used in the world. A laser impulse causes evaporation of the material removed. It is recommended that, during the process, gas (air or neutral gas) be blown to remove the non-evaporated melted material from a gap. The gap depth is dependent mainly on the power density and the time of duration of the laser beam impulse.

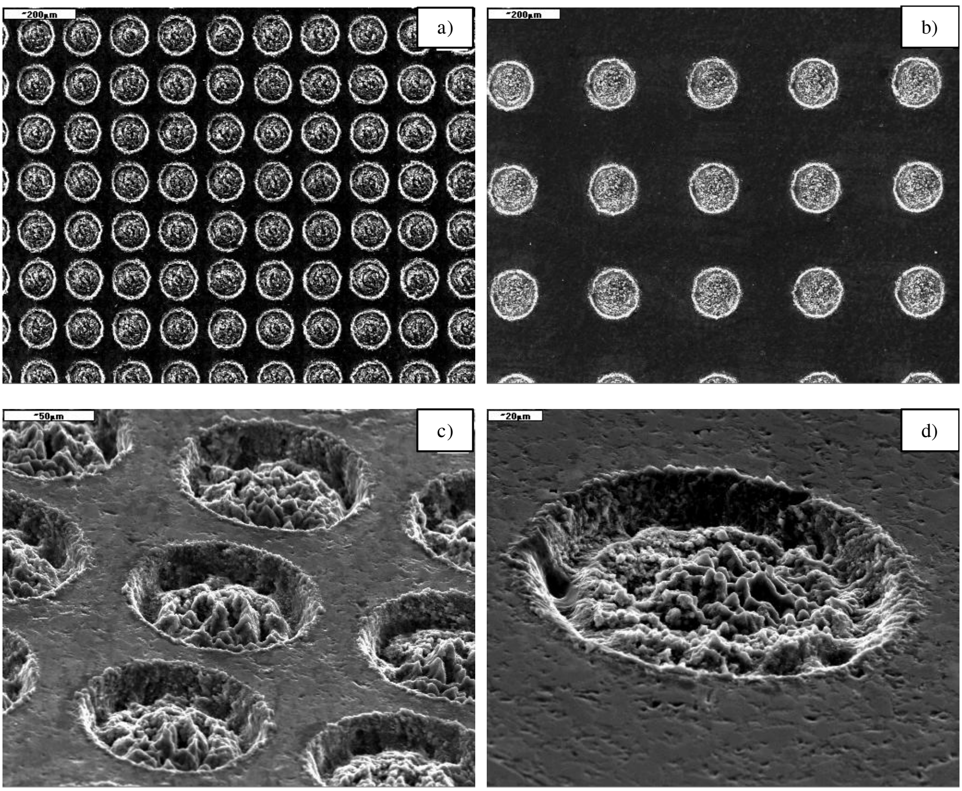
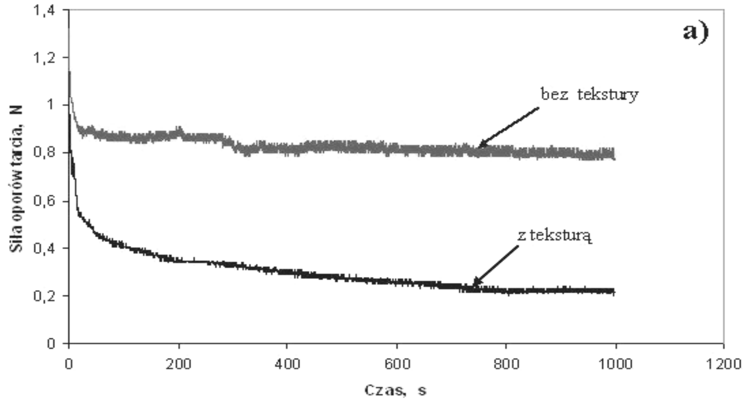


Fig. 6. View of the laser-textured surface a) degree of blackening – 51%, b) degree of blackening – 23%, c), d) views of the cavities
Rys. 6. Widok powierzchni teksturowanej laserowo a) stopień zaczernienia 51%, b) stopień zaczernienia 23%, c), d) widoki pojedynczych wgłębień

The tests were conducted for SiC rings with the following dimensions: outer diameter, d_o = 35.3 mm, inner diameter, d_i = 25.1 mm, height, h = 7 mm. The ring surfaces were textured with an ESI 5200 Nd:YAG laser (impulse mode). The laser operated at the third harmonic (wavelength λ = 355 nm).

The following parameters of the laser erosion process were assumed on the basis of the results: the range of laser spot diameters, d = 0.78 – 150 µm; the range of laser power, P = 0.37 – 0.4 W; the range of the beam velocity V = 15.7 – 23.56 mm/s; the distance from the focus Δf = 0 mm; and the frequency of repetition, f = 6400 Hz.

The cavities were formed in two stages (two steps). In the first stage, the laser moved along a spiral path drilling a cavity up to a specified diameter. During the second step, the remaining products of the machining process were removed from the cavity bottom with single laser impulses (strokes), their number and frequency being pre-determined.



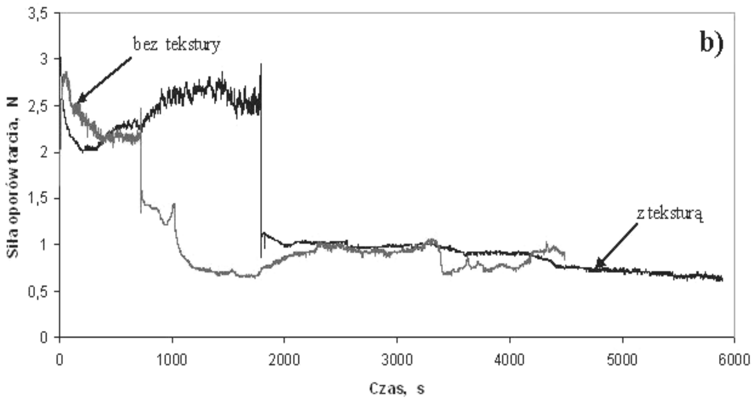


Fig. 7. Results of tribological tests obtained for specimens with and without texture: a) v = 0.6 m/s and Q = 25 N, b) v = 1 m/s and Q = 15 N

Rys. 7. Wyniki badań tribologicznych – próbka z teksturą oraz próbka bez tekstury: a) v = 0,6 m/s i Q = 25 N, b) v = 1 m/s i Q = 15 N

The tribological tests were conducted by means of a T-01M pin-on-disc device; however, the pin was replaced by a bearing ball with a diameter of 6.3 mm chamfered in such a way that the circular flat surface had a diameter of 4.5 mm. The ball was mounted in a fitting frame, which made it possible for the flat surface to be arranged parallel to the ring in contact. The extensive research described is now at the recognition stage.

Two series of tests were conducted, and the objective was to assess the suitability of the research method. The experiments involved observing the changes in the friction resistance during the comparative gears of the test machine using textured and non-textured rings.

The first series of tests performed at various rotational velocities (v_1 = = 0.3 m/s, v_2 = 0.6 m/s and v_3 = 1 m/s) and various loads (Q_1 = 10 N, Q_2 = 25 N and Q_3 = 40 N) involved continuous wick lubrication with a paraffin oil (Fig. 7a). In the second series, the sliding velocity was v = 1 m/s and the load was Q = 15 N. The test gear included a dry mode followed by a wet mode. A drop of lubricant - cosmetic kerosene or paraffin oil - was applied on the ring raceway only once. It was necessary to measure the time after which the value of the friction coefficient increased (Fig. 7b).

The results show that the method used in the tests is suitable for assessing the effectiveness of the geometrical surface texture of sliding pairs under mixed friction. The texture cavities were used as micro-containers of the lubricant. Their influence on the friction process was determined.

References

[1] Agarwal A., Dahotre N.: *Pulse electrode deposition of superhard boride coatings on ferrous alloy.* Surface & Coatings Technology 106 (1998) 242–250.

[2] Antoszewski B., Radek N., Tarelnik W., Wajs E.: *Electro discharge and laser texturing of sliding face of mechanical seals.* IX Intenationale Conference HERVICON-2005, Sumy, Ukraina, t. 3, 115–123.

[3] Radek N., Antoszewski B.: *Laser treatment of electro-spark deposited coatings.* Materials Engineering, Vol. 12, No 4 (2005) 13–15.

[4] Miernikiewicz A.: *Doświadczalno-teoretyczne podstawy obróbki elektroerozyjnej (EDM).* Politechnika Krakowska – Rozprawy, (2000) 274.

[5] Abel Tobias: *Laser honing creates an environmental breakthrough* Australian Manufacturing Technology July 2007 (50–51).

[6] Ryk G., Klingerman Y., Etsion I.Ł.: *Experimental Investigation of Laser Surface Texturing for Reciprocating Automotive Components* Tribologz Transactions Vol 45 2002 4, 444+449.

[7] Dausinger F., Hügel H., Konov V.: *Micro-machining with Ultrashort Laser Pulses: From Basic Understanding to Technical Applications,* in proceedings of Conference ALT 02, 5–20 September 2002, Adelboden (Switzerland).

[8] Tönshoff H. K., Ostendorf A., Körber K., Barsch N.: *Ablation and Cutting of Planar Silicon Devices Using Femtosecond Laser Pulses*, in Applied Physics A 77 (2003), p. 237–242.

[9] Antoszewski B.: *Właściwości laserowo i plazmowo modyfikowanych ślizgowych węzłów tarcia na przykładzie uszczelnień czołowych.* Monografia Politechnika Świętokrzyska 1999.

[10] Galinov I.V., Luban R.B.: *Mass transfer trends during electrospark alloying.* Surface & Coatings Technology, 79, 1996, p. 9.
[11] Liu J., Wang R., Qian Y.: *The formation of a single-pulse electrospark deposition spot.* Surface & Coatings Technology, 200, 2005, p. 2433.
[12] Radek N., Antoszewski B.: *Laser treatment of electro-spark deposited coatings.* Materials Engineering, 4, 2005, p.13.
[13] Antoszewski B., Radek N., Tarelnik W., Wajs E.: *Electro discharge and laser texturing of sliding face of mechanical seals.* IX Intenationale Conference HERVICON-Sumy, Ukraina, t. 3, 2005, p. 115.
[14] Pawlowski L.: *The science and engineering of thermal spray coatings.* John Wiley & Sons Ltd, Chichester 1995.
[15] Zhang, Jialiang; Kobayashi, Akira; *Excitation temperature of smart spraying plasmas produced from modulated arc discharge.* Vacuum Volume: 80, Issue: 11–12, September 7, 2006, pp. 1185–1189.
[16] Fukumasa, Osamu; Tagashira, Ryuma; Tachino, Kazufumi; Mukunoki, Hirotaka; *Spraying of MgO films with a well-controlled plasma jet.* Surface and Coatings Technology Volume: 169–170, Complete, June 2, 2003, pp. 579–582.
[17] Xu Dong-Yan, Chen Xi: *Effects of surrounding gas on the long laminar argon plasma jet characteristics.* International Communications in Heat and Mass Transfer Volume: 32, Issue: 7, July, 2005, pp. 939–946.
[18] Morks M.F., Kobayashi A.: *Effect of gun current on the microstructure and crystallinity of plasma sprayed hydroxyapatite coatings.* Applied Surface Science Volume: 253, Issue: 17, June 30, 2007, pp. 7136–7142.
[19] Mariaux Gilles; Vardelle Armelle: *3-D time-dependent modelling of the plasma spray process.* Part 1: flow modelling. International Journal of Thermal Sciences Volume: 44, Issue: 4, April, 2005, pp. 357–366.
[20] Salhi Z., Klein D., Gougeon P., Coddet C.: *Development of coating by thermal plasma spraying under very low-pressure condition <1mbar.* Vacuum Volume: 77, Issue: 2, January 17, 2005, pp. 145–150.
[21] Ma W., Pan W.X., Wu C.K.: *Preliminary investigations on low-pressure laminar plasma spray processing.* Surface and Coatings Technology Volume: 191, Issue: 2-3, February 21, 2005, pp. 166–174.
[22] Borisov Y., Chernyshow A., Korzhick V., Murashov A.: *Plasma spraying of coatings using a protective nozzle.* Proc. of 2nd Plasma-Technik Symp., Lucerne 1991.
[23] Beauvais S., Guipont V., Borit F., Jeandin M., Español M., Khor K.A., Robisson A.: *Process-microstructure-property relationships in controlled atmosphere plasma spraying of ceramics.* Surface and Coatings Technology Volume: 183, Issue: 2–3, May 24, 2004, pp. 204–211.
[24] Sarafoglou Ch.I., Pantelis D.I., Beauvais S., Jeandin M.: *Study of Al2O3 coatings on AISI 316 stainless steel obtained by controlled atmosphere plasma spraying (CAPS).* Surface & Coatings Technology Volume: 202, Issue: 1, November 15, 2007, pp. 155–161.
[25] Miyoshi K.: *Durability evaluation of selected solid lubricating films.* Wear 251 (2001) 1061–1067.
[26] Li Chang-Jiu, Sun Bo: *Microstructure and property of Al2O3 coating microplasma-sprayed using a novel hollow cathode torch.* Materials Letters Volume: 58, Issue: 1–2, January, 2004, pp. 179–183.
[27] Barbezat G., Zierhut. J., Landes K.D.*: Triplex- a high perfomance plasma torch.* Proc of United Thermal Spray Conference'99, Düsseldorf 1999.
[28] Nassenstein K., Peschka W.: *Development of a new three cathode-plasma-gun.* Proc. of International Thermal Spray Conference, Essen 2002.
[29] Mauer G., Basen R., Stover D.: *Preliminary study of the TriplexPro-200 gun for atmospheric plasma spraying of yttria stabilized zirconia.* Proc of 3rd Recontres Projection Internationales Thermique, Lille 2007.

[30] Barbezat G.: *The internal plasma spraying on powerful technology for the aerospace and automotive industries.* Proc. of 16th International Thermal Spray Conference, Singapore 2001.
[31] Barbezat G.: *Application of thermal spraying in the automobile industry.* Surface and CoatingsTechnology 201 (2006) 2028–2031.
[32] Ernst P., Barbezat G.: *Thermal spray application in powertain contribute to the saving energy and material resources*. Proc of 3rd Recontres Projection Internationales Thermique, Lille 2007.
[33] Planche M.P., Liao H., Normand B., Coddet C.: *Relationships between NiCrBSi particle characteristics and corresponding coating properties using different thermal spraying processes.* Surface and Coatings Technology 200 (2005) 2465–2473.
[34] Rodriguez J., Martin A., Fernandez R., Fernandez J.: *An experimental study of the wear perfomance of NiCrBSi thermal spray coatings.* Wear 255 (2003) 950–955.
[35] Miguel J.M., Guilemany J.M., Vizczino S.: *Tribological study of NiCrBSi coating obtained by different processes.* Tribology International 36 (2003) 181–187.
[36] Navas C., Colaco R., Damborenea J., Vilar R.: *Abrasive wear behaviour of laser clad and flame sprayed-melted NiCrBSi coatings.* Surface and Coatings Technology 200 (2006) 6854–6862.
[37] Zhao W-M., Wang Y., Dong L-X., Wu K-Y., Xue J.: *Corrosion mechanism of NiCrBSi coatings deposited by HVOF.* Surface and Coatings Technology 190 (2005) 293–298.
[38] Żórawski W.: *Właściwości natryskiwanych plazmowo i naddźwiękowo powłok kompozytowych zawierających smar stały.* Praca doktorska Politechnika Świętokrzyska Kielce 2004.

Manuscript received by Editorial Board, November 11th, 2009

Kształtowanie przeciwzużyciowych warstw powierzchniowych na elementach części maszyn

S t r e s z c z e n i e

W referacie poruszone są wybrane problemy technologiczne i badawcze dotyczące kształtowania warstw powierzchniowych, ukierunkowane na ograniczenie zużycia części maszyn. W szczególności zaprezentowane zostaną trzy problemy.

I problem – natryskiwanie plazmowe i naddźwiękowe powłok przeciwzużyciowych zawierających w swojej strukturze smar stały. Wyniki prezentowanych badań dotyczą zmian własności powłok z NiCrBSi natryskiwanych plazmowo i naddźwiękowo z dodatkiem tlenku żelaza jako składnikiem stanowiącym smar stały. Wykazano wpływ sposobu natryskiwania na zachowanie się fazy stanowiącej smar stały oraz stwierdzono skuteczność dodatku tlenku żelaza jako dodatku zmniejszającego opory tarcia. II problem – wytwarzanie metodą elektroiskrową warstw przejściowych oraz przeciwciernych na powierzchniach panewek łożysk ślizgowych. Wyniki przeprowadzonych badań dotyczą wytwarzania przeciwciernych warstw ze srebra, indu i cyny nanoszonych elektroiskrowo na powierzchnie panewek wykonanych z brązu B83. Wykazano skuteczność i przydatność tych cienkich (30 µm) i miękkich warstw w procesie docierania i tworzenia niskotarciowych struktur powierzchniowych. III problem – kształtowanie geometrycznej tekstury powierzchniowej dla obniżenia oporów tarcia i zwiększenia siły nośnej. Wyniki przedstawionych badań dotyczą zagadnień technologicznych wykonania tekstury metodą erozji laserowej i elektroerozji.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

JAROSŁAW SĘP*

The flow oil analysis in the gap of a journal bearing with a circumferential groove

Key words

Journal bearing, oil flow, finite element method.

Słowa kluczowe

Łożysko ślizgowe, przepływ oleju, metoda elementów skończonych.

Summary

The article presents the research results of a simulation of oil flow in a circumferentially grooved journal bearing. A three-dimensional, adiabatic flow was considered and the Navier-Stokes equations together with the equation of energy were used to describe it. The system of equations was solved applying the finite element method. The numerical flow analyses carried out showed that an appropriately sized groove on the journal not only does not impair the load capacity of a hydrodynamic journal bearing, but it can even increase it. The calculations were also made for an analysis of flow effects in the oil film.

1. Introduction

Journal bearings with grooves or cavities in mating surfaces show, under some conditions, better properties than standard ones with smooth-surface

* Faculty of Mechanical Engineering and Aeronautics, Rzeszów University of Technology, Al. Powstańców Warszawy 8, 35-959 Rzeszów, Poland, e-mail: jsztmiop@prz.edu.pl.

mating components [11, 12]. They are, among other things, less vulnerable to the wearing effect of oil impurities [9]. However, in the case of hydrodynamic slide bearings, grooved mating surfaces may considerably decrease load capacity [2, 3, 10]. There are works claiming that grooves always reduce the load capacity of a bearing compared with a pair of smoothly surfaced components [4]. This view is also considered right by some researches studying the hydrodynamic lubrication of slide bearings. It follows from the previous works of the author [7, 8] on the initial modelling of a spiral-grooved journal bearing that, under some circumstances, the journal grooves may enhance the bearing load capacity compared with a smooth journal bearing. The article presents the first stage of research with a view to explaining what causes the effect. A bearing with a circumferentially grooved journal was considered.

2. A model of bearing with a circumferential groove in the journal

A circumferentially grooved journal bearing was schematically shown in Fig. 1. The measurements describing the groove are its width **s** and depth **g**. It was assumed that the axis of symmetry of the groove is in the middle of the bearing sleeve. While modelling the bearing, the journal and sleeve surfaces were represented by mathematical functions. The sleeve surface S1 outside the feed groove was described as

$$x \in \langle 0 : 2\Pi r \rangle, \quad y = R + m \cdot \cos\left(\frac{x}{r}\right), \quad z \in \langle 0 : b \rangle \tag{2.1}$$

The journal surface was

$$x \in \langle 0 : 2\Pi r \rangle, \quad y = r + A \cdot e^{-B[(z-b/2)]^2}, \quad z \in \langle 0 : b \rangle \tag{2.2}$$

In 2.2, coefficient A and B define the depth and width of the groove, respectively. The supply groove was modelled as a cube of length b_r, width s_r and height h_r (Fig. 2).

The depth of the groove in the surface does not exceed 100 μm, so it is comparable with the amount of oil clearance. That makes it necessary to modify the standard, hydrodynamic theory of lubrication. The typical simplifying assumptions relating to, e.g. a constant pressure value along the bearing clearance (along axis y) and lack of the effect of a number of oil speed constituent gradients, do not fit the reality. Thus, it is necessary to consider three- dimensional flow described by the Navier-Stokes equations as well as energy and continuity equations. The following assumptions were made for the analysis of oil flow in the examined bearing:

- Oil is Newtonian liquid.
- Flow is laminar.

- Flow at a fixed time t (quasi-static model) is considered.
- There is no field of body forces.
- Oil is incompressible.
- Oil density is independent of temperature.
- Oil viscosity depends only on temperature.
- Thermal conditions are fixed.
- Specific heat and oil thermal conductivity coefficients are constant values.

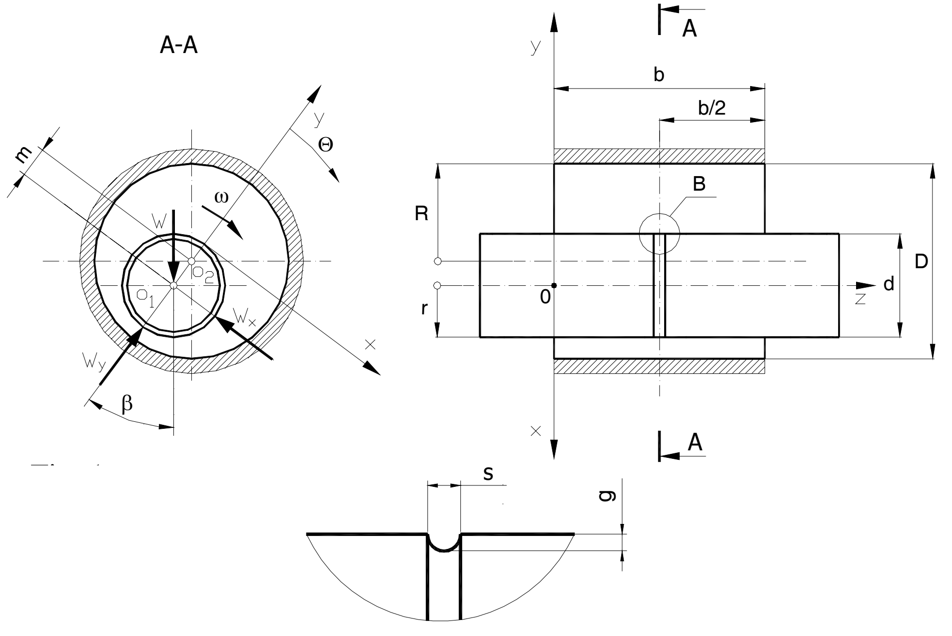


Fig. 1. Journal bearing with circumferentially grooved journal: D(R) – diameter (radius) of the sleeve, d – diameter (radius) of the journal, b – width of the bearing, s – width of the groove, g – depth of the groove, m – eccentricity of the journal centre O_1 relative to the sleeve centre O_2, W – bearing load capacity, W_x – load capacity component in the direction of axis x, W_y – load capacity component in the direction of axis y, β – attitude angle , θ – angular coordinate measured from the maximum height of the bearing clearance, ω – angular velocity of the journal
Rys. 1. Łożysko ślizgowe z czopem z obwodowym rowkiem: D(R) – średnica (promień) panewki, d – średnica (promień) czopa, b – szerokość łożyska, s – szerokość rowka, g – głębokość rowka, m – mimośrodowość środka czopa O_1 względem środka panewki O_2 , W – nośność łożyska, W_x – składowa nośności w kierunku osi x, W_y – składowa nośności względem osi y , β – kąt położenia linii środków, Θ – współrzędna kątowa mierzona od miejsca, gdzie wysokość szczeliny smarowej jest największa, ω – prędkość kątowa czopa

The radius of curvature of a lubricating film is so large, compared with the film thickness, that it is satisfactory to work with rectangular coordinates referred to the film surfaces (Fig.2). For the above assumptions, the Navier-Stokes equations are as follows [1]:

$$\rho\left(u\frac{\partial u}{r\partial\Theta}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=$$
$$=-\frac{\partial p}{r\partial\Theta}+2\frac{\partial}{r^2\partial\Theta}\left(\eta\frac{\partial u}{\partial\Theta}\right)+\frac{\partial}{\partial y}\left[\eta\left(\frac{\partial u}{\partial y}+\frac{\partial v}{r\partial\Theta}\right)\right]+\frac{\partial}{\partial z}\left[\eta\left(\frac{\partial w}{r\partial\Theta}+\frac{\partial u}{\partial z}\right)\right] \tag{2.3}$$

$$\rho\left(u\frac{\partial v}{r\partial\Theta}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=$$
$$=-\frac{\partial p}{\partial y}+2\frac{\partial}{\partial y}\left(\eta\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left[\eta\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+\frac{\partial}{r\partial\Theta}\left[\eta\left(\frac{\partial u}{\partial y}+\frac{\partial v}{r\partial\Theta}\right)\right] \tag{2.4}$$

$$\rho\left(u\frac{\partial w}{r\partial\Theta}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=$$
$$=-\frac{\partial p}{\partial z}+2\frac{\partial}{\partial z}\left(\eta\frac{\partial w}{\partial z}\right)+\frac{\partial}{r\partial\Theta}\left[\eta\left(\frac{\partial w}{r\partial\Theta}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\eta\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]. \tag{2.5}$$

The flow continuity equation is

$$\frac{\partial(\eta u)}{r\partial\Theta}+\frac{\partial(\eta v)}{\partial y}+\frac{\partial(\eta w)}{\partial z}=0\,, \tag{2.6}$$

However, the energy equation is

$$\rho c\left(u\frac{\partial T}{r\partial\Theta}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=k\left(\frac{\partial^2 T}{r\partial\Theta^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\eta\Phi\,, \tag{2.7}$$

where the function of energy dissipation is

$$\Phi=\left\{2\left[\left(\frac{\partial u}{r\partial\Theta}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{r\partial\Theta}\right)^2+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2+\left(\frac{\partial w}{r\partial\Theta}+\frac{\partial u}{\partial z}\right)^2\right\} \tag{2.8}$$

The dependence of oil dynamic viscosity on temperature is described as follows:

$$\eta(T)=0{,}0625\cdot e^{\left(-7{,}973+\frac{661246}{T^2}\right)} \tag{2.9}$$

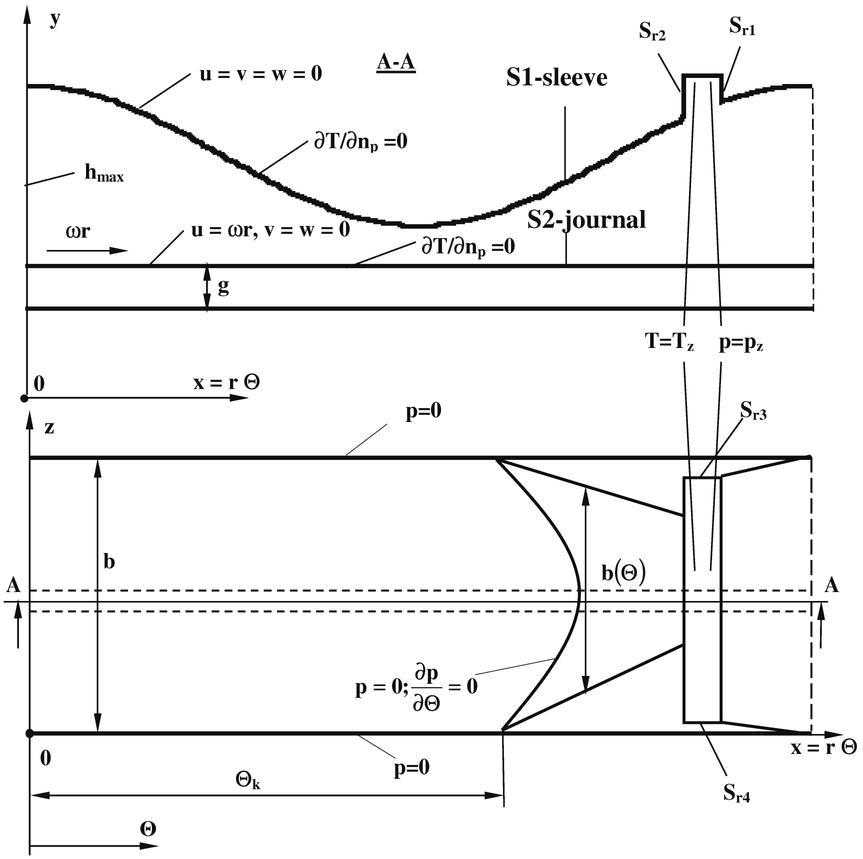


Fig. 2. Development of journal and sleeve working surfaces together with boundary conditions: p-pressure in oil layer, p_z – feed pressure, T – temperature, T_z – supply temperature, h_{max} – maximum height of bearing interface, b – bearing width, S_{r1}, S_{r2}, S_{r3}, S_{r4} – surfaces limiting supply groove, θ – angular coordinate measured from the point where oil clearance is the highest, $θ_k$ – coordinate from which onwards oil film begins to taper, ω – journal angular velocity, n_p – surface normal

Rys. 2. Rozwinięcie powierzchni roboczych czopa I panewki wraz z warunkami brzegowymi: p – ciśnienie w warstwie oleju, p_z – ciśnienie zasilania, T – temperatura, T_z – temperatura zasilania, h_{max} – maksymalna wysokość szczeliny smarowej, b – szerokość łożyska, S_{r1}, S_{r2}, S_{r3}, S_{r4} – powierzchnie ograniczające rowek smarowy, Θ – współrzędna kątowa mierzona od miejsca, gdzie wysokość szczeliny smarowej jest największa, $Θ_k$ – współrzędna, począwszy od której następuje zwężanie filmu olejowego, ω – prędkość kątowa czopa, n_p – normalna do powierzchni

The dependence (2.9) was obtained from investigations of LAN-46 oil, which was used as lubricating agent [6].

The following boundary conditions (Fig.2) were assumed to define the pressure area and flow velocity:

– Supply groove pressure equals supply pressure p_z;

$$p = p_z . \tag{2.10}$$

– Oil pressure on the exit sleeve edges in the axial direction equals ambient pressure which was assumed to be the reference point equal 0.

$$p(\Theta, z = 0) = p(\Theta, z = b) = 0. \tag{2.11}$$

– Pressure in the idle area of the oil clearance equals zero;

$$p(\Theta, z)_n = 0. \tag{2.12}$$

– end of oil film is the point locus where the pressure equals the ambient pressure and pressure gradient equals zero;

$$p_{\Theta=\Theta_{x,z}} = 0 \text{ oraz } \left(\frac{\partial p}{\partial \Theta}\right)_{\Theta=\Theta_{x,z}} = 0, \tag{2.13}$$

– Journal speed equals ωr, and the journal does only rotary motion. Therefore, on the S2 surface:

$$u = \omega r,\ v = w = 0\,\big|_{S2}. \tag{2.14}$$

– The sleeve is motionless; therefore, on the S1 surface and on the surfaces limiting the feed groove:

$$u = v = w = 0\big|_{S1,Sr1,Sr2,Sr3,Sr4}, \tag{2.15}$$

– In the oil clearance, the following dependencies are also met**:**

$$p(\Theta = 0) = p(\Theta = 2\Pi), \tag{2.16}$$

$$u(\Theta = 0) = u(\Theta = 2\Pi), \tag{2.17}$$

$$v(\Theta = 0) = v(\Theta = 2\Pi), \tag{2.18}$$

$$w(\Theta = 0) = w(\Theta = 2\Pi). \tag{2.19}$$

As a consequence of assuming the adiabatic flow model, the following boundary conditions were postulated to define the temperature field:

– The groove is totally filled with oil at the temperature denoted as Tz (the effect of streams getting mixed in the groove was ignored, since their mixing in the oil film was assumed).
– The stream of heat penetrating through the journal and the sleeve surfaces equals 0. Therefore;

$$\frac{\partial T}{\partial n}\Big|_{S1} = \frac{\partial T}{\partial n}\Big|_{S2} = 0 \tag{2.20}$$

where n means normal to the surface

Additionally, it was assumed that

$$T(\Theta = 0) = T(\Theta = 2\Pi) \tag{2.21}$$

3. Calculation methodology

The set of equations (2.3)–(2.7) was made discrete by applying the method of finite elements. One of the variants of the weighted, residual method, the Garlekin method, was used. The obtained set of equations was made linear, making use of the Newton-Raphson method and than solved by the Gauss elimination method.

From tetrahedral 78672 to 101232, 4-node, spatial elements were generated in the oil clearance volume, depending on the size of the groove. The mesh of the finite elements is shown in Fig. 3. The solution procedure was carried out using the ADINA 8.1 programme packets.

The above presented calculation method was verified by comparing the obtained results with those found in the literature of experimental research results [5].

The following quantities were chosen to compare the calculation results at this stage:

– maximum pressure in oil film $\mathbf{p_m}$,
– oil film load capacity **W**:

$$W = \sqrt{(W_x)^2 + (W_y)^2} \tag{3.1}$$

where:

$$W_x = r \int_0^b \int_0^{\Theta_k} p \sin\Theta \, d\Theta \, dz, \tag{3.2}$$

$$W_y = -r \int_0^b \int_0^{\Theta_k} p \cos\Theta \, d\Theta \, dz, \tag{3.3}$$

– attitude angle β:

$$\beta = \operatorname{arctg}\left|\frac{W_x}{W_y}\right|, \tag{3.4}$$

– maximum temperature in oil film $\mathbf{T_m}$,
– maximum oil flow velocity component in the direction of axis x – $\mathbf{u_m}$,
– maximum oil flow velocity component in direction of axis y – $\mathbf{v_m}$,

– maximum oil flow velocity component in the direction of axis z – $\mathbf{w_m}$,
– oil flow rate:

$$q_o = 2\int_0^h \int_0^{\Theta_k} w\ r d\Theta dy\,. \tag{3.5}$$

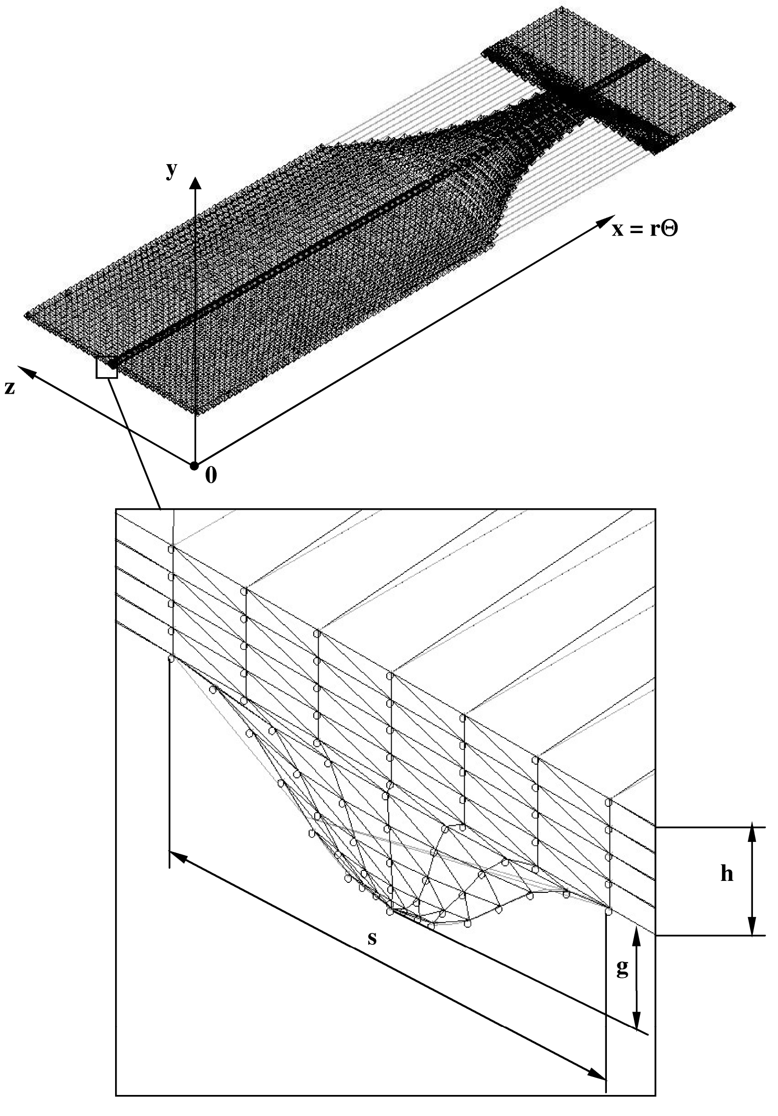


Fig. 3. Mesh of finite elements
Rys. 3. Siatka elementów skończonych

The calculations were done at the following values of the parameters describing the oil and the oil clearance:

- Journal radius r = 0.0316 m, sleeve radius R = 0.0317275 m,
- Bearing length b = 0.063 m,
- Oil density ρ = 880 kg/m^3, oil specific heat c = 2000 J/(kg·K),
- Oil heat conductivity k = 0.145 W/(m·K),
- Journal angular velocity ω = 20 rad/s, $p_z = 0$, T_z =293 K.

4. Results and their analysis

The effect of the groove geometry on the bearing characteristics for four relative eccentricity ratios is $\varepsilon = m/(R-r)$. Based on the initial research, nine geometric variants of the groove were distinguished. The results of the calculations are listed in Tables 1 through 4. The calculations carried out show that for the smallest analysed relative eccentricity ($\varepsilon = 0.195$) the circumferential groove on the journal causes a slight load capacity increase (up to 4.5% for the smallest section) in the case of seven analysed dimensions. Only for 1.0 mm wide and 0.2 and 0.25 deep groves, there occurs a slight load capacity decrease (up to 1.5% for the largest analysed section). For the relative eccentricity $\varepsilon = 0.44$, for three analysed grooves (0.2 and 0.6mm in width, 0.15 mm in depth and 0.2 mm in width and depth), it was noted that there occurred a very small (up to 1%) increase in load capacity. For the other six grooves, the capacity decreases (down to 4.5% for the biggest tested section).

Table 1. Characteristics of circumferentially grooved journal for $\varepsilon = 0.195$
Tabela 1. Charakterystyki łożyska z czopem z obwodowym rowkiem dla ε = 0,195

g $\cdot 10^{-3}$[m]	**s** $\cdot 10^{-3}$[m]	**W** [N]	$\mathbf{p_m}$ $\cdot 10^5$ [Pa]	$\mathbf{u_m}$ [m/s]	$\mathbf{v_m}$ [m/s]	$\mathbf{w_m}$ [m/s]	$\mathbf{T_m}$ [K]	$\mathbf{q_o}$ $\cdot 10^{-6}$[m^3/s]	β [rad]
0	0	**58.50**	**0.270**	**0.646**	**0.049**	**0.070**	**294.7**	**0.821**	**1.234**
0.15	0.2	**61.09**	**0.281**	**0.672**	**0.054**	**0.070**	**295.0**	**0.776**	**1.286**
0.15	0.6	**59.54**	**0.276**	**0.672**	**0.055**	**0.070**	**295.0**	**0.773**	**1.288**
0.15	1.0	**58.92**	**0.272**	**0.672**	**0.060**	**0.069**	**295.0**	**0.770**	**1.290**
0.20	0.2	**60.10**	**0.281**	**0.672**	**0.054**	**0.070**	**295.0**	**0.776**	**1.286**
0.20	0.6	**59.32**	**0.275**	**0.672**	**0.057**	**0.070**	**295.0**	**0.773**	**1.289**
0.20	1.0	**58.34**	**0.267**	**0.672**	**0.065**	**0.069**	**295.0**	**0.767**	**1.292**
0.25	0.2	**60.10**	**0.281**	**0.672**	**0.054**	**0.070**	**295.0**	**0.776**	**1.285**
0.25	0.6	**59.05**	**0.273**	**0.672**	**0.058**	**0.070**	**295.0**	**0.771**	**1.289**
0.25	1.0	**57.64**	**0.262**	**0.672**	**0.070**	**0.069**	**295.0**	**0.763**	**1.295**

Table 2. Characteristics of circumferentially grooved journal for ε = 0.44
Tabela 2. Charakterystyki łożyska z czopem z obwodowym rowkiem dla ε = 0,44

g $\cdot 10^{-3}$[m]	s $\cdot 10^{-3}$[m]	W [N]	p_m $\cdot 10^5$ [Pa]	u_m [m/s]	v_m [m/s]	w_m [m/s]	T_m [K]	q_o $\cdot 10^{-6}$[m^3/s]	β [rad]
0	0	**160.05**	**0.786**	**0.733**	**0.399**	**0.154**	**295.8**	**1.703**	**0.963**
0.15	0.2	**162.97**	**0.884**	**0.774**	**0.216**	**0.175**	**294.9**	**1.962**	**1.117**
0.15	0.6	**160.33**	**0.853**	**0.781**	**0.217**	**0.174**	**294.9**	**1.955**	**1.120**
0.15	1.0	**158.05**	**0.826**	**0.785**	**0.218**	**0.173**	**294.9**	**1.947**	**1.122**
0.20	0.2	**162.86**	**0.883**	**0.774**	**0.216**	**0.175**	**294.9**	**1.962**	**1.117**
0.20	0.6	**159.31**	**0.839**	**0.869**	**0.217**	**0.173**	**294.9**	**1.951**	**1.120**
0.20	1.0	**155.74**	**0.801**	**0.880**	**0.217**	**0.171**	**294.9**	**1.939**	**1.125**
0.25	0.2	**162.85**	**0.883**	**0.774**	**0.217**	**0.173**	**294.8**	**1.962**	**1.117**
0.25	0.6	**158.09**	**0.825**	**0.939**	**0.217**	**0.173**	**294.8**	**1.948**	**1.122**
0.25	1.0	**153.01**	**0.773**	**0.965**	**0.217**	**0.173**	**294.8**	**1.929**	**1.129**

Table 3. Characteristics of circumferentially grooved journal for ε = 0.69
Tabela 3. Charakterystyki łożyska z czopem z obwodowym rowkiem dla ε = 0,69

g $\cdot 10^{-3}$[m]	s $\cdot 10^{-3}$[m]	W [N]	p_m $\cdot 10^5$ [Pa]	u_m [m/s]	v_m [m/s]	w_m [m/s]	T_m [K]	q_o $\cdot 10^{-6}$[m^3/s]	β [rad]
0	0	**358.20**	**2.102**	**0.719**	**0.354**	**0.256**	**299.4**	**2.716**	**0.688**
0.15	0.2	**377.47**	**2.515**	**0.982**	**0.229**	**0.277**	**297.4**	**2.854**	**0.794**
0.15	0.6	**363.36**	**2.279**	**1.220**	**0.230**	**0.274**	**297.4**	**2.842**	**0.801**
0.15	1.0	**350.69**	**2.155**	**1.180**	**0.231**	**0.273**	**297.4**	**2.826**	**0.810**
0.20	0.2	**377.11**	**2.505**	**1.037**	**0.230**	**0.277**	**297.4**	**2.854**	**0.794**
0.20	0.6	**356.39**	**2.203**	**1.447**	**0.231**	**0.273**	**297.4**	**2.834**	**0.806**
0.20	1.0	**337.87**	**2.032**	**1.393**	**0.231**	**0.269**	**297.3**	**2.812**	**0.822**
0.25	0.2	**376.69**	**2.501**	**1.053**	**0.230**	**0.277**	**297.4**	**2.854**	**0.794**
0.25	0.6	**348.94**	**2.128**	**1.571**	**0.231**	**0.271**	**297.4**	**2.826**	**0.812**
0.25	1.0	**324.46**	**1.928**	**1.474**	**0.231**	**0.265**	**297.3**	**2.794**	**0.834**

Table 4. Characteristics of circumferentially grooved journal for ε = 0.87
Tabela 4. Charakterystyki łożyska z czopem z obwodowym rowkiem dla ε = 0,87

g $\cdot 10^{-3}$[m]	s $\cdot 10^{-3}$[m]	W [N]	p_m $\cdot 10^5$ [Pa]	u_m [m/s]	v_m [m/s]	w_m [m/s]	T_m [K]	q_o $\cdot 10^{-6}$[m^3/s]	β [rad]
0	0	**658.40**	**4.540**	**0.725**	**0.117**	**0.318**	**303.5**	**3.304**	**0.467**
0.15	0.2	**784.78**	**6.911**	**1.990**	**0.069**	**0.346**	**300.9**	**3.392**	**0.572**
0.15	0.6	**718.97**	**6.155**	**1.917**	**0.066**	**0.340**	**300.7**	**3.376**	**0.558**
0.15	1.0	**682.15**	**5.926**	**1.670**	**0.069**	**0.335**	**300.6**	**3.358**	**0.598**
0.20	0.2	**780.75**	**6.828**	**2.088**	**0.066**	**0.346**	**300.9**	**3.396**	**0.572**
0.20	0.6	**693.45**	**5.977**	**2.137**	**0.066**	**0.337**	**300.6**	**3.364**	**0.595**
0.20	1.0	**649.57**	**5.756**	**1.868**	**0.075**	**0.330**	**300.6**	**3.338**	**0.608**
0.25	0.2	**776.83**	**6.749**	**2.022**	**0.066**	**0.346**	**300.9**	**3.394**	**0.573**
0.25	0.6	**670.96**	**5.856**	**2.129**	**0.067**	**0.343**	**300.5**	**3.352**	**0.603**
0.25	1.0	**622.57**	**5.624**	**1.881**	**0.080**	**0.325**	**300.5**	**3.314**	**0.615**

At $\varepsilon = 0.69$, the capacity load increases for the same groove sections, as for $\varepsilon = 0.44$ (to 5% for the smallest section). For the rest of the sections, the load capacity decreases (to 9.5%).

For a relative eccentricity ratio of $\varepsilon = 0.87$, for the seven analysed grooves, there occurs an increase in load capacity (up to 19% for the smallest section); whereas, the remaining two grooves cause a load capacity decrease (to 5.5%). In all the cases analysed, the highest load capacity of the bearing occurs at the smallest investigated groove section (it is higher than in the case of a smooth journal bearing); whereas, the lowest load capacity is shown by the bearing with the largest groove considered. For the analysed bearing geometry and the assumed oil and rotational speed, a circumferential groove of the appropriate width and (section) depth enhances bearing load capacity. The load capacity changes are accompanied by those of oil flow velocity. The observed changes refer in particular to the circumferential velocity u. For the least analysed relative eccentricity value, they are still not very significant. For all the nine investigated geometric variations of the groove, the maximum velocity of the flow in the circumferential direction (u_m) has the same values and is by 4% higher than that for a smooth journal.

At $\varepsilon = 0.44$, the value of the parameter u_m is from 5.5% (the smallest groove) to 24.5% (the largest groove) higher than that for a bearing with grooveless journal.

An increment in relative eccentricity causes a further increase in the maximum velocity of oil flow in the circumferential direction. For $\varepsilon = 0.69$, it increases from 36.5% (the smallest groove) to almost 120% (the groove of 0.6 mm in width and 0.25 mm in depth). At $\varepsilon = 0.87$, the maximum velocity of oil flow in the circumferential direction is from more than two to almost three time as big as that in the case of a grooveless journal.

It is also noteworthy that the maximum oil film temperature in a circumferentially grooved journal bearing is smaller than that for a smooth journal bearing. The maximum temperature in a plain journal bearing occurs in the idle area halfway along the width of the bearing, right before the feed groove. In the circumferentially grooved journal bearing, the height of the bearing clearance at that place increases locally (through the groove). That brings about a decrease in the maximum temperature.

The calculated results indicate that a circumferential groove in the journal of a bearing significantly changes its characteristics compared to a standard bearing. To find out the causes of these changes, complex analyses of the phenomena in the oil film [6] were carried out.

To sum up the most significant flow phenomena occurring in the oil film of a circumferentially grooved bearing as well as their effect on the assumed geometry, oil, feed pressure and the journal rotational velocity, the following should be noted:

1. Within the groove boundary and its adjacent area, there forms a lower pressure area (Fig. 4). Its dimensions increase with the increase in the groove size and relative eccentricity. There forms a characteristic hydrodynamic pressure distribution in the oil film in which two local maxima, separated by a

low-pressure area, appear. Increasing the groove dimensions and relative eccentricity results in the pressure maximum shifting in the direction of the bearing edge.

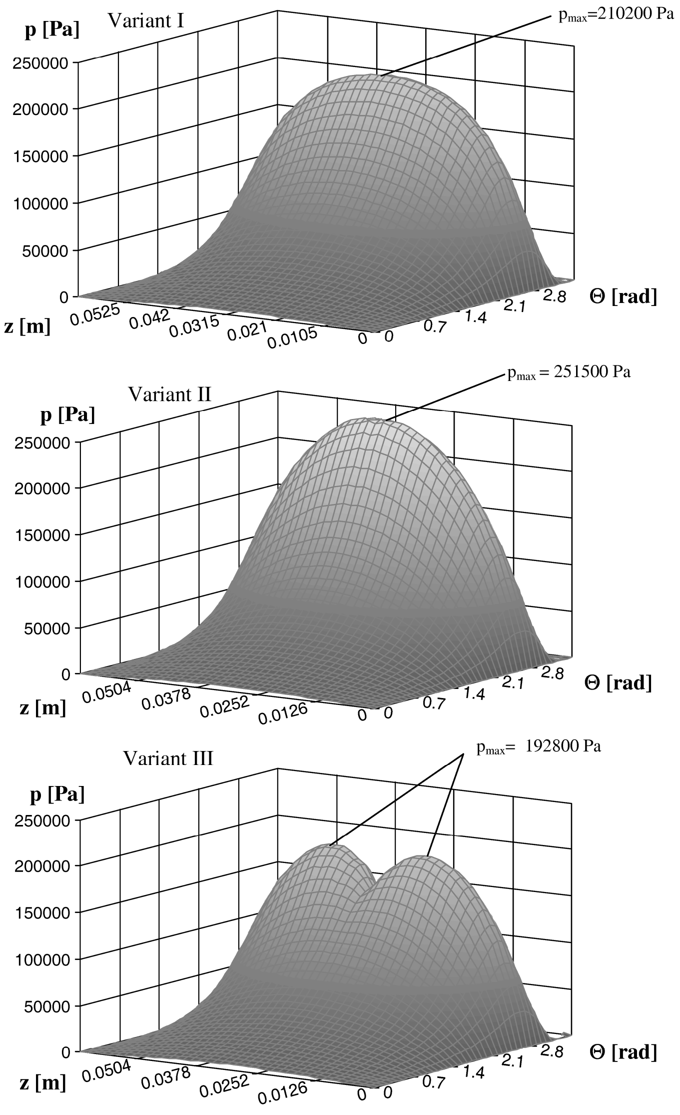


Fig. 4. Distribution of the hydrodynamic pressure in the oil film on the journal surface (y = r) for ε = 0.69; variant I – smooth journal, variant II – journal with the smallest investigated groove, variant III – journal with the biggest investigated groove

Rys. 4. Ciśnienie hydrodynamiczne w filmie olejowym na powierzchni czopa (y = r) dla ε = 0,69; wariant 1 – gładki czop, wariant 2 – czop z najmniejszym z badanych rowków, wariant 3 – czop z największym z badanych rowków

2. In the oil film area, there forms a zone from which oil flows into the groove (before the minimum bearing clearance height) and a zone where oil flows out of the groove (behind the minimum bearing clearance). An increase in the groove size and relative eccentricity brings about an increase in the axial velocity at which oil flows in and out of the groove.
3. Oil flows into the groove from either side. The inflowing streams block each other, which results in the following (Fig. 5):
   – There occurs a local increase in the circumferential oil flow velocity. In the case of high eccentricities (0.69 and 0.87), there also appears backward flow within the groove area.
   – For the most of the analysed geometric variants of a circumferentially grooved bearing, the maximum oil pressure in the oil film is higher than the maximum pressure of oil in a smooth journal bearing.

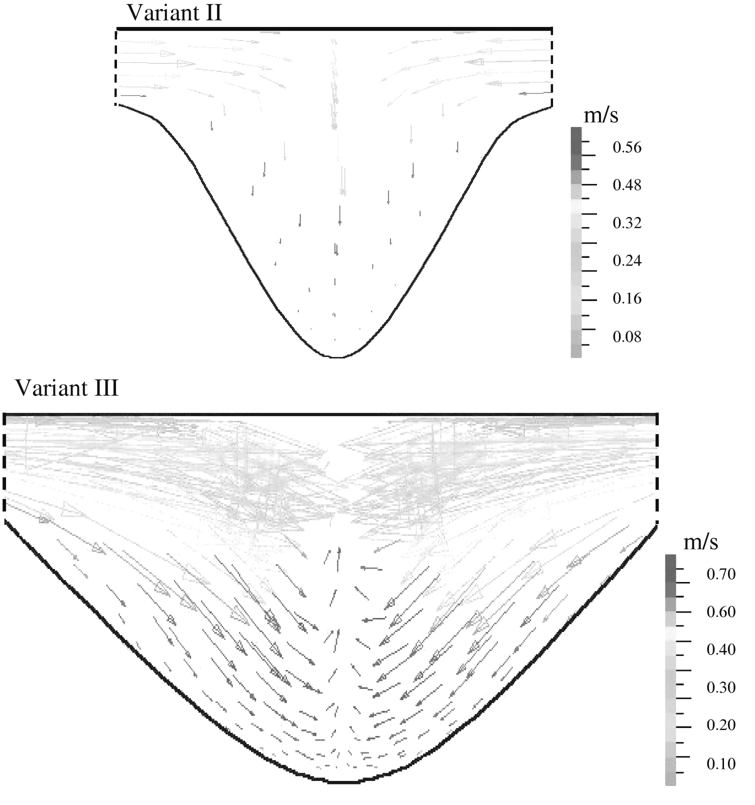


Fig. 5. Oil flow within groove for ε = 0.69; variant II – journal with the smallest investigated groove, variant III- journal with the largest investigated groove (cross-section in maximum pressure place)
Rys. 5. Przepływ oleju w rowku dla ε = 0,69; wariant 2 – czop z najmniejszym z badanych rowków, wariant 3 – czop z największym z badanych rowków (przekrój poprzeczny w miejscu występowania maksymalnego ciśnienia

4. For a small sized circumferential groove, the lowered pressure area is small and, due to an increase in the oil film maximum pressure, the load capacity of the bearing improves.
5. For all the analysed relative eccentricities, a circumferential groove of 0.15 mm in depth (60% of bearing clearance) and of up to 0.6 mm in width (four times the depth) increases the bearing load capacity. However, a groove of 0.25 mm in depth (bearing clearance) and 1 mm in width (also four times the depth) causes, for all the investigated eccentricities, a decrease in load capacity compared to a smooth journal bearing.

5. Conclusions

1. If a circumferential groove on a journal, in the case when its axis of symmetry, is halfway along the width of the sleeve and its dimensions have been appropriately selected, it can cause an increase in the bearing load capacity compared to a smooth journal bearing. This is due to a change in the oil flow conditions compared to a standard bearing.
2. Oil flows into the groove from either side, and the inflowing streams block each other's flow in the axial direction. That results in a characteristic hydrodynamic pressure distribution, where there form two local maxima separated by a lowered pressure zone. There is also a local increase in oil flow velocity in the circumferential direction.
3. At the appropriate groove dimensions, due to the above described phenomena, hydrodynamic pressure attains higher values than those for a standard slide bearing, and the zone of lowered pressure between local extrema is small. This results in an effect of increased load capacity. However, when the groove is too big, the local maxima show smaller values than those in the case of a standard bearing. Furthermore, the pressure decrease between them is remarkable, and, in such a case, a load capacity decrease can be observed.

References

[1] Gross W.A., Matsch L.A., Castelli V., Eshel A., Vohr J.H., Wildmann M.: *Fluid film lubrication.* A Wiley-Interscience Publication, New York, Toronto 1980.

[2] Kang K., Rhim Y., Sung K.: *A study of the oil-lubricated herringbone-grooved journal bearing-part 1: numerical Analysis.* Transactions of the ASME, Journal of Tribology, vol. 118, 1996, 906–911.

[3] Kawabata N., Ozawa Y., Kamaya S., Miyake Y.: *Static characteristics of the regular and reversible rotation type herringbone grooved journal bearing.* Transactions of the ASME, Journal of Tribology, vol. 111, 1989, 484–490.

[4] Król M.: *Badania wpływu mikrogeometrii na obciążalność poprzecznych łożysk ślizgowych.* Zagadnienia Eksploatacji Maszyn, nr 1(73), 1988, 15–25.

[5] Merc T.: *Przepływ oleju w nieroboczej części poprzecznego łożyska ślizgowego*. Rozprawa doktorska, Politechnika Łódzka, Łódź 1981.
[6] Sęp J.: *Właściwości filmu olejowego w poprzecznych łożyskach ślizgowych z nietypową geometrią czopa*. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2006.
[7] Sęp J.: *Three-dimensional hydrodynamic analysis of a journal bearing with a two-component surface layer*. Tribology International, vol. 38, 2005, 97–104.
[8] Sęp J.: *Trójwymiarowa hydrodynamiczna analiza łożyska z czopem ze śrubowym rowkiem.* Tribologia nr 5, 2003, 447–458.
[9] Sęp J., Kucaba-Piętal A.: *Experimental testing of journal bearings with two-component surface layer in the presence of an oil abrasive contaminant.* Wear, vol. 249, 2001, 1090–1095.
[10] Stolarski T.A., Khan M.Z.: *Steady-state performance of oil lubricated helical grooved journal bearings.* Tribology Transactions, vol. 38, 1995, 459–465.
[11] Wierzcholski K.: *A new concept of the changes of memory capacity of fluid dynamics HDD micro-bearings.* Tribologia, vol. 4 (220), 2008, 267–273.
[12] Wierzcholski K., Miszczak A.: *Capacity enhancement in HDD conical micro-bearings.* Tribologia, vol. 4 (226), 2009, 251–258.

Manuscript received by Editorial Board, June 19th, 2009

Analiza przepływu oleju w łożysku ślizgowym z rowkiem na czopie

S t r e s z c z e n i e

W artykule przedstawiono rezultaty komputerowej symulacji przepływu oleju w poprzecznym łożysku ślizgowym z rowkiem na czopie. Rozważono trójwymiarowy adiabatyczny przepływ oleju opisany równaniami Naviera-Stokesa wraz z równaniami ciągłości przepływu i energii. Układ równań rozwiązano metodą elementów skończonych. Wyniki analiz numerycznych wskazały, że obwodowy rowek na czopie o odpowiednio dobranych wymiarach nie powoduje zmniejszenia nośności łożyska. Na podstawie przeprowadzonych obliczeń zidentyfikowano także zjawiska przepływowe w filmie olejowym analizowanego łożyska.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

HENRYK TOMASZEK[*], MARIUSZ WAŻNY[**]

The modelling of the reliability of selected devices in an aircraft under conditions of the accumulation of effects of destructive processes

Key words

Reliability, limit state, diagnostic parameter, nominal value, deviation from nominal value.

Słowa kluczowe

Niezawodność, stan graniczny, parametr diagnostyczny, wartość nominalna, odchyłka od wartości nominalnej.

Summary

The article presents the way of determining the operational reliability of a device under conditions of destructive processes leading to the change of value of diagnostic parameters. It was assumed that, among diagnostic parameters determining the technical state of a device, there is a dominant parameter. Its values are the highest ones and the limit state is reached in the fastest way. It was assumed that effects of destructive processes accumulate, e.g. increase variance. The model of the symmetric random walk of the deviation value from the nominal value of the dominant parameter was used to determine the reliability.

[*] Air Force Institute of Technology, ul. Księcia Bolesława 6, 01-494 Warszawa, Poland skr. poczt. (post-office box) 96.
[**] Militatry Univesity of Technology WAT, ul. Kaliskiego 2, 00-908 Warszawa 49, Poland.

1. Introduction

Examining the reliability of aircraft in operation connects with forecasting their technical state. In most cases, this state is described with the use of diagnostic parameters. The change of their values enables the evaluation of the technical state change of aircraft devices. Destructive processes occurring during aircraft operation have a decisive influence on the change of diagnostic parameters. Examples of such processes are as follows:

- Wear processes of construction elements;
- Processes connected with surface wear which lead to the change of element sizes or the increase in clearances connected with the deterioration of the state of cooperating surfaces;
- Corrosion and ageing processes, which cause systems to get out of adjustment.

The physics and analytical description of these processes create lots of difficulties due to their complexity. That is why, different simplifications are used to describe the effects of these processes. Due to a wide range of the effects of these processes, usually only one process is considered. In this article, we will consider and describe the effects of ageing processes leading to the change of diagnostic parameter values.

Parameters describing a technical state of a device change due to ageing processes and internal conditions of a device, which are connected with its operation. Effects of these processes can lead to the following:

- A random increase of parameter values in the function of operation time;
- A random decrease of parameter values in the function of operation;
- A random fluctuation of parameter values in the function of operation time.

In this article, we will consider the case when the diagnostic parameter value changes undergo random fluctuations around the nominal value.

The following establishments are accepted:

1) The number of diagnostic parameters for the device that is being considered is N, i.e. the vector of the technical state has the following form

$$X = \left[x_1 + x_2 + \ldots x_N\right].$$

Diagnostic parameter values are independent, i.e. the change of value of one of them does not result in the change of values of other parameters.

2) The reliability state of a device is determined according to a selected diagnostic parameter (for that the exceedance of the limit value is reached in the fastest way). This parameter is regarded as a dominant one and is marked with x.

3) If current values of a dominant parameter are included in the range

$$X \in \left\lfloor x_d , x_g \right\rfloor$$

where: x_d – the lower limit value of a dominant parameter, and
x_g – the upper limit value of a dominant parameter,

a device is considered to be able to work. Otherwise, the device is considered to be unable to work.

2. The model of the evaluation of the reliability state of a device

It is assumed that

1) The mean value of a dominant diagnostic parameter agrees with the nominal value and is a constant value. Ageing processes lead to the increase of the variance of deviation value from the nominal value
2) Deviation value is determined in the following way:

$$\begin{aligned} z &= x_p - x_n \qquad \text{for} \qquad x_p > x_n, \\ -z &= x_p - x_n \qquad \text{for} \qquad x_p < x_n. \end{aligned} \tag{1}$$

where: x_p – the measured value of a dominant parameter,
x_n – the nominal value of a dominant diagnostic parameter.

3) The check-up of a diagnostic parameter is performed at the time interval Δt;
4) The measurement of a diagnostic parameter is performed in the discrete system with step h, where $h = \frac{x_p - x_n}{L}$, and L is selected suitably.
5) Parameter deviations from the nominal value has the following discrete values:

$$z_1 = lh \qquad \text{where} \qquad 1 = ...,-2,-1,0,1,2,...$$

6) The diagram of changes of parameter deviation value is presented in Fig. 1.

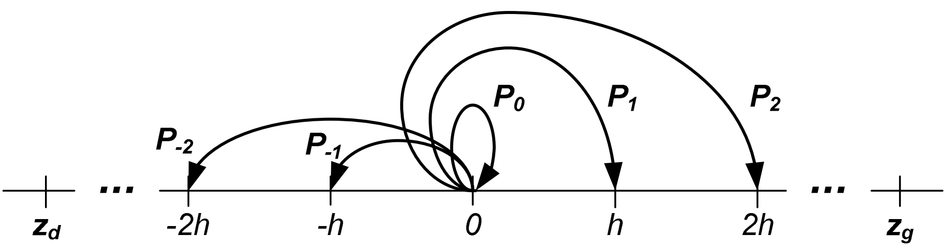


Fig. 1. The diagram of changes of diagnostic parameter deviation
Rys. 1. Schemat zmian odchyłki parametru diagnostycznego

7) At the time interval Δt, changes of diagnostic parameter deviation can equal to 0, h, $2h$, $-h$, $-2h$ with the probability P_0, P_1, P_2, P_{-1}, P_{-2}, where:

$$P_0 + P_1 + P_2 + P_{-1} + P_{-2} = 1 .$$

Thus, other values of parameter deviation at the time interval Δt are unlikely.

Having the above-mentioned assumptions, we can move to the determination of the diagram of the dynamics of changes of diagnostic parameter deviation. Having sufficiently long operation time and large number of measurements of parameter deviations, we can move from the probability of adopting particular values by deviation to the description of changes with the use of the density function.

Let $u(z,t)$ mean the density function of deviation value at the time $t=\Delta tk$ (where k means k-th measurement of the parameter z).

Having the above mentioned determinations and assumptions, we can present the dynamics of deviation changes in a probabilistic point of view with the use of the following difference equation:

$$u(z,t + \Delta t) = P_2 u(z - 2h,t) + P_1 u(z - h,t) + P_0 u(z,t) + P_{-2} u(z + 2h,t) + P_{-1} u(z + h,t) \tag{2}$$

The difference equation (2) can be converted to the partial differential equation with the use of the following approximation:

$$u(z,t + \Delta t) \cong u(z,t) + \frac{\partial U(z,t)}{\partial t} \Delta t ,$$

$$u(z - 2h,t) = u(z,t) - \frac{\partial u(z,t)}{\partial z} 2h + \frac{1}{2} \frac{\partial^2 u(z,t)}{\partial z^2} (2h)^2 ,$$

$$u(z - h,t) = u(z,t) - \frac{\partial u(z,t)}{\partial z} h + \frac{1}{2} \frac{\partial^2 u(z,t)}{\partial z^2} h^2 ,$$

$$u(z + 2h,t) \cong u(z,t) + \frac{\partial u(z,t)}{\partial y} 2h + \frac{1}{2} \frac{\partial^2 u(z,t)}{\partial y^2} (2h)^2 ,$$

$$u(z + h,t) \cong u(z,t) + \frac{\partial u(z,t)}{\partial y} h + \frac{1}{2} \frac{\partial^2 u(z,t)}{\partial y^2} h^2 .$$

The way of converting the difference equation (2) to the partial differential equation is presented in the treatise [1]. Thus, we obtain

$$\frac{\partial u(z,t)}{\partial t} = -b\frac{\partial u(z,t)}{\partial z} + \frac{1}{2}a\frac{\partial^2 u(z,t)}{\partial z^2}. \tag{3}$$

where:

$$b = \frac{(2P_2 + P_1 - P_{-1} - 2P_{-2})h}{\Delta t}, \tag{4}$$

$$a = \frac{(4P_2 + P_1 + P_{-1} + 2P_{-2})h^2}{\Delta t}. \tag{5}$$

The partial equation (3) for the symmetric walk of parameter deviation, i.e. $P_2 = P_{-2}$ i $P_1 = P_{-1}$ has the following form:

$$\frac{\partial u(z,t)}{\partial t} = \frac{1}{2}a\frac{\partial^2 u(z,t)}{\partial z^2}. \tag{6}$$

The solution of the partial differential equation (6) is the following density function:

$$u(z,t) = \frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}. \tag{7}$$

In order to confirm that the function (7) is the solution of the equation (6), we must calculate derivatives in the equation (6) and check whether the left side is equal to the right side.

$$\frac{\partial u(z,t)}{\partial t} = \frac{-\frac{1}{2}2\pi a(2\pi at)^{-\frac{1}{2}}}{2\pi at}e^{-\frac{z^2}{2at}} + \frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}\left(-\frac{z^2 2a}{4a^2t^2}\right) =$$

$$= \frac{-\pi a}{\sqrt{2\pi at}\,2\pi at}e^{-\frac{z^2}{2at}} + \frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}\left(-\frac{z^2}{2at^2}\right) = u(z,t)\left(\frac{z^2 - at}{2at^2}\right),$$

$$\frac{\partial u(z,t)}{\partial t} = u(z,t)\left(\frac{z^2 - at}{2at^2}\right),$$

$$\frac{\partial^2 u(z,t)}{\partial z^2} = u(z,t)\left(\frac{z^2 - at}{a^2t^2}\right).$$

Substituting derivatives obtained into the equation (6), we obtain

$$\frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}\left(\frac{z^2 - at}{2at^2}\right) = \frac{1}{2}a\left(\frac{z^2 - at}{a^2t^2}\right)\frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}. \tag{8}$$

The dependence (8) shows that the density function (7) is the solution of equation (6), and we can use the function to determine the reliability of a device.

The reliability of a device, which was determined according to the selected dominant diagnostic parameter, will be as follows:

$$R(t)=\int_{z_d}^{z_g} \frac{1}{\sqrt{2\pi at}}\, e^{-\frac{z^2}{2at}}\, dz\,. \tag{9}$$

where: z_d – the lower limit of parameter deviation;
z_g – the upper limit of parameter deviation.

Considering symmetric changes of deviation, the unreliability of a device can be written in the following form:

$$Q(t)=\int_{-\infty}^{-z_d} u(z,t)\, dz+\int_{z_g}^{\infty} u(z,t)\, dz=2\int_{z_g}^{\infty} u(z,t)\, dz\,, \tag{10}$$

where:

$$u(z,t)=\frac{1}{\sqrt{2\pi at}}\, e^{-\frac{z^2}{2at}}\, dz\,.$$

3. Determining the time distribution of the exceedance of limit values by deviation value

Using the density function (7) and the dependence (10), then the time density function of limit state exceedance, we obtain

$$f(t)=\frac{\partial}{\partial t} Q(t,z_g,z_d). \tag{11}$$

Thus, we can write

$$f(t)=2\int_{zg}^{\infty}\left\{\frac{\partial}{\partial t} Q(t,z_g,z_d)\right\}dz\,.$$

Thus:

$$f(t)=2\int_{zg}^{\infty}\left\{u(z,t)\left(\frac{z^2-at}{2at^2}\right)\right\}dz\,. \tag{12}$$

In order to calculate the integral in the dependence (12), we must determine the antiderivative.

We can determine the antiderivative with the use of the antiderivative in the following form:

$$w(z,t)=u(z,t)\Theta(z,t). \tag{13}$$

where: $\Theta(z,t)$ – is the unknown expression.

The derivative of the antiderivative $w(z,t)$ with respect to parameter deviation will be

$$\frac{\partial w(z,t)}{\partial z}=u'(z,t)\Theta(z,t)+u(z,t)\Theta'(z,t). \tag{14}$$

The derivative of the antiderivative with respect to deviation shall be equal to the integrand expression in the dependence (12).

Thus, after determining the derivative $\frac{\partial u(z,t)}{\partial z}$ we obtain:

$$\frac{\partial w(z,t)}{\partial z}=\underbrace{\frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}dz}_{u(z,t)}\left(-\frac{z}{at}\right)\underbrace{\left(\ ?\ \right)}_{\Theta(z,t)}+\underbrace{\frac{1}{\sqrt{2\pi at}}e^{-\frac{z^2}{2at}}dz}_{u(z,t)}\underbrace{\left(\ ?\ \right)}_{\Theta'(z,t)}.$$

Thus:

$$\begin{aligned}\Theta(z,t)&=-\frac{z}{2t},\\ \Theta'(z,t)&=-\frac{1}{2t}.\end{aligned} \tag{15}$$

We check whether we obtain the integrand in the dependence (12)

$$\left[\left(-\frac{z}{at}\right)\left(-\frac{z}{2t}\right)-\frac{1}{2t}\right]=\frac{z^2}{2at^2}-\frac{t}{2t^2}=\frac{z^2-at}{2at^2}.$$

The antiderivative has the following form:

$$w(z,t)=u(z,t)\left(-\frac{z}{2t}\right). \tag{16}$$

Using the dependence (16), we can calculate the integral in the dependence (12), and we obtain the function of the first passage of the limit state. Thus,

$$f(t,z_g)=2w(z,t)\Big|_{z_g}^{\infty}=2u(z_g,t)\left(\frac{z_g}{2t}\right). \tag{17}$$

where:

$$u(z_g,t)=\frac{1}{\sqrt{2\pi at}}e^{-\frac{z_g^2}{2at}}.$$

Then, we check whether the function (17) is the function of the first passage of the limit state, i.e. we must demonstrate that

$$\int_0^\infty 2u\left(z_g, t\right)\left(\frac{z_g}{2t}\right)dt \overset{?}{=} 1. \tag{18}$$

Thus:

$$2\int_0^\infty \left(\frac{z_g}{2t}\right)\frac{1}{\sqrt{2\pi at}}\, e^{-\frac{z_g^2}{2at}}dt = \int_0^\infty \frac{z_g}{t\sqrt{2\pi at}}\, e^{-\frac{z_g^2}{2at}}dt =$$

$$= \frac{z_g}{\sqrt{2\pi a}}\int_0^\infty \frac{1}{t\sqrt{t}}\, e^{-\frac{z_g^2}{2at}}dt = \frac{z_g}{\sqrt{2\pi a}}\int_0^\infty \frac{1}{t^{\frac{3}{2}}}\, e^{-\frac{1}{2\frac{a}{z_g^2}t}}dt.$$

The following equality shall occur:

$$\int_0^\infty t^{\frac{3}{2}}\, e^{-\frac{1}{2\frac{a}{z_g^2}t}}dt \overset{?}{=} \frac{\sqrt{2\pi a}}{z_g}. \tag{19}$$

We check the equation (19) by calculating the integral

$$\int_0^\infty t^{\frac{3}{2}}\, e^{-\frac{1}{2\frac{a}{z_g^2}t}}dt = \frac{\sqrt{2\pi a}}{z_g}.$$

For this purpose, we make a substitution

$$u = \frac{1}{2\frac{a}{z_g^2}t}, \quad \text{hence} \quad t = \frac{z_g^2}{2a}\frac{1}{u},$$

$$dt = \frac{z_g^2}{2a}\left(-\frac{1}{u^2}\right)du.$$

Thus,

$$\int_0^\infty \left(\frac{z_g^2}{2a}\frac{1}{u}\right)^{-\frac{3}{2}} e^{-u}\frac{z_g^2}{2a}\left(-\frac{1}{u^2}\right)du = \left(\frac{z_g^2}{2a}\right)^{-\frac{3}{2}}\frac{z_g^2}{2a}\int_0^\infty\left(\frac{1}{u}\right)^{-\frac{3}{2}}\left(-\frac{1}{u^2}\right)e^{-u}du =$$

$$= \frac{(2a)^{\frac{3}{2}}}{z_g^3}\frac{z_g^2}{2a}\int_0^\infty\left(\frac{1}{u}\right)^{-\frac{1}{2}}e^{-u}du = \frac{(2a)^{\frac{1}{2}}}{z_g}\underbrace{\int_0^\infty u^{-\frac{1}{2}}e^{-u}du}_{\Gamma\left(\frac{1}{2}\right)=\sqrt{\pi}} = \frac{\sqrt{2\pi a}}{z_g}. \tag{20}$$

Thus, the solution of the integral from the formula (19) is $\frac{\sqrt{2\pi a}}{z_g}$, which validates the equality (19).

4. Final remarks

Conditions in which the operation process of aircraft proceeds (changes of temperature and pressure, oscillations, etc.) cause the accumulation of destructive factor influences on devices mounted on board. The method presented enables the determination of the reliability of a device. The reliability of a device with respect to the diagnostic parameter considered can be determined with the use of the dependence (9) or the distribution of the limit state exceedance (17) and the following formula:

$$R(t) = 1 - \int_0^t f(t, z_g)dz.$$

In a similar way, we can determine the dependence in the case of the unsymmetrical walk of the diagnostic parameter deviation.

References

[1] Będkowski L., Dąbrowski T.: *Podstawy eksploatacji,* cz. 1. *Podstawy diagnostyki technicznej*. WAT, Warszawa 2000.

[2] Gerebach J.B., Kordowski CH.B.: *Modele niezawodnościowe obiektów technicznych*. Wydawnictwo Naukowo-Techniczne. Warszawa 1968.

[3] Szczepanik R., Tomaszek H.: *Zarys metody oceny niezawodności i trwałości urządzeń lotniczych z uwzględnieniem stanów granicznych*. Problemy eksploatacji Nr 3, 2005, s. 247÷256.

[4] Szczepanik R., Tomaszek H.: *Metoda określenia rozkładu czasu do przekroczenia stanu granicznego*. ZEM Zeszyt 4(144), 2005, s. 35÷44.

[5] Szczepanik R., Tomaszek H.: *Niektóre charakterystyki rozkładu czasu przekraczania stanu granicznego*. ZEM Zeszyt 1(145), 2006, s. 99÷105.
[6] Tomaszek H., Żurek J., Jasztal M.: *Prognozowanie uszkodzeń zagrażających bezpieczeństwu lotów statków powietrznych*. Wydawnictwo Naukowe Instytutu Technologii Eksploatacji, Radom 2008.
[7] Tomaszek H., Ważny M.: *Zarys metody oceny wpływu skutków działania procesów destrukcyjnych na stan techniczny systemów celowniczych*. ZEM Zeszyt 3(147), 2006, s. 91÷102.
[8] Tomaszek H., Ważny M.: *Rozkład czasu narastania odchyłek parametrów diagnostycznych lotniczych systemów celowniczych do wartości granicznych*. ZEM Zeszyt 4(148) 2006, s. 81÷90.
[9] Żurek J.: *Modele oceny niezawodności obiektów technicznych*. Materiały Konferencyjne na temat „Problematyka normalizacji, jakości i kodyfikacji w aspekcie integracji z NATO i UE", Warszawa 2009, s. 81÷90.

Manuscript received by Editorial Board, October 12th, 2009

Modelowanie niezawodności wybranych urządzeń statku powietrznego w warunkach kumulowania skutków działania procesów destrukcyjnych

S t r e s z c z e n i e

W artykule przedstawiono sposób określenia eksploatacyjnej niezawodności urządzenia w warunkach działania destrukcyjnych procesów powodujących zmiany wartości parametrów diagnostycznych. Przyjęto, że wśród parametrów diagnostycznych, określających stan techniczny urządzenia, istnieje parametr dominujący, którego zmiany wartości są największe i najszybciej osiągany jest stan graniczny. Założono, że skutki działania procesów destrukcyjnych kumulują się np. wzrostem wariancji. Do określenia zależności na niezawodność wykorzystano model symetrycznego błądzenia przypadkowego wartości odchyłki od wartości nominalnej parametru dominującego.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

HENRYK TOMASZEK*, JÓZEF ŻUREK*, SŁAWOMIR STĘPIEŃ**

Operation of an aircraft with risk of its loss

K e y w o r d s

Reliability, risk, intensity, probability.

S ł o w a k l u c z o w e

Niezawodność, ryzyko, intenstywność, prawdopodobieństwo.

S u m m a r y

The subject of this paper concerns the way of an aircraft operation in which there are three states: the operational state "1", the state of repair "2", and the state of a complete loss of airworthiness "3". Transition between states results from the intensity of damages and repairs and the intensity of reaching the state of a complete lack of airworthiness. The paper assumes three diagrams of possible transitions between states. The assumed diagrams were supplemented with sets of difference equations, which were transformed into sets of differential equations. Their solutions provided dependencies for the probability of operational state $P_1(t)$, the probability of repair $P_2(t)$, and the probability of a complete loss of airworthiness $P_3(t)$. The obtained dependencies enabled preparation of graphs, which is helpful in interpreting the safety of flights of an aircraft.

* Air Force Institute of Technology, ul. Księcia Bolesława 6, 01-494 Warszawa 46, Poland.
** Militatry Univesity of Technology WAT, ul. Kaliskiego 2, 00-908 Warszawa, Poland.

1. Introduction

Deliberations on the safety of flying are the reason for the need of analysing different methods of the operation of aircraft. This paper analyses three ways of operating aircraft. These ways include the following states:

- The state of reliability "1": the probability $P_1(t)$ describes an aircraft in this state;
- The state of repair "2": the probability $P_2(t)$ describes an aircraft in this state; and,
- The state of a complete lack of airworthiness "3": the probability $P_3(t)$ describes an aircraft in this state.

There are three variants of operation:

- The first variant presented in Figure 1.
- The second variant presented in Figure 2.
- The third variant presented in Figure 3.

Possible transitions between the states are symbolised by arrows. A driving force of a transition between states is the intensity of damages and repairs, and the intensity of transition to the state of a complete lack of airworthiness.

The following issues were presented for the above-mentioned ways of operating aircraft:

- Sets of difference equations;
- Sets of differential equations; and,
- Solutions of sets of equations for individual variants.

The obtained dependencies of probabilities for individual variants were used to present their graph in the function of time.

2. The introduction of equation sets for the assumed diagrams of operation

The first variant

In this diagram of an aircraft operation, the considered issue concerns the transition from the operational state "1" to the state of repair "2" with the intensity λ_1; on the other hand, there is possibility of transition from the state of repair "2" to the operational state "1" with the intensity μ or to the state of a complete lack of airworthiness "3" with the intensity λ_2. The state of a complete lack of airworthiness is an absorbing state. Figure 1 presents a graph of transitions between the states. The graph includes the above-mentioned quantities and probabilities of staying in the following states: $P_1(t)$, $P_2(t)$, $P_3(t)$.

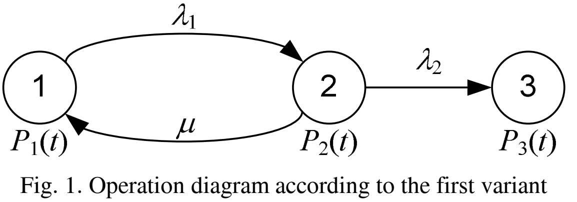


Fig. 1. Operation diagram according to the first variant
Rys. 1. Schemat eksploatacji według pierwszego wariantu

The following set of difference equations can be arranged for such an operation diagram:

$$\begin{cases} P_1(t+\Delta t) = (1-\lambda_1 \Delta t)P_1(t) + \mu \Delta t P_2(t) \\ P_2(t+\Delta t) = \lambda_1 \Delta t P_1(t) + (1-\mu \Delta t)(1-\lambda_2 \Delta t)P_2(t) \\ P_3(t+\Delta t) = P_3(t) + \lambda_2 \Delta t P_2(t). \end{cases} \tag{1}$$

For the first variant of operation, after transformations, we obtain the following set of equations:

$$\begin{cases} P_1'(t) = -\lambda_1 P_1(t) + \mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t) - (\mu + \lambda_2)P_2(t) \\ P_3'(t) = \lambda_2 P_2(t). \end{cases} \tag{2}$$

The second variant

This diagram of operation includes the possibility of transition from the operational state "1" to the state of a complete lack of airworthiness with the intensity λ_2; however, it does not include the possibility of transition from the state of repair "2" to the state of a complete lack of airworthiness "3". Figure 2 presents a graph of transitions between the states, other notations are the same as the above.

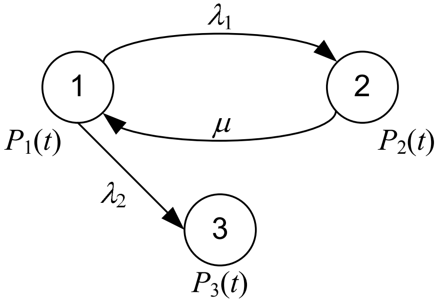


Fig. 2. Operation diagram according to the second variant
Rys. 2. Schemat eksploatacji według drugiego wariantu

In this variant, we can also arrange a set of difference equations illustrating transition between the states.

$$\begin{cases} P_1(t+\Delta t) = (1-\lambda_1 \Delta t)(1-\lambda_2 \Delta t)P_1(t) + \mu \Delta t P_2(t) \\ P_2(t+\Delta t) = \lambda_1 \Delta t P_1(t) + (1-\mu \Delta t)P_2(t) \\ P_3(t+\Delta t) = P_3(t) + \lambda_2 \Delta t P_1(t). \end{cases} \tag{3}$$

In the second variant, after transformations of the set (3), we obtain the following set of differential equations.

$$\begin{cases} P_1'(t) = -(\lambda_1 + \lambda_2)P_1(t) + \mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t) - \mu P_2(t) \\ P_3'(t) = \lambda_2 P_1(t). \end{cases} \tag{4}$$

The third variant

We shall consider the third way of operation.

This diagram of operation includes the possibility of transition from the operational state "1" to the state of a complete lack of airworthiness "3" with the intensity λ_2 and the possibility of transition from the state of repair "2" to state of a complete lack of airworthiness "3" with the intensity λ_3. Figure 3 presents a graph of transitions between the states, other notations are the same as the above. This variant includes both the above-described variants.

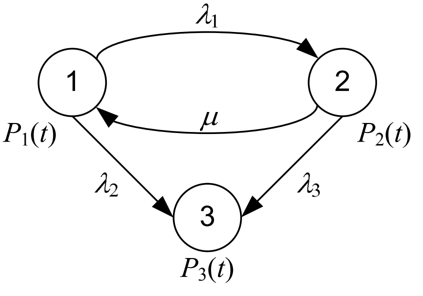


Fig. 3. Operation diagram according to the third variant
Rys. 3. Schemat eksploatacji według trzeciego wariantu

A set of difference equations

$$\begin{cases} P_1(t+\Delta t) = (1-\lambda_1\Delta t)(1-\lambda_2\Delta t)P_1(t) + \mu\Delta t P_2(t) \\ P_2(t+\Delta t) = \lambda_1\Delta t P_1(t) + (1-\lambda_3\Delta t)(1-\mu\Delta t)P_2(t) \\ P_3(t+\Delta t) = P_3(t) + \lambda_2\Delta t P_1(t) + \lambda_3\Delta t P_2(t). \end{cases} \tag{5}$$

From the set (5), we obtained the following set of differential equations

$$\begin{cases} P_1'(t) = -(\lambda_1 + \lambda_2)P_1(t) + \mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t) - (\mu + \lambda_3)P_2(t) \\ P_3'(t) = \lambda_2 P_1(t) + \lambda_3 P_2(t). \end{cases} \tag{6}$$

For all variants, initial conditions are the same:

for $t = 0 \rightarrow P_1(0) = 1, \quad P_2(0) = 0, \quad P_3(0) = 0.$

3. Solution of the set of equations for the accepted conditions

The first variant

In this variant, we obtained the following set of differential equations:

$$\begin{cases} P_1'(t) = -\lambda_1 P_1(t) + \mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t) - (\mu + \lambda_2) P_2(t) \\ P_3'(t) = \lambda_2 P_2(t). \end{cases} \tag{7}$$

As a result of calculations, we obtained [4]:

$$\begin{cases} P_1(t) = \dfrac{r_1 + \lambda_1}{r_1 - r_2} e^{r_2 t} - \dfrac{r_2 + \lambda_1}{r_1 - r_2} e^{r_1 t} \\ P_2(t) = \dfrac{(r_1 + \lambda_1)(r_2 + \lambda_1)}{\mu (r_1 - r_2)} \left[e^{r_2 t} - e^{r_1 t} \right] \\ P_3(t) = \dfrac{\lambda_2 (r_1 + \lambda_1)(r_2 + \lambda_1)}{\mu (r_1 - r_2)} \left[\dfrac{1}{r_2} e^{r_2 t} - \dfrac{1}{r_1} e^{r_1 t} \right] - \dfrac{\lambda_2}{\mu r_1 r_2} (r_2 + \lambda_1)(r_1 + \lambda_1) \end{cases} \tag{8}$$

where:

$$\begin{aligned} r_1 &= \frac{-(\lambda_1 + \lambda_2 + \mu) - \sqrt{(\lambda_1 - \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2) + \mu^2}}{2}, \\ r_2 &= \frac{-(\lambda_1 + \lambda_2 + \mu) + \sqrt{(\lambda_1 - \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2) + \mu^2}}{2}. \end{aligned} \tag{9}$$

The above-presented solution meets the initial conditions, and the sum of determined probabilities equals the 1. The only thing to do is check a graph of the determined functions for large t ($t \rightarrow \infty$). This is included in the paper [4].

The second variant

For this variant of an aircraft operation, the following set of differential equations was introduced:

$$\begin{cases} P_1'(t) = -(\lambda_1+\lambda_2)P_1(t) + \mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t) - \mu P_2(t) \\ P_3'(t) = \lambda_2 P_1(t). \end{cases} \tag{10}$$

As a result of calculations, we obtained:

$$\begin{cases} P_1(t) = -\dfrac{r_2+\lambda_1+\lambda_2}{r_1-r_2}e^{r_1 t} + \dfrac{r_1+\lambda_1+\lambda_2}{r_1-r_2}e^{r_2 t} \\ P_2(t) = -\dfrac{(r_1+\lambda_1+\lambda_2)(r_2+\lambda_1+\lambda_2)}{\mu(r_1-r_2)}\left[e^{r_1 t} - e^{r_2 t}\right] \\ P_3(t) = \dfrac{\lambda_2}{r_1-r_2}\left[-\dfrac{r_2+\lambda_1+\lambda_2}{r_1}e^{r_1 t} + \dfrac{r_1+\lambda_1+\lambda_2}{r_2}e^{r_2 t}\right] + 1, \end{cases} \tag{11}$$

where:

$$\begin{gathered} r_1 = \frac{-(\lambda_1+\lambda_2+\mu) - \sqrt{(\lambda_1+\lambda_2)^2 + 2\mu(\lambda_1-\lambda_2) + \mu^2}}{2}, \\ r_2 = \frac{-(\lambda_1+\lambda_2+\mu) + \sqrt{(\lambda_1+\lambda_2)^2 + 2\mu(\lambda_1-\lambda_2) + \mu^2}}{2}. \end{gathered} \tag{12}$$

The above-presented solution meets the initial conditions, and the sum of determined probabilities equals the 1. The only thing to do is check a graph of the determined functions for large t ($t \to \infty$).

$$\lim_{t\to\infty} P_1(t) = -\frac{r_2+\lambda_1+\lambda_2}{r_1-r_2}\lim_{t\to\infty} e^{r_1 t} + \frac{r_1+\lambda_1+\lambda_2}{r_1-r_2}\lim_{t\to\infty} e^{r_2 t},$$

$$\lim_{t\to\infty} P_2(t) = -\frac{(r_1+\lambda_1+\lambda_2)(r_2+\lambda_1+\lambda_2)}{\mu(r_1-r_2)}\left[\lim_{t\to\infty} e^{r_1 t} - \lim_{t\to\infty} e^{r_2 t}\right],$$

$$\lim_{t\to\infty} P_3(t) = \frac{\lambda_2}{r_1-r_2}\left[-\frac{r_2+\lambda_1+\lambda_2}{r_1}\lim_{t\to\infty} e^{r_1 t} + \frac{r_1+\lambda_1+\lambda_2}{r_2}\lim_{t\to\infty} e^{r_2 t}\right] + 1.$$

Because:

$$r_1 = -\frac{(\lambda_1+\lambda_2+\mu) + \sqrt{(\lambda_1+\lambda_2+\mu)^2 - 4\mu\lambda_2}}{2} < 0,$$

$$r_2 = -\frac{(\lambda_1+\lambda_2+\mu) - \sqrt{(\lambda_1+\lambda_2+\mu)^2 - 4\mu\lambda_2}}{2} < 0,$$

so

$$\lim_{t\to\infty} e^{r_1 t} = 0,$$
$$\lim_{t\to\infty} e^{r_2 t} = 0.$$

And consequently,

$$\lim_{t\to\infty} P_1(t) = 0,$$
$$\lim_{t\to\infty} P_2(t) = 0,$$
$$\lim_{t\to\infty} P_3(t) = 1.$$

Ultimately, we obtained:

$$\begin{cases} P_1(t) = -\dfrac{r_2+\lambda_1+\lambda_2}{r_1-r_2}e^{r_1 t} + \dfrac{r_1+\lambda_1+\lambda_2}{r_1-r_2}e^{r_2 t} \\ P_2(t) = -\dfrac{(r_1+\lambda_1+\lambda_2)(r_2+\lambda_1+\lambda_2)}{\mu(r_1-r_2)}\left[e^{r_1 t} - e^{r_2 t}\right] \\ P_3(t) = \dfrac{\lambda_2}{r_1-r_2}\left[-\dfrac{r_2+\lambda_1+\lambda_2}{r_1}e^{r_1 t} + \dfrac{r_1+\lambda_1+\lambda_2}{r_2}e^{r_2 t}\right] + 1, \end{cases} \tag{13}$$

where:

$$r_1 = \frac{-(\lambda_1+\lambda_2+\mu) - \sqrt{(\lambda_1+\lambda_2)^2 + 2\mu(\lambda_1-\lambda_2) + \mu^2}}{2},$$
$$r_2 = \frac{-(\lambda_1+\lambda_2+\mu) + \sqrt{(\lambda_1+\lambda_2)^2 + 2\mu(\lambda_1-\lambda_2) + \mu^2}}{2}. \tag{14}$$

The probability $P_1(t)$ is a decreasing function of time and adopts values from 1 to 0. On the other hand, the probability $P_3(t)$ is an increasing function and adopts values from 0 to 1. The probability $P_2(t)$ has one specific extremum (maximum) in the following point:

$$t = t_{extr} = \frac{1}{r_2 - r_1}\ln\frac{r_1}{r_2}, \tag{15}$$

of the following value:

$$P_2(t_{extr}) = \frac{\lambda_1}{\sqrt{\mu\lambda_2}}\left(\frac{(\lambda_1+\lambda_2+\mu)+\sqrt{(\lambda_1+\lambda_2)^2+2\mu(\lambda_1-\lambda_2)+\mu^2}}{2\sqrt{\mu\lambda_2}}\right)^{\frac{-(\lambda_1+\lambda_2+\mu)}{\sqrt{(\lambda_1+\lambda_2)^2+2\mu(\lambda_1-\lambda_2)+\mu^2}}}. \tag{16}$$

The third variant

In this variant, transition between the states is described by the following set of differential equations:

$$\begin{cases} P_1'(t) = -(\lambda_1+\lambda_2)P_1(t)+\mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t)-(\mu+\lambda_3)P_2(t) \\ P_3'(t) = \lambda_2 P_1(t)+\lambda_3 P_2(t). \end{cases} \tag{17}$$

As a result of calculations, we obtained:

$$\begin{cases} P_1(t) = -\dfrac{r_2+\lambda_1+\lambda_2}{r_1-r_2}e^{r_1 t}+\dfrac{r_1+\lambda_1+\lambda_2}{r_1-r_2}e^{r_2 t} \\ P_2(t) = \dfrac{(r_1+\lambda_1+\lambda_2)(r_2+\lambda_1+\lambda_2)}{(r_1-r_2)\mu}\left(-e^{r_1 t}+e^{r_2 t}\right) \\ P_3(t) = -\dfrac{r_2+\lambda_1+\lambda_2}{r_1-r_2}\dfrac{(r_1+\lambda_1+\lambda_2)\lambda_3+\lambda_2\mu}{\mu r_1}e^{r_1 t} + \\ +\dfrac{r_1+\lambda_1+\lambda_2}{r_1-r_2}\dfrac{(r_2+\lambda_1+\lambda_2)\lambda_3+\lambda_2\mu}{\mu r_2}e^{r_2 t}+1, \end{cases} \tag{18}$$

where:

$$r_1 = \frac{-(\lambda_1+\lambda_2+\lambda_3+\mu)-\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2},$$
$$r_2 = \frac{-(\lambda_1+\lambda_2+\lambda_3+\mu)+\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2}. \tag{19}$$

The above-presented solution meets the initial conditions, and the sum of determined probabilities equals 1. The only thing to do is check a graph of the determined functions for large t ($t \to \infty$).

$$\lim_{t\to\infty} P_1(t) = -\frac{r_2+\lambda_1+\lambda_2}{r_1-r_2}\lim_{t\to\infty} e^{r_1 t} + \frac{r_1+\lambda_1+\lambda_2}{r_1-r_2}\lim_{t\to\infty} e^{r_2 t},$$

$$\lim_{t\to\infty} P_2(t) = \frac{(r_1+\lambda_1+\lambda_2)(r_2+\lambda_1+\lambda_2)}{(r_1-r_2)\mu}\left(-\lim_{t\to\infty} e^{r_1 t} + \lim_{t\to\infty} e^{r_2 t}\right),$$

$$\lim_{t\to\infty} P_3(t) = -\frac{r_2+\lambda_1+\lambda_2}{r_1-r_2}\frac{(r_1+\lambda_1+\lambda_2)\lambda_3+\lambda_2\mu}{\mu r_1}\lim_{t\to\infty} e^{r_1 t} +$$

$$+\frac{r_1+\lambda_1+\lambda_2}{r_1-r_2}\frac{(r_2+\lambda_1+\lambda_2)\lambda_3+\lambda_2\mu}{\mu r_2}\lim_{t\to\infty} e^{r_2 t} + 1.$$

Because:

$$r_1 = \frac{-(\lambda_1+\lambda_2+\lambda_3+\mu)-\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2} < 0,$$

$$r_2 = \frac{-(\lambda_1+\lambda_2+\lambda_3+\mu)+\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2} < 0,$$

so

$$\lim_{t\to\infty} e^{r_1 t} = 0,$$

$$\lim_{t\to\infty} e^{r_2 t} = 0.$$

And consequently:

$$\lim_{t\to\infty} P_1(t) = 0,$$

$$\lim_{t\to\infty} P_2(t) = 0,$$

$$\lim_{t\to\infty} P_3(t) = 1.$$

Ultimately, we obtained:

$$\begin{cases} P_1(t) = -\dfrac{r_2+\lambda_1+\lambda_2}{r_1-r_2} e^{r_1 t} + \dfrac{r_1+\lambda_1+\lambda_2}{r_1-r_2} e^{r_2 t} \\ P_2(t) = \dfrac{(r_1+\lambda_1+\lambda_2)(r_2+\lambda_1+\lambda_2)}{(r_1-r_2)\mu}\left(-e^{r_1 t}+e^{r_2 t}\right) \\ P_3(t) = -\dfrac{r_2+\lambda_1+\lambda_2}{r_1-r_2}\dfrac{(r_1+\lambda_1+\lambda_2)\lambda_3+\lambda_2\mu}{\mu r_1} e^{r_1 t} + \\ +\dfrac{r_1+\lambda_1+\lambda_2}{r_1-r_2}\dfrac{(r_2+\lambda_1+\lambda_2)\lambda_3+\lambda_2\mu}{\mu r_2} e^{r_2 t} + 1, \end{cases} \tag{20}$$

where:

$$r_1 = \frac{-(\lambda_1+\lambda_2+\lambda_3+\mu)-\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2},$$
$$r_2 = \frac{-(\lambda_1+\lambda_2+\lambda_3+\mu)+\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2}. \tag{21}$$

The probability $P_1(t)$ is a decreasing function of time and adopts values from 1 to 0. On the other hand, the probability $P_3(t)$ is an increasing function and adopts values from 0 to 1. The probability $P_2(t)$ has one specific extremum (maximum) in the following point:

$$t = t_{extr} = \frac{1}{r_2 - r_1}\ln\frac{r_1}{r_2}, \tag{22}$$

of the following value:

$$P_2(t_{extr}) = \frac{\lambda_1}{\sqrt{(\lambda_1+\lambda_2)(\lambda_3+\mu)-\mu\lambda_1}}\left(\frac{(\lambda_1+\lambda_2+\lambda_3+\mu)+\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}{2\sqrt{(\lambda_1+\lambda_2)(\lambda_3+\mu)-\mu\lambda_1}}\right)^{-\frac{\lambda_1+\lambda_2+\lambda_3+\mu}{\sqrt{(\lambda_1+\lambda_2-\lambda_3-\mu)^2+4\mu\lambda_1}}}. \tag{23}$$

4. Graphic presentation of results

The further part includes graphs of the changes of probabilities calculated in particular variants. The graphs aim at showing the character of these changes. The graphs were developed for hypothetical data:

Variant 1: $\lambda_1 = 0.009 : \lambda_2 = 0.008 : \mu = 0.01$.
Variant 2: $\lambda_1 = 0.009 : \lambda_2 = 0.008 : \mu = 0.01$.
Variant 3: $\lambda_1 = 0.009 : \lambda_2 = 0.007 : \lambda_3 = 0.001 : \mu = 0.01$.

A unit of intensity is the inverse of the accepted unit of time.

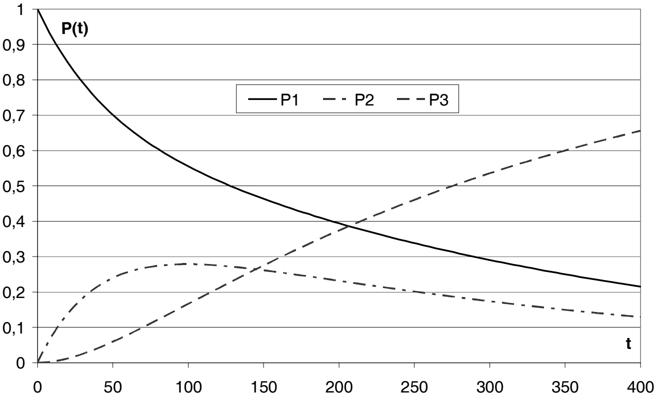


Fig. 4. Change of probabilities according to the first variant
Rys. 4. Zmiana prawdopodobieństwa wg wariantu pierwszego

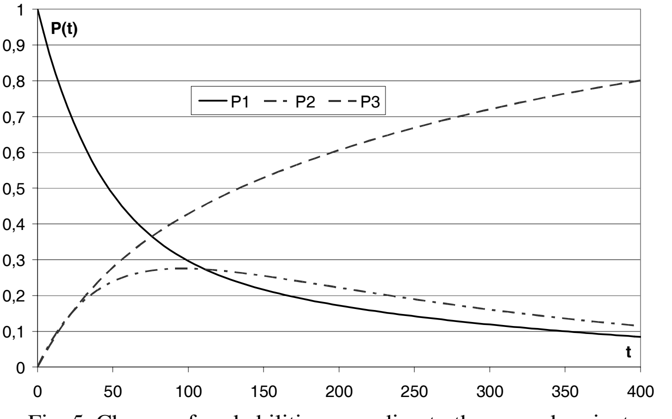


Fig. 5. Change of probabilities according to the second variant
Rys. 5. Zmiana prawdopodobieństwa wg wariantu drugiego

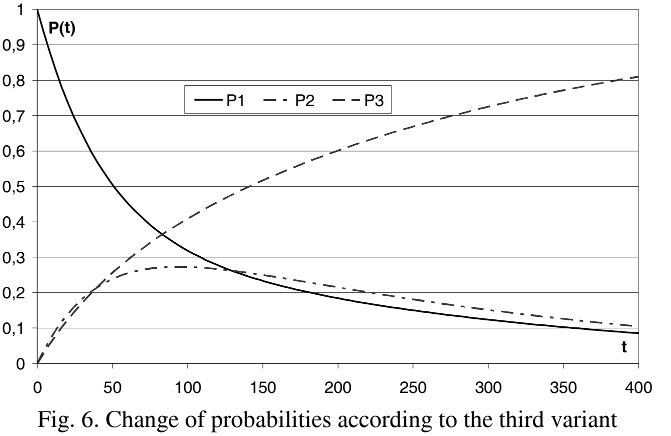


Fig. 6. Change of probabilities according to the third variant
Rys. 6. Zmiana prawdopodobieństwa wg wariantu trzeciego

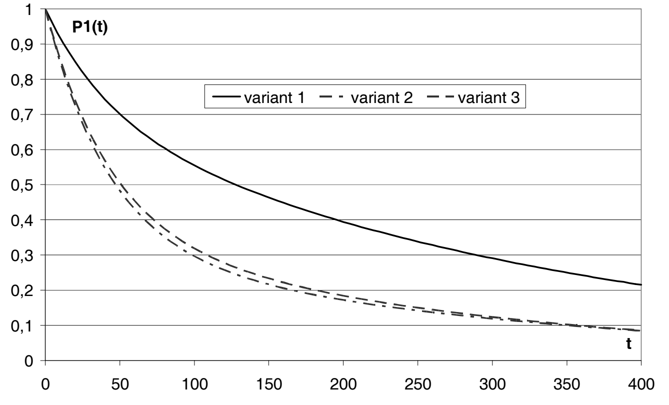


Fig. 7. Change of the probability $P_1(t)$ according to the variants
Rys. 7. Zmiana prawdopodobieństwa $P_1(t)$ wg wariantów

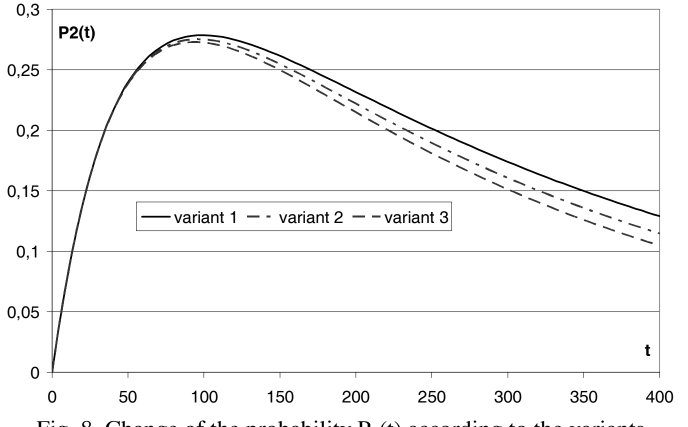


Fig. 8. Change of the probability $P_2(t)$ according to the variants
Rys. 8. Zmiana prawdopodobieństwa $P_2(t)$ wg wariantów

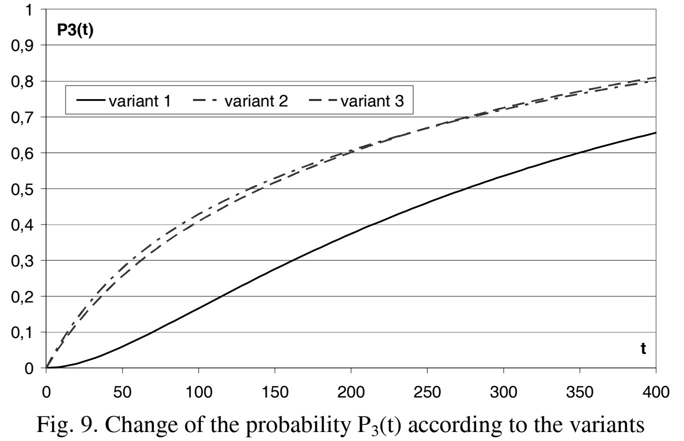


Fig. 9. Change of the probability $P_3(t)$ according to the variants
Rys. 9. Zmiana prawdopodobieństwa $P_3(t)$ wg wariantów

5. Final remarks

Data used for graphic presentation and results of calculations are selected randomly. Characters of the graphs of probabilities for all variants are similar.

Figure 7 presents a graph of the probability $P_1(t)$ for the assumed variants. The graph shows that differences in values of this probability are small for the second and third variant. The probability $P_1(t)$ for the first variant differs markedly from the other variants.

It shall be stressed that the analysis of the operation of aircraft according to the assumed diagrams is simplified, if particular intensities are considered as constant values.

The above-presented results can be used to examine the safety of flights of aircraft with the use of the renewal theory. In this case, the probability $P_1(t)$ will function as readiness coefficient. The example of such deliberations is presented in the paper [4].

Literature

[1] Jaźwiński J., Ważyńska-Fiok K.: *Bezpieczeństwo systemów*, PWN, Warszawa 1993.

[2] Borgoń J., Jaźwiński J., Sikorski H., Ważyńska-Fiok K.: *Niezawodność statków powietrznych*, ITWL, Warszawa 1992.

[3] Gniedenko B. W., Bielajew J.K., Sołowiew A.D.: *Metody matematyczne w teorii niezawodności*, WNT, Warszawa 1968.

[4] Tomaszek H., Żurek J., Stępień S.: *The aircraft maintenance with its renovation and the risk of its loss*, Scientific problems of machines operation and maintenance 4 (156) vol. 43, 2008, pp. 39÷49.

[5] Tomaszek H., Wróblewski H.: *Podstawy oceny efektywności eksploatacji systemów uzbrojenia lotniczego*. Dom Wydawniczy - Bellona, Warszawa 2001.

Manuscript received by Editorial Board, December 06th, 2009

Eksploatacja statku powietrznego z ryzykiem jego utraty

Przedmiotem pracy jest sposób eksploatacji statku powietrznego, w którym wyróżnia się stan zdatności „1”, stan naprawy „2” i stan całkowitej utraty zdatności „3”. Przejście między stanami następuje w wyniku intensywności uszkodzeń, naprawy i intensywności osiągania stanu całkowitej niezdatności.

W pracy przyjęto trzy schematy możliwych przejść między stanami. Dla tak przyjętych schematów ułożono układy równań różnicowych, z których po przekształceniu otrzymano układy równań różniczkowych.

Rozwiązując układy równań otrzymano zależności na prawdopodobieństwo zdatności $P_1(t)$, prawdopodobieństwo przebywania statku w naprawie $P_2(t)$ i prawdopodobieństwo całkowitej utraty zdatności $P_3(t)$.

Otrzymane zależności pozwoliły na sporządzenie wykresów, co ułatwia interpretację bezpieczeństwa lotów statku powietrznego.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

STANISŁAW DUER*

Determination of an expert knowledge base for servicing of a repairable technical object

Key words

Servicing process, expert system, neural networks, diagnostic information.

Słowa kluczowe

Proces obsługiwania, systemy ekspertowe, sieci neuronowe, informacja diagnostyczna.

Summary

The paper presents a method to design a system to service repairable (military) technical objects, with an artificial neural network. It includes a diagram and structure of a servicing system with a neural network. The way in which the object's servicing information is designed was presented. The manner was presented in which the internal structure was the transformation of a complex object with its functional elements to the form of the object's servicing structure. Analytical basis was presented for the realisation of the servicing of a technical object. A method was described for a conversion of diagnostic information and the expert's specialist knowledge to the form of the set of servicing information.

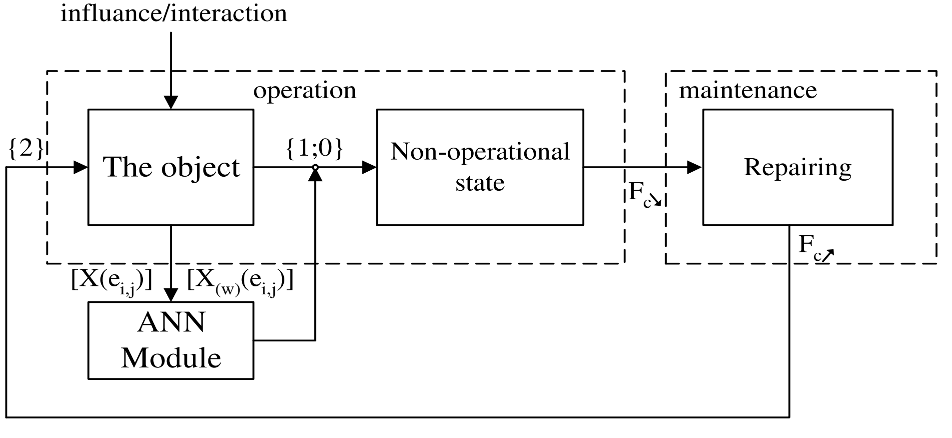
* Koszalin University of Technology, Department of Mechanical Engineering, Racławicka 15/17, 75-620 Koszalin, Poland, e-mail: stanislaw.duer@tu.koszalin.pl

1. Introduction

Technical objects used in the operation process (Fig. 1) are exposed to external reactions, and to energy changes (ageing processes, etc.). The state of a technical object used in the process of operation is different after a certain period from the nominal state for which the said object was designed. The effect of this unfavourable process is diminishing functional properties. For this reason, the quality of the use of the object is subject to changes, and it usually deteriorates.

In the process of operation [1, 5, 9, 10, 11, 16], the state of the technical object operated is different from the nominal state (usability) for which the said object was designed. In view of the fact that various influences act on the object, there occur ageing changes in it and the functional (constructional) elements wear. The effect of this disadvantageous process is its decreasing functional properties.

Then, technical objects go to the state of unfitness or incomplete fitness (with a trivalent evaluation of states) and no longer realise their operational functions. The scatter of the values of the qualitative function of the operation of an object in the operation space is of a decreasing nature. In order to counteract random changes of the function of the quality of the operation of an object, and in order to maximise this function, technical servicing is organised (Fig. 1).



where: $X(e_{i,j})$ – diagnostic signal in j^{th} element of i^{th} set; $X_{(w)}(e_{i,j})$ – model signal for $X(e_{i,j})$ signal; F_C - function of the use of the object, $W(\varepsilon(e_{i,j})=\{2, 1, 0\})$ – diagnostic information-value of state assessment logic for element "j" within "i" module of the object.

Fig. 1. Diagram of operation process for technical object utilising artificial neural network
Rys. 1. Schemat procesu eksploatacji wykorzystującego sztuczną sieć neuronową

2. The model of an expert servicing system of a technical object

A particularly important element of the maintenance system is the knowledge base (Fig. 2). It can be defined as a specialised set of the object's maintenance information which is determined by the following: the maintenance structure of the object $\{W_z(e_{i,j})\}$, the set of rules for maintenance (repairing) $\{R_r\}$, and the set of preventive activities $\{A(e_{i,j})\}$.

It is evident from the analysis (Fig. 2) that the process of the renovation of an object in an analytical approach consists in the transfer of the object's usability features from the level of the plane of the current use (ω) to the level of the plane of nominal usability features (M_E). The function that renovates the object in the servicing system is presented in the form of the following dependence:

$$M_E\left(e_{i,j}\right) = f\left(W\left(z\left(e_{i,j}\right)\right); A_l\left(e_{i,j}\right); R_r\left(e_{i,j}\right)\right) \tag{1}$$

Where: $\{W_z(e_{i,j})$ – the maintenance structure of the object $\}$, $\{R_r(e_{i,j})\}$ – the set of rules for maintenance (repairing), $\{A(e_{i,j})\}$ – the set of preventive activities, $\{M_E(e_{i,j})\}$ – the maintenance system produces a set of maintenance information.

As a result, the maintenance system [3, 4, 6, 12] produces a set of maintenance information $\{M_E(e_{i,j})\}$, which will be used for the organisation of the object's rational (optimised) maintenance system.

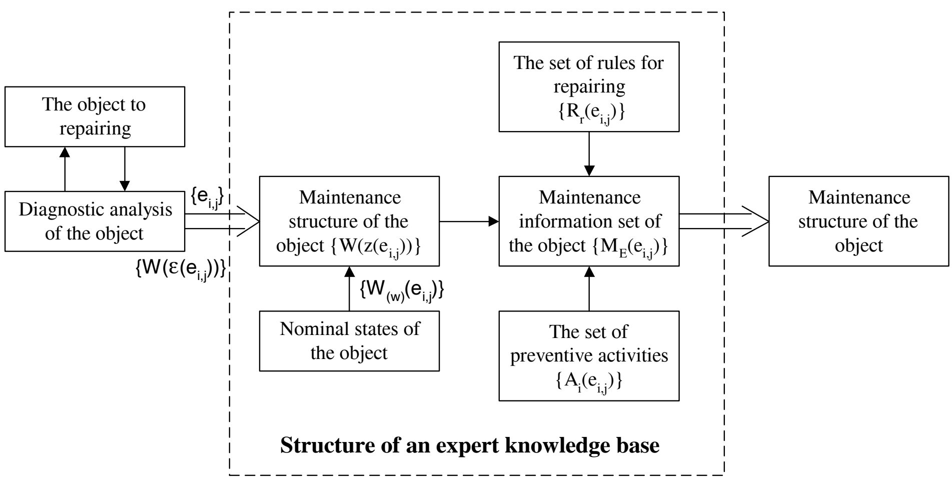


Fig. 2. Diagram of a servicing system with an artificial neural network
Rys. 2. Schemat procesu obsługiwania obiektu technicznego wykorzystującego sztuczną sieć neuronową

A set of the object's servicing information, which constitutes the basis in the process of designing of the structure of the servicing system, is presented in the form of the following dependence:

$$M_E(e_{i,j}) = \{M(e_{i,j}), W(z(e_{i,j}))A_l, R_r\} \quad (2)$$

where: $\{M(e_{i,j})\}$ – a set of elements of the object's servicing structure, $\{W(z(e_{i,j}))\}$ – resulting diagnostic information from the comparison of the object's states, $\{R_r\}$ – a set of servicing rules, $\{A(e_{i,j})\}$ – a set of preventative activities which renovate servicing elements.

2.1. Diagnostic system with an artificial neural network ANN

The division of the object's internal structure $\{e_{i,j}\}$ accepted in the paper explicitly defines the depth of penetration into this structure. The accepted division is considered sufficient, if we distinguish the basic module-element in the structure of the object. One of the purposes of the functional-diagnostic analysis is the determination of the object's state. The object's state is determined on the basis of an examination of the set of output (diagnostic) signals $\{X(e_{i,j})\}$(Table 1) [2, 7, 13. 14, 15]. The set of its functional elements $\{e_{i,j}\}$ determined during a diagnostic study of the object constitutes the basis for the list included in the table of a set of diagnostic signals (Table 1).

Table 1. Table of object's input diagnostic signals
Tabela 1. Tabela sygnałów diagnostycznych obiektu

Object	Level of object E_i	Vector of initial diagnostic signals $\{X(e_{i,j})\}$				
		$X(e_{1,1})$	...	$X(e_{i,j})$	...	$X(e_{i,J})$
O	E_1	$X(e_{1,1})$	...	$X(e_{1,j})$	...	$X(e_{1,J})$
	⋮	⋮	...	⋮	...	⋮
	E_i	$X(e_{i,1})$	...	$X(e_{i,j})$	...	$X(e_{i,J})$
	⋮	⋮	...	⋮	...	⋮
	E_I	$X(e_{I,1})$	...	$X(e_{I,j})$	...	$X(e_{I,J})$

where: $X(e_{i,j})$ – diagnostic signal of j^{th} element in i^{th} assembly.

The ANN network developed is presented in Fig. 3. It consists of three layers: F_1 – input layer, F_2 – output layer, and an intermediate layer. The input cells of layer F_1 process the initial diagnostic information according to the scheme presented in Fig. 3 and 4. The whole of the issue of information processing by ANN neurons [7, 14] takes place in D-dimension diagnostic space (ω) (see Fig. 1) determined by the elementary signal vectors (X_n). The input signal in the form of $X_n = [x_1(\mathrm{e}_{i,j}), x_2(\mathrm{e}_{i,j}),..., x_n(\mathrm{e}_{i,j})\ ]^T$ is being passed to all neurons of ANN's input layer.

The input cells memorise the vectors of signal standards $\{X_n\}$. Based upon that, the neurons from the input layer determine the measures of similarity between the input signal vector and its standard and the length of the input signal $\{X_n\}$ to all vectors of weights $w_{i,j} = [w_1, w_2, \ldots, w_n]^T$, where $i = 1, \ldots, N$. In the ANN network presented in Fig. 3, the neuron (i) placed in layer F_1 is connected to neuron (j) placed in layer F_2, where: $j = 1,2,\ldots N$.

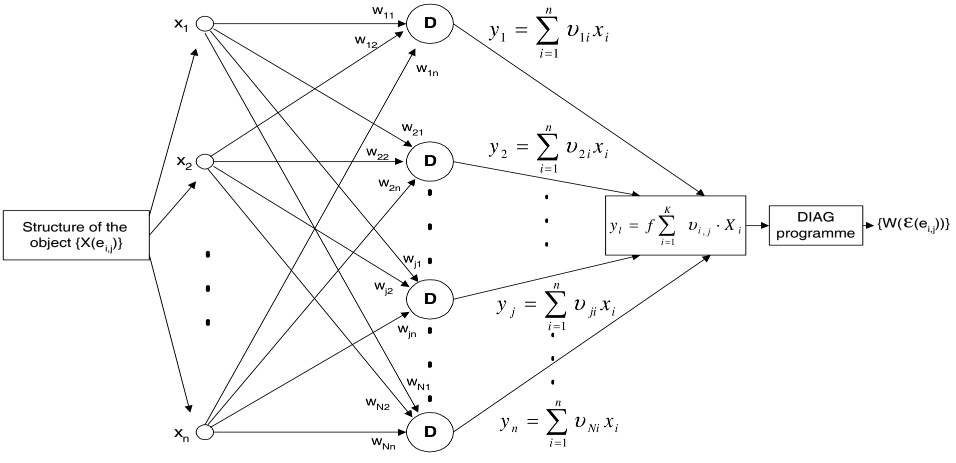


Fig. 3. Diagram of neural networks
Rys. 3. Struktura sztucznej sieci neuronowej

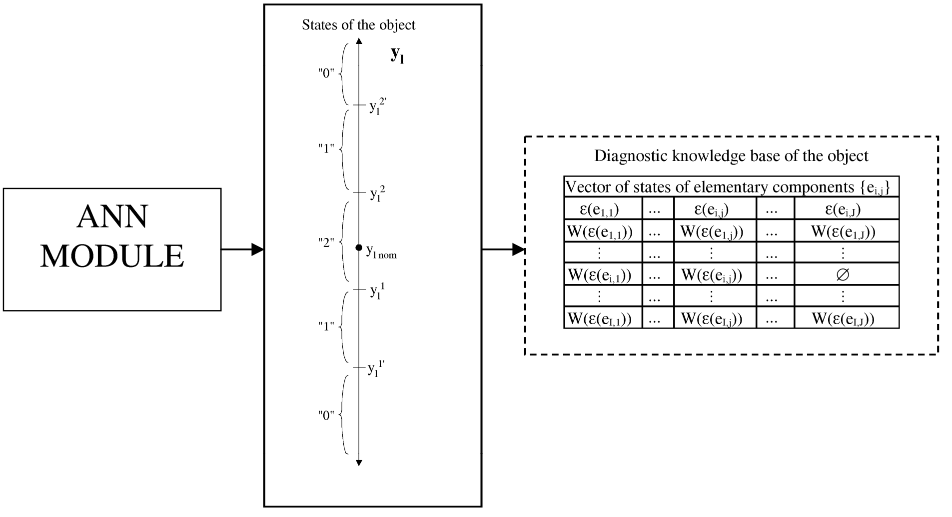
The value of its output function (Fig. 3) is s derived from the relation (3)

$$y_l = f \sum_{i=1}^{K} \upsilon_{i,j} \cdot X_i \tag{3}$$

where: $\upsilon_{i,j}$ – weight coefficient.

The determination of the value of the network's output function $\{y_l\}$ made it possible to explicitly determine the set of elementary vectors of signals which describe the diagnostic space of object (ω). In view of the fact that the purpose of a diagnosis of the object [2, 4, 8, 9] is the recognition of its state in the values of the accepted logic of states' assessment, the results obtained in the form of relations (4, 5 and 6) were subject to the classification process according to the diagram presented in Fig. 4.

On the final stage of the work of a neural network, a classification process of the object's states is realised according to the algorithm (Fig. 4). For this purpose, to determine the values of the output function as determined by the network, proper classes of the object's states in the values of the three-value logic {2, 1, 0}[5, 6, 7] were assigned according to the classification diagram.



where: (y_l^1, y_l^2) – the range of non-significant changes of the outputs; ($y_l^{1'}$, y_l^1) and (y_l^2, $y_l^{2'}$)) – the range of significant changes of the outputs, (($-\infty$, $y_l^{1'}$) and ($y_l^{2'}$,+ ∞)) – the range of inadmissible changes of the outputs

Fig. 4. Range of variability of diagnostic signal features in the diagnostic DIAG programme

Rys. 4. Przedziały zmian wartości sygnałów diagnostycznych w diagnostycznym programie DIAG

The classes of states of elementary components $\{e_{i,j}\}$ are defined as the following:

$$\left(W\left(\varepsilon\left(e_{i,j}\right)\right)=2\right) \Leftrightarrow \left\{y_l \in \left(y_l^1, y_l^2\right)\right\} \tag{4}$$

where: (y_l^1, y_l^2) – the range of non-significant changes of the output function values (y_l).

$$\left(W\left(\varepsilon\left(e_{i,j}\right)\right)=1\right) \Leftrightarrow \left\{y_l \in \left(y_l^{1'}, y_l^{1}\right)\cup\left(y_l^{2}, y_l^{2'}\right)\right\} \tag{5}$$

where: ($y_l^{1'}$, y_l^1) and (y_l^2, $y_l^{2'}$)) – the range of significant changes of the output function values (y_l).

$$\left(W\left(\varepsilon\left(e_{i,j}\right)\right)=0\right) \Leftrightarrow \left\{y_l \in \left(-\infty, y_l^{1'}\right)\cup\left(y_l^{2'}, +\infty\right)\right\} \tag{6}$$

where: (($-\infty$, $y_l^{1'}$) and ($y_l^{2'}$,+ ∞)) – the range of non-admissible changes of the output function values (y_l).

The results of the object's diagnosis obtained from the relation (4, 5 and 6) are presented in Table 2.

Table 2. Table of object's states
Tabela 2. Tabela stanów obiektu

State of object	State of module	Vector of states of elementary components $\{e_{i,j}\}$				
		$\varepsilon(e_{1,1})$	...	$\varepsilon(e_{i,j})$	...	$\varepsilon(e_{I,J})$
$W(\varepsilon(O))$	$W(\varepsilon(E_1))$	$W(\varepsilon(e_{1,1}))$	...	$W(\varepsilon(e_{1,j}))$	...	$W(\varepsilon(e_{1,J}))$
	$\vdots$	$\vdots$	...	$\vdots$	...	$\vdots$
	$W(\varepsilon(E_i))$	$W(\varepsilon(e_{i,1}))$	...	$W(\varepsilon(e_{i,j}))$	...	$\varnothing$
	$\vdots$	$\vdots$	...	$\vdots$	...	$\vdots$
	$W(\varepsilon(E_I))$	$W(\varepsilon(e_{I,1}))$	...	$W(\varepsilon(e_{I,j}))$	...	$W(\varepsilon(e_{I,J}))$

where: $W(\varepsilon(e_{i,j}))$ – value of state assessment logics for j^{th} element within i^{th} module (from the set of the accepted three-value logic of states' assessment) – {2, 1, 0}), $\varnothing$ – symbol complementing the size of table.

3. Creation of an expert knowledge base for servicing of a repairable a technical object

3.1. Preparation of the set of the elements of the object's maintenance structure

The methods for the minimisation of the set of checks presented in [2, 4] impose specific requirements for the set of elementary components. The elementary component can have, in this case, any number of signal inputs but only one output. In the determined set of the object's functional elements, only those elements will be used during the maintenance whose states required repair. For this purpose, a relation for the comparison of the states of the object's elements included in (Table 1) with their standards was developed in accordance with the following:

$$\left(\underset{e_{i,j\in\{E_i\}}}{\vee} W\left(\varepsilon\left(e_{i,j}\right)\right) \mapsto \underset{e_{i,j\in\{E_i\}}}{\vee} W_w\left(\varepsilon\left(e_{i,j}\right)\right) \right) \Rightarrow \underset{e_{i,j\in\{E_i\}}}{\vee} W\left(z\left(e_{i,j}\right)\right) \tag{7}$$

where: $W(\varepsilon(e_{i,j}))$ – the value of state assessment logics for j^{th} element within i^{th} module of the object, $W_w(\varepsilon(e_{i,j}))$ – the standard value of state assessment logics for for j^{th} element within i^{th} module of the object, $W(z(e_{i,j}))$ – the resulting value of the state assessment logics for for j^{th} element within i^{th} module of the object, $\mapsto$ – comparison relation, $\Rightarrow$ – resulting relation.

The result of the expert's activity described with dependence (1) is the determination of an initial set of maintenance information in the form of a set of elements that need to be repaired. In the further step, a comparison of the states of the object's elements included in (Table 2) with their patterns takes place. Based on the results of such a comparison, an identification of the object's elements with the state value {2} – usability states is made. Such elements are not subject to prevention. They are crossed out and are replaced by symbol "⊗" in the table. Therefore, an initial set of maintenance information is obtained and presented in Table 3.

Table 3. Table of initial maintenance information
Tabela 3. Tabela pośredniej informacji obsługowej

The level of maintenance structure of the object	Vector of element's states $(e_{i,j})$				
	$z(e_{1,1})$	...	$z(e_{i,j})$	...	$z(e_{i,J})$
1	$W(z(e_{1,1}))$	...	$W(z(e_{1,j}))$	...	⊗
⋮	⋮	...	⋮	...	⋮
i	$W(z(e_{i,1}))$	...	$W(z(e_{i,j}))$	...	$W(z(e_{i,J}))$
⋮	⋮	...	⋮	...	⋮
I	$W(z(e_{I,1}))$	...	$W(z(e_{I,j}))$	...	⊗

where: $W(z(e_{i,j}))$ – z^{th} value of state assessment logics for j^{th} element within i^{th} module of the object, ⊗ – table's size completion symbol.

3.2. Classification of the elements of the internal structure of a technical object

Control of the quantity of the qualitative usability function (F_C) in the operation process requires, among other things, recognition and description of an object's internal structure, the nature of its work, etc. In modern systems for the servicing of technical objects, with a computer-aided organisation of this process, an important role is played in them by specialist (expert) databases. This specialist set of information concerning the object of servicing is determined on the basis of a description of the elements of the object's servicing structure, the grouping of them into classes, and the assigning of a specific subset of preventative activities to them, which are characteristic only of a given class of the elements of the structure.

The results obtained were presented in Table 4.

Table 4. Classes of operational elements of the object
Tabela 4. Klasy elementów obsługowych obiektu

Level of Maintenance structure of the object	Classes of operational elements of the object $\{s(e_{i,j})\}$				
	$(e_{1,1})$	...	$(e_{i,j})$	...	$(e_{i,J})$
1	$s(e_{1,1})$	...	$s(e_{1,j})$	...	$s(e_{1,J})$
⋮	⋮	...	⋮	...	⋮
i	$s(e_{i,1})$	...	$s(e_{i,j})$	...	$s(e_{i,J})$
⋮	⋮	...	⋮	...	⋮
I	$s(e_{I,1})$	...	$s(e_{I,j})$	...	$s(e_{I,J})$

where: $s(e_{i,j})$ – classes of the elements of maintenance structure of the object {s = (I – electronic, II – mechatronic, III – electric, IV – electromechanic, V – pneumatic, VI – hydraulic, VII – mechanic, VIII – digital)}.

3.3. Determination of the set of preventive activities to renovate the servicing object

The servicing of the elements of different classes [1, 2] can be realised by the performing of a group of activities from the subset of preventive activities, which is presents the following dependence:

$$\{A_l\}=\{a_1, a_2, ..., a_l, ..., a_L\} \tag{8}$$

Where: $\{A_l\}$ = {a_1 – replacing the element with a new one, a_2 – servicing, adjustment, tuning, regeneration, conservation, lubrication, cleaning, re-filling of working fluids, control check-up.}

Each maintenance activity from (Table 5) is related to its proper value of the function of the servicing of servicing elements. Such values can be determined only in an empirical way; thus, it is convenient to present them with fuzzy logic values, e.g. <*none, small, average, full*> [8, 9, 10].

Table 5. The set of preventive activities
Tabela 5. Zbiór czynności profilaktycznych

Set of preventive activities	Code for the activity a_l	The value of servicing function
replacing the element with a new one	a_1	complete
servicing	a_2	small
adjustment	a_3	small
tuning	a_4	average
regeneration	a_5	average
servicing	a_6	average
conservation	a_7	small
lubrication	a_8	small
cleaning	a_9	small
re-filling of working fluids	a_{10}	small
control check-up	a_{11}	none

An assumption is accepted in the paper that the maintenance structure of the object is determined by a set of maintenance elements (levels, and maintenance layers in these). For this reason, the determined set of preventive activities $\{A(e_{i,j})\}$ possesses a structure which is compliant with the object's maintenance structure (levels, and layers of preventive activities in these). The developed set of preventive activities to renovate the object presents the following dependence:

$$\{A(e_{i,j})\}=s(e_{i,j})\{a_1, a_2, ..., a_l, ..., a_L\} \tag{9}$$

where: s – classes of groups of maintenance elements, s = {I – electronic, II – mechatronic, III – electric, IV – electro – mechanical, V – pneumatic, VI – hydraulic, VII – mechanical, VIII – digital}.

3.4. Determination of the set of preventive activities to renovate the servicing object

From the determined set of preventive activities (see 5), their subsets were determined and assigned [2, 3, 6, 5, 8, 12, 14] to further elements of the set of the object's maintenance structure on the basis of the following dependence:

$$R_r: \quad if \;\; W_Z(e_{i,j}) \;\; then \;\; for \;\; M(e_{i,j}) \rightarrow \{a_l\} = M_E(e_{i,j}) \tag{10}$$

where: R_r – r^{th} rule of maintenance, → – symbol of assignment, $\{a_l\}$ – the subset of l^{th} activities from the set of preventive activities.

The maintenance information set $\{M_E(e_{i,j})\}$ in the form (Tables 4 and 5) was transformed to the final form of the set of maintenance information, which directly determines the structure of the object's maintenance system (cf. Table 6).

Table 6. The structure of object's maintenance system
Tabela 6. Struktura system obsługiwania obiektu

Structure of object's maintenance system $\{M_E(e_{i,j})\}$	
Elements of maintenance structure	**Elements of structure** of maintenance activities
$e_{i,j}$	$\{a_l\}$
$e_{1,1}$	$\{s(a_1, a_2,...,a_l,...,a_L)\}$
⋮	⋮
$e_{i,j}$	$\{s(a_1, a_2,...,a_l,...,a_L)\}$
⋮	⋮
$e_{I,J}$	$\{s(a_1, a_2,...,a_l,...,a_L)\}$

where: s – classes of the elements of maintenance structure of the object {s = (I – electronic, II – mechatronic, III – electric, IV – electromechanic, V – pneumatic, VI – hydraulic, VII – mechanic, VIII – digital)}.

The set of operational rules $\{R_r(e_{i,j})\}$ constitutes an important subset of the set of operational information. The set of operational rules was compiled according to the algorithm presented in the article. For this purpose, the previously obtained results in the form of stage sets of operational information were used, which were put in Tables 3, 4, 5 and 6. The dependencies (9 and 10) were used for the development of this set of information, as well as sets of information, which were presented in Tables 3, 4, 5 and 6. The results obtained are presented in Table 7 and Fig. 5.

The effect of the method presented in the article is the determined set of service information, which was presented in the form of $\{M_E(e_{i,j})\}$. This specialist knowledge base (a set of maintenance information) constitutes the basis for the designing of a reliable system of the maintenance (prevention) of a technical object. A maintenance system (Fig. 5) is understood to be a dynamic set that consists of a specialist who organises and supervises this system, means of maintenance (tools, materials, etc.), and the object of the maintenance presented in the form of a model of the object of maintenance, and relationships between them.

Table 7. The set of operational rules for the object
Tabela 7. Zbiór reguł obsługowych obiektu

Element no. in the object	Rules of operation
$e_{1,1}$	R_1: If $\varepsilon(e_{1,1})$ is $\{1\}$ then $M(e_{1,1}) \rightarrow \{5,7,8,11\} = M_E(e_{1,1})$
$\vdots$	$\vdots$
$e_{1,j}$	R_2: If $\varepsilon(e_{1,j})$ is $\{\otimes\}$ then $M(e_{1,j}) = M_E(e_{1,j})$
$\vdots$	$\vdots$
$e_{1,J}$	R_3: If $\varepsilon(e_{1,J})$ is $\{\otimes\}$ then $M(e_{1,J}) = M_E(e_{1,J})$
$\vdots$	$\vdots$
$e_{i,1}$	R_4: If $\varepsilon(e_{1,4})$ is $\{\otimes\}$ then $M(e_{i,1}) = M_E(e_{i,1})$
$\vdots$	$\vdots$
$e_{i,j}$	R_5: If $\varepsilon(e_{i,j})$ is $\{\otimes\}$ then $M(e_{i,j}) = M_E(e_{i,j})$
$\vdots$	$\vdots$
$e_{i,J}$	R_6: If $\varepsilon(e_{i,J})$ is $\{1\}$ then $M(e_{i,J}) \rightarrow \{6,8,10,11\} = M_E(e_{i,J})$
$\vdots$	$\vdots$
$e_{I,1}$	R_7: If $\varepsilon(e_{I,1})$ is $\{\otimes\}$ then $M(e_{I,1}) = M_E(e_{I,1})$
$\vdots$	$\vdots$
$e_{I,j}$	R_8: If $\varepsilon(e_{I,j})$ is $\{\otimes\}$ then $M(e_{I,j}) = M_E(e_{I,j})$
$\vdots$	$\vdots$
$e_{I,J}$	R_9: If $\varepsilon(e_{I,J})$ is $\{\otimes\}$ then $M(e_{I,J}) = M_E(e_{I,J})$

The model of the object of service is determined by a set of the maintenance elements of the object $\{(e_{i,j})\}$, i.e. such elements which possess states (with a trivalent evaluation of states): incomplete usability: state-{1}, or a non-operation state-{0}, and are subject to regeneration in the maintenance system. The obtained maintenance information $\{M_E(e_{i,j})\}$, as a result of the application of the method proposed, allows one to design a reliable system of the maintenance of the object. The designing of a maintenance system consists in the determination of the structure of the maintenance system (Fig. 5), which is composed of the following: the object's maintenance elements, the prevention activities (depending of the state) selected by an expert, including the maintenance means for a given element {A(ei,j)}, and maintenance rules $\{R_r(e_{i,j})\}$.

The issues presented in the article of the building of a set of operating information concerns various fields of knowledge, including technical diagnostics, the theory of operation, information technology, expert systems,

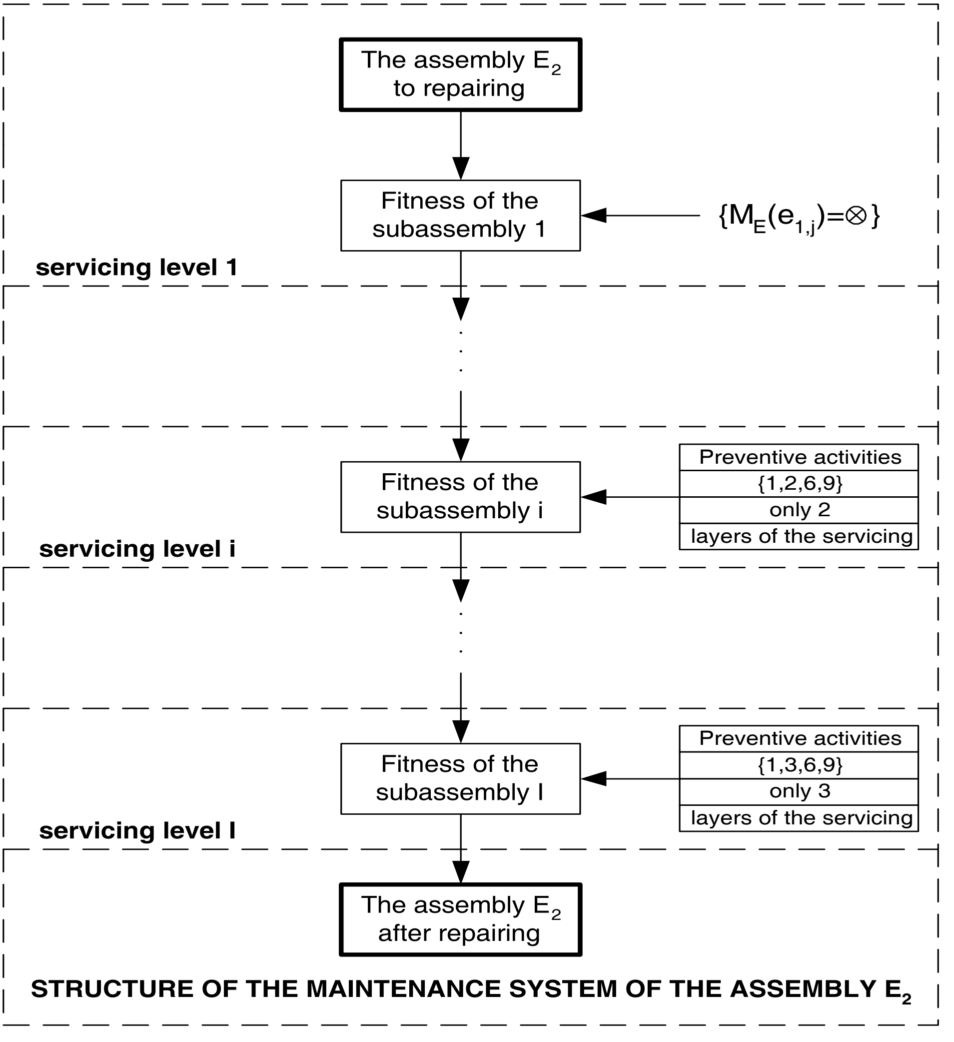


Fig. 5. Structure of the maintenance of the assembly E_2 (example)
Rys. 5. Schemat struktury systemu obsługiwania w zespole E_2 (przykład)

fuzzy sets, artificial neural networks, etc. Each of these fields is well and broadly worked out in the literature. It is the author's opinion that one can claim, with full responsibility, that even the basic problem, that is the use of diagnostic information obtained in the diagnosing process of a technical object in the designing and organisation of the operation process, is being constantly developed in various aspects (directions). However, there is no full description in the literature of methods to develop ways and algorithms for the processing of diagnostic information obtained by diagnostic systems: an artificial neural network, etc., to the form of an expert knowledge base of a maintenance system, presented in a computer programming language.

5. Conclusions

The paper presents a method to organise servicing of technical objects with the required short shutdown time (aeroplanes, radio-location systems, etc.). The basis of the method proposed is the use of information developed by an artificial neural network. The idea of the preventative method proposed is as follows: a technical object is used while its state is constantly recognised (monitored) by a neural network. In the case when a diagnostic system recognises the state of an incomplete usability {1} or non-usability {0}, then the time is determined when a renovation of the object should begin in the servicing system. A strategy of this type of servicing of technical objects is known as [4, 5, 6] preventative treatment, according to the state with control of parameters. This method is being constantly perfected and improved. A characteristic feature of this method is an elimination of costly and time-consuming repairs. An expected time of the use of an object is accepted, which is limited only by the reliability of its functional elements, which can also be systematically modified in accordance with the needs.

The method of prevention of objects according to the state requires that two problems be solved, and in the literature, they are being developed independently. The first one of them concerns the development of a method to determine the date of the execution of maintenance (i.e. when the regeneration of the object should begin). This issue is the domain of the theory of forecasting of the object’s states in time and is continuously being developed. The second issue is the construction (designing) of an effective system for the maintenance of a technical object. In the author’s opinion, the method presented in the article serves as an answer to the second issue. The author explicitly states that the research results presented are unique and innovative in the light of the existing literature.

References

[1] Będkowski L., Dąbrowski T.: *Podstawy eksploatacji* cz. 2. Wyd. WAT, Warszawa 2006, p. 187.

[2] Białko M.: *Podstawowe właściwości sieci neuronowych i hybrydowych systemów ekspertowych.* Wyd. Politechniki Koszalińskiej, Koszalin 2000, p. 341.

[3] Buchannan B., Shortliffe E.: *Rule – Based expert systems.* Addison – Wesley Publishing Company 1985, p. 387.

[4] Duer S., Duer R.: *Computer diagnostic system with expert knowledge for state’s control of technical objects.* “SYSTEM MODELLING CONTROL – SMC’2005”. Proceedings of the 11th International Conference on “System Modelling Control”, Zakopane, Poland. Wyd. EXIT, Warszawa 2005, pp. 69–77.

[5] Duer S.: *The concept of assistant system for analogue class technical object servicing.* Sixth International Conference On Unconventional Elektromechanical And Electrical System UEES′04. Alushta, The Crimea, Ukraine, 2004, pp. 687–690.

[6] Duer S.: *System ekspertowy wykorzystujący trójwartościową informację diagnostyczną wspomagający obsługiwanie złożonego obiektu technicznego.* Zagadnienia Eksploatacji Maszyn Z. 4(152) VOL. 42, 2007, pp. 195–208.
[7] Duer S.: *An algorithm for the diagnosis of reparable technical objects utilizing artificial neural Network.* Scientific Problems Of Machines Operation And Maintenance, Committee Of Machine Engineering Polish Academy Of Sciences. Vol. 43, No. 1(53) 2008, pp. 101–113.
[8] Duer S., Duer R., Duer P., Płocha I.: *Measurement system for the diagnosis of analogue technical objects with the use of artificial neural networks.* Academic Journals, Poznan University of Technology, s. Electrical Engineering, No. (59) 2009, pp. 61–72.
[9] Duer S.: *Classification of the elements of the object's maintenance structure of a reparable technical object.* Scientific Problems Of Machines Operation And Maintenance, Committee Of Machine Engineering Polish Academy Of Sciences. 2009 (in publishing),
[10] Duer S.: *Wykorzystanie sztucznej sieci neuronowej w systemie ekspertowym obsługującym układ sterowania silnikiem iskrowym typu Motronic.* VII Krajowa Konferencja Inżynierii Wiedzy i Systemów Ekspertowych, Politechnika Wrocławska, 2009, (in publishing).
[11] Dhillon B.S.: *Applied Reliability and Quality, Fundamentals*, Methodos and Procedures. Springer – Verlag London Limited 2006, p. 186.
[12] Hayer-Roth F., Waterman D., Lenat D.: *Building expert systems.* Addison – Wesley Publishing Company 1983, p. 321.
[13] Hojjat A., Shih – Lin hung.: *Machine learning, neural networks, genetic algorithms and fuzzy systems.* John Walley End Sons, Inc 1995, p. 398.
[14] Madan M. Gupta, Liang Jin and Noriyasu Homma: *Static and Dynamic Neural Networks, From Fundamentals to Advanced Theory.* John Walley End Sons, Inc 2003, p. 718.
[15] Mańdziuk J.: *Sieci neuronowe typu Hpofielda, teoria i przykłady zastosowań.* Wyd. EXIT Warszawa 2000, p. 262.
[16] Nakagawa T.: *Maintenance Theory of Reliability.* Springer – Verlag London Limited 2005, p. 264.

Manuscript received by Editorial Board, July 19th, 2009

Wyznaczanie ekspertowej bazy wiedzy do obsługiwania naprawialnego obiektu technicznego

S t r e s z c z e n i e

W pracy zaprezentowano metodę projektowania systemu obsługiwania naprawialnych obiektów technicznych, ze sztuczną siecią neuronową. Opisano w nim schemat i strukturę systemu obsługiwania z siecią neuronową. Zaprezentowano sposób wyznaczania informacji obsługowej obiektu. Przedstawiono sposób przekształcania struktury wewnętrznej złożonego obiektu z jego elementami funkcjonalnymi do postaci struktury obsługowej obiektu. Zaprezentowano analityczne podstawy realizacji obsługiwania technicznego obiektu. Opisano metodę przekształcania informacji diagnostycznej i wiedzy specjalistycznej eksperta do postaci zbioru informacji obsługowej.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

ANDRZEJ KATUNIN*

Self-heating effect in laminate plates during harmonic forced loading

Key words

Self-heating, polymer laminates, diagnostics of laminates, model-based diagnostics.

Słowa kluczowe

Samorozgrzewanie, laminaty polimerowe, diagnostyka laminatów, diagnostyka wsparta modelowo.

Summary

Laminate structures on a polymer base are widely used in many responsible applications. Therefore, behaviour of these structures must be predictable in different physical conditions and working loads. Behaviour of polymers can be described by an elastic rheological model only in static loading and specific thermophysical conditions, while, in the case of harmonic loading, it must be described using a viscoelastic model. Out-of-phase oscillations between stress and strain amplitudes cause energy dissipation, which introduce heating processes. An important phenomenon in polymers is self-heating. There are two approaches for the interpretation of the phenomenon: macromechanical, which base on energy dissipation, and micromechanical, which is based on the friction of broken polymer chains. The increase of self-heating temperature is dangerous in during exploitation in the case of polymers, because polymers possess a low glass transition temperature and a low heat transfer coefficient. The paper deals with three cases of the geometry of the structure: rectangular cantilever plate, circular clamped plate, and ring plate

* Department of Fundamentals of Machinery Design, Faculty of Mechanical Engineering, Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland, e-mail: andrzej.katunin@polsl.pl

clamped on internal edge. These models are often used in many engineering solutions. The high-accuracy dependencies for laminate rigidity homogenisation are also presented. A solution to the heat generation problem in steady state is also shown. Furthermore, the possibility of obtaining self-heating temperature in non-steady state based on an approximate model is presented. Identification and evaluation of area of the laminates where the self-heating effect appeared allow one to specify the degradation degree evaluation and the residual life prediction of the laminate.

1. Introduction

Laminate structures on a polymer base are used more frequently in many responsible elements such as turbine blades, helicopter propellers, rotors, the bottoms of containers and many others. Therefore, the behaviour of the laminate must be predictable during all phases of exploitation and in different physical conditions and working loads. One important phenomena occurring during exploitation of laminates is the self-heating process. It is initialised during cyclic loading as an effect of dissipative energy. Polymers in a glassy state (such as thermoplasts) can be described by an elastic rheological model only in static loads, small strains, and specific thermophysical conditions. When time-varying loading is applied, polymers must be described by a viscoelastic rheological model. Therefore, oscillations of stress and strain amplitudes are out-of-phase (Fig.1) and cause energy dissipation in the form of heat. This phenomenon can create dangerous states in the exploited system or part, because most polymers are characterised by a low glass-transition temperature and a low heat transfer coefficient. In such conditions of operation, the internal temperature increases to the glass-transition temperature (Fig. 2), and this can cause catastrophic consequences [1]. Therefore, the parameters of dangerous states and the character of property changes of the laminate must be investigated and applied both in design and maintenance phases.

Research on the phenomena of self-heating in polymers was initiated by Ratner and Korobov [2, 3] in late 1960s. In these works, the authors experimentally investigated the character of time-temperature curves and proposed basic dependencies between heat generation and changing phase angle δ between stress and strain amplitudes. They postulated that the breakdown of polymer is characterised by the critical temperature, when δ reaches the maximum value [2] and applied it in Zhurkov's micromechanical fatigue model [3].

The main research on self-heating was made by Karnaukhov's scientific group from S. P. Timoshenko Institute of Mechanics of National Academy of Sciences of Ukraine [4–6]. In their research, several problems of coupled thermoviscoelasticity were investigated. In [5] the resulting constitutive equations were investigated in complete and approximate formulation of thermomechanical viscoelasticity and were presented for different geometrical models.

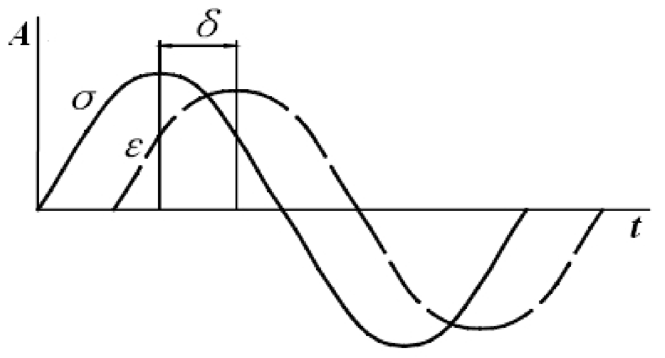


Fig.1. Out-of-phase stress-strain amplitudes of a viscoelastic material
Rys. 1. Niewspółfazowe amplitudy naprężeń odkształceń dla materiału lekkosprężystego

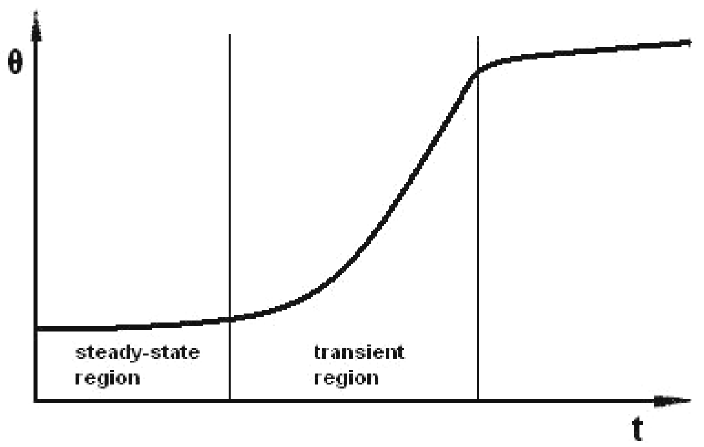


Fig.2. Self-heating temperature increasing during cyclic deformations [3]
Rys. 2. Wzrost temperatury samorozgrzania podczas cyklicznych odkształceń

The research on the mentioned phenomena was continued by Molinari's group from Paul Verlaine University [7, 8]. In [8], the dynamic thermomechanical response of a viscoelastic beam subjected to pure bending was described. The storage and loss moduli, according to the approximate formulation [5], as functions of frequency and temperature in steady states were assumed.

In this paper, the problem of self-heating was investigated on other types of geometry: a cantilever rectangular plate forced uniformly on the free edge and clamped circular plate with axial loading. As the research shows [1, 9, 10], there is a necessity to investigate these structures for predicting the degree of degradation of laminates. The geometrical structures under the author's consideration have important meaning in applied engineering solutions; therefore, their behaviour was investigated.

2. Problem formulation

Let us consider a cantilever rectangular transversal isotropic multilayer thin plate with k layers subjected to Kirchhoff's plate theory with length l, width b and thickness h. The plate is uniformly loaded by a harmonic force $P(t)$ on the free edge. The model can be simplified to a one-dimensional one, because, in case of pure bending, $u(x,0,t)=u(x,b,t)$ is constant, where t is time variable. The mechanical boundary and initial conditions can be presented by the following:

$$u(0,t)=0\,,\ \frac{\partial u(0,t)}{\partial y}=0\,; \qquad D\frac{\partial^3 u(L,t)}{\partial y^3}=-P(t)\,; \tag{1}$$

where D is substitutive flexural rigidity of laminate, and P is:

$$P(t)=P_0 \sin \omega t. \tag{2}$$

For determining rigidity of the laminate plate according to the assumed simplification, the homogenisation can be used [1]. In case of isotropic materials, the flexural rigidity D can be expressed as follows:

$$D=\frac{Eh^3}{12\left(1-\nu^2\right)}, \tag{3}$$

where E is Young's flexural modulus and ν is Poisson's ratio.

In the transversal isotropy case, the flexural rigidity (3) becomes a matrix:

$$[D]=\begin{bmatrix} D_{11} & D_{12} & 0 \\ & D_{22} & 0 \\ sym. & & D_{33} \end{bmatrix}, \qquad \{D_{ij}\}_k=\frac{1}{3}\sum_{k=1}^{n}[Q_{ij}]_k\left(z_k^3-z_{k-1}^3\right), \tag{4}$$

where Q_{ij} denote elasticity matrix coefficients, and z is the distance from the k-th lamina to the mid-plane of plate. For describing ply orientations different then 0^0, the cosine matrix must be taken into consideration. After several transformations, the substitutive flexural rigidity can be obtained.

$$D=\frac{1}{6}\sum_{k=1}^{n}\left(D_{11k}+D_{22k}+\frac{1}{6}D_{33k}\right). \tag{5}$$

Considering (4), and introducing the flexibility matrix and cosine matrix, we obtain the following formula based on material parameters:

$$D = \frac{1}{36}\sum_{k=1}^{n}\frac{z_k^3 - z_{k-1}^3}{1-\nu_{12}\nu_{21}}\left[\cos^2\phi_k \sin^2\phi_k\left(E_1 + E_2\nu_{21}(22+\nu_{21}) - \frac{48G_{12}}{1-\nu_{12}\nu_{21}}\right) + \cos^4\phi_k\left(E_1 + E_2 + \frac{G_{12}}{1-\nu_{12}\nu_{21}}\right) + \sin^4\phi_k\left(E_1 + E_2 - \frac{G_{12}}{1-\nu_{12}\nu_{21}}\right)\right]. \qquad (6)$$

3. Viscoelastic behaviour of laminate

According to the viscoelastic behaviour of the harmonically loaded laminate plate, Boltzmann-Volterra equation (7) can be used for describing the behaviour of the material [11]:

$$E\varepsilon(t) = \sigma(t) + \int_0^t \Pi(t-\tau)d\tau\,, \qquad (7)$$

where $\Pi(t-\tau)$ is a relaxation kernel. Let us consider the stress tensor:

$$\sigma_{ij} = s_{ij} - \frac{1}{3}\sigma_{ij}\delta_{ij}\,, \qquad (8)$$

where s_{ij} is the stress deviator and δ_{ij} is the Kronecker's delta. In the investigated case, the subscripts i=j=1 under the assumption of pure bending, and (8) can be simplified to

$$\sigma_{11} = \frac{3}{2}s_{11}\,. \qquad (9)$$

The deviatoric stress s_{11} and temperature dependence can be presented as (compare with [8]) while taking into consideration (6) and (7).

$$s_{11} = 2D_e(\theta)\varepsilon_{11} + 2\int_0^t D(t-\tau,\theta)\frac{d\varepsilon_{11}}{d\tau}d\tau\,. \qquad (10)$$

The equilibrium modulus D_e depends only on temperature θ and does not depend on time, because, using the generalised Maxwell model of viscoelastic material, the time dependence of rigidity (in our case) can be presented as

$$D(t) = D_e + \sum_{i=1}^{I} D_i \exp\left(-\frac{t}{\tau}\right), \qquad (11)$$

where I is the number of Maxwell elements. According to (11), $D(0)=\sum_{i=0}^{I} D_i$, $D_e = D$. The under-integral part $D(t-\tau,\theta)$ denotes the resolvent kernel in comparison with (7).

Taking into consideration (2), the strain in time dependency is expressed as

$$\varepsilon_{11}(u,t)=\frac{2u}{h}\varepsilon_0 \sin \omega t\,. \tag{12}$$

In cyclic loading, the temperature and strain will be oscillating equivalently. According to small evolution of temperature in one cycle, we can use the averaged value per cycle:

$$\theta_a = f\int_t^{t+T}\theta(t)dt\,, \tag{13}$$

where $f=\omega/2\pi$ denotes frequency and T denotes cycle period. Following the assumptions mentioned above, the deviatoric stress can be expressed as

$$s_{11}=\frac{4u}{h}\left[D_e(\theta_a)+\varepsilon_0\hat{D}(\omega,\theta_a)\right], \tag{14}$$

where

$$\hat{D}(\omega,\theta_a)=\int_0^{\infty} D(\vartheta,\theta_a)\exp(-i\omega\vartheta)d\vartheta\,,\quad \vartheta=t-\tau \tag{15}$$

is a complex rigidity, which decomposes in the form:

$$\hat{D}(\omega,\theta_a)=D'(\omega,\theta_a)+iD''(\omega,\theta_a), \tag{16}$$

$$\begin{aligned} D'(\omega,\theta_a)&=\omega\int_0^{\infty} D(t,\theta_a)\sin(\omega t)dt\,,\\ D''(\omega,\theta_a)&=\omega\int_0^{\infty} D(t,\theta_a)\cos(\omega t)dt\,, \end{aligned} \tag{17}$$

In Fig. 2, the complex rigidity and its components were presented on a hysteresis loop. The expression $(17)_1$ is an elastic energy component, and we will call it “stored rigidity,” and $(17)_2$ is the viscous energy component, which is dissipated as heat, and we will call it “loss rigidity.” Finally, after substitution (17) to (14), we obtain

$$s_{11} = \frac{4u}{h}\left[D_e(\theta_a) + \varepsilon_0\left(D'(\omega,\theta_a)\sin\omega t + D''(\omega,\theta_a)\cos\omega t\right)\right]. \tag{18}$$

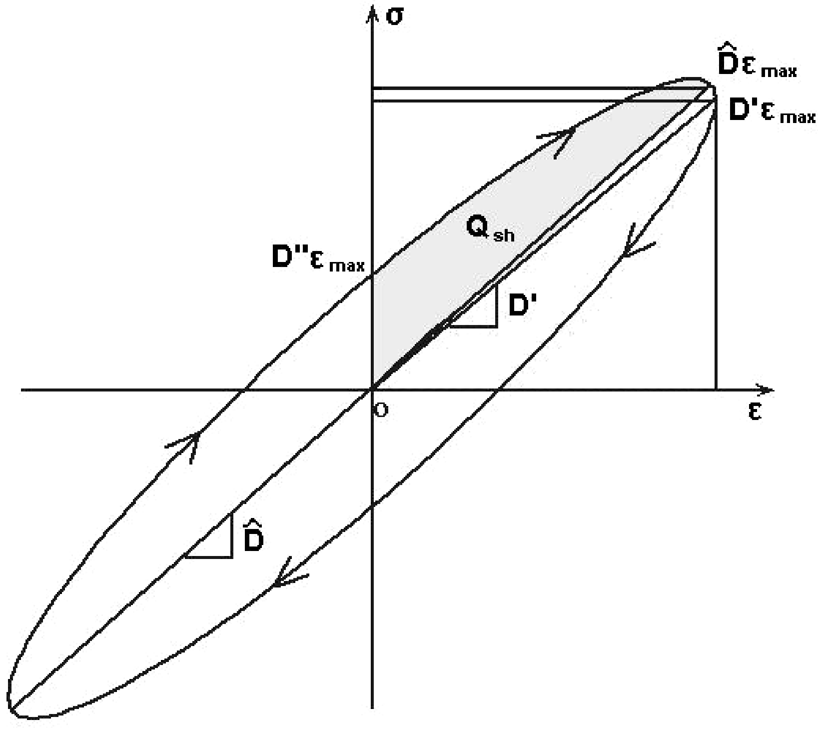


Fig.3. Typical hysteresis loop with complex rigidity, its components and dissipated energy
Rys. 3. Typowa pętla histerezy ze sztywnością zespoloną, jej składowymi i energią dyssypowaną

4. Heat transfer and temperature distribution

Heat transfer due to thermal processes in the laminate can be described by a linear heat equation with the assumption of homogeneity of the material (see Section 2) and thermal isotropy:

$$\rho c\frac{\partial\theta}{\partial t} - \lambda\frac{\partial^2\theta}{\partial u^2} = Q_{sh}, \tag{19}$$

where ρ is the material density, c is the specific heat capacity, λ is the thermal conductivity, and Q_{sh} is an energy dissipated per unit time and unit volume. Here we assumed that the thermomechanical properties in (19) do not depend on temperature.

Let us consider the energy dissipation from a mechanical point of view. We can write the next expression according to the area of a hysteresis loop:

$$Q_{sh} = f\int_0^T \sigma_{11}\dot{\varepsilon}_{11}dt\,. \tag{20}$$

The heat conduction with surroundings, i.e. thermal boundary conditions, can be presented by

$$\begin{gathered}\theta = \theta_r \quad \text{for} \quad u = 0\,,\\ \lambda\frac{\partial\theta}{\partial u} = -\alpha\left(\theta_a - \theta_0\right) \quad \text{for} \quad u = \pm\frac{h}{2}\,,\end{gathered} \tag{21}$$

where α is the heat transfer coefficient, θ_0 and θ_r are an external temperature and reference temperature, respectively, and h is the thickness of the plate.

By substituting (9) and (18) to (20), the cycle-averaged dissipated energy calculates as

$$Q_{sh} = 6\omega\varepsilon_0^2u^2h^{-2}D''\left(\omega,\theta_a\right). \tag{22}$$

According to the experimental research presented in [2], the temperature evolution of dissipated energy can be divided into three regions (see Fig. 2). The first one corresponds to the steady state, when the balance between heat from energy dissipation and heat conducted to surroundings takes place. The second one is for the non-steady state, when the heat from dissipated energy is growing (when stiffness is decreasing). In the last region, the temperature has stabilised and demonstrates the linear behaviour. As it can be noticed, the non-stationary temperature evolution is determined by the loss of rigidity, i.e. the heat equation (19) can be reduced to a steady state form for the first and third regions. Taking into consideration the self-heating energy (22), the heat transfer equation for the presented problem was constructed:

$$\lambda\frac{d^2\theta}{du^2} + 6\omega\varepsilon_0^2u^2h^{-2}D''\left(\omega,\theta_a\right) = 0\,. \tag{23}$$

Taking into account the boundary conditions (21), the governing equation (23) was solved as follows:

$$\theta(u) = \frac{3}{2}D''\left(\omega,\theta_a\right)\frac{\omega\varepsilon_0^2u^3(2u-h)\left(1-\alpha\lambda^{-1}\right)}{h^2(\lambda-\alpha)} + \frac{2u\theta_r}{h(\lambda-\alpha)}\left(1+\alpha-\alpha\frac{\theta_0}{\theta_r}\right) + \theta_r\,. \tag{24}$$

The non-stationary temperature evolution (second region) occurs when the rigidity loss increases. The critical point of temperature evolution is the value of a glass-transition temperature θ_g. We seek the state where $\theta_a \le \theta_g$. Based on FEM model [12], the temperature in non-steady state can be obtained using the following dependence:

$$\theta(t', \omega) = \theta_g - f \exp(-gt'), \tag{25}$$

where $f = 34.04$ and $g = 2.3987 \cdot 10^{-5}$ are approximation constants, t` is the time variable. The rigidity loss function in the non-steady state can be determined by substitution (25) to (24).

5. Other geometry cases

Similarly for the investigated phenomena for cantilever rectangular plate, we can obtain solutions by analogy for circular plates.

Let us consider a circular transversal isotropic multilayer thin plate with k layers clamped on the edge, according to Kirchhoff-Love's plate theory, with radius R and thickness h loaded by concentrated harmonic force $P(t)$ in the centre. According to the axi-symmetrical problem, boundary conditions can be presented as follows:

$$u(R) = 0; \quad \frac{\partial u(R)}{\partial y} = 0; \quad D\frac{\partial^3 u(0)}{\partial y^3} = -P(t); \tag{26}$$

where $P(t)$ is defined by (2).

In the same way, we can present boundary conditions for a ring plate with thickness h clamped on the internal edge with radius R_1 and loaded by force $P(t)$ distributed on the external edge with radius R_2:

$$u(R_1) = 0; \quad \frac{\partial u(R_1)}{\partial y} = 0; \quad D\frac{\partial^3 u(R_2)}{\partial y^3} = -P(t). \tag{27}$$

The investigated phenomenon is applicable to other one-dimensional systems or systems, which can be reduced to one-dimensional systems.

6. Conclusions and remarks

The superposition method was used for obtaining the dissipation energy and self-heating temperature in plate laminate structures in steady and non-steady states in cross-section and axial loading. The new homogenisation method of laminate stiffness, while taking into consideration variable laminas orientations, was proposed, which gives high-accuracy results (near 0.5% relative error). The viscoelastic behaviour of the laminate was determined by the complex rigidity, where the initial rigidity was determined by laminate's homogenised rigidity and used for obtaining self-heating energy. The steady state expression for temperature in the coupled problem was obtained and non-steady state was determined by the approximate solution of the numerical model. To verify the obtained solution, it is necessary to investigate the complex rigidity variability experimentally in different temperatures and loading frequencies. Also, it is shown that the proposed solution can be applied for other geometry structures, e.g. circular clamped plate or ring plate in case of axi-symmetrical loading, and generally it can be applied for one-dimensional systems and systems reduced to one-dimension.

The most interesting for the presented phenomena is the coupled problem solution in the horizontal section of laminate, which can be obtained by solving the two-dimensional heat transfer represented by Poisson's partial differential equation. The next problem is to take into consideration the non-ideal contact of the laminas in the coupled problem.

The obtained dependencies can be applied in residual life evaluation as well and used in the model-based diagnostics for polymer laminates. In addition, the understanding and describing the self-heating effect allows one to specify diagnostics and monitoring methods for laminates..

References

[1] Katunin A., Moczulski W.: *The conception of a methodology of degradation degree evaluation of laminates*, Maintenance and Reliability, 1 (41), 2009, pp. 33–38.

[2] Ratner S.B., Korobov V.I.: *Self-heating of plastics during cyclic deformation*, Mekhanika Polimerov, vol. 1, No. 3, 1965, pp. 93–100.

[3] Ratner S.B., Korobov V.I., Agamalyan S.G.: *Mechanical and thermal fracture of plastics under cyclic strains*, Fiziko-Khimicheskaya Mekhanika Materialov, vol. 5, No. 1, 1969, pp. 88–93.

[4] Karnaukhov V.G.: *Modeling the oscillations and dissipative heating of inelastic bodies,* International Applied Mechanics, vol. 29, No. 10, 1993.

[5] Senchenkov I.K., Zhuk Ya.A., Karnaukhov V.G.: *Modeling the thermomechanical behaviour of physically nonlinear materials under monoharmonic loading,* International Applied Mechanics, vol. 40, No. 9, 2004.

[6] Karnaukhov V.G., Kirichok I.F.: *Vibrations and dissipative heating of viscoelastic beam under moving load*, International Applied Mechanics, vol. 41, No. 1, 2005.

[7] Dinzart F., Molinari A.: *Linear stability analysis for thermoviscoplastic material under cyclic axial loading,* Continuum Mech. Termodyn., 17, 2005, pp. 83–99.

[8] Dinzart F., Molinari A., Herbach R.: *Thermomechanical response of viscoelastic beam under cyclic bending; self-heating and thermal failure,* Arch. Mech., 60, 1, 2008, pp. 59–85.

[9] Moczulski W., Katunin A.: *Research on model-based and experimental evaluation of degradation of composite laminates,* Proc. Of 4th International Congress on Technical Diagnostics "Diagnostics '2008", p. 130, Olsztyn 2008.

[10] Katunin A.: *Influence of self-heating temperature on fatigue stiffness of multilayered composite plate on polymer base* [in Russian], Prikladnaya Mekhanika, vol. 45, No. 3, 2009.

[11] Minenkov B.V., Stasenko I.V.: *Stiffness of plastic details* [in Russian], Mashinostroenie, Moscow, 1977.
[12] Katunin A.: *About self-activating temperature modeling In laminate* [in Polish], 2nd Scientific Conference "Computer methods – 2008", pp. 21–24, Gliwice 2008.

Manuscript received by Editorial Board, July 19th, 2008

Efekt samorozgrzewania w płytach laminatowych podczas harmonicznych obciążeń wymuszonych

S t r e s z c z e n i e

Struktury laminatowe o osnowie polimerowej są szeroko stosowane w wielu odpowiedzialnych aplikacjach. Dlatego zachowanie tych struktur powinno być przewidywalne w różnych warunkach fizycznych i warunkach obciążeń. Polimery mogą być opisane sprężystym modelem reologicznym tylko przy statycznym obciążaniu i odpowiednich warunkach termofizycznych. W przypadku obciążeń harmonicznych polimery powinny być opisywane modelem lepkosprężystym. Niewspółfazowość oscylacji pomiędzy amplitudami naprężeń i odkształceń powoduje dyssypację energii, co jest przyczyną generowania ciepła. Ważnym zjawiskiem w polimerach jest samorozgrzanie, które wynika z dyssypacji energii w ujęciu makromechanicznym lub z tarcia pomiędzy zerwanymi łańcuchami polimerowymi w ujęciu mikromechanicznym. Wzrost temperatury samorozgrzania jest niebezpieczny ze względów eksploatacyjnych w przypadku polimerów, gdyż charakteryzują się one niską temperaturą zeszklenia oraz niskim współczynnikiem przewodności cieplnej. Przy wzroście temperatury własności materiałowe stuktury maleją aż do jej zniszczenia. W pracy rozpatrzono trzy przypadki geometrii struktur: prostokątna płyta jednostronnie utwierdzona, okrągła płyta utwierdzona na brzegu oraz płyta pierścieniowa utwierdzona na wewnętrznym promieniu. Takie modele często używa się w wielu rozwiązaniach inżynierskich. W rozważaniach zaprezentowano zależności dla homogenizacji sztywności laminatu o wysokiej dokładności. Zostało przedstawione rozwiązanie zagadnienia generowania ciepła w stanie ustalonym, a także przedstawiono możliwość otrzymania temperatury samorozgrzania w stanie nieustalonym na podstawie modelu aproksymacyjnego. Identyfikacja i oszacowanie obszaru laminatu objętego efektem samorozgrzania umożliwia sprecyzowanie oceny stopnia degradacji i predykcji wytrzymałości resztkowej laminatu.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

ZBIGNIEW KŁOS*, PRZEMYSŁAW KURCZEWSKI*

LCA in Poznań and Poland. Research teams and their achievements

K e y w o r d s

LCA, Poznań, Poland, research centres, research activities.

S ł o w a k l u c z o w e

LCA, Poznań, Polska, centra badawcze, działalność badawcza.

S u m m a r y

Increasing interest of different organisations (industrial companies, governmental authorities, consultancy agencies and non-governmental organisations) in the environmental evaluation of products has caused the need of tools for its realisation. Some attempts have already been made in this field in the world, mainly for every-day life consumer products (packaging, hygiene wares and cleaners, simple household equipment, etc.). In the paper, the history and actual situation in research on LCA in Poznań (in detail) and in Poland (briefly) is presented. The main LCA research centres, key figures working there, and their professional activities are characterised.

1. Introductory remarks. early activities in the field of LCA

Each new branch of science looks for its roots. The same is with LCA. Some papers showing the need of more complex environmental analysis of

* Poznań University of Technology, Faculty of Working Machines and Transportation, Institute of Working Machines and Transportation Piotrowo 3 St., 60-965 Poznań, Poland.

products were published in seventies, but the LC approach appeared in publications in the end of eighties, as showed in his fundamental book G. Huppes [1]. The history of introduction of LCA into research practice in Poland is similar. Some already "pre-historical" activities connected with Life Cycle frames were done in second part of eighties. They are connected with research centre, located at Poznań University of Technology (PUT). As a first such activities one can consider the following:

- The first paper on LCA: Rozważania o celowości wyznaczania środowiskowego kosztu istnienia maszyn i urządzeń (Considerations on the Usefulness of Determination of Environmental Expenditure of the Existence of Machines and Devices), published in Zeszyty Naukowe Politechniki Poznańskiej (Scientific Works of PUT), seria: Maszyny Robocze i Pojazdy (series: Machines and Vehicles) in 1986 (author: Zbigniew Kłos);
- The first book on LCA related issues, written by Zbigniew Kłos: Sozologiczność obiektów technicznych. Studium wartościowania wpływu maszyn i urządzeń na środowisko (Environment Protection Oriented Property of Technical Objects. A Study of Valuation of Machines and Devices Influence on Environment), published by Wydawnictwo Politechniki Poznańskiej (Editions of PUT) in 1990; and,
- The first PhD thesis was Ekobilansowanie maszyn i urzadzeń na przykładzie sprężarek powietrza (Ecobalancing of Machines and Devices with the Example of Air Compressors) was defended by Grzegorz Laskowski (supervisor: Prof. Zbigniew Klos) at Faculty of Machines and Vehicles, PUT in 1999.

The first other activities in nineties include the following:

- Participation in work activities of European LCA research groups; Zbigniew Kłos as a member of SETAC-Europe Workgroup on LCA and Conceptually Related Programmes (1994-95) and member of SETAC-Europe WG on LCA Case Studies (1994-96);
- Participation in European Union Research Programme LCANET in 1996-97 and in European Union Concerted Action CHAINET in 1998-2000 (Zbigniew Kłos);
- The creation and further development of original methodology for quantification of technical objects influence on environment (elaborated in late eighties and presented in 1990 in the above mentioned first LCA book) with examples of application (idea, assumptions and structure of this method are similar to those developed at the beginning of 90s ties in well known UBP-method and in works elaborated in CML);
- A scientific stay in the famous LCA centre – CML, University of Leiden in May-June 1995, where Zbigniew Kłos was a contractor of TEMPUS/ PHARE programme;
- A cycle of ten conferences focused on TQM and environmental problems (first conference – 1992), presenting also ecobalancing problems and actual state of art on LCA studies in Poland; and,
- Attempts of LCA application as a tool for assessment of environmental impacts of different objects: coal electrodes produced by Zakłady Elektrod

Węglowych S.A. (1998), machines and appliances in Pofamia S.A. (1999) and selected products of the company PoWoGaz S.A. (1999), as well as other specific projects on diagnosis and environmental optimisation of the production processes in different companies, e.g. PoWoGaz S.A., Trepko, Amica.

Next, PhDs devoted to the LCA related issues, defended mainly at the Faculty of Machines and Transport, PUT, are shown in Table 1.

Table 1. PhDs in area of LCA at PUT
Tabela 1. Doktoraty w obszarze LCA w Politechnice Poznańskiej

PhD student	Title	Supervisor	Defended in
Grzegorz Laskowski	Ekobilansowanie maszyn i urzadzeń na przykładzie sprężarek powietrza (Ecobalancing of Machines and Devices with the Example of Air Compressors)	Prof. Zbigniew Kłos	1999
Przemysław Kurczewski	Ekobilansowa ocena wybranych procesów w przemyśle spożywczym (Ecobalancial Assessment of Chosen Packaging Processes in Food Industry)	Prof. Zbigniew Kłos	2001
Anna Jurek	Zagadnienia wpływu maszyn i urządzeń na środowisko (Issues of Environmental Influence Assessment of Machines and Appliances	Prof. Zbigniew Kłos	Prepared in PUT, defended at Faculty of Mechanical Engineering, Wroclaw University of Technology in 2003
Piotr Radomski	Zastosowanie oceny cyklu życia jako narzędzia decyzyjnego w prośrodowiskowym rozwoju maszyn przemysłu spożywczego (Application of LCA as a Decision Making Tool for Ecodesigning of Food Industry Machines and Devices)	Prof. Zbigniew Kłos	2004
Agnieszka Merkisz-Guranowska	Wieloaspektowa analiza uwarunkowań rozwiązania recyklingu samochodów osobowych w Polsce (Multi-aspect analysis of solution conditions of car recycling in Poland)	Prof. Zbigniew Kłos	2004
Jędrzej Kasprzak	Ekobilansowa analiza procesow eksploatacji i likwidacji maszyn I urządzeń przemysłu spożywczego (Ecobalancing Analysis of Operation Period and Disposal Processes of Food Industry Machines and Devices)	Prof. Zbigniew Kłos	2006

2. Presentation of Poznań Research Groups

2.1. Research Group on Ecobalancing and Quality at Poznań University of Technology

Actually the Group main members are Zbigniew Kłos (head of Group), Przemysław Kurczewski, Jędrzej Kasprzak, Robert Lewicki, and Krzysztof Koper. Some details about the members of the Group are presented below in Table 2.

Table 2. Research Group on Ecobalancing and Quality in PUT
Tabela 2. Zespół badawczy ds. ekobilansowania i jakości w Politechnice Poznańskiej

Name	Education	Professional activities	Publications	Areas of scientific and technical work
Zbigniew Kłos	1972 - M.Sc. in Mechanical Engineering at PUT, 1979 - Ph.D. at PUT, 1990 - D.Sc. (post doctoral thesis) at PUT, 1994 - Associate Professor at PUT in the field of quality and sustainable development, 2001 - Professor	– member of the International Research Group on Wear of Engineering Materials of OECD – member of the Jury of Polish Quality Award member of Society of Environmental Toxicology and Chemistry (SETAC) – member of SETAC-Europe Workgroups on LCA, LCANET and CHAINET – member of the Jury of Poznan International Fairs Golden Medal Competition – council member of Individual Polish Quality Award Committee – contractor of TEMPUS/PHARE grant N IMG-94-PL-2027, carried out at Rijks Universiteit Leiden, NL – member of Management Committee COST 530 Action „Sustainable Materials Technologies" – head of Doctoral Studies at the Faculty	6 books 9 textbooks 245 other publications	– development of LCA methodology – method of cumulative environmental costs – investigations on ecological criteria of technical objects (mainly machines and devices for food processing industry) – development of quantitative estimation methods of technical objects influence on environment (director of the projects granted by Polish State Committee for Scientific Research) – development of idea of corporate culture model for organisations – elaboration of standard methods dealing with application of reliability in

Name	Education	Professional activities	Publications	Areas of scientific and technical work
		of Machines and Transportation PUT – former Vice-Dean of the Faculty (1993-1996, 1999–2005)		technology, including calculation of indices for sliding pairs – introduction of environmental criteria into the framework of Polish Quality Award Competition
Przemysław Kurczewski	1997 – M.Sc. at PUT, Faculty of Machines and Motor Vehicles, field of study: mechanical engineering, title of diploma work (M.Sc.): Environmentally oriented analysis of the quality of the compressors for the food industry, 2001 – Ph.D. at PUT, title of Ph.D. thesis: Ecobalancing assessment of chosen packaging processes in food industry	– member of Society of Environmental Toxicology and Chemistry (SETAC) – member of Management Committee COST 530 Action “Sustainable Materials Technologies” – member of Life Cycle Costing Working Group (SETAC – Europe) – member of Committee of Quality Award for Wielkopolska Region – vice-chairman of Organizing Committee of conferences in the field of quality and environment (2004, 2006)	3 books more than 60 other publications	– analysis oriented on reduction of overall life cycle impacts of products – optimisation of technical objects with respect to environmental issues – application of LCA in design process – research in area of control of technical and quality of technical objects – development of the complex quality assessment methods – Life Cycle Management methodology development
Jędrzej Kasprzak	2002 – M.Sc. at PUT, Faculty of Machines and Transportation, field of study: mechanical engineering, title of diploma work (M.Sc.): Consideration of environmental aspects in the	– member of Society of Environmental Toxicology and Chemistry (SETAC) – member of COST 530 Action “Sustainable Materials Technologies” – member of Organising Committee of conference in the field of quality and	1 book almost 30 other publications	– ecobalancing of technical objects – environment protection in the industry – environmental impacts of operation period of technical objects – application of LCA in operation

Name	Education	Professional activities	Publications	Areas of scientific and technical work
	designing of food industry machines and devices, 2006 – Ph.D. at PUT, title of Ph.D. thesis: Ecobalancing analysis of operation period and disposal processes of food industry machines and devices	environment – member of the Organising Committee of the International Summer School of Practical and Technical Problems Solving in Mechanics, Material Engineering and Transportation		processes – refurbishment processes of food industry machinery – analysis oriented on reduction of overall life cycle impacts of products – optimization of technical objects with respect to environmental issues
Robert Lewicki	2004 – M.Sc. at PUT, Faculty of Machines and Motor Vehicles, field of study: ecology of transport, title of diploma work (M.Sc.): The analysis of environmental effects of different scenarios of car recycling, 2004 – now – doctoral studies at PUT – Faculty of Working Machines and Transportation, 2006 – opened Ph. D. Course title of Ph.D. thesis: Environmental analysis of consequences of motor vehicles utilization	– member of the Polish Scientific Society of Combustion Engines – member of Organising Committee of conference in the field of quality and environment – member and chairman of the Organising Committee of the International Summer School of Practical and Technical Problems Solving in Mechanics, Material Engineering and Transportation		– environment protection in the industry – ecobalancing of technical objects – environmental impact of products' end of life – analysis of car recycling processes in Poland – mechanics of machines and appliances – basis of combustion engines construction
Krzysztof Koper	2007 – M.Sc. at Silesian University of Technology, Faculty of Organisation and Management, field of study: quality and technology	– member of the Organising Committee of the International Interdisciplinary Technical Conference of Young Scientists *InterTech* – member of the	5 publications	– quality and environmental management – technical objects quality factors with special attention given to environmental

Name	Education	Professional activities	Publications	Areas of scientific and technical work
	management, 2007 – now – doctoral studies at PUT – Faculty of Machines and Transport	Organising Committee of the International Summer School of Practical and Technical Problems Solving in Mechanics, Material Engineering and Transportation		impacts connected with object's usage and disposal – environmental impact of upgrading processes – sustainable development issues

The following are common activities including applications and participation in the 5 and 6 FP:

- MAKE-IT – Manufacturing Management Based on Knowledge and Information Technology Category – Competitive and Sustainable Growth Key action – Innovative products, processes and organisation Objectives – Intelligent production; efficient production, including design, manufacturing and control;
- HEADS – Harmonisation and Integration of European Analytical Databases for Sustainability Category – Integrated Projects Field - Sustainable development, global changes and ecosystems;
- IN-SUSTAIN – The implementation of Integrated Product Policy Category - Network of Excellence Field - Nanotechnologies and nanosciences, knowledge-based multifunctional materials and new production processes and devices (Optimisation of „production-use-consumption" interactions);
- PSIE – Post-graduate School of Industrial Ecology Category - Maria Curie Conferences and Training Courses Field - Maria Curie Actions;
- PROTEKO – Centre of Excellence for Proecological Technical Solutions (Centrum Doskonałości Proekologicznych Rozwiązań Technicznych) Category - Network of Excellence; and,
- Life Cycle Inventories for Environmentally Conscious Manufacturing Category - European Cooperation in the field of Scientific and Technical Research Field - COST 530 Action - Sustainable Materials Technology (Zbigniew Klos, Przemyslaw Kurczewski – members of the Management Committee).

2.2. Research Group at the Poznań University of Economics

Actually the Group members are Zenon Foltynowicz (head of the Group), Anna Lewandowska, Joanna Witczak, and Hanna Pondel, as well as PhD students Renata Bogucka, Barbara Borucka, Agata Kowal, Tomasz Alankiewicz, and Rafał Ostrowski. The activities of the Group members are presented in Table 3.

Table 3. Research Group at the Poznań University of Economics
Tabela 3. Zespół badawczy w Uniwersytecie Ekonomicznym w Poznaniu

Name	Education	Professional activities	Publications	Areas of scientific and technical work
Zenon Foltynowicz	1974 - M.Sc. in Chemistry at the Faculty of Chemistry, Adam Mickiewicz University (AMU) in Poznań 1981 - Ph.D. in Chemistry at AMU 1990 - D.Sc. (post doctoral thesis) at AMU 1998 - Associate Professor at the Poznan University of Economics, Faculty of Commodity Science	– vice-president and member of SETAC Central Eastern European Countries branch – member of the IGWT (International Society of Technology and Commodity Science) – member of Polish Society of Commodity Science – member of Technical Committee 270 Environmental Management in Polish Committee for Standardisation – Chairman of 7th and 8th Int. Symposium “Current trends in commodity science” – member of the editorial board of the Polish Journal of Commodity Science 2005 – founder and head of Product Ecology Department at the Faculty of Commodity Science 2005 – now - dean of Faculty of Commodity	1 book 5 textbooks more than 120 other publications 29 patents 7 technologies	– environmental management systems (EMS) – implementation in Polish enterprises – ISO 14040x and ISO 14020x standards – translation into Polish and implementation in Poland; – environmental waste management, specially packaging waste – new solution in the field of packaging (oxygen scavengers, biodegradable materials) – nanocomposites and polymers – polymer recycling – intellectual properties protection

		Science at the Poznań University of Economics; (1999–2005 vice-dean)		
Anna Lewandowska	2000 – M.Sc. in Commodity Science, Poznań University of Economics, 2004 – Ph.D. in Economics Science, Poznań University of Economics, 2004 – Marie Curie fellowship, Institute of Environmental Science (CML), Leiden University	– member of SETAC Europe and SETAC CEEC – supervisor of the student's scientific circle Eco-business – member of the Commission on Promotion of the Faculty of Commodity Science	3 books 3 textbooks more than 40 other publications	– product ecology and life cycle management (LCM) – life cycle assessment (LCA) – design for environment (DfE)
Joanna Witczak	1998 – M.Sc. in Environmental Protection, Adam Mickiewicz University (AMU) in Poznan 2000 – M.Sc. in Commodity Science, Poznan University of Economics 2008 – Ph.D. in Economics Science, Poznan University of Economics	Member of the Commission on Promotion of the Faculty of Commodity Science Member of the Organising Committee of the 10th IcomSC'09	over 10 oublications	– product ecology – green marketing – consumer behaviour – organic food market

The scientific activities of the Group:

- Political and legal aspects of environment's protection (environmental policy of Poland and UE, UE directives),
- The investigation of relations between products and environment, (i.e. sustainable development, Cleaner Production),
- Environmental management systems (EMS),
- Environmental life cycle assessments (LCAs),
- Design for environment (DfE),
- Green marketing,
- Ecolabelling,
- Ecological food and agriculture, and
- Biodegradable nanocomposites.

2.3. Research Group in Institute of Timber Technology

Publications:

- Wawrzynkiewicz Z.: Analiza cyklu życia (LCA – life cycle analysis) jako podstawa do przyznawania ekoznaków wybranym produktom drzewnym. Etap I. Rozpoznanie stanu zagadnienia. ITD maszynopis 1997
- Wawrzynkiewicz Z.: Analiza cyklu życia w badaniach drewna i wyrobów z drewna. Holz-Zentralblatt. Gazeta Drzewna (7/8), 1999
- Wawrzynkiewicz Z.: LCA pomoże ocenić oddziaływanie wyrobu na środowisko. Polski. Holz-Zentralblatt. Gazeta Drzewna nr 11, 2004
- Lewandowska A., Noskowiak A., Wawrzynkiewicz Z.: Specyfika przemysłu drzewnego w badaniach LCA; Gazeta Drzewna Polski Holz-Zentralblatt, (11) 2004, s. 16
- Strykowski W., Lewandowska A., Noskowiak A., Wawrzynkiewicz Z.: Środowiskowa ocena cyklu życia (LCA) w przemyśle drzewnym – możliwości i wyzwania; Drewno Wood; 48 (174) 2005, s. 55–56

Book:

- Strykowski W., Lewandowska A., Noskowiak A., Wawrzynkiewicz Z.: Środowiskowa ocena cyklu życia (LCA) wyrobów drzewnych; wyd. Instytut Technologii Drewna, Poznań; ISBN 83-915727-6-5
- Project led by ITD:
- Project No. 4T08E 05025: Zarządzanie środowiskiem w przemyśle drzewnym z wykorzystaniem Oceny Cyklu Życia (LCA) (2003–2005)

3. Other research groups in Poland

3. 1. Research Group at Polish Academy of Sciences – Mineral and Energy

Economy Research Institute (MEERI)

The scientific activities of the Institute:

- The assessment of efficiency and profitability of new investments in the mineral resources economy and waste management;
- The assessment of the possibilities and economics of renewable energy sources use;
- Municipal waste management, especially the use of biogas by cities and communes;
- The analysis of risk in geotechnical projects concerning the underground storage of hazardous waste; and,
- The legal and economic aspects of industrial waste storage in exhausted mine sites.

Joanna Kulczycka, PhD – head of the Group:

- Professional activities:
  - A member of technical group for waste management created under the auspices of the Ministry of the Environment,
  - A member of working group for ISO 14040-14049 nomenclature and application in Poland,
  - A authorised person for LICYMIN and LIFETIME (projects in FP5),
  - A sub-contractor for the CLOTADAM project,
  - Involved in European Waste Management project Interreg 3C, and
  - Coordinator of two projects realised in Poland within Structural Funds.
- Publications:
  - 1 book and over 40 publications
- Polish projects performed:
  - Methodology of the ecological LCA on the example of selected processes in the chemistry and mining industry (2003-06),
  - New technology for use of post-flotation tailing for backfilling – including Best Available Techniques No. 6 T12 2004 C/06378 (2004-06),
  - The analysis and evaluation of possibilities to conduct ecological tax reform in Poland (2005),
- EU projects performed:
  LICYMIN (1999-2003) – scope of the work:
  LIFETIME (2001-03) – scope of the work:
  OSELCA (2004) – scope of the work:

3.2. ABB Group – Polish branch

- History of LCA practice:
- Polish branch strategy of LCA:
  Supporting of the LCA data base development oriented on environmentally oriented activities in the ABB Group,
  Cooperation with Chalmers University of Technology,
  The replacement of own LCA software by commercial LCA tools,
  Continuous education and training programs, and
  LCA application as a common tool to the studies oriented on Environmental Product Declaration in ABB products.

3.3. Research Group at University of Zielona Góra, Faculty of Management – Department of Environment and Public Economy Management

Actually, the Group members are Professor Magdalena Graczyk (head of the Group), Joanna Zarębska Ph.D. (2004) – *Algorithms of ecological balances of selected packaging,* Janusz Adamczyk Ph.D. (2006) – *LCA application in the environmental evaluation of the building* and Leszek Kaźmierczak - opened Ph. D. course – “LCA application in the assessment of ecological risk.”

3.4. Research Group at Central Institute of Mining (CIM)

The Group is leaded by Activities (internal projects):

- 1999 – LCA of selected products made from plastics, Describing of the rules of ecodesign of the products made from nonferro materials;
- 2000 – Ecodesign and LCA of computers using SimaPro 4.0;
- 2002 – Describing of the ecobalance methodology for different branches of industry;
- 2003 – Application of the EPS method in the LCA of selected products;
- 2004 – Methodology of the data collection based on the ISO 14048, as the main phase of the LCA study; and,
- 2005 – Assessment of the environmental efficiency of the PCV and PP pipe production.

Conclusions

Review of the situation in LCA and related areas allows drawing the following conclusions:

1) LCA centres are located mainly in academic centres, at university or scientific institutions and are engaged in research, standardisation, foresight and expert activities; and they are weakly inter-communicated.
2) There are different areas of projects covered, specially oriented on environmental interactions, identification, including conceptual studies and Environmental Product Declarations, ecological risk assessment, ecodesign, and LCM.
3) The range of analysed objects covers packaging, packaging machines and packaging systems, means of transport and transportation systems, investments in the mineral resources, energy sources and technical objects in the energy industry, building engineering, selected products from PCV, PP and different polymer materials.

   Desired activities for future are listed below:

   - More effective communication of the LCA research results to the outside world, specially industry and decision makers in administration;
   - More advanced introduction of the LCA approach to the higher education;
   - The integration of the LCA community in frame of conferences, common projects, as well as in experts environment; and
   - The introduction of the LCA issues to the structure of the organisation of science (at least in Poland).

We hope that quarterly “Exploitation Problems of Machines” will aid in our attempts to continue to play a significant role.

References

[1] Huppes G.: *Macro-environmental policy: principles and design* (Ph.D. thesis). Rijksuniversiteit Leiden, Leiden 1993.

Manuscript received by Editorial Board, December 01st, 2008

LCA w Poznaniu i w Polsce. Zespoły badawcze i ich osiągnięcia

S t r e s z c z e n i e

Wzrastające zainteresowanie różnych organizacji (przedsiębiorstw przemysłowych, władz administracyjnych, firm konsultacyjnych i organizacji pozarządowych) środowiskową oceną produktów wywołało potrzebę powstania metod dla jej realizacji. Pewne próby w tym zakresie zostały już dokonane na świecie, a dotyczyły one głównie przedmiotów codziennego użytku (opakowań, środków higienicznych i czystości, drobnego sprzętu gospodarstwa domowego itd.). W artykule zaprezentowana jest historia i aktualna sytuacja w zakresie badań z dziedziny LCA w Poznaniu (szczegółowo) i w Polsce (skrótowo). Scharakteryzowano ważniejsze centra badawcze i istotniejsze osoby działające w tym zakresie, przedstawiając zakres ich zaangażowania.

SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (158) 2009

PRZEMYSŁAW KURCZEWSKI*

Life Cycle Management as a concept for industrial application

Key words

Management, life cycle, quality, environment, cost.

Słowa kluczowe

Zarządzanie, cykl życia, jakość, środowisko, koszt.

Summary

In the paper, LCM (Life Cycle Management) is defined as the application of life cycle thinking concept to modern business practice, with the aim to manage the total life cycle of products and services towards more sustainable production and consumption. Relevant systems, methods and tools connected with LCM concept are presented, specially: TQM, ISO 9000, ISO 14000, ecodesign. There is indicated that the application of various elements of management system may differ due to different purposes and different interested parties. While quality management systems deal with customer needs, environmental management systems address the needs of a broad range of interested parties and evolving needs of society for environmental protection.

The problem of introduction of LCM is of key importance for small and medium enterprises (SME), because they constitute, in Western World, almost 2/3 of the private sector and represent a major source of growth in employment, through new business start-ups. Thus, the SME sector becomes an important target for growth of competitiveness, innovation and environmental policies and practices but reveals low awareness of environmental issues.

* Poznań University of Technology, Faculty of Working Machines and Transportation, Institute of Working Machines and Transportation Piotrowo 3 St., 60-965 Poznań, Poland.

1. Introduction

Among main the directions of organization development is minimizing of generated environmental impacts connected with economic cost minimizing. Some companies undertake various efforts to reduce the impact of their products or services on the environment. Sometimes, even the entire "life" of products or services are considered to meet requirements of sustainable development and to create an environmental image of the organization. Life Cycle Management (LCM) can support various activities oriented to environmental improvements. Although LCM is still rather a concept then the consequently structured regulation, it has the chance to be formed in the future in the shape of integrated tool. Some tools or solutions of another nature, which could assist LCM implementation in companies, are analysed in this paper.

2. Scope of lcm concept

Environmental burden generated by products results from the interrelated decisions made at various stages of a product's life. Therefore, it is necessary to support the products' creation with different tools and methodologies that enable an assessment of the environmental consequences in each stage. But at the beginning, to create an environment friendly product, life cycle thinking should be a common phenomenon in organization, because of the following:

- It expands the traditional focus on products and manufacturing processes to incorporate economic, environmental and social aspects associated with a product over its entire life cycle.
- It is oriented to reduce resource use from the environment and emissions to the environment and to improve the social performance in various stages of a product's life.
- Achieved results of life cycle thinking combine different and very important for the companies, results, since cleaner products and processes, provide a competitive advantage to products and the company [1].

Although life cycle thinking is called the best way to environmental improvements, the practical solutions to achieve environmentally oriented goals are established in the concept of Life Cycle Management. LCM is defined in the following ways:

- LCM is the application of life cycle thinking to modern business practice with the aim to manage the total life cycle of an organization's products and services towards more sustainable consumption and production.
- LCM is systematic integration of sustainability, e.g. in company strategy and planning, product design and development, purchasing decisions and communication programs,

- LCM is integrated management framework of concepts, techniques and procedures incorporating environmental, economic, and social aspects of products, processes and organizations.
- LCM is voluntary and can be gradually adapted to the specific needs and characteristics of individual organizations [1].
- LCM is a dynamic process; organizations may begin with small goals with the resources they have and get more ambitious ones over time [2].

Generally, LCM can be established as a practical approach to optimization focused on minimizing the environmental burdens associated with products and services over their entire "life" through better, environmentally oriented, decision making. LCM should attract the developed companies in Poland and other CEE countries, as a support tool on their way to improve their environmental image [3]. The basis for LCM incorporation to organizations in CEE countries should be focused on introducing in organizations the rules of Total Quality Management and the regulations of such standards as ISO 9001 (Quality systems – Model for quality assurance in design, development, production, installation and servicing) and ISO 14001 (Environmental management systems – Specification with guidance for use).

Typology of the strategies, systems, concepts, and different tools is presented in the Table 1.

Table 1. Strategies, systems, concepts, and tools useful in LCM [1]
Tabela 1. Strategie, systemy, koncepcje i narzędzia użyteczne w LCM [1]

Policies/Strategies	Sustainable Development, Integrated Product Policy, Cleaner Production, Eco-efficiency, etc.
Systems/Processes	TQM, EFQM model, Integrated and Environmental Management Systems, e.g. ISO 9000/14000, EMAS, Extended Producer Responsibility, Environmental Communication, etc.
Concepts/Programs	Design for Environment, Supply Chain Management, Public Green Procurement, Green Accounting, Supplier Evaluation, etc.
Tools/Techniques	Analytical: LCA, MFA, SFA, I/O, LCC, etc. Procedural: Audits, Checklists, Labelling, etc. Supportive: Weighting, Uncertainty, etc.
Data/Information/ Model	Data: Databases, Controlling Information, Best Practice Benchmarks, References

3. LCM connections with TQM

Some methods useful for LCM applications are coming from the TQM area. They could be applied at the different levels of economy, being especially suitable in the organizations [4]. TQM as a way of organization management, which is characterized by system approach, orientation on strategic goals, ability to continuous and for ever improvement, includes close contacts from one side with suppliers and customers from the other side. It should allow for easier negotiations with them on environmental topics. Practically, the steps of formalization and implementation of TQM may include:

– Establishing, by organization board, the team in charge of TQM policy implementation,
– Self-evaluation of managerial staff,
– Training of all employees on TQM policy,
– Training of all employees on psychological and social work environment,
– Internal and external promotion of TQM policy,
– Self evaluation of the company,
– Rendering the source materials to all supervisors,
– Contest for the most interesting solution within TQM, and
– Establishing quality circles and developing their methodology.

The above mentioned aspects indicate the crucial role of TQM in the process of LCM implementation. The reason is that LCM should become part of an organization's policies, so that its importance encompasses all levels of the organization. LCM policies should be visionary and long-range, while also being realistic and concrete, parallel to its types of goals. There are at least three different types of features common for TQM and LCM:

– Internal readiness and commitment to continuous improvements,
– The desire for life cycle improvement of products, and
– The desire to take the complex characteristics of products a step further by reporting and marketing activities and thereby create general organizational successes.

Additionally, the natural consequence of TQM can be common participation of range of employees who ensure that the LCM initiatives will be deeply rooted in the organization and that the focus will be on concrete improvements to a product. Furthermore, broad participation in LCM activities ensures that the LCM program does not die if a key employee involved leaves the organization [1].

4. LCM connections with ISO 9001

The ISO 9001 is one of international standards dealing with quality system requirements that can be used for external quality assurance purposes. The quality assurance model encompasses: design, development, production, installation, and servicing. There are several elements of this model which include the activities influencing the environment:

– Management responsibility – managers shall define and document their policy for quality, which shall be relevant to the expectations and needs of customers (initiation of actions to prevent the occurrence of any nonconformities related to the product, process and quality system, also connected with environment);
– Design control – establishing and maintaining of documented procedures to control and verify the design of the product in order to ensure that the specified

requirements are met (design input requirements reacting to the product, including environmentally related items);
- Purchasing – establishing and maintaining the procedures ensuring that the purchased product conforms to specific requirements (the supplier shall evaluate and select subcontractors on the basis of their ability to meet subcontract requirements including the environment influences);
- Process control – identification and planning the production, installation and service processes, which directly affect quality (environment) and shall ensure that these processes are carried out under controlled conditions;
- Inspection and testing – establishing and maintaining of documented procedures for inspection and testing activities in order to verify that the specified requirements for the product are met (the supplier shall ensure that incoming product is not processed until it has been inspected of otherwise verified as conforming to environment requirements); and,
- Corrective and preventive action – establishing and maintaining documented procedures for implementing corrective and preventive action appropriate to the magnitude of problems.

In practice, a system based on an international standard ISO 9001 can help the organization to address strategic planning, overall management, product and process development, procurement, production, distribution, marketing, communication and other functions in a more systematic and comprehensive approach. The organization will typically, in the beginning, focus on what is going on at the site and those inputs and outputs connected to its own activities. After achieving the easy improvements of quality the organization will have to expand its focus [1].

5. LCM connections with ISO 14001

International standards covering environmental management (e.g. ISO 14001) are intended to provide organizations with the elements of an effective environmental management system, which can be integrated with other management requirements, to assist organizations to achieve environmental and economic goals [5]. The ISO 14001 standard specifies the requirements of such an environmental system, which could be applicable to all types and sizes of organizations and to accommodate diverse geographical, cultural and social conditions. A system of this kind enables an organization to establish and assess the effectiveness of procedures to set an environmental policy and objectives, achieve conformance with them, and demonstrate such conformance to others. The overall aim of this standard is to support environmental protection and prevention of pollution in balance with socio-economic needs. Many of the requirements may be addressed concurrently or revisited at any time.

In the ISO 14001 standard requirements for an environmental management system are specified, to enable an organization to formulate policy and objectives taking into account legislative requirements and information about significant environmental impacts. It applies to those environmental aspects, which the organization can control and over which it can be expected to have an influence.

The organization shall establish and maintain an environmental management system, the requirements of which are in following fields:

- Environmental policy,
- Objectives and targets,
- Planning,
- Legal and other requirements,
- Environmental management programs,
- Implementation and operation,
- Operational control,
- Emergency preparedness and response, and
- Monitoring and measurement.

The ISO standards on environmental management systems and tools can assist in the process, but common sense is still needed, e.g. do not to implement one or the other side alone, but use the synergy of combining by product-oriented environmental management systems. Product oriented environmental management overlaps with the concept of LCM or corresponds to the environmental dimension of LCM. An examples from Netherlands and Denmark show, good practice in product-oriented environmental management means:

- A link between organization environmental initiatives and the market,
- Complemental environmental studies with market studies and analysis of interested parties expectations,
- Direct integration of environmental requirements into the product development,
- Common and continuous analysis, improvement objectives setting, networking and evaluation activities, and
- Knowledge building [1].

On the base of above-mentioned information, it is easy to indicate that success of product oriented management systems implementation in companies depends on the stage of specific organization in the ecodesign and formalized environmental (and quality) management learning curves.

6. LCM connections with Design

LCM plays a special role in product design oriented also on environmental goals. It is called design for environment (DfE) or eco-design. DfE is defined as “the systematic process by which companies design products and processes in an environmentally conscious way" [6, 7]. The scope of DfE encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention, and waste management [8]. The topic of DfE is especially important in the connection with the environmentally oriented assessment of the designed product. It is worth remembering that early assessment of environmental aspects incorporated to the designing phase can lead to effective design improvement and to improve the environmental image of the product. On the base of [9], the place of design in the new product development process is presented on the Figure 1.

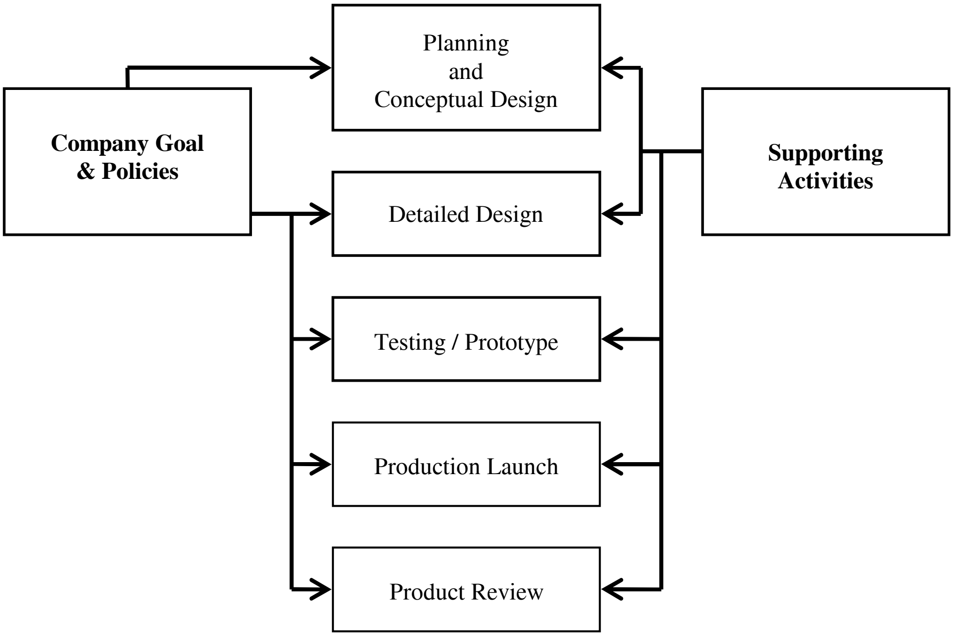


Fig. 1. New product development process
Rys. 1. Proces rozwoju nowego produktu

Design seems to be commonly treated as the crucial phase, which has an influence on the environmental image of the final product. The reason is that design determines:

- 70–80% of the total project life cycle costs, and
- Most of the total life cycle environmental impacts.

Additionally, it is worth remembering that early assessment of environmental aspects incorporated into the designing phase can lead to effective design improvement and to improve the environmental image of the product. The following steps of DfE can be distinguished [1]:

- Link the significant environmental parameters to relevant environmental strategies.
- Identify relevant implementation measures for the improvement of the environmental parameters belonging to a certain environmental strategy.
- Develop redesign tasks for the chosen implementation.
- Develop product specification, and it should consists of fixed and desired specifications.
- Identify the function of the reference product and then add a new function and/or modify an existing function based on the product specification.
- Generate ideas to realize the function.
- Generate variants – assembling idea corresponding to each function of the newly improved product generates the variants.
- Develop a product concept by selecting variant – variants are evaluated against criteria such as economic, technical, social, and environmental ones.
- Continuing detailed embodiment design, layout, testing, prototype, production and market launch.

7. The case of refrigerators

As an example of advanced LCM application connected with ecodesign project, the case study of refrigerator optimization is presented in this paper. Realized stages of the project included:

- Ecodesign team formation,
- Goal definition,
- Object of reference specification (LCA, LCC and LCWE),
- Target definition, and
- Designing and testing.

The first goal of the study was to determine the general guidelines and principles of environmental improvements of refrigerators. Also, economical and social aspects were analysed from the perspective of refrigerator life cycle. Results of the first stage of the study were focused on different aspects, important for the design processes. Particularly, a matrix of information about the environmental view of different components' compositions of refrigerators have been created. Such data were concentrated on the following issues, which should be helpful for designers and product managers: life cycle conscious decision making, risk information approaches, on-line monitoring of degradation processes of the materials and components, and prediction models and verification of remaining lifetime.

In this stage, it was necessary to answer the following questions:

- Can changes in the used materials improve the environmental image of the refrigerator's life cycle?

– Can changes in the production processes be reflected in the decrease of the environmental impacts?
– What activities should be implemented in the project to minimize environmental burdens in the life cycle of refrigerator?

Further stages of the case study (conceptual design, detailed design and research) has also been carried out by the team of experts. Analysed variants of the changes in the construction of refrigerators are specified in the Table 2.

Table 2. Ecodesign tasks and ways of their execution [10]
Tabela 2. Zadania ekoprojektowe i ich wykonanie [10]

Ecodesign task	**Way of execution**	**Number of variant**
Energy consumption reduction to the level of 218 kWh/year	Substitution of existing aggregate for more efficient aggregate	1
	Application of one aggregate (instead of two aggregates)	2
	Application of more energy efficient refrigerant	3
	Improvement of thermal insulation	4
	Replacement of traditional (electrical) aggregate by magnetic aggregate	5
Reduction of noise level to 38 dB (A)	Application of materials minimizing acoustic vibration of aggregate	6
	Replacement of traditional (electrical) aggregate by magnetic aggregate	5
	Substitution of aggregate	1
	Application of one aggregate (instead of two aggregates)	2
	Improvement of thermal and acoustic insulation	4
Reduction of number of harmful substances by 25%	Application of more environment friendly (incl. energy efficient) refrigerant	3
	Elimination of chloroparaffins	7
Reduction of disassembly time to 30 minutes	Reduction of the number of permanent joints by 10%	8
	Reduction of number of used materials by 5%	9
	Application of one aggregate (instead of two aggregates)	2
Reduction of refrigerator mass	Application of one aggregate (instead of two aggregates)	2
	Reduction of number of used materials by 5%	9
	Reduction of the packaging mass	10
Assurance of recovery index on the level of 80%	Reduction of number of used materials by 5%	9
	Application of more environment friendly refrigerant	3

The final results of the project are improved refrigerators. Some innovative solutions have been applied in consequence of ecodesign and LCM detailed studies. They were worked out in the following areas [10]:
- The application of one modern aggregate (16% better result of LCA and 11% better result of LCC),
- The application of more energy efficient refrigerant (8% better result of LCA and 3% better result of LCC), and
- The improvement of thermal and acoustic insulation (6% better result of LCA and 5% better result of LCC).

7. Conclusions

Life Cycle Management suggested in this paper includes a lot of systems, methods and tools, but the most important nowadays are DfE or eco-design and other product life cycle based concepts. Companies with a Life Cycle Management system in place will have increased possibilities to comply with such product-related legislation, because early integration of environmental and social concerns into the design and development cycle is expected to reduce costs, promote innovation, facilitate supply chain integration and assure greening initiatives.

Observed factors limiting implementation of LCM are [1]:

1) The form of the perspective of product development process:
   - Environmental criteria, which are not always included in the design process,
   - The lack of environmental information flow between companies and suppliers,
   - A diverse level of environmental understanding,
   - A lack of a system of reviewing environmental design alternatives, and
   - No need of environmental product design specification.
2) The form of the perspective of useful tools:
   - Limited environmental design abilities (methodology, checklist for design, software, etc.),
   - The lack of list of environmentally preferred materials for product design,
   - A very limited practice of reporting of environmental improvements to the product,
   - LCA studies for any product, which are not carried out, and
   - A lack of performance indicators in design processes.
3) The form of the perspective of life cycle thinking:
   - No need of product design for disassembly or recycling for example,
   - No need of easy servicing – this is not always a requirement,
   - The use phase, which is not typically considered with respect to the environmental requirements, especially energy consumption, and
   - No plan to have a remanufacturing facility.
4) The form of the perspective of managing aspects:

– The lack of formal and structured educational and training programme,
– The lack of design involvement in the environmental policy in the company, and
– A limited responsibility for the products throughout the life-cycle.

The problem of the introduction of LCM is of key importance for small and medium enterprises (SME), which are an important target for competitiveness, innovation and environmental policies and practices, but reveals low awareness of environmental issues. The fields that should be strongly developed in practice are environmental life-cycle assessment and life-cycle costing. They should change the image of design practice to be a driving wheel for LCM implementation in the future.

References

[1] Jensen A. A., Remmen A.: *UNEP guide to Life Cycle Management – a bridge to sustainable products,* Background report for a United Nations Environment Programme, 2005.
[2] Hunkeler D. et al.: *Life cycle management,* SETAC, Brussels 2003.
[3] Kurczewski P., Kłos Z.: *Proceedings of the conference: Design methods for practice*, Zielona Góra 2006.
[4] Kłos Z.: *Introduction of TQM strategy to Polish enterprises – analysis of conditions.* Organizacja I Kierowanie, 1996, nr 1.
[5] Kłos Z.: *Introduction of Life Cycle Management to companies, supported by TQM and ISO standards,* in: Proceedings of 1st International Conference on Life Cycle Management, Copenhagen 2001.
[6] Lenox M., Jordan B., Ehrenfeld J.: *The diffusion of design for environment: a survey for current practice,* in: International Symposium on Electronics and the Environment, Dallas 1996.
[7] Zhang H. C., Kuo T. C., Lu H., Huang S. H.: *Environmentally conscious design and manufacturing*: A state-of-the-art survey, Journal of Manufacturing Systems, 1997, vol. 16, nr 5.
[8] *Environmental Consciousness: A strategic competitiveness issues for the electronics and computer industry,* Comprehensive report: Analysis and synthesis, task force reports and appendices, Microelectronics and Computer Technology Corporation, 1993.
[9] ISO/TR: 14062: 2003, Environmental management – Integrating environmental aspects into product design and development, Geneva 2003.
[10] Kurczewski P., Lewandowska A. e al.: *Rules of environmental designing of technical object for the need of their life cycle management*, KMB Druk, Poznań 2008.

Manuscript received by Editorial Board, December 01st, 2008

Zarządzanie cyklem życia jako koncepcja do stosowania w przemyśle

S t r e s z c z e n i e

W artykule zdefiniowano zagadnienie LCM (zarządzania cyklem życia) jako sposób zastosowania koncepcji myślenia kategoriami cyklu życia w nowoczesnej praktyce biznesowej, z ukierunkowaniem na zarządzanie całym cyklem życia produktów lub usług, by osiągać bardziej zrównoważoną produkcję i konsumpcję. Zaprezentowano odpowiednie systemy, metody i narzędzia związane z koncepcją LCM, w tym szczególnie TQM, ISO 9000, ISO 14000, ekoprojektowanie. Wskazano, że wprowadzenie poszczególnych składowych systemu zarządzania

może zależeć od różnych celów i poszczególnych zainteresowanych stron. Podczas gdy systemy zarządzania jakością ukierunkowane są na oczekiwania klientów, systemy zarządzania środowiskiem uwzględniają potrzeby szerszej grupy zainteresowanych stron, rozszerzając oczekiwania społeczne o aspekty ochrony środowiska.

Problematyka wdrażania LCM ma kluczowe znaczenie dla małych i średnich przedsiębiorstw (MŚP), ponieważ w „krajach zachodnich" kształtują one blisko 2/3 prywatnego sektora gospodarki i są głównym źródłem wzrostu zatrudnienia poprzez uruchamianie nowych przedsięwzięć gospodarczych. Z tego powodu sektor MŚP staje się ważnym obszarem wzrostu konkurencyjności, innowacyjności oraz kształtowania polityki i działalności środowiskowej, jednak ujawnia się w nim niska świadomość problemów środowiskowych.