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Lifetime prediction of bearings in on-board starter generator

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Abstract. Ensuring flight safety for passengers as well as crew is the most important aspect of modern aviation, and in order to achieve this, it is necessary to be able to forecast the durability of individual components. The present contribution illustrates the results of a computational analysis to determine the possibility of analysing the prediction of bearing durability in on-board rotating equipment from the point of view of thermal fatigue. In this study, a method developed at the Air Force Institute of Technology was used for analysis, which allowed to determine the bearing durability from the flight altitude profile. Two aircraft have been chosen for analysis - a military M-28 and a civilian Embraer. As a result of the analysis were obtained: the bearing durability in on-board rotating devices, average operation time between failures, as well as failure rate. In conclusion, the practical applicability of this approach is demonstrated by the fact that even with a limited number of flight parameters, it is possible to estimate bearing durability and increase flight safety by regular inspections.

Keywords: aircraft; durability of bearing; failure mode; mathematical model; temperature profile

1. Introduction

In order to improve safety, a number of day-to-day and cyclical inspections are carried out on the aircraft. With the aim of achieving the highest required standard, the most important issues is to predict and avoid the possible faults. To reach this goal, the data from operating process are used to build mathematical models, allowing to calculate the lifetime of a given element. As was stated by Carrera (2002), stress fields related to the temperature variations often represent a contributing factor and, in some cases, are the main causes of the failure structures. The component whose durability can be calculated from the ambient temperature are bearings in on-board rotating devices. One of the parts of the aircraft, which lifetime depends on thermal conditions, is bearing in rotating devices. Due to the difficulty of abrasion measurement, the relation between durability of the bearings and the altitude of flight can be used. Bearing is an element of these machines, which are strongly influenced by thermal conditions (Cinefra *et al.* 2015). Based on the change of ambient temperature, it is possible to determine the durability of bearings in on-board rotating devices without any interference.

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2. Literature review

The aging of aircraft equipment and components occurs as a result of their properties degrading over time. It is the result of the interaction of operational, structural and technological factors as a function of time. This is due to various physical and chemical phenomena which lead to the degradation of aircraft characteristics and capabilities. The literature distinguishes moral, economic and physical aging (Patra *et al*. 2019).

As it was stated by Brushan (2013), moral aging of an aircraft occurs when the performance and production indicators of aircraft and their components or devices are disadvantageous in comparison with modern aircraft.

As it was mentioned by Urban and Hoskova-Mayerova (2017) the economic aging of the aircraft is the result of physical aging, which involves additional labor and costs for maintaining airworthiness, technical and operational readiness and the effects of deteriorating safety.

Physical aging of the aircraft is the process of change in components of installations and equipment as a result of degradation of performance and properties. This is due to the effects of macro- and micro-phenomenon forces on aircraft installations and equipment. Physical aging of aircraft occurs as a result of the following factors: mechanical, electrical and magnetic, energetic, atmospheric, environmental, chemical and electrochemical factors as well as exploitation and maintenance.

The rolling bearing is a fundamental component of the traction motor. It is the essential connecting part between the rotating elements (rotor, shaft) and the non-rotating parts (stator, housing). Their thermal characteristics influence bearing life and its overall performance (Wang *et al*. 2020b). Frequent changes in speed, load, external environment and other factors tend to generate heat inside the bearing under high friction conditions, which causes various mechanical faults such as sticking, plastic deformation, cage damage, etc. and poses a threat to safe and stable operation of rolling bearings, as it has been described by Yu (2015).

Basically, there are two types of failures that can occur in electric motors, mechanical failure and electrical failure. Both of these failures suggest that the motor components most likely to result in failures are bearing and stator winding. To be effective, predictive maintenance programs should contain a trending factor that will address degradation of these components (Dulci *et al*. 2006, Pandey *et al*. 2012). In most of the industry bearings, faults are uncovered through vibration signals. Industrial systems are, however, still based on vibration signals as they are the only reliable media. The vibration level of the machine is measured with the help of sensors. These are proximity sensor, velocity transducer and accelerometer. As it was described by Singh and Vishwakarma, (2015) accelerometers are mostly used for vibration analysis.

In order to guarantee safe flight operations, it is necessary to forecast remaining useful life (RUL) (Wang *et al*. 2020a) of rolling bearings in the engine. Taking into consideration the existing research, current attempts to predict RUL can be classified into two main categories: model-based approaches (Farmakopoulos *et al*. 2013) and data-driven approaches, studied for example by Sharanya *et al*. 2020, Smith *et al*. 2009. In general, a complex system such as an aircraft engine contains many components and a complicated structure, which makes its failure challenging and difficult to predict, it is hardly possible to develop an accurate physics-based model. However, although data-driven approaches do not require much a priori knowledge of the system for prediction, the reliability is needed for forecasting before being able to predict the RUL for most data-driven models. This results in the problem of finding suitable forecasting algorithms (Brossier *et al.* 2020).

The main model-based approaches can be summarized as:

- those modeled on material degradation;
- based on the temperature profile of the operating device.

The last one is the most important from the point of view of this analysis. According to Swaminathan and Sangeetha (2017), modern thermal analysis can be carried out using various techniques such as:

- experimental method;
- lumped parameter thermal model method;
- numerical analysis.

The first one is suitable only for the machine that has already been designed. Based on its thermal behavior, the cooling strategy can be decided. But the accuracy is lower in case of complex structured machines. In aviation, the information about temperature of bearing can be obtained from the flight profile of the plain.

In lumped thermal model, thermal problem is solved using thermal networks that are similar to electrical circuits. The result shows only the overall heat distribution. However, the temperature inside the machine cannot be predicted.

The numerical method is one of the most promising technologies (Inamura *et al*. 2003). It involves numerical analysis computer programs by means of finite element method.

In AN (2020), an elementary welded joint is selected as a representative structural element, and a comparative method of design evaluation is chosen as a design procedure. Through the described method, evaluation of joints or other structural elements subjected to complex loading conditions is rapidly accomplished by a simple test comparing a design standard with superior fatigue life.

Temperature analysis of rolling bearings is often realized through the finite element analysis method (Cao *et al*. 2018, Gloeckner and Rodway 2017), node network method (Hoffmann *et al*. 2006, Jakupovic *et al*. 2013) or computational fluid dynamics method (Baum *et al*. 2021), with the pivotal step being the calculation of the heat generation. Most of these empirical formulas are derived based on geometric models or experimental data (Zaghari *et al*. 2020, Zhang *et al*. 2012) and any rolling bearing model that is a result of a mathematical method is simplified to a standard geometry with a fixed shape and volume described by Wilson and Smith (1977), which, for its approximate calculation, has a certain theoretical value and reference significance on occasions that do not require high accuracy.

The method used in this publication has been developed at the Air Force Institute of Technology and is based on the knowledge of the aircraft flight profile. This method allows to estimate the bearing life on the criterion of only one parameter which is the flight altitude. This approach, in spite of the fact that it simplifies the problem in a certain way, is still very useful, because without the necessity of examining the element directly, it is possible to estimate its durability. This method will be presented in detail later in this paper.

The main contributions of this paper can be summarized as follows:

- since bearings are almost impossible to examine technically in an aircraft, the temperature profile is one of the most readily available pieces of information about the flight path and consequently about bearing wear;
- comparing two aircraft flying at different altitudes allows you to understand how bearing wear depends on the operating process;
- the method is particularly beneficial for the new aircraft because bearing reliability can be inferred from aircraft operated under similar conditions.

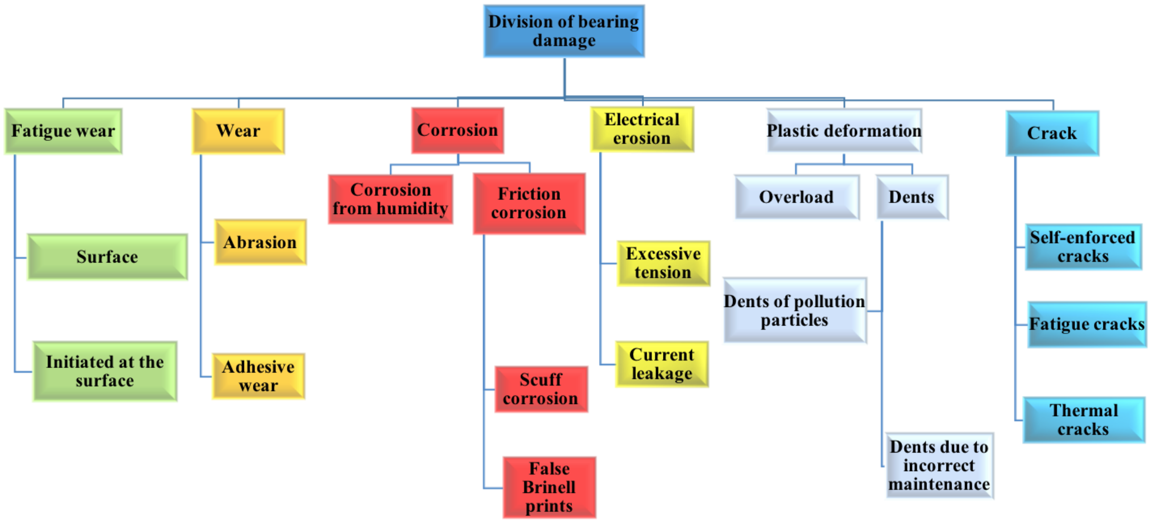

Fig. 1 Division of the failure modes of the starter ball bearing

3. Processes that affect bearing wear

There are plenty of publications on bearing damage and failure (Pontecorvo *et al*. 2015). Various publications can classify bearing damage and failures in different ways and use different terminology. A working group was set up within the ISO organization (see ISO 15243 2017) to define a common classification method and terminology for bearing damage types. The summary of failures modes is presented in Fig. 1.

4. Research methods

The aim of this study was to compare the durability of the direct current (DC) commutator machine bearings in two aircraft: the military M-28 B and the civil Embraer (see AN 2020). Both aircraft were selected due to a similar time of tasks realization. The data were obtained from the operation of the above-mentioned aircraft. Figs. 2 and 3 show an example of a bearing from the aircraft's starter motor, which has worked for 400 hours. The visual analysis of the surface of the outer and inner ring showed no failures (see LOT 2020).

The durability of DC commutator machine bearings was determined using a method developed at the Air Force Institute of Technology. The method is applied to brush motors on the assumption that the brushes have been checked or replaced with the new ones and are not damaged. It allows determining the durability of electric machine bearings on the basis of an estimation of the ambient temperature of the working electric machine. The method can be summarized in the following steps (Fig 4):

1. On the M-28 B military aircraft, barometric altitude data are recorded using a dedicated Flight Driver Recorder on special tapes during each flight. Tapes are downloaded after every flight, which facilitates archiving of individual flights, even very short ones. This makes it possible to prepare an accurate flight profile.

Fig. 2 Views of the outer ring of the starter ball bearing

Fig. 3 Views of the inner ring of the starter ball bearing

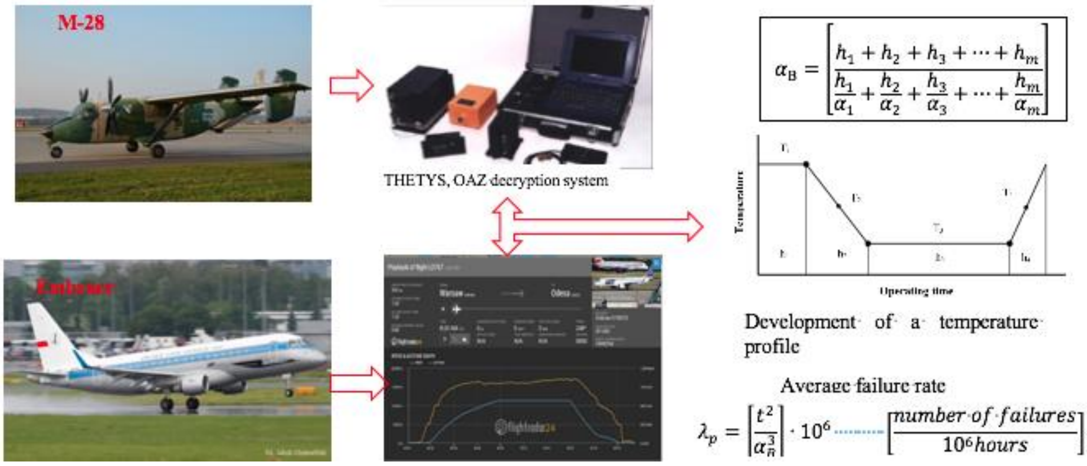

Fig. 4 Summary of the methodology developed at the Air Force Institute of Technology

2. Subsequently for M-28 B, the raw data were transformed by THETYS, OAZ decryption system into an altitude profile of the aircraft. For civil aircraft Embraer, publicly available altitude profile from the Flight Radar service was used.

3. In order to calculate the durability of bearings of the starter generator, the operating temperature of the starter generator was determined on the basis of an altitude flight profile for the selected aircraft. An average temperature profile was computed from the altitude flight profile taking into account the values of the reference atmosphere.

4. The average temperature profile was used for calculations of durability of starter generator bearings.

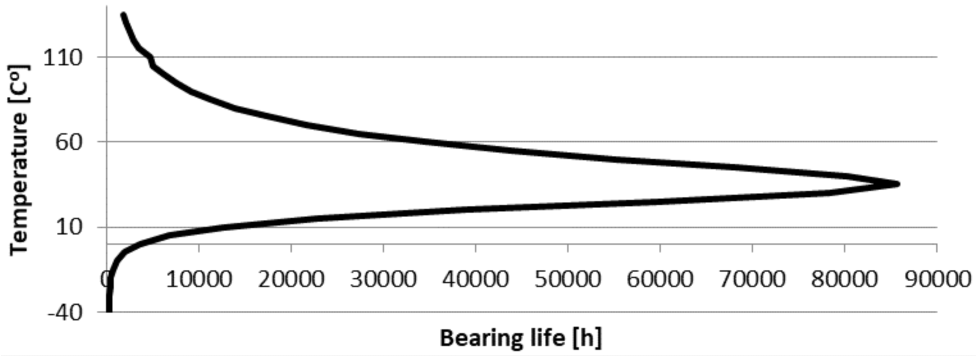

Fig. 5 Durability of bearings in on-board rotating devices depending on ambient temperature calculated by Wilson and Smith (1977)

In order to estimate the reliability and durability of the starter generator bearings on the basis of the temperature flight profile of the aircraft, calculations describing an approximate approach to the determination of the failure rate (the number of failures occurring within a specified time of operation of a given machine) were used. The failure rate, λp, defined on the base of publications MIL-HDBK-217F (1991) as well as Wilson and Smith (1977), can be determined from the relation:

$$\lambda_p = \left[\frac{t^2}{\alpha_B^3}\right] \cdot 10^6 \qquad \left[\frac{number\ of\ failures}{10^6 hours}\right] \tag{1}$$

where:

t - total operating time of the machine;

α_B- bearing life of the electric machine.

The bearing life of an electric machine (see MIL-HDBK-217F (1991) as well as Wilson and Smith (1977)) can be calculated from the following dependency:

$$\alpha_B = \left[10^{\left(A - \frac{B}{T_o + 273}\right)} + \frac{1}{10^{\left(C - \frac{D}{T_o + 273}\right)} + T_m}\right]^{-1} \tag{2}$$

where:

A, *B*, *C*, *D* distribution coefficients equal 2.534, 2357, 20, 4500, respectively,

T_0 – temperature of the environment [°C],

$T_m = 300$ – the lower limit of bearing lifetime [h].

The model for prediction of bearing life was developed on the basis of data collected from the companies operating electric machines. The coefficients of distribution were determined by the empirical method of matching from function to measured data. In order to adjust the coefficients, the linear regression technique was applied.

Durability of bearings in rotating devices depending on the ambient temperature T_o has been shown in Fig. 4. The data presented in Fig. 5 are taken from Wilson and Smith (1977).

When there is a change in the ambient temperature during operation of the electric machine, the bearing life can be calculated based on the following relationship:

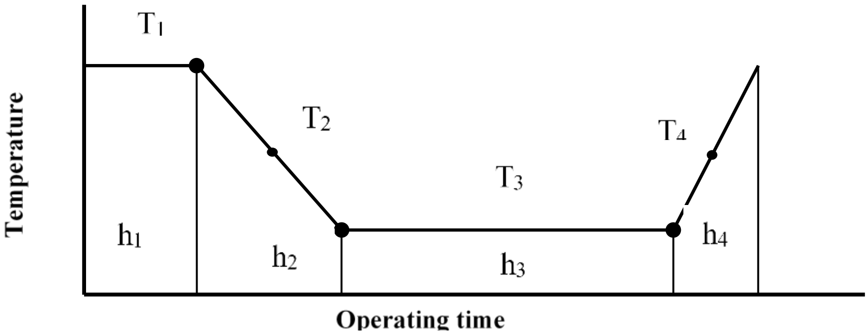

Fig. 6 The change in ambient temperature during operation of the electric machine

$$\alpha_{\mathrm{B}} = \left[\frac{h_1 + h_2 + h_3 + \cdots + h_m}{\frac{h_1}{\alpha_1} + \frac{h_2}{\alpha_2} + \frac{h_3}{\alpha_3} + \cdots + \frac{h_m}{\alpha_m}}\right] \tag{3}$$

where:

$h_1, h_2, h_3, \ldots, h_m$ [h] – operating time at the temperature $T_1, T_2, T_3, \ldots T_m$,

$\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_m$ [h] – bearing life in $T_1, T_2, T_3, \ldots, T_m$.

Fig. 6 graphically shows the changes in ambient temperature during operation of the electrical machine.

The temperature value of T_2 and T_4 is calculated as the arithmetic mean of the extreme temperatures:

$$T_2 = \frac{T_1 + T_3}{2}, \qquad T_4 = \frac{T_3 + T_1}{2}. \tag{4}$$

The average operating time of a bearing to failure can be calculated from the following equation (see MIL-HDBK-217F (1991) as well as Wilson and Smith (1977)):

$$\ln[1 - \mathrm{F(t)}] = -\left(\frac{\mathrm{t}}{\alpha_{\mathrm{B}}}\right)^3 \tag{5}$$

$$\mathrm{t} = \sqrt[3]{0{,}69317} \cdot \alpha_B \tag{6}$$

where F(t) = 0.5.

Taking under consideration that in Wilson and Smith (1977) numbers are mentioned as a universal coefficient. This model can be applied for different types of aircraft.

5. Case study

5.1 The subject of the research - military aircraft M-28 B and passenger aircraft "Embraer"

The M-28 B (Figs. 7-9) is a STOL (Short Take-Off and Landing) class aircraft, which makes it able to perform short take-off and landing operations. The reconnaissance variants and maritime

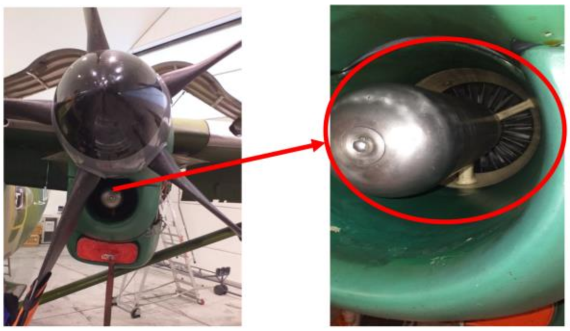

Fig. 8 M-28 B aircraft starter

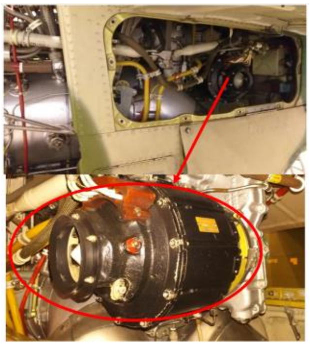

Fig. 9 M-28 B aircraft generator

Fig. 10 Embraer aircraft (see LOT (2020))

patrol are named M-28 B. As it is mentioned in the technical manual Mielec (2001), the presence of a fixed and resistant landing gear allows to operate from airfields or airports with unpaved runways, etc. It is a twin-engine aircraft with a metal upper plane and a half shell fuselage. The on-board rotating devices that are found on the aircraft are: starters, generators, converters and fuel pumps.

Embraer 175 (Fig. 10) is being operated by LOT Polish Airlines. It supports domestic and medium-distance connections. Due to its efficient and effective engines, the aircraft meets strict noise standards, and its floating wing tips - winglets - reduce air resistance, which decreases fuel consumption. Up to 82 passengers may travel on board. After the crash of the Tu-154M government plane, two Embraer 175 was chartered with the crew to handle the flights of the most important people in the country. Despite the regional character of flights, the aircraft is distinguished by its spacious cabin and large cabin baggage compartments, which significantly improves the travel comfort.

5.2 Description of starter generator

The primary source of electrical power for aircraft that we may encounter on board are DC and AC generators.

5.2.1 Characteristics of on-board DC generators

By-pass DC generators used in aviation do not differ in principle from similar machines on the ground. However, differences are found in the design, which is due to the requirements that are placed on aircraft generators. The most important requirements for aircraft generators include:

- reliability of operation both in the air and on the ground;
- low susceptibility to mechanical, electrical and thermal overloads and resistance to chemical compounds;
- usability and repairability;
- absence of electrical, magnetic and acoustic interference affecting the operation of other equipment;
- short standby time;
- appropriate durability.

The main components of the construction of any shunt deck alternator are: the stator, consisting of: the body, the bearing discs, the brush-holder with brushes, the main poles and the commutation poles with windings; rotor, consisting of: armature, commutator, shaft and fan.

5.2.2 Characteristics of the on-board AC generators

The synchronous generators with electromagnetic excitation are used in the aircraft AC electrical system. Depending on what needs exist on a particular type of aircraft, the generator can occur as the only source of electricity in the primary electrical node system (WEE), or together with a DC generator forming a mixed WEE system together. The frequency of the generated voltage and whether it is constant or variable in the case of synchronous generators is determined by the type of drive and the type of electrical energy conversion device. The design and operational determinant placed on airborne AC generators corresponds to the requirements placed on airborne DC generators.

As it was stated by Dabrowski (1977), the synchronous generators used in aviation have:

- excitation windings located on the prominent (uncovered) poles or on the latent poles;
- armature windings located on the stator or on the rotor.

Larger power generators (several tens of kVA) that have the excitation winding on the rotor, are usually equipped with exciters. The exciter is de facto a DC shunt generator with power rating of 4÷10% of the rated power of the synchronous generator. The exciter is built in one housing with the AC generator. The rotors of both machines are joined by the same rotor. The electrical connection between the exciter armature and the excitation winding of the AC generator is realized by slip rings and brushes.

5.2.3 Characteristics of on-board alternator-starters

Nowadays, there is a tendency to use DC generators as generator-starters. The use of the same machines in the generator range as in the motor range is dictated, among other things, by economic reasons. Thanks to this solution, the volume and weight of the starting system is gained. The disadvantage of such solution is higher complexity of combined generator-starter control system.

5.3 Description of input data

The data used in this work comes from the analysis of the operation process of the M-28 B and Embraer aircraft. The average altitude profiles were obtained from the analysed aircraft. Figs. 11 and 12 show examples of flight profiles of the above-mentioned aircraft.

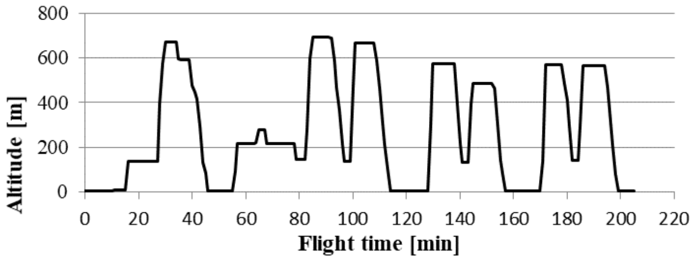

Fig. 11 Flight profile of the M-28 B aircraft

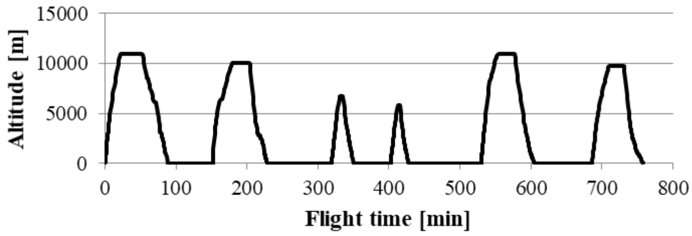

Fig. 12 Flight profile of the Embraer aircraft

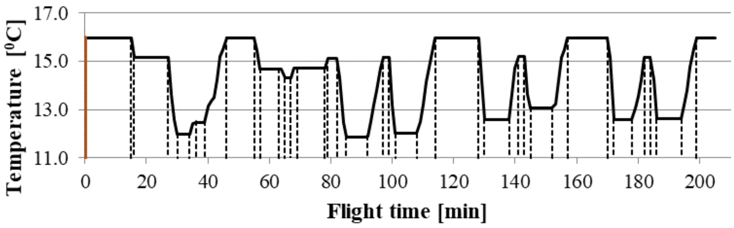

Fig. 13 M-28 B aircraft temperature profile

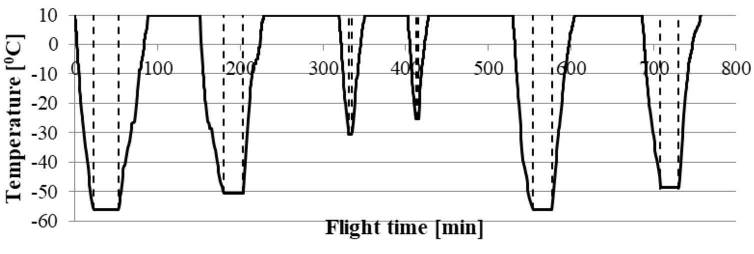

Fig. 14 Embraer aircraft temperature profile

5.4 Temperature profile

On the basis of the flight profiles (shown in Figs. 11 and 12) of both aircraft, M-28 B as well as Embraer, the flight altitude was converted to temperature, by which the life of the bearings of the commutator machines can be calculated. The temperature profiles are presented in Figs. 13 and 14.

5.5 Results

On the basis of flight profiles for military and civil aircraft, the lifetime of bearing has been calculated. For the calculated temperatures, the bearing durability was determined. This is shown for the M-28 B and Embraer aircraft in Tables 1 and 2, respectively.

Based on the determined average temperature profile, the average durability, mean bearing operating time as well as failure rate has been calculated. The results are shown in Table 3.

It was obtained that the military aircraft durability is equal to 14 475 h, when for example the lifetime of Embraer is ca. 580 h. By analysing the temperature profiles of both aircraft, it is possible to observe the difference related to the temperature of the flight operations. For military aircraft, it is between 12 and 16°C, where for civil aircraft, the temperature is between -54 and 10°C. As the bearing life in the adopted method depends on the ambient temperature and duration of stay; the bearing life of civil aircraft is less than that for military aircraft.

Table 1 Durability of the current starter bearing for M-28 B aircraft

Temperature [°C]	Bearing operating time at a given temperature [min]	Durability of bearings [h]
11.9	7	15859
12	11	16050
12.3	2	16536
12.5	3	17036
12.6	22	17239
13.1	7	18288
13.5	3	19167
13.6	10	19392
13.9	9	20081
14	6	20316
14.2	2	20671
14.3	18	20912
14.5	4	21522
14.6	5	21646
14.7	15	8683
14.9	1	22530
15.1	3	23049
15.2	17	23311
15.4	2	23710
15.6	1	24387
16	57	25502

Table 2 Durability of the current starter bearing for Embraer aircraft

Temperature [°C]	Bearing operating time at a given temperature [min]	Durability of bearings [h]
10	392	12599
-8	23	3574
-10	27	1075
-20	103	457
-23	111	400
-25	3	372
-30	4	330
-49	22	301
-51	23	301
-56	51	300

Table 3 Summary of calculation

	M-28 B	Embraer
Durability [h]	14 475	580
Mean bearing operating time [h]	12 810	513
Failure rate $\left[\frac{\text{number of failures}}{10^6\text{hours}}\right]$	54.11	1348.81

6. Conclusions

The article focuses on the issues and methods of conducting research on the durability of on-board bearings of electrical machines based on ambient temperature. The paper compares the lifetime of bearings in a starter generator for civil and military aircraft. The obtained results are consistent with those presented by Wilson and Smith (1977). However, further analysis is needed to compare the obtained results with the operated data. In the further research, with the use of this method, the aircraft should be selected in such a way that the ambient operating temperature of the electrical machines is similar and then the operation process of the electrical machines should be analysed with the applicable normative documentation.

References

AN (2020), M-28 B – Bryza z Mielca na lotnisku; Interia, Warsaw, Poland. https://www.interia.pl/t.

Ashrafifar, A. and Jegarkandi, M.F. (2020), "Fin failure diagnosis for non-linear supersonic air vehicle based on inertial sensors", *Adv. Aircr. Spacecr. Sci.*, **7**(1), 1-17, http://doi.org/10.12989/aas.2020.7.1.001.

Baum, C., Hetzler, H., Schroeders, S., Leister, T. and Seemann, W. (2021), "A computationally efficient nonlinear foil air bearing model for fully coupled, transient rotor dynamic investigations", *Tribol. Int.*, **153**, 106434. https://doi.org/10.1016/j.triboint.2020.106434.

Brossier, P., Niel, D., Changenet, C., Ville, F. and Belmonte, J. (2020), "Experimental and numerical investigations on rolling element bearing thermal behaviour", *Proceedings of the Institution of Mechanical Engineers*, *Part J: Journal of Engineering Tribology*, **235**(4), 842-853. https://doi.org/10.1177/1350650120932335.

Brushan, B. (2013). *Introduction To Tribology*, John Wiley & Sons, New York, U.S.A.
Cao, H., Niu, L., Xi, S. and Chen, X. (2018), "Mechanical model development of rolling bearing-rotor systems: A review", *Mech. Syst. Signal Pr.*, **102**, 37-58. https://doi.org/10.1016/j.ymssp.2017.09.023.
Carrera, E. (2002), "Temperature profile influence on layered plates response considering classical and advanced theories", *AIAA J.*, **40**(9), 1885-1896. https://doi.org/10.2514/2.1868.
Cinefra, M., Valvano, S. and Carrera E. (2015), "Heat conduction and Thermal Stress Analysis of laminated composites by a variable kinematic MITC9 shell element", *Curved Layered Struct.*, **2**(1), 301-320. https://doi.org/10.1515/cls-2015-0017.
Dulci, K.B., Önel, Y.D., and Senol, İ. (2006), "Detection of bearing defects in three-phase induction motors using Park's transform and radial basis function neural networks", *Sādhanā*, **31**(6), 235-244. https://doi.org/10.1007/BF02703379.
Dąbrowski, T. (1977), "Aeronautical Electrical Equipment, vol.3 Aircraft On-board Generators", WAT, Warsaw, Ploand.
Farmakopoulos, M., Thanou, M., Nikolakopoulos, P., Papadopoulos, C. and Tzes , A. (2013), "Control model of active magnetic bearings", *Proceedings of the 3rd International Conference of Engineering Against Failure (ICEAF III)*, Kos, Greece, June.
Gloeckner, P. and Rodway, C. (2017),"The evolution of reliability and efficiency of aerospace bearing systems", *Engineering*, **9**(11), 962-991. http://doi.org/10.4236/eng.2017.911058.
Hoffmann, G.M., Waslander, S.L. and Tomlin, C.J. (2006), "Mutual information methods with particle filters for mobile sensor network control", *Proceedings of the 45th Ieee Conference on Decision and Control*, San Diego, USA, December.
Inamura, S., Sakai, T. and Koich, S. (2003), "A temperature rise analysis of switched reluctance motor due to the core and copper loss by FEM", *IEEE T. Magn.*, **39**(3), 1554-1557. https://doi.org/10.1109/TMAG.2003.810358.
ISO 15243 (2017), Rolling bearings — Damage and failures — Terms, characteristics and causes, International Organization for Standardization; Genève, Swiss
Jakupovic, A., Pavlic, M., Mestrovic, A. and Jovanovic, V. (2013), "Comparison of the Nodes of Knowledge method with other graphical methods for knowledge representation", *Proceedings of 36th International Convention on Information and Communication Technology*, *Electronics and Microelectronics (MIPRO)*, Opatija, Croatia, May.
LOT (2020), Embraer 175; LOT, Warsaw, Poland. https://www.lot.com/pl/pl.
Mielec (2001), *Technical description of the aeroplane BRYZA*, *Part 1 – Fuselage*, Polskie Zakłady Lotnicze Mielec, Mielec, Poland.
MIL-HDBK-217F (1991), *Military Handbook*, *Reliability Prediction of Electronic Equipmen*, Department of Defense, USA.
Pandey, K., Zope, P. and Suralkar, S. (2012), "Review of fault diagnosis in three-phase induction motor. *IJCA"*, *Proceedings of the International Journal of Computer Applications (IJCA)*, Yavatmal, India, September.
Patra, P., Kumar, D., Nowicki, D. and Randall, W. (2019), "Effective management of performance-based contracts for sustainment dominant systems", *Int. J. Prod. Econom.*, **208**, 369-382. https://doi.org/10.1016/j.ijpe.2018.11.025.
Pontecorvo, M.E., Barbarino, S., Gandhi, F.S., Bland, S., Snyder, R., Kudva, J. and White, E.V. (2015), "A load-bearing structural element with energy dissipation capability under harmonic excitation", *Adv. Aircr. Spacecr. Sci.*, **2**(3), 345-365. http://doi.org/10.12989/aas.2015.2.3.345.
Sharanya, S., Venkataraman, R. and Murali, G. (2020), "Analysis of machine learning based fault diagnosis approaches in mechanical and electrical components", *Int. J. Adv. Res. Eng. Tech.*, **11**(10), 80-94. http://doi.org/10.34218/IJARET.11.10.2020.008.
Singh, S. and Vishwakarma, M. (2015), "A review of vibration analysis techniques for rotating machines", *Int. J. Adv. Res. Eng. Tech.*, **4**(3), 757-761. http://doi.org/10.17577/IJERTV4IS030823.
Smith, M., Byington, C., Watson, M., Bharadwaj, S., Swerdon, G., Goebel, K. and Balaban, E. (2009), "Experimental and analytical development of health management for electro-mechanical actuators",

Proceedings of the IEEE Aerospace Conference, Montana, USA, March. https://doi.org/10.1109/AERO.2009.4839660.

Swaminathan, K. and Sangeetha D.M. (2017), “Thermal analysis of FGM plates–A critical review of various modeling techniques and solution methods”, *Compos*. *Struct*., **160**, 43-60. https://doi.org/10.1016/j.compstruct.2016.10.047

Urban, R. and Hoskova-Mayerova, S. (2017), “Threat life cycle and its dynamics”, *Deturope*, **9**(2), 93-109.

Wang, B., Lei, Y., Li, N. and Li, N. (2020a), “A hybrid prognostics approach for estimating remaining useful life of rolling element bearings”, *IEEE T. Reliab*., **69**(1), 401-412. http://doi.org/10.1109/TR.2018.2882682.

Wang, Y., Cao, J., Tong, Q., An, G., Liu, R., Zhang, Y. and Yan, H. (2020b), “Study on the thermal performance and temperature distribution of Ball bearings in the traction motor of a high-speed EMU”, *Appl*. *Sci*., **10(**12), 1-14. https://doi.org/10.3390/app10124373.

Wilson, D. and Smith, R. (1977), *Electric motor reliability model*, Shaker Research Corp., Ballston Lake, New York, USA.

Yu, G. (2015), “Fault feature extraction using independent component analysis with reference and its application on fault diagnosis of rotating machinery”, *Neural Comput*. *Appl*., **26**, 187-198. https://doi.org/10.1007/s00521-014-1726-6.

Zaghari, B., Weddell, A., Esmaeili, K., Bashir, I., Harvey, T., White, N. and Wang, L. (2020), “High-temperature self-powered sensing system for a smart bearing in an aircraft jet engine”, *IEEE T*. *Instrum*. *Meas*., **69**(9), 6165-6174. https://doi.org/10.1109/TIM.2020.2971288.

Zhang, D., Han, X., Newaz, G., Favro, L. and Thomas, R. (2012), “Modelling turbine blade crack detection in sonic IR imaging with a method of creating flat crack surface in finite element analysis”, *Proceedings of AIP Conference*, **1430**(1), 527-532. https://doi.org/10.1063/1.4716272.

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