

Article

Service Life Prediction for Rotating Electrical Machines on Aircraft in Terms of Temperature Loads

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Abstract: This article is focused on the research concerning the calculation of the durability of electrical machines installed in the electrical system of M-28 and C-130 Hercules aircraft. The article presents a method of predicting the service life of aircraft commutator machines, which are the primary source of electrical energy. The result of the research was the determination of the durability of bearings and coils of electrical machines operated on aircraft based on a flight profile analysis. It is problematic to directly measure the wear of bearings and windings of an electric machine on the aircraft. Their usage can be determined from the relation between their wear and the ambient temperature. This research can be used in practice to plan maintenance work on the analyzed aircrafts.

Keywords: durability of electric machines; flight profile analysis



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1. Introduction

Nowadays, transport aircraft involves a wide range of tasks; in addition to transporting people and goods, they can be also used to transport jumpers, train future pilots, transport medical services, and inspect airport equipment systems, maritime patrols, etc.

As a result of the above responsibilities, these aircraft must be available in sufficient numbers and at the right time to meet the tasks.

The availability of the machines is influenced, among other things, by the durability and reliability of the individual components and elements from which the machine is built, as well as the regularity and correctness of their maintenance of the components and elements.

The electrical machines operate under a heavy load, providing power to onboard equipment requiring electricity of different types and voltages. An additional factor negatively affecting the durability of these machines is the temperature prevailing at the cruising altitudes of transport aircraft. Low temperatures affect the wear and tear of the mechanical components working in these machines, and the need to work for long periods of time significantly affects the durability of the bearings, and causes the degradation of the windings, among others. As a result of the above circumstances, these machines require greater attention during maintenance, as well as proper monitoring of their conditions.

This article is a continuation of the topic undertaken in the paper [1] in which the authors determined the reliability of an aircraft electrical machine. The reliability of the electric starter was determined by the wear of its brushes and starter bearings using the ambient temperature on the example of one type of aircraft. In the following article, the authors determined the durability of an aircraft electrical machine based on bearing and winding life, using the average flight profile of an M-28 and a C-130 Hercules aircraft. To determine the durability of the aero-electric machinery used on these aircraft, the change of temperature was used to convert flight altitude into temperature. On this basis, the durability of the aero-electric machines was calculated for both M-28 and C-130 Hercules aircraft.

The article is organized as follows: Section 2 presents the details of electric installation, particularly on the transport aircrafts M-28 and C-130 Hercules. Section 3 describes a theoretical analysis of factors affecting bearing wear and the classification of bearing wear. The method for determining the durability of commutator machines based on the flight profile and the results obtained are then discussed. The entire paper ends with a summary, including conclusions.

2. Background of the Problem

Due to current trends, ASE systems, which are autonomous energy systems, are becoming increasingly important [2]. These are divided into onboard and stationary systems. Onboard ASE systems are used, among others, on aircraft. One of the most important components of an ASE is the generation node, which consists of the mechanical energy source and the BGS, a brushless synchronous generator. In modern systems, the BGS operates at variable speed and frequency. Generators used in aviation usually have a power output of 120–150 kW and a rotational speed of 11,000–23,000 rpm.

Modern electrical power systems used in aircraft are designed according to the “powered-by-wire” concept [3]: the idea is to replace heavy and failing hydraulic and pneumatic equipment with electrical equipment. It will result in several significant improvements related to increased efficiency, reduced weight, and improved safety, as well as reduced repair costs and reduced environmental impact. The above proposals and solutions are also influenced by the increase in power consumed by machines installed over the course of years of development in aeronautical technology and design. This must not only result in the increase in the number of additional systems coming on board with the development of modern designs, but also with the desire to provide passengers with ever-new comfort solutions.

In the mid-20th century, the DC generators used had a voltage of 28 V and a maximum allowable current of 400 A, and power limited to 12 kW. Today, the voltage can be as high as 270 V and power as high as 100 kW in modern combat aircraft [4]. AC generators, which were first used in the 1960s, had a voltage of 115 V and a frequency of 400 Hz, and were quite complex, requiring a speed-stabilization system. Developments in technology allowed systems to be introduced to maintain variable speed but constant frequency [5]. This used a power electronic converter. In recent years, state-of-the-art solutions have used ASEs with fixed voltages of 115 V and 230 V but variable frequencies.

Generally speaking, energy from the engine is used in several forms, such as electrical, mechanical, hydraulic, and pneumatic energy. Mechanical energy is transferred to equipment such as oil, fuel, and hydraulic pumps, as well as to the generator using a suitable gearbox [6]. The control system for the relevant surfaces uses energy in the form of hydraulics, and pneumatic energy is needed for the air-conditioning and anti-icing system. The remaining electrical energy is needed to power the cockpit equipment and other systems for the comfort of the travelers. Engineers working on future designs aim to replace the above components entirely with electricity; such designs are called AEA (all electric aircraft) [7]. The basic components of a modern ASE are a generator with a regulator, power distribution, and an autotransformer with a rectifier and power distribution into AC and DC. There are usually several power generators on board a modern aircraft. These include main generators driven directly or using a gearbox connected to the engine, auxiliary generators—an auxiliary power unit (APU) with small capacities, which are used in an emergency to provide power to essential systems. A ground power unit (GPU) generator is used on the ground.

2.1. Transport Aircraft M-28

M-28 aircraft’s electrical equipment includes a 200/115 V three-phase AC electrical power system with a frequency of 400 Hz, a 36 V three-phase AC electrical power system with a frequency of 400 Hz, and a 28 V DC electrical power system [8,9]. The 200/115 V three-phase AC power source includes two GT16PCz8 alternators, as presented in Figure 1.



Figure 1. GT16PCz8 generator installation.

These generators are connected via reducers to the propeller turbine shafts. The generators have a grounded neutral conductor, which allows three-phase AC consumers of 200 V single-phase AC of 115 V to be connected to the electrical system. Each alternator supplies its own group of consumers. In the event of failure of one alternator, its buses are automatically switched to those of the operating alternator. In the event of failure of both generators, the emergency source of 115 V AC power is the PO-250A converter converting 28 V DC to 115 V AC (Figure 2).



Figure 2. Installation of the PT-125C inverter.

The power sources for the 36 V three-phase AC power supply are two TS310SO4B transformers and a PT-125C inverter. The transformers operate simultaneously to form two independent channels. In the event of failure of one transformer, its buses are automatically switched over to those of the operating transformer. If the transformers or generators fail, the PT-125C inverter is the emergency source [10]. The emergency 36 V rails are connected to the rails of the TR-2 transformer, and upon its failure, the PT-125C inverter is automatically or manually switched on and the emergency rails are connected to its output (even with the TR-1 transformer in operation). The 27 V DC power sources are two WU6B rectifiers and two batteries. In normal operation of all DC power sources, the installation operates in two independent channels. Each channel comprises a rectifier device and one battery operating in parallel. When one of the rectifier units fails or when starting the engines, the installation switches to parallel operation of the channels. In the event of failure of both rectifiers, the electrical supply system switches to an incomplete emergency supply, during which the AC supply to consumers is provided by generators and transformers, and the DC supply to a limited number of consumers is provided by batteries. The power supply to the consumers is secured within 1 h of flight. In the case of

failure of either rectifiers or alternators, the emergency power source is the batteries, which provide power to the receivers within 30 min.

2.2. C-130 Hercules

The C-130 Hercules [11] electrical installation equipment includes five AC generators and batteries. The construction of the installation and its components are shown in Figure 3. Each engine drives one 40 kVA generator, and an air turbine (ATM) drives a 20 kVA AC generator.

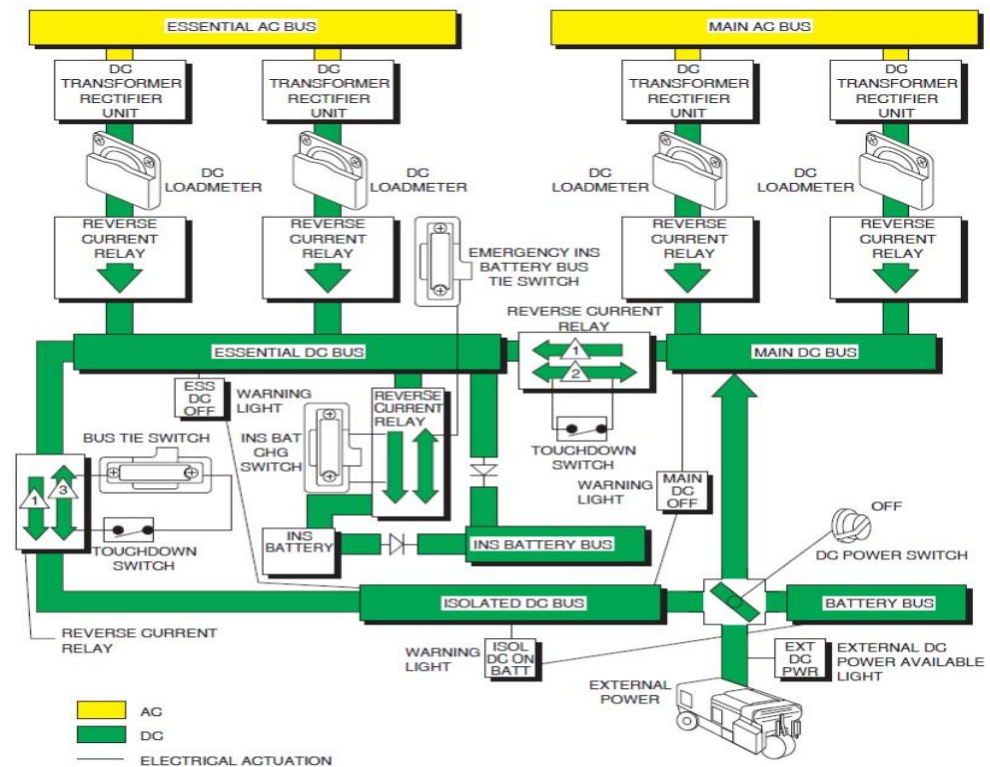


Figure 3. Electrical wiring diagram of C-130 Hercules. Own elaboration based on the internal material and expert knowledge.

The air turbine is sufficiently well cooled, which results in an output of 30 kVA during continuous operation. The electricity generated by these generators is used to supply the plant with 28 V DC, 200/115 V three-phase AC at 400 Hz, and 115 V single-phase AC at 400 Hz. Each 40 kVA generator is connected via relays to four buses: the left-hand bus, the essential bus, the main bus, and the right-hand bus. The relay system works in such a way as to supply power to all buses from at least two motors. When only one generator is operating, power will only be sent to the main and primary buses. The gas turbine engine mounted downstream and above the gas turbine compressor only supplies power to the primary bus. The generator (Figure 4) connected to the air turbine is deactivated during engine startup to protect against voltage drop when the air turbine speed drops.



Figure 4. Generator integrated on the engine.

2.3. DC Power Supply

Four transformer rectifier units are connected to the primary and main AC buses to provide DC power. The transformer rectifier units convert AC to 28 V DC. The AC main and primary bus can be supplied from any motor-driven power generator. The AC primary bus is also powered by an air turbine and thus can be used as a DC source. Transformer rectifier units supply the main and DC primary buses.

2.4. Side AC Electrical Installation

A single 250 VA inverter provides 115 V three-phase power at 400 Hz. The inverter is supplied with DC current and can therefore be supplied with battery current in an emergency. During normal operation, it supplies the transformer via the base rail, which converts the three-phase current into single-phase current [12].

2.5. Gas Turbine

The gas turbine motor (air turbine motor; ATM) [13], is a single-stage axial turbine used to drive a 20 kVA generator that supplies the plant with 115/200 V three-phase AC current. The air used to power the ATM comes from a gas turbine compressor (GTC) or external sources. During flight, ATM operation is assisted by air coupled from the engines. ATM operation is controlled by a velocity-sensitive butterfly valve. If the flow velocity is too high, the valve closes and must be manually unlocked. A suitable cooling fan for the ATM power generator is mounted in and powered from the generator.

3. Properties of Bearings

A rotating bearing is a product that must be manufactured with high precision. Bearing components are manufactured with precise sizing, often to the nearest millimeter, and these dimensions are checked many times during successive production stages. However, after some time, the appearance and performance of these bearings change due to operation in circumstances far from ideal. These circumstances can promote bearing failure, a reduction in running time, and often premature permanent wear. It is important to understand the processes contributing to the above problems and how to avoid them.

3.1. Factors Determining Bearing Wear

In ISO 15243, the factors affecting bearing wear are grouped into six categories. The standard identifies six forms of basic damage or initial signs of failure [14], which occur after a particular bearing has already been manufactured:

- Fatigue, which causes changes in the material's structure caused by cyclic loading under normal operating conditions. The phenomenon is noticeable when the component is rotated, and a flaking process is observed on the material surface. This process

can be prevented by using the right lubricant, in the right quantity, replacing it after a suitable period of time, and by properly sealing the bearing and abrasion of the material from which the component is manufactured.

- Abrasive wear is the gradual removal of material from its surface during operation and is caused by contamination of the lubricant. Continued operation of the bearing results in an increasing level of contamination of the lubricant and, thus, a continuous deterioration of the bearing's smooth running. Adhesive wiping, which is the second type of wiping, occurs at the point of contact between two rotating components. The wiping material is located between the rotating parts, causing heavy loads. To prevent this effect, the components must be sealed properly so that no dirt can penetrate, and the lubricant must be continuously checked for cleanliness. In addition, the prevention of adhesive wiping requires the use of the right lubricant, in the right quantity, as well as regular checks and the use of appropriate seals.
- Corrosion, among which the following types can be distinguished: corrosion caused by moisture; corrosion caused by friction.
- Another type of corrosion is electrical erosion. During the flow of electrical charges through a steel bearing, damage will occur between contacting parts even if the charges are not large. The processes on the surfaces are similar to those that occur during arc welding, where they are momentarily welded together. As the bearing continues to work, part of the surface detaches, leaving characteristic pits.
- Plastic deformation, caused by forces acting on the components that lead to deformation of shape or the formation of pits in the surface. They are often caused by an improper mounting technique or a strong impact at low bearing speed.
- Damage to the bearing can also occur during installation. If the wrong tools are used to mount the bearing, excessive forces are applied, or the bearing is mounted in an unsuitable location, permanent damage to the bearing may occur.
- Damage to the bearing may also occur during operation when the bearing is subjected to bending moments created when the bearing is placed in a location where clearances develop over time. If the bearing itself is so complex that, within it, the components move loosely between each other, additional heat is generated, the effect of which leads to cracks [15–17].

Once specific critical temperature values are reached, a certain energy level is reached which activates the progression of phase and structural transformations. Positive temperatures are usually considered in catalogues where we find tribological data. At temperatures below 0 °C, radical changes occur. Such temperatures only prevail high in the air space.

3.2. Ground Wear Causes of Airplane Commutator Machine Brushes

The brushes in electrical machines interact with the commutator or slip rings. Therefore, the brush design and materials used depend on the type of contact. It is therefore possible to make a brush with high copper content to obtain a low resistance or to prepare graphite accordingly to obtain wear resistance [18]. Considering that brushes are subject to continuous wear during operation, a constant contact pressure is required, the force of which is predetermined for a specific design solution. If little contact pressure is applied, this will result in excessive sparking (caused by arcing) and accelerated burning of the contact area. Conversely, application of excessive contact pressure will result in greater power loss to mechanical friction and faster abrasion of the contacts. Proper pressure of the brushes against the commutator is provided by springs [19]. As the brushes are abraded, and at the same time pressed against the contact area, there is a need for a flexible electrical connection between the brush itself and the rest of the electrical supply or discharge system. Therefore, braided copper cables are used to allow the brushes to move freely to provide a flexible connection. In design solutions such as autotransformers or wire potentiometers, where there is a relatively low brush travel speed, brush wear is practically neglected. In such a solution, the brushes may be permanently attached to a spring element and are not structurally designed for frequent replacement.

As the brushes wear over time, they need to be replaced with new brushes as part of the service. If the brushes interact with the commutator, the surface of the commutator should be inspected regularly to remove the effects of mechanical abrasion and arc burnout. The brushes of commutator machines are subject to wear every time commutator machines are used. This wear is caused by both friction and electrical wear that occurs due to the current flowing through the electrical contact [20].

The wear classification of aircraft brushes of commutator machines is graphically shown in Figure 5.

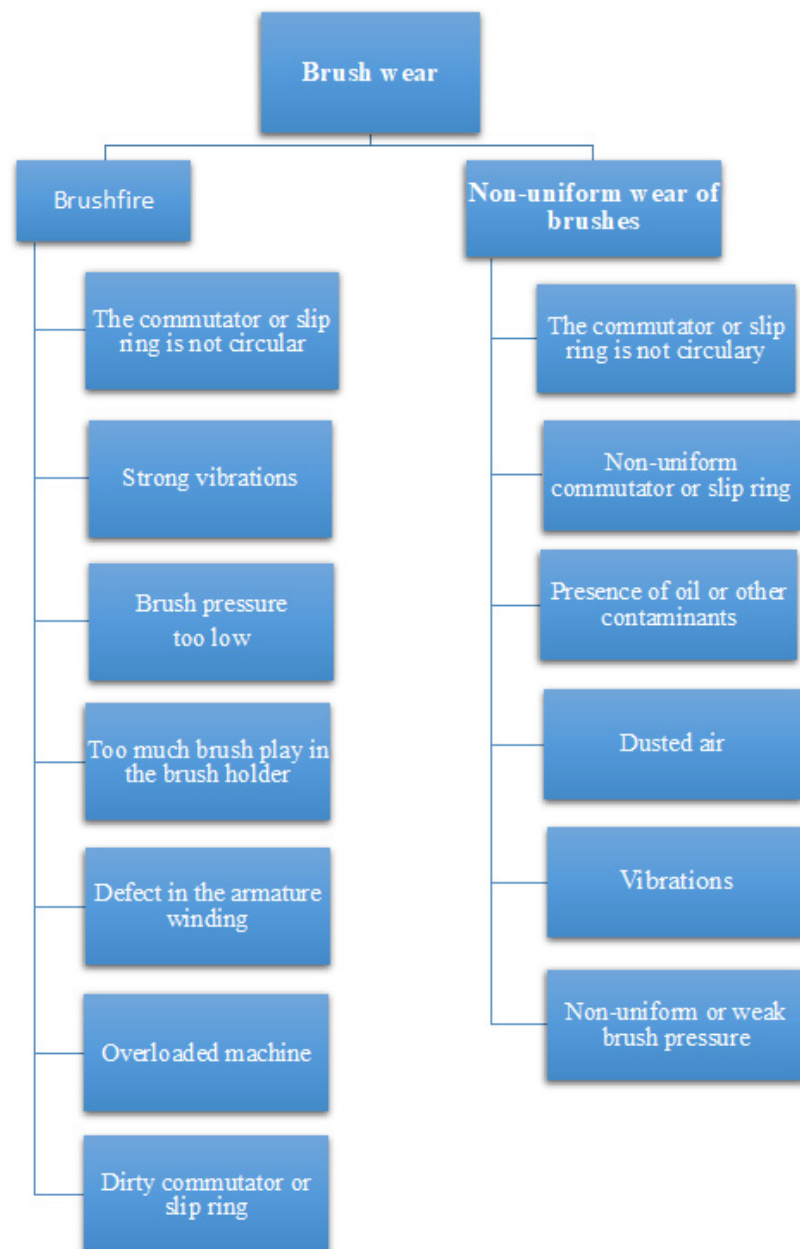


Figure 5. Brush wear classification. Own elaboration on basis of [21].

3.3. Low Ambient Temperatures and the Durability of Machinery

Ambient temperatures are a significant important factor with a very high impact on the performance and durability of machinery. Electrical machines used in aviation operate during flight at high altitudes and, therefore, low temperatures. However, at the design stage, the engineer selects the right type and parameters of machine components for the operating environment, the proper lubricant, and many other parameters. Low

temperature significantly affects the density of the lubricant, which increases the moments acting on the bearing and slippage. Low temperatures also lead to a loss of elasticity by the seals used, which leads to leaks, i.e., loss of lubricant and the possibility of contaminants entering the machine. Further, certain components become brittle at very low temperatures, which can completely destroy the working component.

4. Methods of Research

In the analyses of the failure models for electrical machines, two competing models were selected: a model that takes into account bearing failures and a model that handles winding failures. Both models can be accounted for by a Weibull cumulative distribution. The mathematical model for both failures was developed for different variables. Thus, a full model was developed to analyze the risk of a failure. In preparing these models, parameters such as temperature, speed, and engine type were taken into account [1,22,23].

The models also take into account low temperatures. As the ambient temperature drops, there may be a point where the lubricant loses its performance and approaches a solid state. It can be expected that the lubrication mechanism does not cease to function at the exact temperature but is subject to a transitional range where lubrication becomes marginal. According to this assumption, there must be a temperature at which the life of the bearing does not increase, but begins to decrease as the temperature decreases. Low-temperature tests carried out resulted in sporadic bearing damage after short periods of operation in the $-38\text{ }^{\circ}\text{C}$ ambient range. The damage was considered indicative of marginal lubrication.

The researchers were concerned about the bearing torque at low temperatures.

In all low-temperature lubricant torque measurement tests, a temperature is reached where the torque increases rapidly as the temperature decreases. If the research proves that the increase in torque levels can be partly related to marginal lubrication, then the transition temperature to high torque operation may indicate reduced lubrication and bearing life. According to the research, this happens when the bearing temperature is around $16\text{ }^{\circ}\text{C}$, and this means that around this temperature, and lower, bearing life starts to decrease [23]:

$$\alpha_B = \left(10^{2.534 - \frac{2357}{T_{amb.} + 273}} + \frac{1}{10^{(20 - \frac{4500}{T_{amb.} + 273})} + 300} \right)^{-1}, \quad (1)$$

where

α_B —bearing life of an electric machine;

$T_{amb.}$ —ambient temperature.

Winding failures constitute the second major problem occurring during machine operation. Most often, these failures are caused by an early damage to the insulation resulting from chemical transformations, the occurrence of which is strongly related to temperature and humidity. To simplify the calculations and the model so that ambient temperature can be used, the effect of machine quality and size on the durability characteristics have been removed. The model is used when there is no additional knowledge of the machine being analyzed. The above approach to the model simplifies the analysis and prediction of the life of such a machine so that it is not necessary to use more complex calculations in the absence of parameters such as speed, load, or other environmental parameters in which the machine operates:

$$\alpha_W = 10^{\left(\frac{2357}{T_{amb.} + 273} - 1.83 \right)} \quad (2)$$

where

α_w —durability of an electrical machine winding.

When the ambient temperature during the operation of an electric machine is not constant, the bearing life is calculated based on the following dependence [23,24]:

$$\alpha_B = \left[\frac{h_1 + h_2 + h_3 + \dots + h_m}{\frac{h_1}{\alpha_1} + \frac{h_2}{\alpha_2} + \frac{h_3}{\alpha_3} + \dots + \frac{h_m}{\alpha_m}} \right], \quad (3)$$

where

h_1 —operating time at T_1 ;

h_2 —operating time at T_2 ;

h_3 —operating time at T_3 ;

h_m —operating time at T_m ;

α_1 —bearing durability at T_1 ;

α_2 —bearing durability at T_2 ;

α_3 —bearing durability at T_3 ;

α_m —bearing durability at T_m .

Figure 6 graphically shows the variation of the ambient temperature during the operation of the electric machine. The temperature values T_2 and T_4 are calculated as the arithmetic mean of the extreme temperatures [25]:

$$T_2 = \frac{T_1 + T_3}{2}, T_4 = \frac{T_3 + T_5}{2} \quad (4)$$

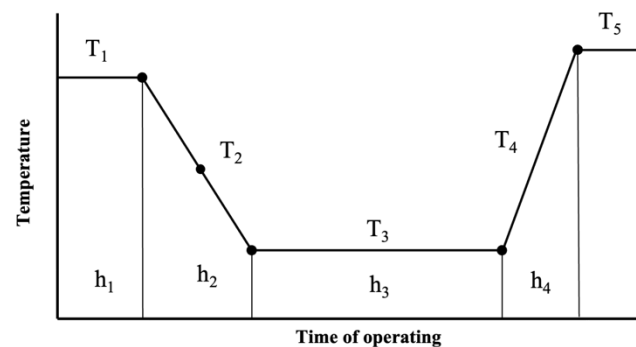


Figure 6. Variation in ambient temperature during operation of an electrical machine.

Equations (1) and (2) were developed to predict when a machine failure will occur due to damage or wear of the bearing and winding separately. However, when the machine is used, problems can occur with both the bearing and the winding. Therefore, a model was developed that took into account the previous two. This model can predict up to 75% of failures during machine operation. We can achieve an additional 11% with a more complex model using additional technical parameters of the equipment.

$$\ln(1 - F(t)) = - \left[\left(\frac{t}{a_B} \right)^3 + \frac{t}{a_W} \right] \quad (5)$$

where

$F(t)$ —is the percentage of time the machine operates at a given temperature, and in this percentage of this time, failures can occur, e.g., $50\% = 0.5 = F(t)$.

Equation (5) must be transformed to calculate t (h), which is the operating time we are looking for.

$$t = \alpha_B \left[\sqrt[3]{0.4657 + \sqrt{0.12011 + 0.03704 \left(\frac{\alpha_B}{\alpha_w} \right)^3}} + \sqrt[3]{0.34657 - \sqrt{0.12011 + 0.03704 \left(\frac{\alpha_B}{\alpha_w} \right)^3}} \right] \quad (6)$$

Failure Rate of an Electrical Machine

The failure rate defines the ratio of the number of failures occurring during a certain time interval to the number of machines at the beginning of that time divided by the length of the time interval. An increasing failure rate indicates an increase in the wear and tear of the machine. In the case under study, precalculated data were used to determine the failure rate, for which the ambient temperature parameter was applied.

$$\lambda_t = \left[\frac{t^2}{\alpha_B^3} + \frac{1}{\alpha_w} \right] \times 10^6, \quad (7)$$

where

t —total operating time of the machine (h);
 α_B —bearing durability of the electric machine;
 α_w —winding durability of the electric machine.

5. Results—Aircraft Profiles

5.1. M-28 Aircraft

The application used at OKL to analyze data from M-28 is intuitive software. It allows an in-depth analysis of data from detailed flights. Tapes are ripped after each flight, making it easy to archive individual flights, even those that are very short. The abovementioned advantages allowed the acquisition of accurate information and made it much easier to enter it into tables and formulas, which had a significant impact on obtaining the accurate results needed to determine the durability and reliability of the machines.

The example data are presented in Table 1.

Table 1. Flight data for each month, average of 3 flights.

Month	Barometric Altitude (ft)
January	3827
February	5585
March	3086
April	6745
May	2948
June	3078
July	5300
August	1735
September	2307
October	3683
November	6373
December	5376

The example aircraft profile for M-28 is presented in Figure 7.

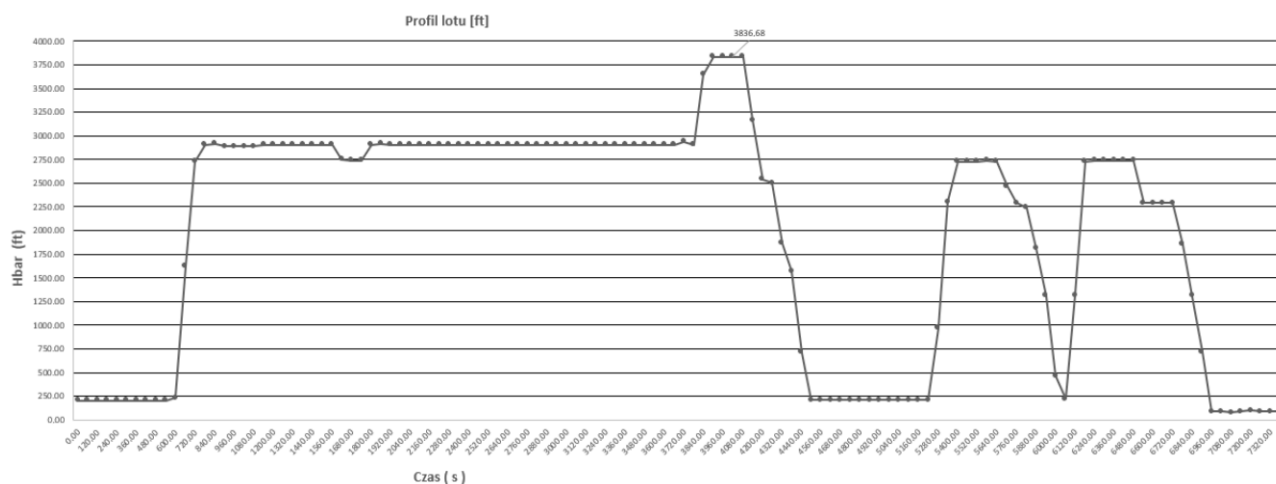


Figure 7. Example of flight parameter display M-28 aircraft.

5.2. C-130 Hercules Aircraft

The main difference between the way OKL data are analyzed and archived between the Hercules and M-28 aircraft is that M-28 tapes are ripped after each flight, while the Hercules tapes are only ripped once a month. This leads to considerable difficulties in working on the data in the software. The OKL software of the Hercules aircraft, compared to the method of display used to analyze the data from M-28 cassettes, is considerably less intuitive, has fewer functions, and prevents chronological and orderly storage of flight data. Because of the above disadvantages, the data are, rather, used for analysis when it is necessary, and the recorder itself plays more of a “catastrophic” role. These problems are also due to the age of the recorder used, which does not work properly with the new software. Therefore, for the analysis of flight heights, the temporally relative information about the highest flight in approximately every month was used. The example method of parameter display is presented in Figures 8 and 9.

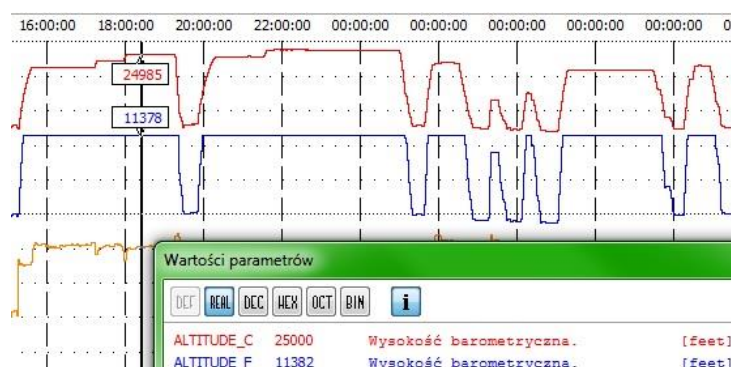


Figure 8. Example of flight data in January.

The timeline can also be observed; however, the record ends after 24 h and then indicates 0, as can be seen in Figure 8 for the month of January. It takes a very long time to find the right piece of data that relates to the flight you are looking for. Two types of barometric altitudes are stored in the recorder. One is referred to as accurate, however, and the other is not. It is still unclear where this nomenclature came from or why there is such a big difference between them. Table 2 shows the average flight values for the 12 months of 2019.

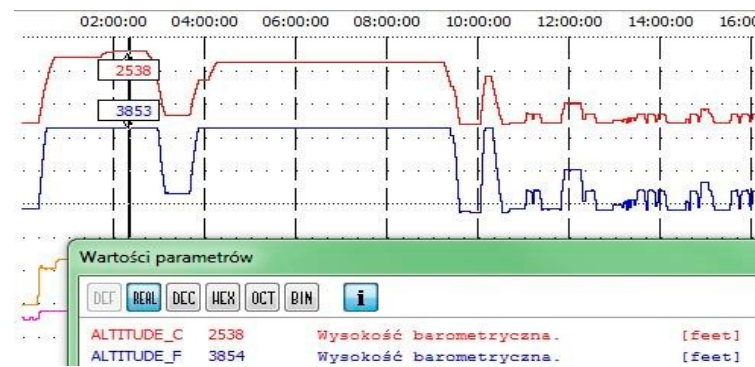


Figure 9. Example of flight data in April.

Table 2. Monthly flight data.

Month	Barometric Altitude (ft)
January	24,985
February	23,129
Marc	24,325
April	2538
May	24,235
June	25,147
July	13,172
August	18,139
September	24,297
October	24,135
November	21,269
December	16,166

5.3. M-28 Aircraft

Illustrative calculation of bear durability for one flight of M-28 aircraft:

$$H_{\text{bar}_{\text{aver}}} = 3827 \text{ (ft)}$$

$H_{\text{bar}_{\text{aver}}}$ —average height for one month (January).

$$T_{\text{amb.}} = 15 \text{ (}^{\circ}\text{C)} - 3827 \text{ (ft)} / 1000 \text{ (ft)} \times 2 \text{ (}^{\circ}\text{C)} = 7.34 \text{ (}^{\circ}\text{C)}$$

$T_{\text{amb.}}$ —ambient temperature prevailing at flight altitude according to ISA ($^{\circ}\text{C}$).

$$\alpha_B = \left(10^{2.534 - \frac{2357}{T_{\text{amb.}} + 273}} + \frac{1}{10^{(20 - \frac{4500}{T_{\text{amb.}} + 273}) + 300}} \right)^{-1} = 9068,46 \quad (8)$$

$$\alpha_W = 10^{\left(\frac{2357}{T_{\text{amb.}} + 273} - 1.83 \right)} = 3,779,792.11 \quad (9)$$

$$t = \alpha_B \left[\sqrt[3]{0.34657 + \sqrt{0.12011 + 0.03704 \left(\frac{\alpha_B}{\alpha_w} \right)^3}} + \sqrt[3]{0.34657 - \sqrt{0.12011 + 0.03704 \left(\frac{\alpha_B}{\alpha_w} \right)^3}} \right] = 9068.46 \left[\sqrt[3]{0.34657 + \sqrt{0.12011 + 0.03704 \left(\frac{9068.46}{3,779,792.11} \right)^3}} + \sqrt[3]{0.34657 - \sqrt{0.12011 + 0.03704 \left(\frac{9068.46}{3,779,792.11} \right)^3}} \right] = 2528.28 \quad (10)$$

$$\lambda_t = \left[\frac{t^2}{\alpha_B^3} + \frac{1}{\alpha_w} \right] \times 10^6 = \left[\frac{t^2}{9068.46^3} + \frac{1}{3,779,792.11} \right] \times 10^6 = 8.83 \quad (11)$$

The ISA temperature is equal to the ambient temperature of the $T_{\text{amb.}}$ at the flight altitude of the aircraft. The results from the altitudes obtained and, thus, the ambient temperatures according to ISA are presented in Table 3.

Table 3. Temperature values according to ISA and calculated operating time for M-28 aircraft.

Hbar (ft)	TISA (°C)	Calculated Operating Time t (h)
3827	7.3	2528
5585	3.8	1621
3086	8.8	3040
6745	1.5	1207
2948	9.1	3146
3078	8.8	3046
5300	4.4	1743
1735	11.5	4229
2307	10.4	3682
3683	7.6	2620
6373	2.3	1327
5376	4.3	1710

The average value of the calculated operating times of the electric machine calculated from the data in Table 3 is 2491 h. Based on the calculated operating times and using Equation (7), the predicted number of failures was calculated for M-28 aircraft (Table 4).

Table 4. The predicted number of failures for M-28 aircraft.

Calculated Operating Time t (h)	Calculated Number of Failures per 10 ⁶ Hours of Operation λ_t
2528	8.83
1621	13.56
3040	7.42
1207	18.12
3146	7.18
3046	7.40
1743	12.64
4229	5.47
3682	6.21
2620	8.53
1327	16.51
1710	12.88

5.4. C-130 Hercules

By analogy with M-28 aircraft, data for C-130 Hercules aircraft were collected. The obtained results for the recorded altitudes and, correspondingly, ambient temperatures in accordance with the ISA are presented in Table 5.

Table 5. Temperature values according to ISA and calculated operating time for C-130 Hercules aircraft.

Hbar (ft)	TISA (°C)	Calculated Operating Time t (h)
24,985	−34.9	87
23,129	−31.3	90
24,325	−33.6	88
2538	9.9	3479
24,235	−33.5	88
25,147	−35.3	86
13,172	−11.3	260
18,139	−21.3	120
24,297	−33.6	88
24,135	−33.3	88
21,269	−27.5	96
16,166	−17.3	153

The average value of the calculated operating times of the electric machine calculated from the data in the table is 400 h. Based on the calculated operating time and Formula (7), the predicted number of failures was calculated for C-130 Hercules aircraft (Table 6).

Table 6. The predicted number of failures for C-130 Hercules aircraft.

Calculated Operating Time t (h)	Calculated Number of Failures per 10 ⁶ Hours of Operation λ_t
87	248.79
90	239.71
88	246.13
3479	6.54
88	245.72
86	249.36
260	83.34
120	179.64
88	246.00
88	245.26
96	224.36
153	141.21

6. Summary and Conclusions

Based on the calculations conducted, bearing operating times were determined for the two transport aircraft types. For M-28 aircraft, the working time averaged 2491 h, and for C-130 Hercules aircraft, 400 h. According to technical data and expert advice, the calculations differ from manufacturers' recommendations and instructions. In the case of M-28, this is due to regular maintenance carried out every 400 h, which includes an overhaul of the equipment and a change of lubricants. It results in an increase in operating time up to a maximum interoverhaul residual life of 5000 h. For C-130 Hercules, this is most likely due to the materials and technology used in the construction of the generator, as well as the simplicity of its design, since, despite the harshest operating conditions, there are rarely any failures that necessitate replacement.

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