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BUILDING OF PROBABILISTIC- STATISTICAL MODEL OF ENGINE FAILURES

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***Abstract**: the article is devoted to the construction of probabilistic-statistical models for the reliability of engines of various aircraft. The probabilistic-statistical model is based on the Weibull distribution. The constructed model of reliability allows to estimate the reliability, operating time, gamma- percentile resource. The model includes an adequacy test based on the* χ^2 *distribution. Models are universal and can be used for military and civil aircraft.*

***Keywords:** probabilistic-statistical model of operation, aircraft, Weibull distribution, reliability function, gamma-percentile resource, operating time .*

1. INTRODUCTION

The engine is the basic element of the working element of any aviation system.

In addition, the engine is an expensive piece of equipment whose failures must be minimized. The quality of engine performance has an impact on flight safety, and improving safety a priority for both civil and military aviation.

Purpose of the work: building of failure model for the CF34-10E and CFM56-3B1 engines, analyzing the obtained data statistics, identifying the causes of failures.

Work tasks:

– building and implementation of probabilistic-statistical model;
– causes of failures identification and analysis;
– calculation and evaluation of certain reliability characteristics of engines.

The relevance of the topic is due to the provision of safety by preventing the occurrence of failures and reducing their intensity.

The scientific novelty of the topic lies in establishing links between the use of natural science methods of probabilistic-statistical modeling for solving and implementing reliability problems in the operation of aircraft engines [1-3].

The results obtained with the help of the model can be used as recommendations when carrying out maintenance work when servicing equipment on BOEING 737-300 aircraft with CFM56-3B1 engines and EMBRAER 175/195 with CF34-10E engines in addition to the existing analytical systems.

2. MATERIALS AND METHODS

Aircraft engines can be divided into three broad groups:

– piston;
– jet engines;
– missile.

Let us discuss jet engines in detail. According to the creation of jet thrust, jet engines are divided into direct and indirect reaction engines. Direct-acting engines include turbojet, bypass turbojet, turbojet with afterburner, bypass turbojet with afterburner. Indirect reaction engines are turboprop, turboshaft, turbopropfan [4].

The work deals with CF34-10E and CFM56-3B1 engines.

The article compares the engines of the Boeing 737-300 and EMBRAER 175/195 aircraft. Airplanes fly with the help of bypass turbojet engines with a high bypass ratio, so we will analyze this type of aircraft engines in more detail.

Bypass turbojet engines are based on the principle of attaching an additional mass of air to the turbojet engine passing through the outer circuit of the engine, which makes it possible to obtain engines with a higher flight efficiency compared to conventional turbojet engines.

After passing through the inlet, the air enters the low-pressure compressor, called the fan. After the fan, the air is divided into two streams. Part of the air enters the outer circuit and, bypassing the combustion chamber, forms a jet stream in the nozzle. The other part of the air passes through an internal circuit that is completely identical to the turbojet, with the difference that the last stages of the turbine in the turbojet are the fan drive.

One of the most important parameters of a bypass turbojet engine is the bypass ratio (m), that is, the ratio of air flow through the external circuit to the air flow through the internal circuit.

A turbojet engine with a high bypass ratio (m>2) is a turbofan engine. Here, the low-pressure compressor is converted into a fan, which differs from the compressor in a smaller number of steps and a larger diameter, and the hot jet practically does not mix with the cold one.

All bypass turbojet engines can be divided into two groups: bypass turbojet engines with mixing flows behind the turbine and turbofan engines without mixing flows.

In a mixed-flow bypass turbojet engine, air flows from the external and internal circuits enter a single mixing chamber. In the mixing chamber, these flows are mixed and leave the engine through a single nozzle with a single temperature. The bypass turbojet engines with mixing flows behind the turbine are more efficient, however, the presence of a mixing chamber leads to an increase in the dimensions and weight of the engine.

Advantages of turbofan engines:

– the ability to save fuel without losing power, which is so important for jet engines;

– in addition, these motors are less noisy;

– another advantage is the presence of a simplified reverse thrust system. When braking the aircraft, the thrust of the external circuit is used.

The disadvantages of turbofan engines include:

– a large mass;

– size.

Any additional components of the engine design are an additional weight, which is very important for aviation, and an additional contour of considerable size is a rather significant increase in the mass of the engine. Large dimensions lead to an increase in the value of air drag during flight.

Stages of building a model are the following:

1. Determination of elements with minimum operating time and causes of failures;
2. Building a statistical model;
3. Calculation of reliability characteristics from the model and their comparison with the obtained data;
4. Model estimation.

3. RESULTS AND DISCUSSION

Further in the article, engine models CF34-10E and CFM56-3B1 are built and the main reliability characteristics are calculated.

Following the steps of building the model, the results for the CF34-10E engine were obtained:

Table 1 shows the most frequently failed elements, the reasons for their failures and how to eliminate them.

Table 1. Most common engine failures of CF34-10E

Element	Problem	Action
FAN BLADES	ENG #2 fan blades damage	the fan blade #6 of the rh engine has been replaced
T25 SENSOR	Negative test result	T25 sensor is removed from engine#2
T12 SENSOR	ENG#2 short time dispatch EICAS MSG	the T12 sensor ENG#2 has been replaced
T2.5 TEMP SENSOR	CMC active message: ND T25 CH A-B INPUTS DISAGREEE	ENGINE #2 T2.5 temp sensor is replaced

Next, a statistical model is built, which is based on the Weibull distribution [4].

MTBF for Weibull distribution:

$$\lambda[t] = b\frac{t^{b-1}}{a^{b}} \tag{1}$$

$$T_0 = \frac{M[t]}{\Gamma\left(1+\frac{1}{b}\right)} = M[t] \tag{2}$$

In accordance with the model, the operating time was 7333 hours. The time interval in which failures occur with a given sample is from 4991 hours to 8446 hours.

Based on the model, the results of operating time for CF34-10E were obtained from the Pareto diagram:

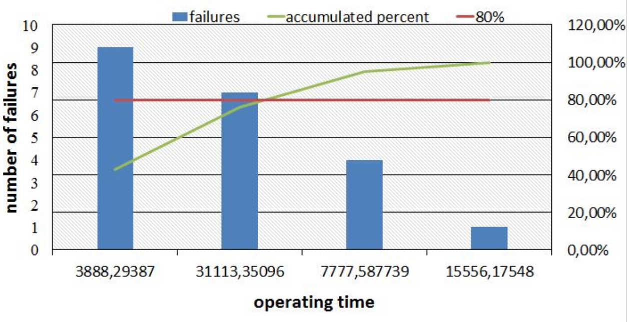

Figure 1. Pareto Diagram for CF34-10E

From Figure 4, the Pareto diagram of the number of failures from the total operating time intervals is obtained. Failure rates above 80% are acceptable and understandable. At the initial stage, the installed equipment is run-in, then stable operation of the engines is observed.

The values of the lifetime bias parameter b and intensity λ were calculated using the maximum likelihood method (MLE)

$$b = \left(\sum_{i=1}^{n}\frac{t_i^{\alpha}}{n}\right)^{\frac{1}{\alpha}} \tag{3}$$

and method of moments

$$b = \frac{\overline{x}}{\Gamma\left(1+\frac{1}{\alpha}\right)} \tag{4}$$

The maximum likelihood method (MLE)– a method for estimating the parameters of an assumed probability distribution given some observed data. It is implemented through the maximization of the likelihood function so that, according to the assumed statistical model, the observed data is the most probable.

The method of moments consists in equating the theoretical methods of distribution with the corresponding empirical moments obtained from the sample.

Since the model is calculated according to Weibull, we estimate the lifetime bias parameter b. The value b obtained is close to the operating time. The result is presented in Table 2.

Table 2. Calculation of the distribution parameter b and λ for the Weibull distribution for engine CF34-10E

	maximum likelihood method	method of moments
$\lambda \cdot 10^6, h^{-1}$	132	135
b, h	7551	7423

At the same time, the calculation error in method of moments with the maximum likelihood method for parameter b was 1,7%. The error in calculating the intensity in the two considered methods was 1,72%.

The article also calculates the gamma- percentile resource with the Weibull distribution law in accordance with the equations (Table 3):

$$T_\gamma = \frac{T_{cp}}{K_b}\left(\ln\frac{1}{\gamma}\right)^{\frac{1}{b}} \qquad (5)$$

$$T_\gamma = H_k^W(1-\gamma)\alpha + b \qquad (6),$$

where H_k^W - quantile Weibull distribution.

The calculation results of the gamma-percentile resource are shown in Table 3

Table 3. Calculation gamma- percentile resource on eq.(5) and (6) for CF34-10E

	Eq. (5) with coefficient of variation	Eq. (6) with quantile
$T_{p\gamma}, h$	7615	7423

At the same time, the calculation the gamma- percentile resource error in eq. (5) with the eq. (6) was 2,5%.

The data obtained are due to a rather short service life, as well as a small failure statistic.

The estimate of the critical value for χ^2 was 7.815, from the experimental data 2.41. This result indicates the adequacy of the model.

For comparison let us analyze the CFM56-3B1 engine.

Table 4. Most common engine failures of CFM56-3B1.

Element	Problem	Action
START SWITCH	Engine 1 start switch does not return to "off" position during start.	The start switch of the first engine has been replaced.
FAN BLADES	The fan blades of the left engine No. 5 and No. 6 show signs of unbanding. Wear more than 0.1 mm.	Two pairs of fan blades (5-24 and 6-25) have been replaced.
THE FAN BLADES	Birdstrikes	Fan blades No. 16, 17, 18 have been replaced.

The operating time for CFM56-3B1 was 6582 hours.

The results of operating time for CFM56-3B1 were obtained from the Pareto diagram:

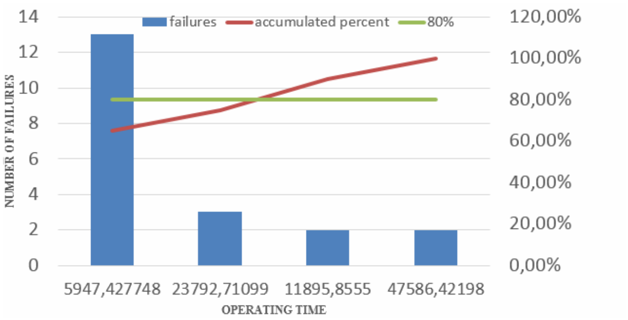

Figure 2. Pareto Diagram for CFM56-3B1

Pareto diagrams will reveal the intervals of elements when maintenance is necessary.

The values of the lifetime bias parameter b and intensity λ were calculated using the maximum likelihood method and method of moments and presented in table 5.

Table 5. Calculation of the distribution parameter b and λ for the Weibull distribution for engine CFM56-3B1

	maximum likelihood method	method of moments
$\lambda \cdot 10^4, h^{-1}$	75	70
b, h	7333	7284

At the same time, the calculation error in method of moments with the maximum likelihood method was 0,6%. Their values were comparable with the calculated operating time. The estimate of the intensity error was 7%.

The result is presented in Table 6.

Table 6. Calculation gamma- percentile resource on eq.(5) and (6) for CFM56-3B1

	Eq. (5) with coefficient of variation	Eq. (6) with quantile
$T_{p\gamma}, h$	6379	6582

At the same time, the calculation the gamma- percentile resource error in eq. (5) with the eq. (6) was 3,1%.

The data obtained are due to a rather short service life, as well as a small failure statistic.

The estimate of the critical value for χ^2 was 7.815, from the experimental data 6,244. This result indicates the adequacy of the model. Thus, based on the constructed engine models, we can conclude on their reliability. The evaluation results are shown in the table 7.

Table 7. The evaluation results.

Parameters	CFM56-3B1	CF34-10E
Operating times	+	-
Pareto diagram	-	+
Indicates the adequacy of the model	-	+
Gamma- percentile resource	-	+
Result	1/4	3/4

The table 7 shows comparisons of some of the reliability characteristics of engines.

Let's come to the main conclusions when comparing the reliability characteristics of engines:

1) it follows from the calculations that the engine CFM56-3B1 has a longer operating time;
2) the interval of reliable operation from the Pareto diagram is higher for the engine CF34-10E;
3) it can be seen from the χ^2 criterion that the engine CF34-10E model is more adequate;
4) the engine CF34-10E has a higher gamma -percentile resource then the CFM56-3B1.

As can be seen from the indicated table, the reliability of the engine CF34-10E is higher.

4. CONCLUSION

The statistics of engine failures of the above aircraft is best described by a model built on the basis of the Weibull distribution. For more successful forecasting, it is necessary to consider a larger fleet of aircraft. This will improve the accuracy of the obtained characteristics and correct the forecast.

The paper considers two types of engines used in civil aircraft- CFM56-3B1 and CF34-10E. The characteristics are calculated within the framework of the model based on the Weibull distribution. Based on the method of moments and the maximum likelihood method, the Weibull distribution parameters were estimated for both engines. The values obtained by the methods for each engine have a high degree of agreement. The error of the obtained results does not exceed 10%.

In the work, the operating time, gamma- percentage resource are calculated, the adequacy of the model is assessed.

The paper compares the obtained parameters for two types of engines. From the comparison it follows that the engine CF34-10E has a higher reliability.

However, the assessment obtained during comparison cannot be considered final, since only a few characteristics were calculated. With a larger number of calculated parameters, a different set of parameters and other initial statistics, the result may be different. The calculation model used, based on the Weibull distribution, can be considered simplified. However, with more statistics of the received data, this model can be extended, which will have a significant impact on its capabilities. As can be seen from the data matching, the model for which the calculations were made allows a good estimate of the parameters indicated in the article.

Model advantages:

- the model is universal;
- model is simple to use;
- model is easy to match.

The constructed model is of practical importance, because:

- it provides an assessment of the characteristics of failures of engine elements and analysis of the obtained parameters;
- it allows you to calculate and evaluate the running time of engines, to carry out a number of preventive measures to eliminate failures;
- it allows you to adjust the performance of restoration, repair and other types of maintenance work;
- for military aircraft, the construction of such models seems necessary, because it allows you to make adjustments to routine and repair work.

The model gives some recommendations for technical operation. The using of condition-based maintenance with parameter control, rather than operating hours, is most beneficial in terms of minimizing maintenance costs.

The model used in the calculation of various reliability parameters is universal, because it can be applied to various types of aircraft. It should be noted that when making additions, it is possible to make reliability assessments not only of engines, but of other aircraft systems.

This model can be useful for assessing the reliability of military aircraft, as it allows you to make operational decisions on repair and operation.

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