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TURBOPROP AND TURBOFAN ENGINES EFFECTIVENESS COMPARISON

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Abstract

The aim of this paper is to compare the effectiveness of the PW 124B/127F turboprop engine on ATR 72-200/500 aircraft and the CFM 56-3B-1 turbofan engine on Boeing 737-300 aircraft. Following a brief overview of these engines, the integrated additive reliability indicator was defined, according to the criteria of safety, operability and economy. Based on the integrated additive reliability indicator, the effectiveness assessment model was defined. The current and the achieved engine's effectiveness were calculated by processing the input data collected by the reliability monitoring department of the national airline. Obtained results confirm a close connection between the reliability and effectiveness and show that the CFM 56-3B1 has higher effectiveness than the PW 124B/127F for the considered fleet operational environment.

Key words*: turboprop engine, turbofan engine, reliability indicators, effectiveness assessment.*

1 INTRODUCTION

The effectiveness of technical systems integrates various reliability, safety, quality, inspection and condition monitoring parameters, as well as other specific factors important for solving critical problems during the design, production and operation of the system. Thereby, when studying effectiveness, one of the elementary problems is to establish a correlation between the previously mentioned factors, which occur during the optimization and establishment of a hierarchical relationship within the set goal function.

From the aspect of flight safety and economy of operation, the propulsion system is one of the most significant aircraft systems, whose primary element, in the narrow sense, is an engine without the associated equipment and subsystems. According to aeronautical terminology, the installation of the aircraft propulsion system includes each component, which is necessary for propulsion and that affects the control of the operation of engines or affects their safety between regular inspections or overhauls. Since the engine is a primary element of the propulsion system, the analysis of the reliability and safety impact on the effectiveness of the aircraft propulsion system is justified to be limited to the level of the engine itself. During the operation of aircraft engines, it is necessary to pay special attention to achieving the designated level of operational reliability and safety, which is the primary goal of the maintenance process. With the introduction of MSG logic during the development of the initial maintenance program, the principle of designing a maintenance system according to the possible consequences of the occurrence of malfunctions was introduced, which appear as the elementary criteria for assessing effectiveness. The effectiveness of an engine can be expressed using the safety, economy and operability criteria, which are included in the MSG-3 approach to aircraft maintenance [1].

1.1. A description of the considered engine types

Based on this MSG-3 principle, the effectiveness of the following two different types of engines is analyzed: the Pratt & Whitney PW 124B/127F turboprop engine and the CFM 56-3B1 turbofan engine.

The PW 124B/127F engine is a three-shaft turboprop engine (Fig. 1) with centrifugal compressors.

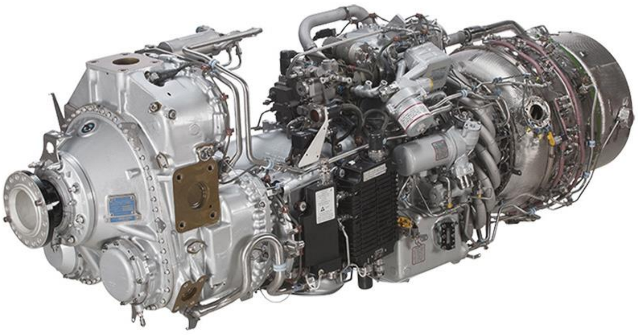

Fig. 1 *The PW 127F engine*

The primary maintenance process of the PW 124B/127F engine is On-Condition (OC), while some components exposed to high thermal stresses are subject to a Hard Time (HT) process. In addition to these components, the propeller and all its parts are also subject to an HT process [2].

The CFM 56-3B1 engine is a two-shaft turbofan engine (Figure 2) with axial compressors, modular construction and a high bypass ratio.

The primary maintenance process of the CFM 56-3B1 engine is also On-Condition (OC). In addition to OC components, some engine components, known as life-limited parts (LLPs), require replacement after their life expiry regardless of their condition [3]. An example of these components includes the elements of the hot section of the engine.

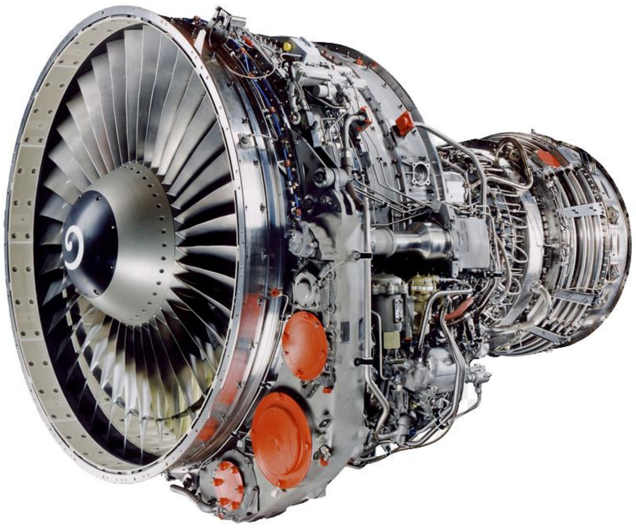

***Fig. 2** The CFM 56-3B1 engine*

2 THE EFFECTIVENESS ASSESSMENT MODEL

The effectiveness of aircraft engines can be regarded from the safety, economy and operability viewpoint. The problem of evaluating the effectiveness of aircraft turbine engines reduces to assessing the impact of reliability indicators on the previous three effectiveness parameters. Based on this assumption and available data, reliability indicators that describe the effectiveness of aircraft engines can be defined. From the safety aspect, the aircraft engine's effectiveness depends on the number of engine In-Flight Shut Downs (IFSDs). According to the economy criterion, it depends on the number of Unscheduled Engine Removals (UERs) from the aircraft. In terms of operability, the effectiveness of aircraft engines depends on the number of Technical Delays (TDs), greater than 15 minutes, which are a consequence of the malfunction of aircraft engines. When assessing the overall effectiveness, it is necessary to include all the above criteria and perform their weighting. Determination of weighting coefficients usually depends on the expert's assessment. However, this approach to the problem has an insufficient property of objectivity, which leads to the conclusion that two studies on the same issue may result in different solutions.

The assessment of the PW 124B/127F and the CFM 56-3B1 engines' effectiveness uses the data collected by the reliability monitoring department of the national airline *AirSERBIA* for all aircraft in their fleet. Based on insight into the monthly fleet reliability reports from 2007 to 2015, the following required input data were determined [4]:

- total number of aircraft (a/c) in fleet,
- average number of a/c in service,
- number of a/c revenue take-offs,
- number of a/c flying hours,
- number of engine flight hours,
- number of engine flight cycles,
- number of engine in-flight shutdowns,
- number of unscheduled engine removals,
- number of scheduled engine removals,
- number of engine caused technical delays (>15 min).

After determining the input data related to the reliability of aircraft engines, it is necessary to define the methodology for calculating the reliability indicators.

An engine's In-Flight Shut Down Rate, K_{IFSD}, expressed per 1000 engine flight hours represents the ratio of the number of engine's in-flight shutdowns, N_{IFSD}, either commanded by the crew or as a result of a flameout and the number of Engine Flight Hours (EFH) in the observed period of operation:

$$K_{\mathrm{IFSD}} = \frac{N_{\mathrm{IFSD}}}{\mathrm{EFH}} \cdot 1000 \tag{1}$$

The Rates of Scheduled Engine Removals, K_{SER}, and Unscheduled Engine Removals, K_{UER}, expressed per 1000 engine flight hours, are the ratios between the number of scheduled, N_{SER}, and unscheduled, N_{UER}, engine removals and the number of Engine Flight Hours (EFH) in the observed period of operation:

$$K_{\mathrm{SER}} = \frac{N_{\mathrm{SER}}}{\mathrm{EFH}} \cdot 1000 \quad K_{\mathrm{UER}} = \frac{N_{\mathrm{UER}}}{\mathrm{EFH}} \cdot 1000 \tag{2}$$

The Rate of Technical Delays, K_{TD}, expressed per 100 revenue take-offs represents the ratio of the number of technical delays over 15 minutes resulting from engine malfunction detection and removal, N_{TD}, and the number of revenue take-offs, $N_{\mathrm{RT/O}}$, in the observed period of operation:

$$K_{\mathrm{TD}} = \frac{N_{\mathrm{TD}}}{N_{\mathrm{RT/O}}} \cdot 100 \tag{3}$$

The calculation of the reliability indicators in this paper uses 12-months rolling averages to obtain values that show the overall trend of the corresponding reliability indicator. After this calculation, it is necessary to define the upper control values of each reliability indicator, known as the Alert Values, which separate the normal from the abnormal range of reliability indicator values.

Alert value for the engine in-flight shutdown rate was selected from the 120-minute Extended Twin-Engine Operations (ETOPS) requirement (A_{IFSD} = 0.05) [5]. Alert values for other reliability indicators (the rates of scheduled and unscheduled engine removals and technical delays rate caused by the engine) were determined from the general model for the upper control values according to the following relation:

$$A_j = K_{j,avg} + 3 \cdot \sigma_j \tag{4}$$

where A_j designates the alert value of the reliability indicator, $K_{j,avg}$ is the average value of the 12-months rolling average rate of the reliability indicator K_j and σ_j is the standard deviation [6].

Most airlines use the previous 12 months period to calculate the average value and the standard deviation of the 3-months rolling average value of the reliability indicator. In this paper, we use the previous 24 months period to calculate the average value and the standard deviation of the 12-months rolling average value of the reliability indicator.

$$K_{j,avg} = \frac{1}{24} \sum_{i=1}^{24} K_{j,i} \tag{5}$$

$$\sigma_j = \sqrt{\frac{1}{24}\sum_{i=1}^{24}\left(K_{j,i} - K_{j,avg}\right)^2} \tag{6}$$

The alert values calculated in this way are adopted to be constant during the current calendar year.

After determining the reliability indicators and their alert values, the relative reliability indicators were defined using the following expressions:

$$\bar{K}_{\mathrm{IFSD}} = \frac{K_{\mathrm{IFSD}}}{A_{\mathrm{IFSD}}} \tag{7}$$

$$\bar{K}_{\mathrm{UER}} = \frac{K_{\mathrm{UER}}}{A_{\mathrm{UER}}} \tag{8}$$

$$\bar{K}_{\mathrm{TD}} = \frac{K_{\mathrm{TD}}}{A_{\mathrm{TD}}} \tag{9}$$

where $\bar{K}_{\mathrm{IFSD}}$, $\bar{K}_{\mathrm{UER}}$ and $\bar{K}_{\mathrm{TD}}$ designate relative reliability indicators of the engine in-flight shutdowns, unscheduled removals and technical delays respectively, while A_{IFSD}, A_{UER} and A_{TD} are the corresponding alert values.

The integrated reliability indicator of the engine, $\bar{K}_{\mathrm{ENG}}$, combines the impact of the considered events (IFSD, UER and TD) according to the adopted criteria of engine effectiveness. To define this integrated reliability indicator the following general expression is used [7]:

$$\bar{K}_{\mathrm{ENG}} = \frac{1}{3}\cdot\left(\bar{K}_{\mathrm{IFSD}}^{k_{\mathrm{IFSD}}} + \bar{K}_{\mathrm{UER}}^{k_{\mathrm{UER}}} + \bar{K}_{\mathrm{TD}}^{k_{\mathrm{TD}}}\right) \tag{10}$$

where coefficients k_{IFSD}, k_{UER} and k_{TD} represent the impact factor of individual events (IFSD, UER and TD) on the integrated reliability indicator of the engine. By a quantitative analysis of these impacts under the given criteria of engine's effectiveness, adopted values of the considered coefficients are [8]: $k_{\mathrm{IFSD}} = 2$, $k_{\mathrm{UER}} = 1$ and $k_{\mathrm{TD}} = 1$. Therefore, Eq. (10) can now be written as:

$$\bar{K}_{\mathrm{ENG}} = \frac{1}{3}\cdot\left(\bar{K}_{\mathrm{IFSD}}^{2} + \bar{K}_{\mathrm{UER}} + \bar{K}_{\mathrm{TD}}\right) \tag{11}$$

The previous relation indicates the importance of the engine in-flight shutdown rate as a safety parameter compared to other reliability indicators. However, Eq. (11) requires correction due to different parts resources in the engine. This correction can be made through the relative costs of scheduled engine maintenance, $\bar{C}_{\mathrm{SER}}$:

$$\bar{C}_{\mathrm{SER}} = \frac{K_{\mathrm{SER}}}{A_{\mathrm{UER}}} \tag{12}$$

The integrated additive reliability indicator of the engine, $\bar{K}_{\mathrm{ADD}}$, can be defined by combining Eq. (11) with Eq. (12):

$$\bar{K}_{\mathrm{ADD}} = \bar{K}_{\mathrm{ENG}} + \bar{C}_{\mathrm{SER}} \tag{13}$$

By knowing the relative indicators and the integral additive reliability indicator, it is possible to determine the effectiveness of an engine. The effectiveness of an engine can be considered as current effectiveness, e_i, i.e. the effectiveness in the i-th time section (usually at the end of a month), and as the achieved effectiveness, E, according to total accumulated flight hours in the observed calendar period. The current and the achieved effectiveness of the aircraft engine are determined using the following expressions:

$$e_i = \frac{1}{1+\bar{K}_{\mathrm{ADD},i}} \tag{14}$$

$$E = \frac{1}{\sum_{i=1}^{n}\mathrm{EFH}_i}\cdot\sum_{i=1}^{n}\frac{\mathrm{EFH}_i}{1+\bar{K}_{\mathrm{ADD},i}} \tag{15}$$

where n designates the number of observed calendar periods (i.e. number of months).

3 RESULTS AND DISCUSSION

The calculation of both relative and integrated additive reliability indicators for the PW 124B/127F and the CFM 56-3B1 engine covers the period from 2010 to 2015. Figures 3 and 4 present the results of this calculation.

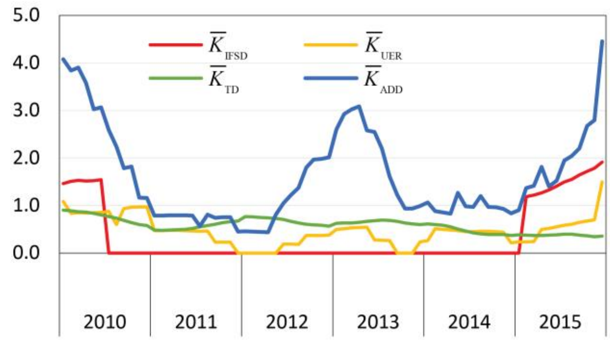

Fig. 3 *Reliability indicators for the PW 124B/127F engine*

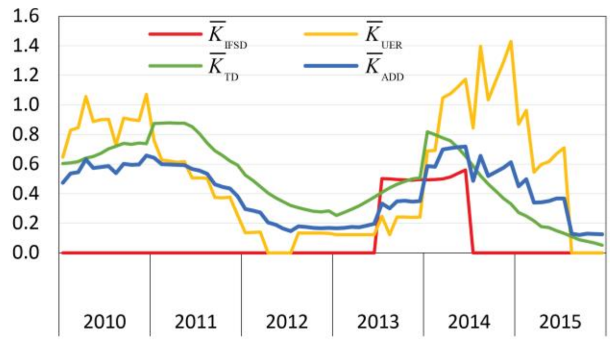

Fig. 4 *Reliability indicators for the CFM 56-3B1 engine*

Figures 3 and 4 show that integrated additive engine reliability indicators follow the overall trend of change of the individual relative reliability indicators. Figure 3 indicates that relative indicators of engine in-flight shutdowns and unscheduled removals in the observed period have a dominant influence on the integrated additive reliability indicator value for the PW 124B/127F engine. On the other hand, Figure 4 shows the pronounced effect of all considered relative reliability indicators in the observed period on the integrated additive reliability indicator value for the CFM 56-

3B1 engine, which can be explained by the combined influence of the engine's average age and total flight hours achieved. By comparing the values of the integrated additive reliability indicators from Figures 3 and 4, it can be noticed that in the given operating conditions, the CFM 56-3B1 engine shows a higher level of operational reliability than the PW 124B/127F engine.

Results of calculating the effectiveness of the PW 124B/127F and the CFM 56-3B1 engine in the observed period, obtained by applying previous relations, are presented in Figs. 5 and 6.

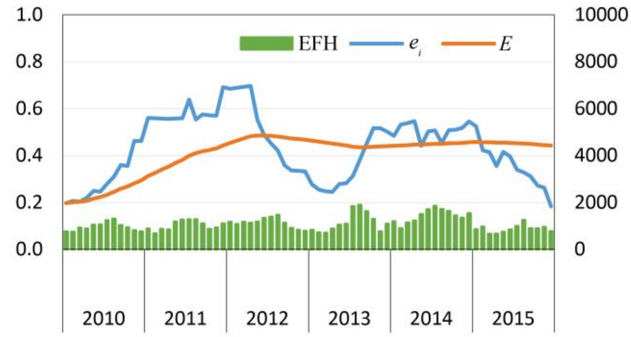

Fig. 5 *Effectiveness of the PW 124B/127F engine*

Figure 5 shows that the current effectiveness level depends on the number of considered engine events, mainly on the number of in-flight shutdowns. Two IFSD events occurred in the observed period, one in the middle of 2009 and the other at the beginning of 2015, leading to a sharp rise of the integrated additive reliability indicator value (Fig. 3) and a noticeable drop in the current effectiveness level (Fig. 5). The consideration of the achieved effectiveness level should cover the current effectiveness level and total engine flight hours. The rise of achieved effectiveness of the PW 124B/127F engine at the beginning of the observed period is a result of the increase in the current effectiveness value, considering that total engine flight hours have a typical seasonal character, as shown in Figure 5.

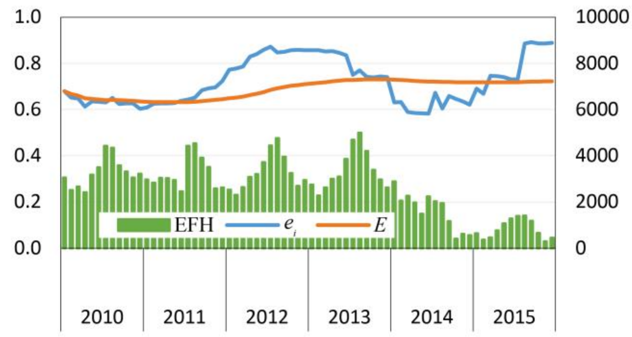

Fig. 6 *Effectiveness of the CFM 56-3B1 engine*

Figure 6 shows a noticeable increase in the current effectiveness level for the CFM 56-3B1 engine during 2012, considering the small number of engine events and the unchanged seasonal fleet utilization rate. One IFSD event in the middle of 2013 led to a decrease in the current effectiveness level, which extended to 2014, resulting from the applied 12-months rolling averages calculation method. The achieved effectiveness remained stable during the observed period due to the combined effect of influencing factors. After 2013, the newly formed company AirSERBIA gradually introduced Airbus A319-100 and A320-200 aircraft into their fleet and reduced the number of Boeing 737-300 aircraft, which resulted in a reduction of the utilization of the Boeing 737-300 aircraft, without significantly affecting the considered effectiveness parameters.

A comparison of the achieved effectiveness of the CFM 56-3B and the PW 124B/127F engine during the observed period is shown in Figure 7.

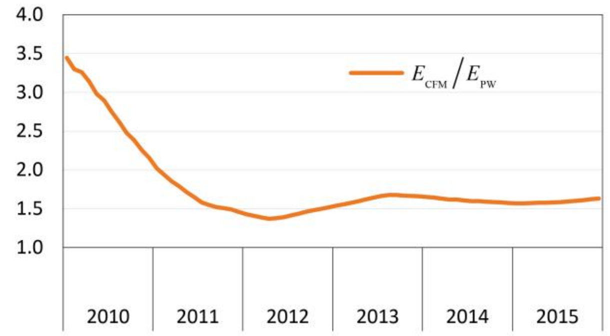

Fig. 7 *Ratio of the achieved effectiveness of the CFM 56-3B1 and the PW 124B/127F engines*

During the observed period and for the considered operating conditions, the CFM 56-3B1 engine showed a higher value of achieved effectiveness than the PW 124B/127F engine because of different design characteristics and component resource levels. Achieving a greater engine effectiveness level requires constant improvements in engine design, component resources and, what is more important, in the quality of the engine maintenance process.

4 CONCLUSION

The effectiveness of aircraft turbine engines is one of the parameters that indicate the quality of aircraft operation, which can be analyzed through reliability indicators in relation to the criteria of safety, economy and operability. Through appropriate reliability indicators, whose values are monitored on a monthly basis, it is possible to continuously monitor the reliability of the entire population of components in the fleet during operation. Depending on the value of the reliability indicators, it is possible to make appropriate modifications to the aircraft operation and maintenance process, to maintain the reliability of the components at a satisfactory level.

Based on the analysis of reliability and effectiveness of aircraft engines, shown on a numerical example of comparison of two different types of turbine engines, it was found that the CFM 56-3B1 engine shows a higher level of reliability and efficiency than the PW 124B/127F engine. Moreover, in addition to factors of a structural-technological nature, the applied maintenance concept and component resource levels are also significant elements, which can largely influence the effectiveness of the aircraft and its engine. Determining the level of achieved effectiveness gives the possibility of monitoring and quantification of the quality of system operation, expressed on the basis of the presented output characteristics.

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