Reliability Levels Estimation of JT8D-9 and CFM56-3 Turbojet Engines

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This paper deals with estimation of aircraft engine reliability level, based on the rates of significant engine events, including in-flight shut downs, technical delays caused by engine malfunction and engine unscheduled removals. Introducing relative rates of engine events as individual reliability indicators, the function of joint measure of engine reliability level is used in the form, which expresses the influence of engine reliability on safety and costs. Based on the total number of engine flight hours realized in given calendar period, the measure of achieved engine reliability levels is proposed. The model of aircraft jet engine reliability level estimation is applied on real data, recorded for JT8D-9 and CFM56-3 turbojet engines. The obtained results approve higher achieved reliability level of CFM56-3, as a high-bypass turbofan engine, in regard to the older type of JT8D-9 engine.

Keywords: *reliability level, aircraft engine, events rate, measures.*

1. INTRODUCTION

From the aspect of flight safety and costs, engine is undoubtedly one of the most important aircraft components. Therefore, airlines must pay special attention to the engine reliability performances. During the fleet utilization process, it is necessary to reach, monitor and maintain a required level of its reliability.

As engines are concerned, airlines are monitoring the events, which indicate manifestation of unreliability occurrences, related to flight safety, and/or airline operator costs. These events are mainly represented by engine in-flight shutdowns and engine unscheduled removals. The determination of corresponding rates of engine in-flight shut downs K_{IFSD} and unscheduled engine removals K_{PSM} is performed separately for each type of engine using relations [1]:

$$K_{IFSD} = 1000\frac{N_{IFSD}}{T_m}, \quad K_{PSM} = 1000\frac{N_{PSM}}{T_m}, \quad (1)$$

where N_{ISFD} – is the total number of in-flight shut down events, and N_{PSM} – is the number of engine unscheduled removals.

The total number of engine hours is: $T_m = n_m T_{FH}$, where n_m - is the number of the given type of engine per aircraft, and T_{FH} - is the number of total flying hours of the fleet of aircrafts with the given type of engine.

When discussing engine reliability level influence on the fleet operation process, it is often necessary to take into consideration. technical delays caused by the engine malfunction Corresponding rate of technical delays K_{TK}, monitored according to ATA-72 chapter, in relation to engine as a cause of delays per 100 scheduled take-offs is given as [1]:

$$K_{TK} = 100\frac{N_{TK}}{N_{BC}}, \quad (2)$$

where N_{TK} - is the number of technical delays ≥ 15 minutes in the observed time period and N_{BC} - is the total number of scheduled take-offs in the same time period, which are the sum of all revenue take-offs and all flight cancellations caused by any technical reason.

Previously mentioned rates of events represent engine unreliability features according to their meaning. In other words, if the given rates of events are lower, then the engine reliability level is higher, and from the viewpoint of reliability estimation, these rates of events can be treated as individual reliability indicators.

However, the overall estimation of engine reliability level should take into account the joint measure of reliability level. This joint measure is a function of individual indicators (rates of engine events), based on the analysis of their influence on flight safety, fleet operating capabilities and engine maintenance costs.

2. JOINT MEASURE OF RELIABILITY LEVEL

According to MSG-3 document [2] in the Systems Power plant Logic Diagram, evident functional failure was assigned in one of two basic categories: operating safety (if failure has direct adverse effect on flight safety) and operating capability (if failure has direct adverse operational effect).

Applied on aircraft propulsion system, the rate of engine in-flight shut downs is important when analyzing the influence of engine reliability on flight safety as the primary criterion of reliability level estimation. In order to understand the influence of engine reliability on operating capability more completely, it is necessary to

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include the rate of technical delays caused by engine malfunction and related to operatively as the second criterion of reliability level estimation. In addition to previous, the rate of engine unscheduled removals, as the third criterion of reliability level estimation, enables estimation of influence of reliability on maintenance costs.

The problem of establishing the joint measure of aircraft engine reliability level is essentially connected to the influence of engine reliability on flight safety and costs. A degree of this influence can be determined by introducing relative reliability measures related to accepted upper control limits. Application of relative measures is present in different problems and areas especially in the analysis of critical failures of high-reliability systems, such as aircraft turbine engines.

By assigning appropriate upper control limits, so-called alert values (A_{IFSD}, A_{PSM}, A_{TK}), to every rate of engine events (K_{IFSD}, K_{PSM}, K_{TK}), relative rates of engine in-flight shut downs, unscheduled engine removals and technical delays, are given by:

$$\overline{K}_{\mathrm{IFSD}} = \frac{K_{\mathrm{IFSD}}}{A_{\mathrm{IFSD}}}, \; \overline{K}_{\mathrm{PSM}} = \frac{K_{\mathrm{PSM}}}{A_{\mathrm{PSM}}}, \; \overline{K}_{\mathrm{TK}} = \frac{K_{\mathrm{TK}}}{A_{\mathrm{TK}}}. \quad (3)$$

The reason for accepting the upper limits of event rates as the alert values is the fact that exceeded alert values indicate a potential presence of systematic negative factors. From airliner's point of view, increasing and exceeding the limiting value of relative rates of events above 1, implies the necessity of undertaking certain maintenance and management activity, spending additional resources and increasing costs in fleet utilization process.

Based on relative reliability indicators, function of the joint measure of aircraft engine reliability level is used in the form that enables single-valued estimation of reliability level that integrates the influence of reliability on safety, operatively and maintenance costs. Introduction of this function is accomplished by the application of the event flow superposition principle [3], according to which the overall flow is equal to the sum of individual component flows, whereas the individual flows are included in overall flow by a degree of their influence on reliability level.

The function of overall relative coefficient of engine events $\overline{K}$, which includes the differences in quantitative influence of individual relative reliability indicators (relative rates of engine events) on overall reliability level, can be presented as:

$$\overline{K} = \frac{1}{n}\sum_{j=1}^{n} \overline{K}_j^{k_j}, \quad (4)$$

where $\overline{K}_j$ - is individual relative rate of j-th event, n - is the number of considered types of events and k_j - is a degree of influence of j-th relative reliability indicator on the overall reliability level.

Applying function (4) on relative rates of engine events, corresponding overall relative coefficient of engine events $\overline{K}_{\mathrm{m}}$ can be written in the form:

$$\overline{K}_{\mathrm{m}} = \frac{1}{3}\left(\overline{K}_{\mathrm{IFSD}}^{k_{\mathrm{IFSD}}} + \overline{K}_{\mathrm{TK}}^{k_{\mathrm{TK}}} + \overline{K}_{\mathrm{PSM}}^{k_{\mathrm{PSM}}}\right), \quad (5)$$

where k_{IFSD}, k_{TK}, k_{PSM} - are powers of the rates of in-flight shut downs, technical delays caused by engine malfunction and engine unscheduled removals, respectively.

The influence of engine reliability on flight safety is evaluated using the probability of in-flight shut down of such number of engines, for which the remaining number of operative engine(s) is insufficient for safely continuation of flight [4].

For Extended Range Operation With Two Engine Airplanes (ETOPS), product of in-flight shut down rate of second engine and diversion flight time after the failure of the first engine, presents the complete propulsion system failure probability [5]. Following recommendations of ETOPS rules the analysis of engine reliability influence on flight safety [4] showed that the power of relative rate of in-flight shut down is: $k_{\mathrm{IFSD}} = 2$.

The analysis of relation between relative rates of engine events and direct operating costs, applied on linear model of dependence between costs and number of technical delays [6] and unscheduled engine removals, showed that: $k_{\mathrm{TK}} = 1$ and $k_{\mathrm{PSM}} = 1$.

Therefore, the overall relative coefficient of engine events, according to relation (5), can be calculated as:

$$\overline{K}_{\mathrm{m}} = \frac{1}{3}\left(\overline{K}_{\mathrm{IFSD}}^{2} + \overline{K}_{\mathrm{TK}} + \overline{K}_{\mathrm{PSM}}\right). \quad (6)$$

3.1 Achieved engine reliability level

Reliability parameters introduced in previous consideration actually express engine unreliability features, which is acceptable from the viewpoint of reliability level estimation. It can be concluded that inverse relation exists between derived overall relative coefficient of engine events and engine reliability level.

From the aspect of reliability level evaluation, the problem of adopting appropriate function, which represents the joint measure of aircraft engine reliability level $\overline{r}_{\mathrm{m}}$, can be reduced by selecting a function that satisfies the following general conditions:

$$\overline{K}_{\mathrm{m}} = 0 \;\Rightarrow\; \overline{r}_{\mathrm{m}} = 1 \quad \text{and} \quad \overline{K}_{\mathrm{m}} \to \infty \;\Rightarrow\; \overline{r}_{\mathrm{m}} \to 0 .$$

Therefore, proposed function of the joint measure of engine reliability level can be presented in the following form:

$$\overline{r}_{\mathrm{m}} = \frac{1}{1+\overline{K}_{\mathrm{m}}} . \quad (7)$$

Previous relations indicate that the exponent of relative rate of in-flight shut downs confirms dominant influence of safety comparing to the costs, in the case of exceeding upper limit of alert value, or more precisely when $\overline{K}_{\mathrm{IFSD}} > 1$. Proposed joint reliability measure enables airliners to monitor the overall engine reliability level, but it should be emphasized that this function of joint measure states reliability level for accepted alert values and for given engine maintenance program.

In practice, the determination of mentioned reliability indicators is usually done in successive time intervals, where for the i-th interval it can be written:

$$\overline{r}_{\mathrm{m}.i} = \frac{1}{1+\overline{K}_{\mathrm{m}.i}}, \qquad (8)$$

where $\overline{K}_{\mathrm{m}.i}$ - is overall relative coefficient of engine events for the *i*-th interval and $\overline{r}_{\mathrm{m}.i}$ - is joint measure of engine reliability level for the *i*-th interval.

The value of joint measure of engine reliability level can be treated as instantaneous value of engine reliability level in the observed time interval. Moreover, it can be noticed that maximum value of engine reliability level can be $\overline{r}_{\mathrm{m}.i} = 1$ in any i-th time interval, if there was not engine events occurrence during the same time interval.

If the observed calendar period of engine exploitation is divided into certain number of basic calendar units (usually one month) – equal to n, then engine reliability level achieved in observed calendar period $\overline{R}_{\mathrm{m}}$ can be presented in the form:

$$\overline{R}_{\mathrm{m}} = \frac{1}{T_{\mathrm{m}}}\sum_{i=1}^{n}\overline{r}_{\mathrm{m}.i}\cdot T_{\mathrm{m}.i} \ \text{ for } T_{\mathrm{m}} = \sum_{i=1}^{n} T_{\mathrm{m}.i}, \qquad (9)$$

where $T_{\mathrm{m.i}}$ - is the number of engine flight hours realized in i-th calendar unit and T_{m} - is cumulative number of engine flight hours (i.e. observed number of engine flight hours), which are realized in the observed calendar period.

The expression specified for achieved engine reliability level (9), represents the relation between the average value of engine joint reliability level measure and adopted reference value of fleet utilization during the period. The reference value given in expression (9), represents the total number of engine flight hours, realized during fleet utilization process according to scheduled timetable in the observed calendar period.

Using the chosen reference value of total number of engine flight hours, the evaluation of achieved engine reliability level gains comparative value when estimating manifested characteristics for different types of engines, irrespective of the type of aircraft on which these engines are installed. Based on the shown approach to the problem of jet engine reliability level estimation, in the following, the values of reliability levels of JT8D-9 and CFM56-3 engines are determined.

3. RELIABILITY OF JT8D-9 AND CFM56-3 ENGINES

Source data, used as example for engines reliability level estimation, are obtained from experience of one airline operator, and are related to the following types of turbojet engines: JT8D-9 installed on two-engine DC-9-30 and three-engine B-727-200 airplanes, and CFM56-3 installed on two-engine B-737-300 airplane.

Pratt&Whitney JT8D-9 is a twin-spool engine, with low-bypass ratio (1.03), and this model has two versions JT8D-9 and JT8D-9A, with similar performances.

JT8D-9 engine design is accommodated for maintenance procedures of single-independent engine modules. The primary maintenance concept of this engine is HT (Hard Time), but it is supplemented by OC (On Condition) engine performance monitoring process.

Hard Time process includes classical form of shop inspection & restoration works, at predefined time intervals with given tolerances. It is supplemented by On Condition engine performance monitoring in order to help predictive detection of need for premature (pre time limit) engine removal, before engine failure occurs during flight operation, and to help flexible time limits (within tolerances). That helps easier engine scheduled works planning.

CFM International CFM56-3 engine is the first updated model of CFM56 family, specially designed for second generation of Boeing airplanes for short and middle range airline operations (B-737-300/400/500). Constructively, CFM56-3 is a two-shaft turbofan engine, with high-bypass ratio (6.0) and comprises three versions, where CFM56-3B1 is considered here.

Modular designed CFM56-3 engine is divided into 4 main modules, with altogether 17 shop modules, enabling module replacement on the line maintenance level, without engine removal. Maintenance of this engine is based on OC (On Condition) primary process, according to which module operation is accomplished without previously determined time limit, until allowed by module state. Certain components (LLP-Life Limited Parts) on CFM56-3 engine are subjected to limitations regarding running hours and must be replaced in shop before their life expired. Merging modular design of this engine with OC maintenance concept and high values of LLP life limits, reduces the number of shop works and achieves higher quality of utilization process.

The elements of OC process, involved in maintenance concepts of JT8D-9 and CFM56-3 engines are provided by monitoring, recording and analyzing the changes of engine performance parameters during flight, conducting checks on the ground, and applying engine reliability monitoring program.

Reliability level estimation of described engine types is based on real fleet utilization data, for certain calendar period. Input source data were taken from monthly cumulative empirical data recorded monthly in the calendar period from 1985 until 2000 by an airline operator, which operated mentioned engine models on mentioned aircraft types (Table 1).

Table 1. Input data contents

Fleet data	
Flying hours for fleet with given type of aircraft	T_{FH}
Number of engines per given type of aircraft	n_{m}
Total number of scheduled take-offs	N_{BC}

Engine data	
Total number of engine hours	T_{m}
Number of in-flight shut down events	N_{IFSD}
Number of engine unscheduled removals	N_{PSM}
Number of technical delays ≥ 15 minutes (ATA 72)	N_{TK}

For calculating the values of engine events rates according to expressions (1) and (2), and FAA AC 120-42A and JAR Information Leaflet No.20 (Temporary Guidance Material for ETOPS, Airplanes ETOPS Certification and Operation) requirements, the 12-month rolling average method is applied, obtaining the change which adjusts to variation of events flow and may potentially indicate the overall trend of change. Besides, according to mentioned requirements for Upper Control Limit of engine in-flight shutdown, the requirement for 120-minute ETOPS operations is adopted ($A_{\mathrm{IFSD}} = 0.05$).

Upper Control Limits for rates of unscheduled engine removals and technical delays caused by engine malfunction are determined according to the relation $A_j = K_{j.\mathrm{sr}} + 3\sigma_{j}$ j, for the j-th type of event. Additionally, arithmetic mean of j-th event rate $K_{j.\mathrm{sr}}$ and standard deviation σ_j, were determined at the beginning of each calendar year, based on the overall exploitation period, and are used during a given calendar year according to:

$$K_{j.\mathrm{sr}} = \frac{1}{m}\sum_{i=1}^{m} K_{j,i} \text{ and } \sigma_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(K_{j,i} - K_{j.\mathrm{sr}})^2} ,$$

where m - is the number of months from previous time period included in the arithmetic mean.

Thereby, the influence of annual variations, as a result of occurrences of irregular conditions during exploitation, is decreased. The calculation of relative events rates was performed according to the relations (3), for corresponding values of Upper Control Limits, determined in previously showed manner.

Considering the dynamics of introduction of *B-737-300* with CFM56-3 into the airline operator fleet, the following considerations deal with the calendar period from 1988. Calculation of overall relative coefficients of engine events per calendar months $\overline{K}_{\mathrm{m}.i}$ for JT8D-9 and CFM56-3 engines (Figure 1) is performed according to the relation (6).

It should be emphasized that overall relative coefficients of engine events are following the overall trend of change of individual relative rates of engine events.

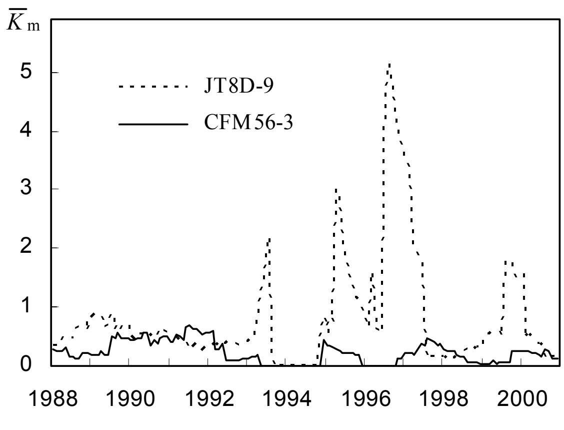

Figure 1. Overall relative coefficient of engine events

The influence of relative rate of in-flight shut downs, dominates in the case of JT8D-9 engine, comparing to CFM56-3, where there dominates the influence of relative rate of technical delays caused by engine malfunction.

Joint measure of engine reliability level per calendar months $\overline{r}_{\mathrm{m}.i}$, determined according to the relation (8), represents the base for determination of achieved engine reliability level value. Achieved engine reliability level $\overline{R}_{\mathrm{m}}$ was calculated according to the relation (9), referring to the total number of engine flight hours as a reference value of engine in flight utilization process, for total flight time realized for *DC-9-30* and *B-727-200* fleet with JT8D-9 (Figure 2) and *B-737-300* fleet with CFM56-3 (Figure 3).

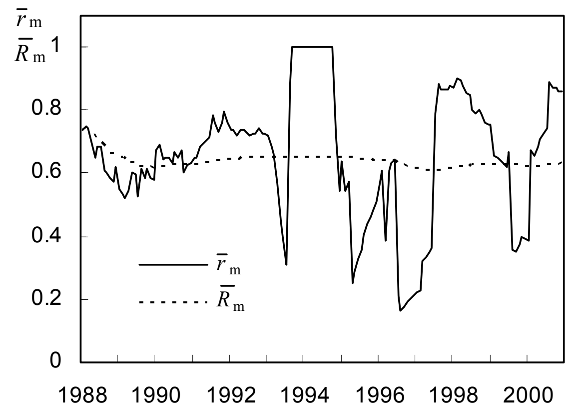

Figure 2. Achieved engine reliability levels of JT8D-9

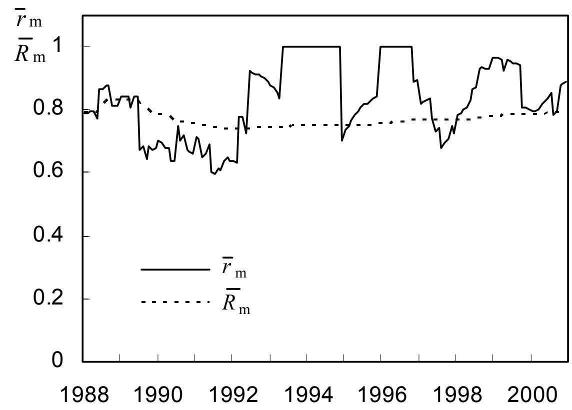

Figure 3. Achieved engine reliability levels of CFM56-3

It can be noticed that joint measure of engine reliability level, as instantaneous value, reaches maximum (i.e. $\overline{r}_{\mathrm{m}.i} = 1$) in certain calendar unit intervals, in which unscheduled engine removals, technical delays caused by engine malfunction or engine inflight shut downs did not occur. According to the established dynamics of fleet utilization process of the observed airline operator, these calendar intervals pertain to the period of low accomplished flight hours values, low fleet utilization and small number of engine events.

This explains high value of joint measure of engine reliability level, which just because of small value of realized flight hours does not have significant influence on achieved reliability level. Achieved engine reliability level, according to accomplished engine flight hours, has relatively high value, shows sensitivity, and follows the trend of change of joint measure of engine reliability level, as instantaneous value.

Additionally, it should be emphasized that proposed measure of achieved reliability level has comparative value and forms real basis for comparison of different engine types, which can be seen from the ratio between achieved reliability levels for considered engine types (Figure 4).

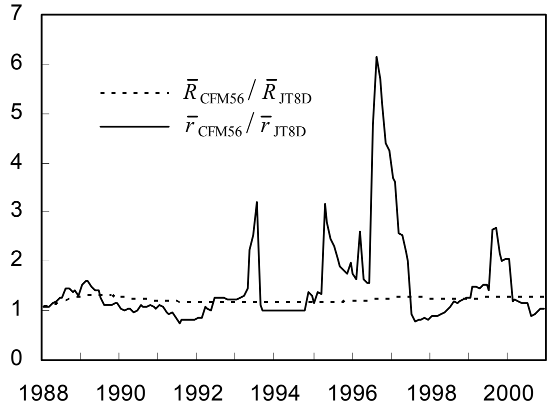

Figure 4. Achieved engine reliability levels ratio

4. CONCLUSIONS

The ratio of achieved engine reliability level values shows that CFM56-3 exerts higher reliability level as compared to JT8D-9 during exploitation, whereas the value of this ratio is approximately 1.2, for the observed calendar time period. This conclusion presents the logical result of not only the differences in design between given engines, but also of the logistic component presence, referre to differences of primary maintenance processes applied.

Determination of achieved engine reliability level, gives the possibility of simplified monitoring and quantification of a system utilization process quality. Proposed measures of engine reliability level can be directly applied in airline operator reliability programs, based on data from common Fleet Reliability Statistics Reports. Certainly, airline operators, according to acquired experience and their requirements, can establish their own degrees of significant operational events rates influence on reliability level estimation criteria. Also, it should be emphasized that proposed measures state reliability level for previously accepted alert values.

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ОЦЕНА НИВОА ПОУЗДАНОСТИ ТУРБОМЛАЗНИХ МОТОРА JT8D-9 И CFM56-3

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Овај рад обрађује оцену нивоа поузданости мотора ваздухоплова, на основу степена појаве значајних догађаја током експлоатације мотора, као што су гашења мотора у лету, кашњења из техничких разлога због неисправности мотора и непланирана скидања мотора са авиона. Увођењем релативних степена појаве ових догађаја, као појединачних показатеља поузданости, искоришћена је функција заједничког измеритеља нивоа поузданости мотора, у облику који изражава утицај поузданости мотора на безбедност и трошкове. На основу укупног броја часова рада мотора, који је остварен у датом интервалу времена, предложен је измеритељ оствареног нивоа поузданости мотора. Модел оцене нивоа поузданости мотора ваздухоплова, примењен је на реалним подацима за турбомлазне моторе типа JT8D-9 и CFM56-3. Добијени резултати потврђују виши ниво поузданости турбомлазног мотора CFM56-3 са високим степеном двоструjности, у односу на старији тип JT8D-9 мотора.