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THE USE OF SOFTWARE “VIRTUAL ENGINE” FOR TIMELY GAS-TURBINE ENGINE FAULT LOCALIZATIONS

F.D. Golberg[1], M.P. Sokolov[1], V.E. Volkov[1] & A.A. Petukhov[1]

[1]Central Institute of Aviation Motors

Abstract

A method for localizing an engine damage using its onboard thermogasdynamic simulation model (OESM), which is used in the automatic control system for engine control and health monitoring, has been developed.

Keywords: onboard engine simulation model, engine health monitoring, mathematical model identification

1. Introduction

One of the most demanded task of engine diagnostics is to localize the damage of its individual components. Timely information about the source of the fault would not only increase an operational safety, but would also provide a significant reduction in the amount of time for detecting and solving problems, and therefore would make an engine maintenance and repair more economical. However, localization of faults according to the list of parameters monitored on the engine in operation seems to be a fairly challenging task. In most cases, non-destructive testing equipment such as endoscopes, vibration and oil analysers, etc. continue to be used to detect the source of problems when engine parameters deviate from its normal values. The application of such equipments almost always offers exact information about engine failures and malfunctions, but requires additional labor-intensive works which should be carried out with certain intervals. The recognition of a certain part in engine flow path where the malfunction has happened would make the GTE maintenance much faster and cheaper. This could be possible by using the software "virtual engine" - an onboard engine simulation model (OESM). It is the thermo-gas-dynamic real-time mathematical model that calculates engine cycle parameters in all its operating conditions. The application of such models is considered as an opportunity to significantly improve the GTE performance [1]. The current computational level of modern digital automatic control systems (ACS) allows to use such models in their software. In this paper, we investigate the possibility of using OESM to recognize an exactly unit of an engine flow path where the abnormality has occurred. It is worth noting that a number of papers [2, 3] are devoted to the application of models for engine health monitoring, but they do not set the challenge of localizing the damaged engine unit.

2. The methodology for detecting a damaged engine unit

The methodology for identifying a faulty unit is based on the fact that any damage to the engine part causes its performance to deteriorate and differ from the performance contained in the OESM. In this case, with the same control factors (fuel flow G_F, guide vanes angle ϕ_C, etc.), which are input parameters for both the engine and the OESM, there is a difference between the engine cycle parameters (rotors speed n_C and n_F, compressor discharge pressure P^*_C, turbine exit temperature T^*_T) calculated by the model and their measured values. By the relation of these differences, it is supposed to detect the damaged unit.

2.1 A composite mathematical model of the engine

In order to develop such a method of identifying a damaged engine unit, a composite mathematical model has been formed, containing:

- a mathematical model of the studied GTE, simulating a "real" engine;

- a mathematical model of the “real” engine ACS;
- OESM built in the ACS (“virtual engine”);
- the block of algorithms for recognition a damaged engine part, containing a module for comparing measured parameters (X_i^{meas}) of the "real" engine with calculated values of the "virtual" engine parameters (X_i^{calc}) and a module recognizing a damaged part in terms of values, magnitudes and signs of differences $\Delta X_i = X_i^{meas} - X_i^{calc}$.;

Figure 1 illustrates the structural scheme of such model.

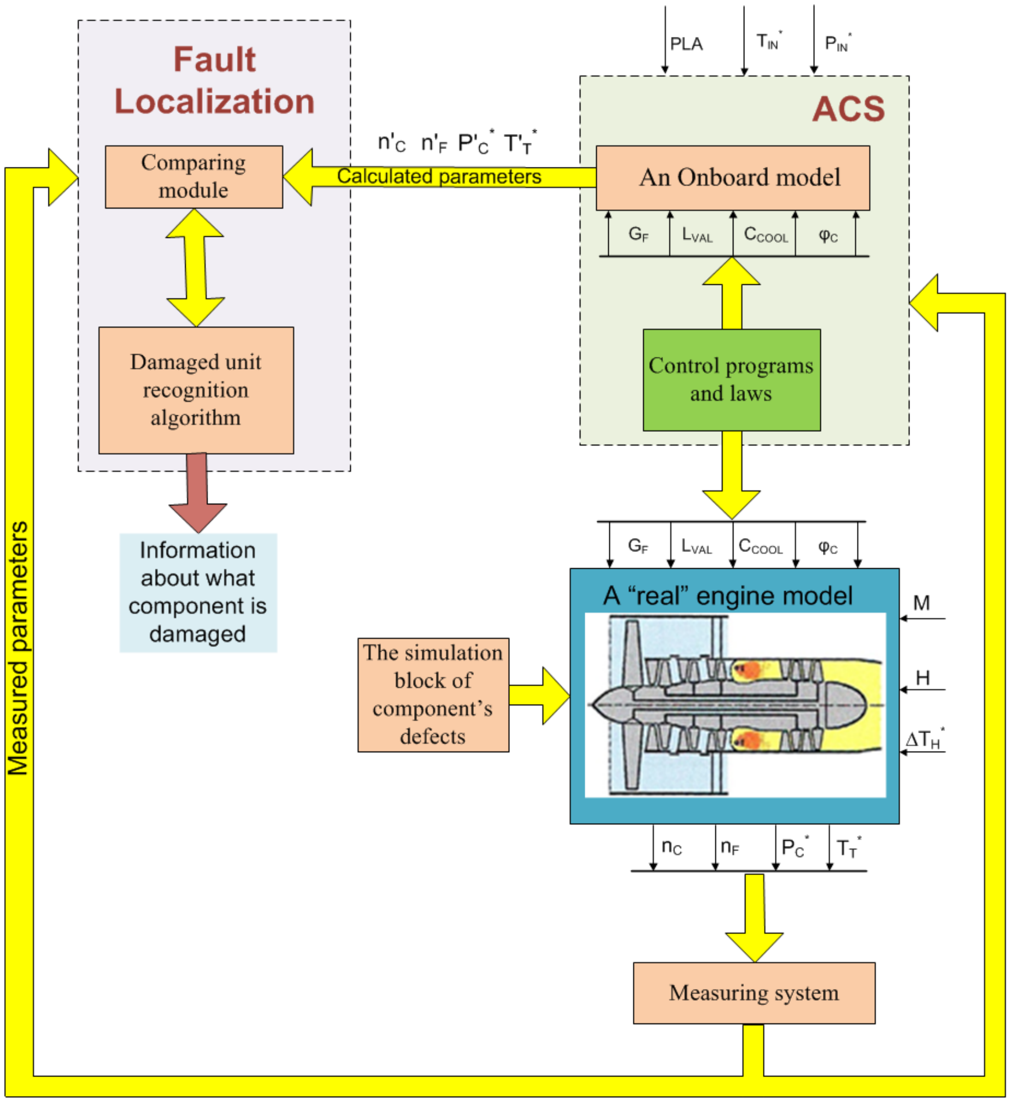

Figure 1 – The structural scheme of the composite mathematical model.

Damage simulation of the "real" engine major units (compressors, turbines, combustion chamber) at various engine power modes and under different flight conditions is carried out sequentially by deteriorating the basic performance of these units in its model:

- in impeller machines – a simultaneous decrease in efficiency and reduced air (gas) flow rate;
- in the combustion chamber – a simultaneous decrease in the fuel combustion efficiency and the stagnation pressure recovery factor.

After that, the measured parameters values (U_{ENG}) of the "real" engine model are compared with the calculated values (U_{MOD}) of these parameters determined by the OESM.

As a result of the investigations carried out with models described above, the sequences of relations allowing definite detection of a damaged unit have been determined for various engine types.

2.2 An algorithm to detect damaged engine unit

An example of an algorithm for such detection for a turbojet engine with a high bypass ratio is shown in Figure 2. Note that for a different engine configuration (turboshaft, afterburning, etc.), these relations and sequence would be different.

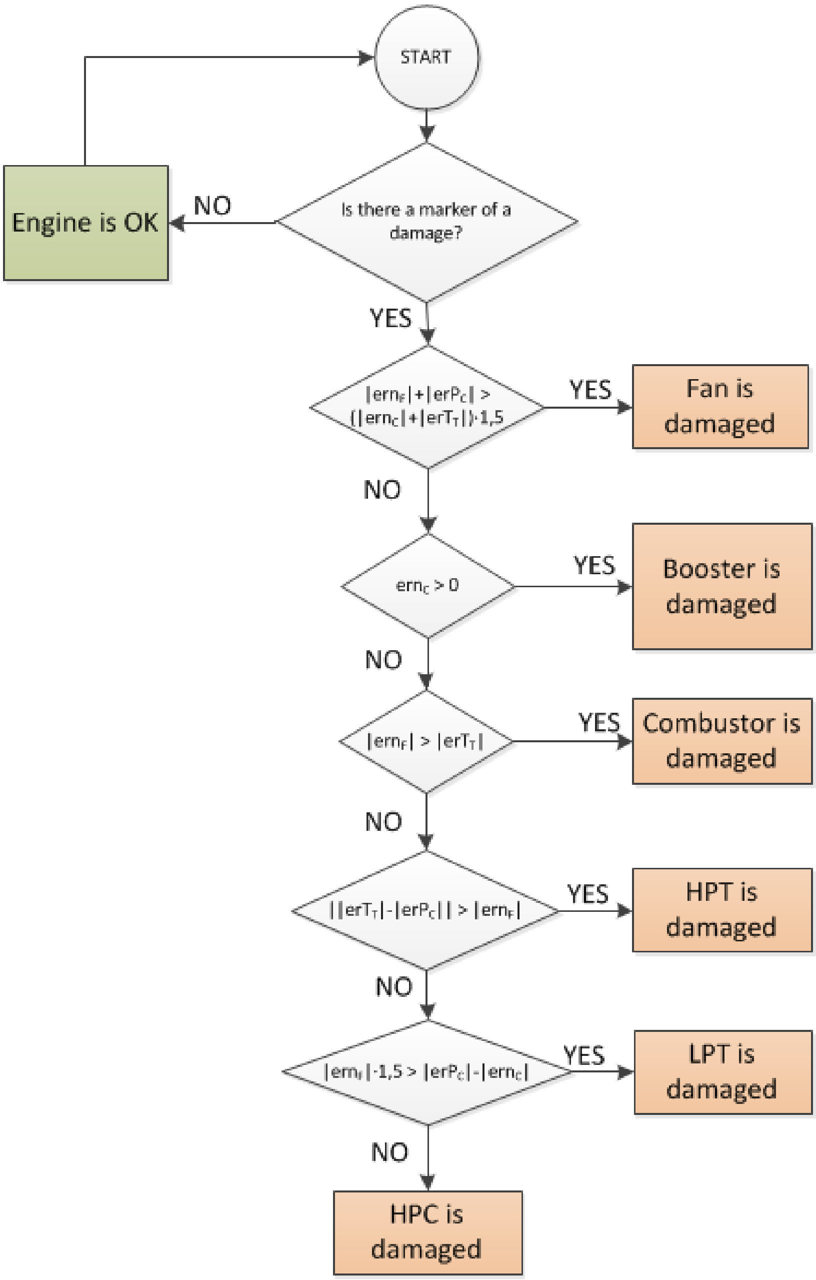

Figure 2 – An example of an algorithm for detecting a damaged unit.

The considered algorithm is implemented in the following way: if there is a symptom of fault in the GTE unit (in the example given, the difference of 4% or more between the measured and calculated values of engine parameters was considered as such a detector), the damage condition of any engine part is recorded. Then, according to this algorithm, the selected relations between the differences er_U of calculated and measured parameters, determined by the formula (1), are sequentially checked.

$$er_U = \frac{U_{ENG} - U_{MOD}}{U_{ENG}} \cdot 100\% \qquad (1)$$

If any of the ratios is satisfied, then the damage to the corresponding unit is recorded and the trouble-shooting stops. Otherwise, the next relation is checked.

The results of this calculation works gave reason to believe that there is the fundamental possibility to detect a damaged GTE unit using the OESM, where this algorithm can be implemented, and to further verify the method using data on the damage effects obtained from engines in operation. This is described in the next section.

3. Verification of the developed methodology according to operating data

In order to verify the developed methodology of damage unit recognition, a study based on flight data was carried out. To do this, we used the data from the turbofan engine in operation with information about change in the parameters of intact engines and engines with two types of typical malfunctions: damage and separation of compressor blades, and combustion chamber burnout. A mathematical model of studied turbofan was developed, similar to the OESM described in the previous section.

In total, the flights of 11 engines without detected faults, 5 engines with damaged HPC and 5 engines with damaged combustion chamber were examined. For each engine, there were from several hundred to several thousand flights during which damage of its components has appeared. The flight data was a set of frames recorded once per second with information about values of all major engine parameters.

While analyzing data for each engine from flights where it was probably intact (the first one or as close to it as possible) and probably damaged (the last one or as close to it as possible) a set of several dozens of consecutive frames corresponding to the flight at cruise or close to it mode was selected in a manner that when the engine parameters did not change, or their change did not exceed 0.5%. At the same time, we were looking for such frames where the fuel flow in the combustion chamber, the temperature and the pressure at the engine inlet were the same or had minimal differences for intact and damaged engine. Further, the values of the parameters in the selected frames were averaged and compared with each other. After analysing the results of these changes, an algorithm to detect the faulty unit (HPC or combustion chamber) similar to the one described in the previous point was developed.

This algorithm was tested using the developed demo software, which includes: a module for converting and reading flight data, a mathematical model of the examined engine, and an algorithm for determining a faulty unit.

A faulty unit is determined as follows: when reading flight data, it searched for the throttle position, high pressure rotor speed and flight altitude, indicating that the engine was operating in cruising mode or close to it. If the values of these parameters were within the specified limits and if there was an attribute of a steady-state mode, the values of the parameters registered in flight were compared with the parameters calculated by the model. If there was a marker of the damage, the ratio specified in the developed algorithm was checked. If it was satisfied, the combustion chamber failure counter was increased by 1, if not, the HPC failure counter was increased by 1. When any of the counters reached a prescribed value, the comparison of parameters was stopped and a message about the damaged engine unit was issued. If these conditions were not met when the end of the file was reached, the engine was considered to be in a good condition.

Confidence estimation of this algorithm through available flight data of engines with 2 types of common failures (damage to the HPC and burnout of the combustion chamber) and engines without failures reveals that the probability of type I errors (false decision about engine fail) is about 35%, and the probability of type II errors (false decision about the good engine condition) is about 30%. The use of the identification procedure for the mathematical model of the engine [4] helps to significantly reduce the percentage of first kind errors (up to 10%), because the difference between the calculated and measured parameters is often caused by a performance change due to the depletion of the engine lifetime, but not damage of its units. But the issue of reducing the number of second kind errors remains relevant, since the difference between calculated and measured parameters in case of engine unit damage was not always as big as it was accepted for starting detection algorithm. The next section describes how you can use the identification procedure to solve this problem.

4. Application of the engine mathematical model identification for localization of damaged unit

4.1 Identification methodology

An identification methodology that does not require significant computation capacity, comparable with required for model calculation, has been developed in CIAM [4]. According to this methodology, the identification is implemented by correction the initial performance of engine components, used as input data in the model. The identification procedure is designed in such a way that the difference between measured values of engine parameters and values of these parameters calculated by the OESM is automatically reduced to zero. Identification algorithms were developed on the basis of the feedback control approach used in typical digital control systems. According to this approach, the controlled target is the onboard model. Its control factors are engine components performance - values of efficiency and reduced flow rate of air or gas, etc ($G_{i\ RED}$, η_i, σ_i). The controlled variables are calculated values of measurable engine parameters. Their measured values are used as trim schedules of these parameters. The structure of identification loop is shown in Figure 3.

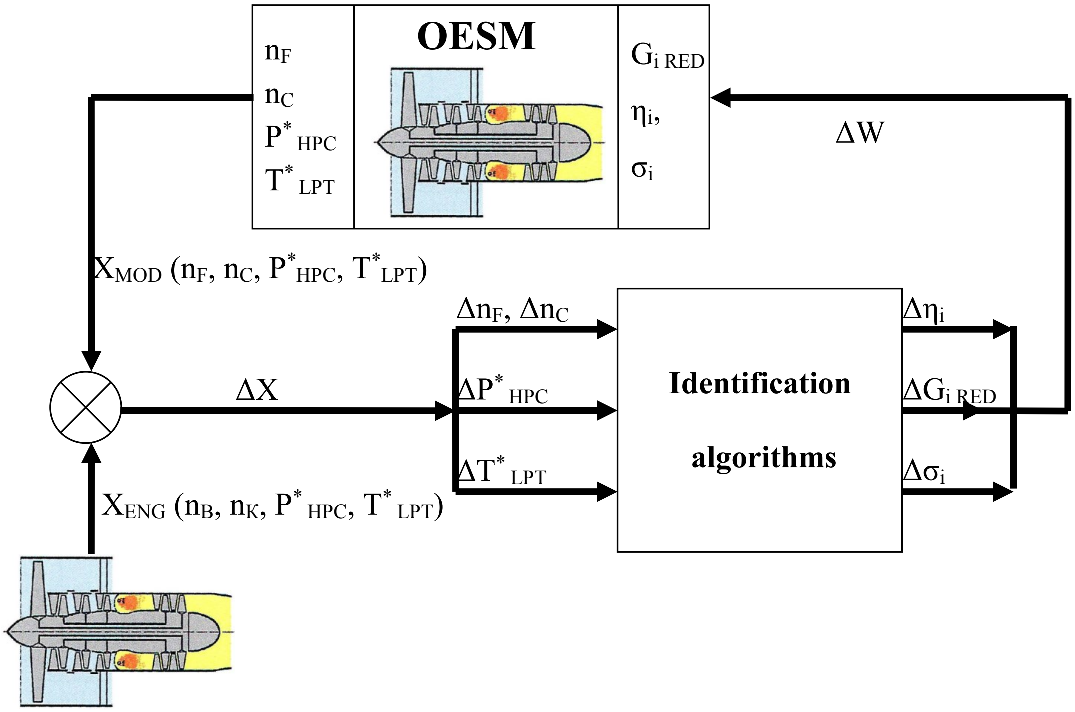

Figure 3 – Block diagram of the identification algorithm.

The identification algorithm works according to the following sequence:

- the differences (ΔX) between the measured values of control parameters and their corresponding calculated values are obtained:

$$\Delta X = X_{ENG} - X_{MOD} \tag{2}$$

- the correction signals (ΔW) are generated to impact the initial performance of engine units in mathematical model according to the relations of the form:

$$T_1 \cdot \frac{d^2\Delta W}{dt^2} + \frac{d\Delta W}{dt} = K \cdot (T_2 \frac{d\Delta X}{dt} + \Delta X) \tag{3}$$

- The correction of engine performance is carried out:

$$W = W + \Delta W \tag{4}$$

where X – control parameters of GTE, W – initial performance of engine units, T_1 – lag time constant, T_2 – lead time constant, K – gain.

4.2 Using the identification method to localize failures

To carry out the study in respect to mentioned operated turbofan, the most optimal relations (the influence coefficients) of the controlled (measurable) variables on identifiable non-measurable parameters under action on performance of various engine components (control factors) were determined. The selected identification algorithm was implemented in the developed mathematical model using the flight data of the engines with detected HPC damage. The parameter values from the flight data were selected at the modes satisfying the following conditions:

- Cruise mode, coming to that mode was checked according to the following condition: (PLA >= 32 **AND** PLA < 58 **AND** H >= 8500 m) **AND** t > 10 sec
- Steady mode, coming to that mode was checked according to the following condition: $(|G_{F\ t+1} - G_{F\ t}| < 0{,}05$ **AND** $|n_{C\ t+1} - n_{C\ t}| < 0{,}5$ **AND** $|T^*_{LPT\ t+1} - T^*_{LPT\ t}| < 3)$ **AND** $t > 100$ sec,

where t, t+1 – parameter value at the current and next second, respectively.

For all flight modes selected according to this algorithm, the average values of the parameters were calculated, which were entered into a 12xN dimension table, where N is the number of engine flights. The resulting table was passed to the input of the mathematical model identification algorithm. The output parameters determined by the mathematical model using these data are the difference between the measured parameters and calculated before the identification, as well as the "additions" (indicated by the index "add" in Figure 4) to the engine performance defined during the identification process. Only those identification loops worked that affect the efficiency of the impeller machines by reducing to zero the values ΔT^*_{LPT} and ΔN_F. Figure 4 shows the process of changing the parameters dn2, add HPC efficiency and add LPT efficiency during identification of the engine.

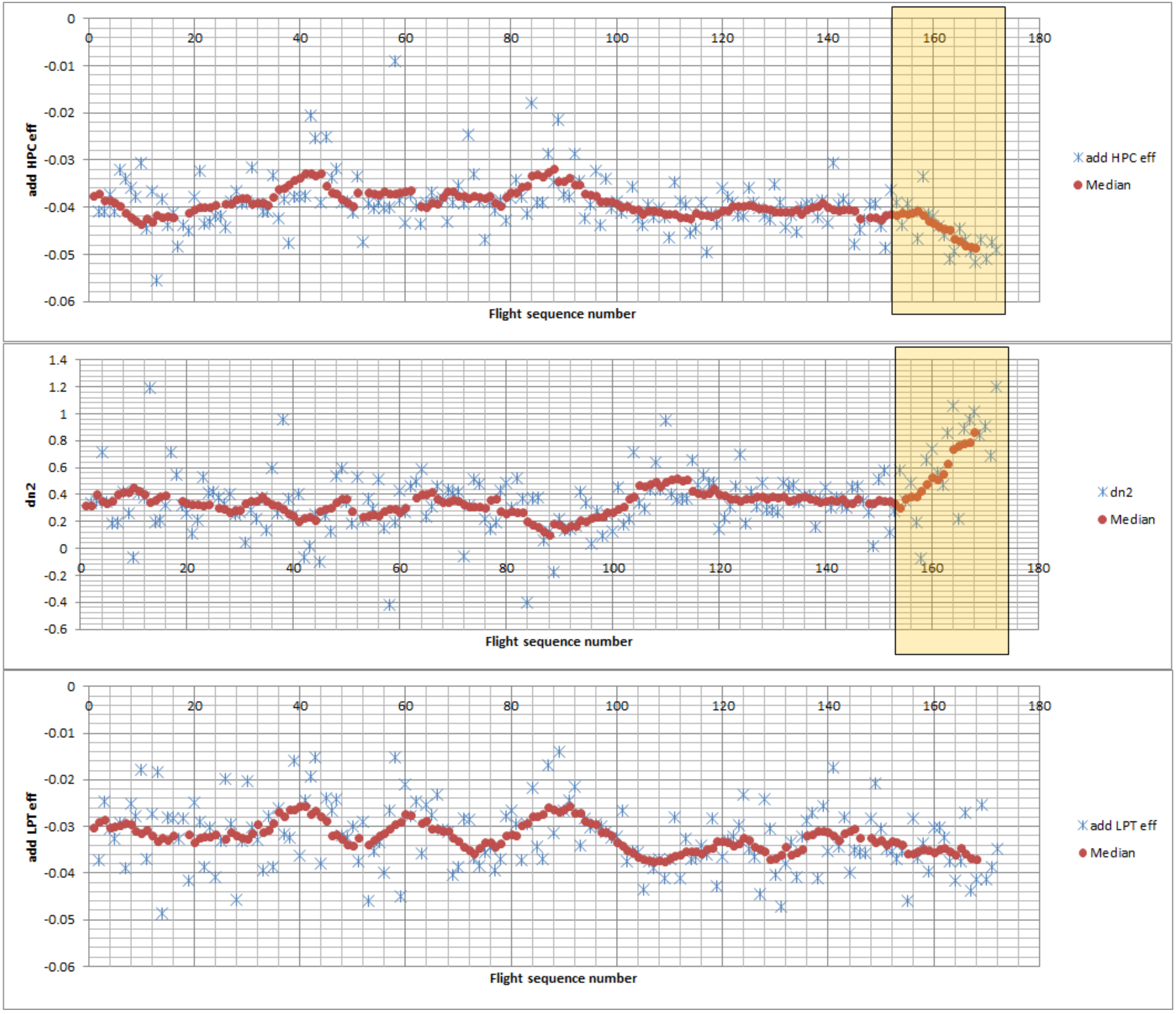

Figure 4 – Time variation of engine parameters during identification.

As is seen from the figure, in the last 15-20 flights, there is a simultaneous decrease in the required impacts on the HPC performance at their constant values for the LPT, and an increase in the calculation error in the high-pressure rotor speed dn2. Such parameters behavior is typical for 4 out of 5 considered engines with damaged HPC. Thus, the reliability of diagnostics according to the available experimental data is 0.8 (the ratio of the number of engines with a detected fault to the actual number of engines with faults).

The obtained value testifies to the satisfactory quality of diagnostics and the possibility of using information about a dramatic change in the impact on the GTE performance as a marker of failure detection. In the future, it is planned to test this method on a larger size of data – engines with various common malfunctions, as well as to test the method on data from intact engines.

5. Conclusions

As a result of computational studies carried out using the created composite mathematical model, algorithms for localizing the damaged engine unit for various GTE configurations have been developed.

The analysis flight data of turbofan engine in operation with damages of its flow path was carried out. Based on these data, the confidence estimation of the developed method for localizing the damaged unit was executed. It was revealed that identification procedure essentially improves the algorithm.

Based on the flight data of the engines with damaged HPC, the identification of the onboard turbofan model was performed using the previously developed methodology. The reliability of diagnosing the damage condition according to the available experimental data is 80%.

6. Contact Author Email Address

vevolkov@ciam.ru

7. Copyright Statement

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