NON-LINEAR OBSERVER OF SINGLE-ROTOR SINGLE-FLOW JET TURBINE ENGINE DURING OPERATION

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Abstract

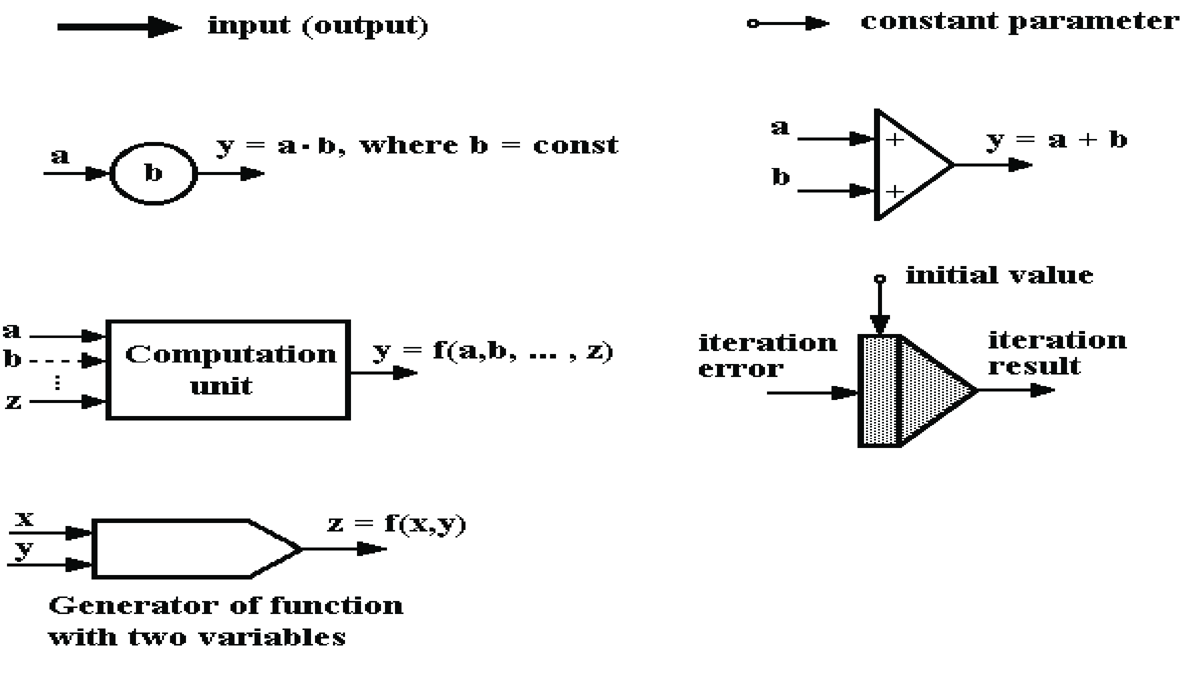
The paper presents a type of observer based on reduced to minimum set of engine parameters measured directly: turbine-compressor rotational speed, engine inlet air pressure and temperature and atmospheric pressure. Results of application in analysis of data recorded during engine operation in non-stationary states of SO-3 engine (powering TS-11 Iskra aircraft) are presented. Possibilities of this observer practical application in turbine engine parameters degradation monitoring during operation are also discussed. Proposed method of jet turbine engine's parameters degradation was not verified during real operation of an engine. Following actual knowledge, it should be verified scientifically. The easiest way is to use data from operation of a specific SO-3 engine.

Nomenclature

CC - combustion chamber
Cj - specific fuel consumption
Cp_{23} - average specific heat of the working medium in the combustion chamber
G2 - mass flow of the working medium at the compressor outlet
$G2_r$ - reduced mass flow of the working medium at the compressor outlet
G3 - mass flow of the working medium at the combustion chamber outlet
$G3_r$ - reduced mass flow of the working medium at the combustion chamber outlet
k_{34}, k_{45} - isentropic exponents
N - convergent nozzle
N - rotational speed of the spool
n_{sr} - reduced rotational speed of the compressor
n_{tr} - reduced rotational speed of the turbine
P0 - total pressure of the working medium at the engine inlet
P1 - total pressure of the working medium in front of the compressor
P2 - total pressure of the working medium behind the compressor
$P2_{start}$ - initial average total pressure of the working medium behind the compressor
$P2_{obs}$ - average total pressure of the working medium behind the compressor, calculated by means of the observer
P4 - total pressure of the working medium in the convergent nozzle
$P4_{start}$ - initial average total pressure of the working medium in the convergent nozzle
PH - ambient pressure
Q - rate of fuel flow
R - engine thrust
Rg - gas constant
t - time

T0 - total temperature of the working medium at the engine inlet
T1 - total temperature of the working medium in front of the compressor
T2 - total temperature of the working medium behind the compressor
T3 - total temperature of the working medium in front of the turbine
T4 - total temperature of the working medium behind the turbine
u_1, u_2 - errors of iteration
w_1, w_2, w_3 - factors of amplification of iterative loops
Wo - fuel calorific value
Wu - air bleed coefficient
ΔT12 - increment of total temperature of the working medium while flowing through the compressor
Π - pressure ratio (of the compressor)
ε - pressure ratio of the working medium while flowing through the turbine
ϕ - rate-of-flow coefficient of a convergent jet nozzle
η_{ks} - efficiency of the combustion chamber
η_t - isentropic efficiency of the turbine
σ_{23} - the total-pressure preservation coefficient for the combustion-chamber flow

Graphical symbols



1. Introduction

One of key problems in jet turbine engines monitoring during operation is problem of measurement of actual values of so called „not-measurable" or „difficult-to-measure" operation parameters, i.e. thrust or total temperature of working medium at the combustion chamber outlet. Especially difficult are measurements in non-stationary states of the engines. From this reason, in K-15 engine project for I-22 IRYDA aircraft different types of so called „non-linear observers" – special algorithms for calculation of „not-measurable" or „difficult-to-measure" parameters actual values based on properly selected sets of easily measurable parameters – were evaluated [7,8,9,10]. Observers may be used for on-line or off-line data processing; in second case values recorded in a special on-board digital data recorder are being processed. In this paper a special type of single-rotor single-flow turbine jet engine SO-3 powering TS-11 ISKRA aircraft is presented. This observer's characteristic feature is, that it is based on reduced to minimum set of parameters measured directly. In Author's opinion, this type of observer can be used successfully for engine's degradation monitoring during its controlled operation.

2. Nonlinear engine's observer

SO-3 engine has been used to Power TS-11 „Iskra" aircraft for many years. So there exists verified simulative model of that engine [8]. On the basis of that model, the observer, shown on figure 1, was elaborated. Its characteristic feature is that it can be used with minimum number of entry parameters (measured directly). Only environmental conditions, flight speed and temperature of the working medium in front of the compressor plus rotational speed of the spool (n) nad its first derivative (dn/dt) are necessary. The derivative can be measured directly with a special sensor, or can be obtained with calculations, by differential operations of rotational speed of the spool values (n). The second method is especially recommended in case of observer application in "off-line" data analysis.

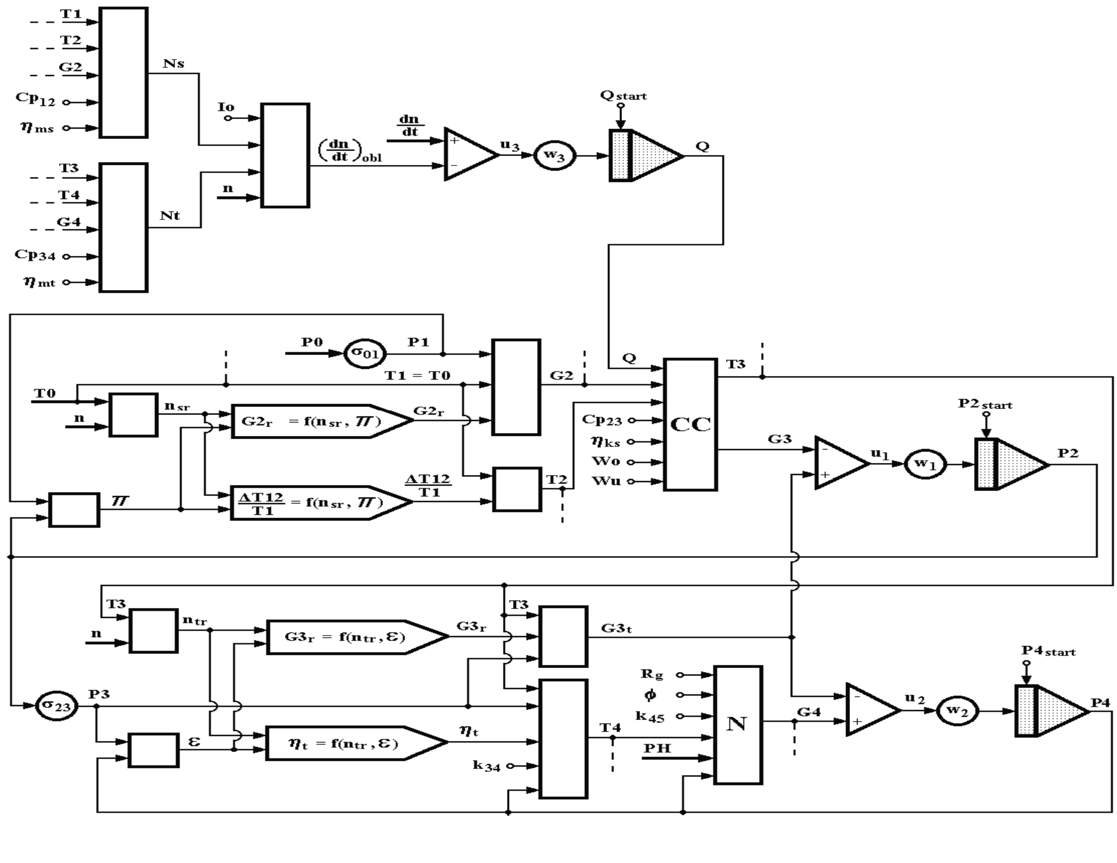


Fig. 1. Analog scheme of SO-3 engine non-linear observer

Fig. 2 is a graph of engine rotational speed as a function of time, recorded during Ground test (full acceleration and deceleration). Fig. 3 presents phase image of rotational speed derivative (dn/dt), obtained by differential calculations of results presented on Fig. 2, as a function of rotational speed (n). Values of both parameters as a function of time were used as entry signals for observer shown on Fig. 1.

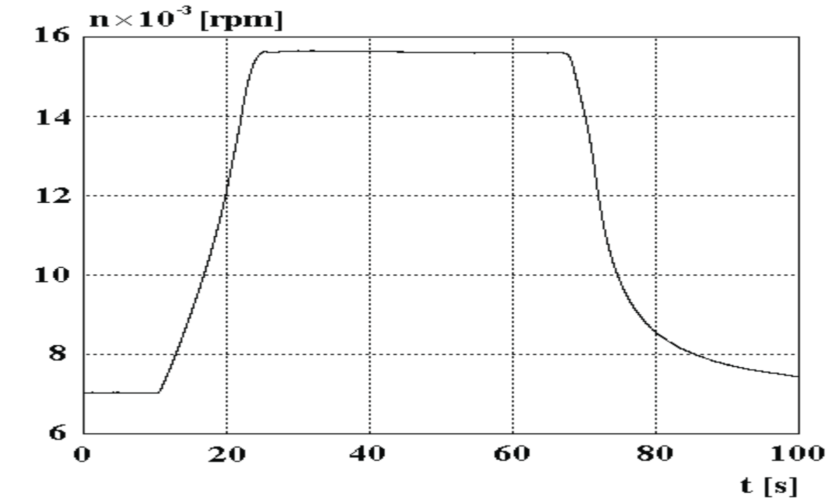


Fig. 2. Rotational speed of a spool of SO-3 engine during full acceleration and deceleration, recorded during ground test of the engine

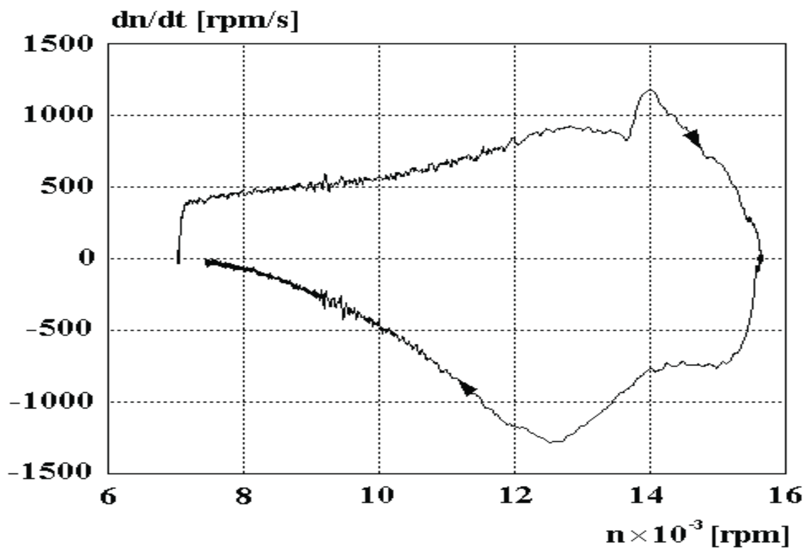


Fig. 3. Derivative of SO-3 engine rotational speed, during full acceleration and deceleration recorded during ground test, as a function of rotational speed

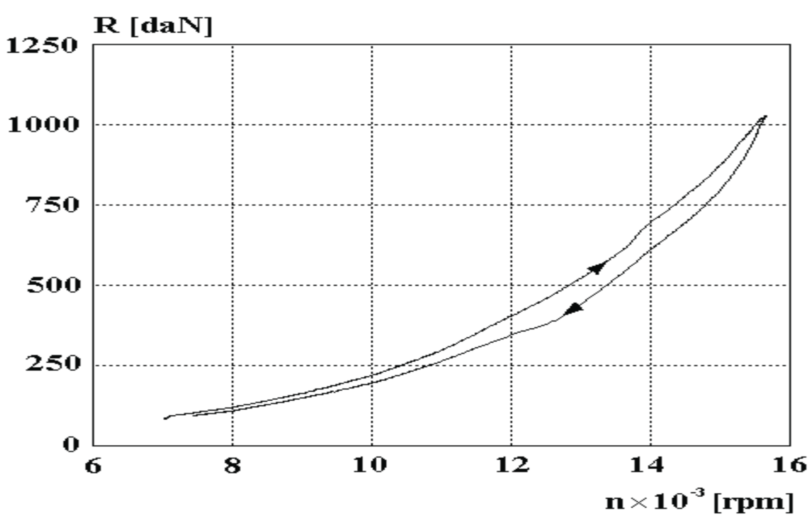


Fig. 4. SO-3 engine thrust during full acceleration and deceleration during ground test, calculated with the non-linear observer

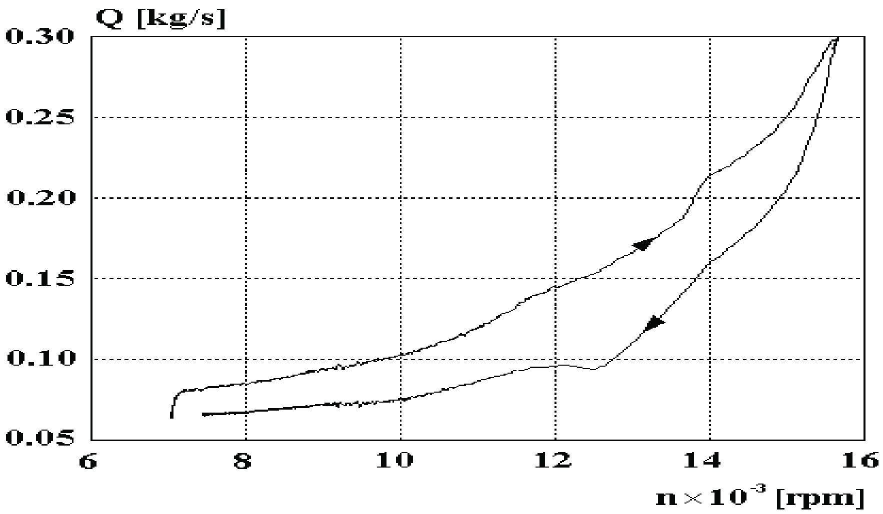


Fig. 5. SO-3 engine fuel flow rate during full acceleration and deceleration during ground test, calculated wit the non-linear observer

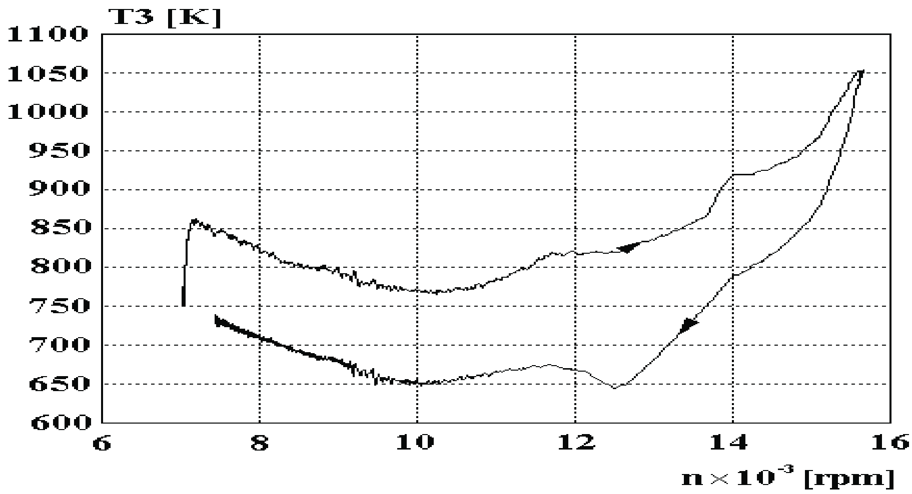


Fig. 6. Temperature of the working medium in front of the SO-3 engine's turbine during ground test, calculated with non-linear observer

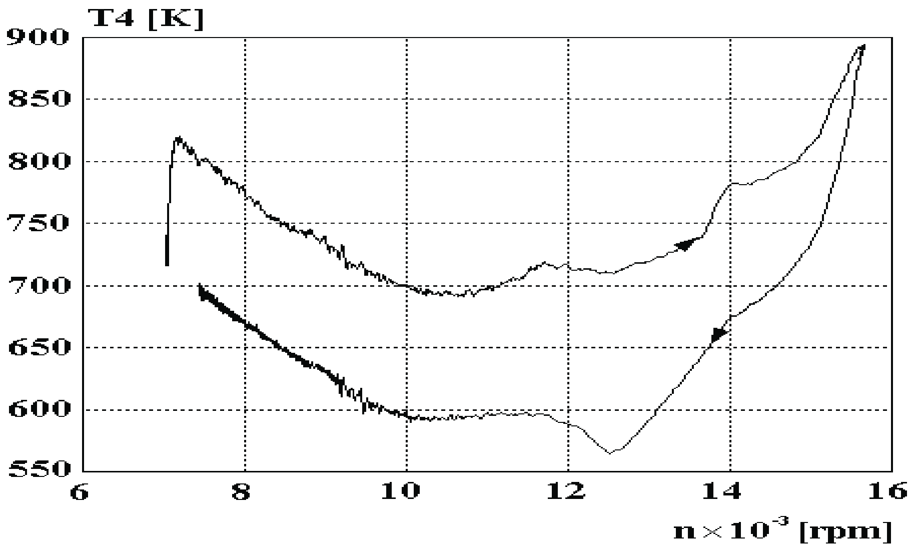


Fig. 7. Temperature of the working medium behind the SO-3 engine's turbine during ground test, calculated with non-linear observer

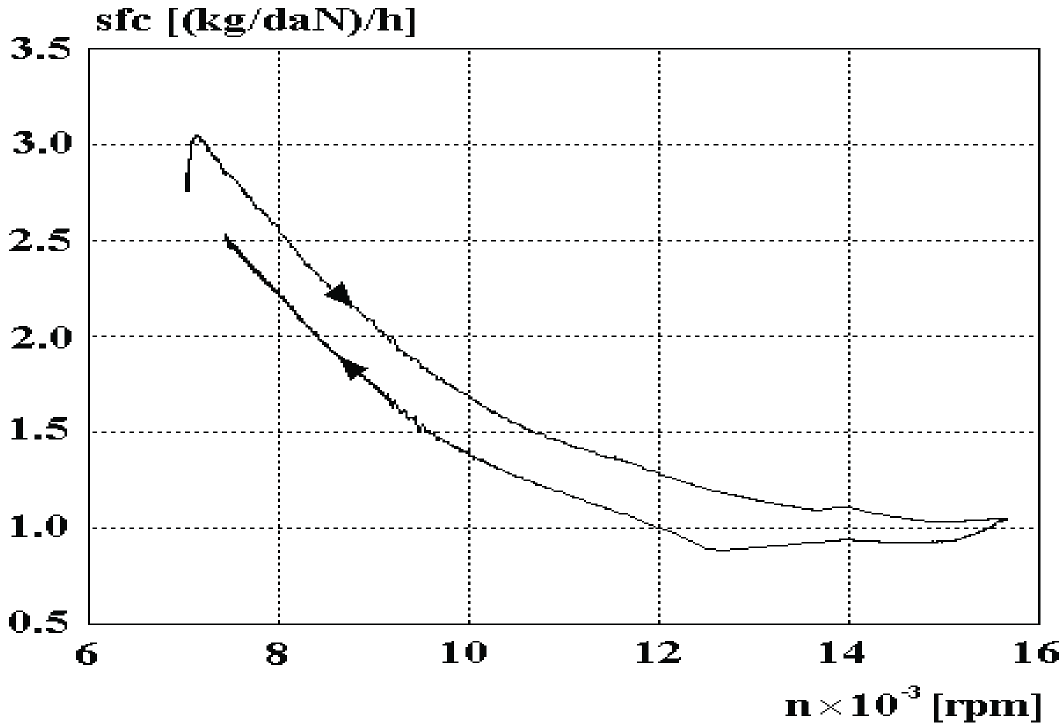


Fig. 8. Specific fuel consumption of SO-3 engine, during full acceleration and deceleration, calculated with the non-linear observer

Fig 4 - 8 present some SO-3 engine's parameters, obtained by described earlier data processing with non linear observer. Especially important application is observing non-measurable directly parameters, like temperature of the working medium in front of the turbine (T3) and engine thrust (R). Shown on fig.4 and fig.8 phase images of thrust and specific fuel consumption were obtained by transformations of entry and exit parameters of the observer.

3. Monitoring of engine degradation during its operation

Possible to observe degradation of turbine engines' parameters during their normal operation results from different reasons, and, shortly, the most important are:

- Geometric deformations of engine's hot sections, due to low cycle mechanical loads and thermal loads with big amplitudes [1].
- Deformation of thermal field of working medium at the end of combustion chamber [5]
- Geometric deformation of compressor and turbine blades resulting from foreign objects damages and erosion from particles in contaminated atmosphere.
- Geometric deformation of compressor blades as a result of contaminated atmosphere.

Geometric deformations of a structure cause increase of tip clearance of turbine's and compressor's blades as a result of contact with non-rotating parts, and decrease in labyrinth sealing quality.

Above mentioned phenomena result in decrease of engine's dynamic properties, especially increase of full acceleration time is observed [9].

In practice, evaluation of a degree of engine's parameters degradation is being done basing on a results of special ground test [10] or on a test bench. In case of ground tests, engine thrust is not being measured. It such case, degradation parameter is easily observed decrease of pressure ratio (*Π*) and increase of working medium temperature and specific fuel consumption. In case of tests on a test bench equipped with a system for thrust measurement, additionally decrease of maximum thrust is observed. In both cases, for the evaluation of a degradation degree, special activities are necessary, and as a result elimination of an aircraft from its operation.

In [1,5] it was shown, that simulative model of jet turbine engine can not precisely restore its dynamic properties. Engine's dynamic properties, especially time of full acceleration, depend on geometric deformations of construction structure and deformation of field of temperature at the end of combustion chamber – so depend on factors describing engine degradation. Described here algorithm of observer is functioning properly assuming that properties of all engine's elements are time invariant. Describing it in a different way, if differences between parameters' values calculated by the observer and values measured directly on operating engine are constant (time invariant), monitored in this way engine's characteristics are constant. Increase of differences, observed after a period of engine operation could be interpreted as a signal of engine's parameters degradation. Only specific criteria need to be defined..

Now criterion can be defined as follows:

$$WK_i = \int_0^t \left| W_s(t) - W_o(t) \right| dt;$$

where: WK_i – criterion of difference for one specific period of engine monitoring,
$W_s(t)$ – specific value of engine's real parameter,
$W_o(t)$ – specific value of a parameter calculated with the observer.

Criterion WK_i should be calculated for a period of time Δt_i, i.e. for one flight or engine operation during ground test. During engine monitoring, values calculated for each flight should be summed after each flight for cumulative value:

$$WK_{zak} := WK_0 + WK_1 + WK_2 + \dots WKi;$$

Every result after each flight or ground test should be placed on a graph presented on Fig.9.

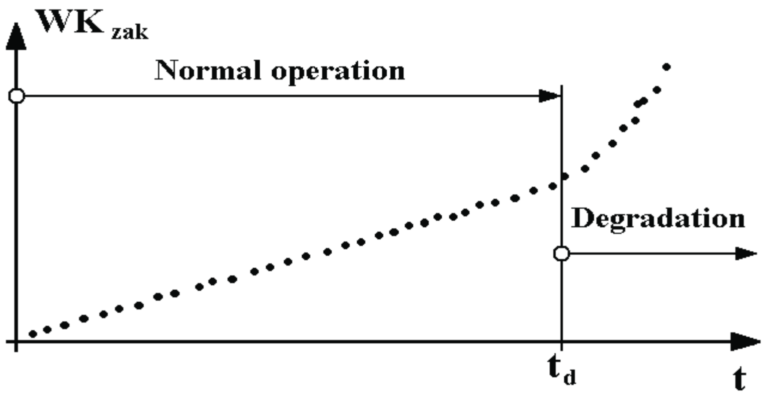


Fig. 9. Visualization of engine's parameters degradation

Engine operation without visible degradation of engine's parameters is characterized by measuring points laying on one straight line. Starting from t_d time the graph presents a hypothetic increase in differences between results of direct measurements of a parameter and its calculated values obtained with the observer, what is a proof for degradation of engine's parameters, according to above described proposition.

One of the most important is, that the observed parameter can not be temperature of the working medium in front of the turbine (T3) or temperature of the working medium behind the turbine (T4). The reason for this is, that actual values calculated with the observer do not contain dynamic errors, and directly measured values of the temperatures contain different to determine measuring errors [7].

4. Conclusions

Following conclusions are a scientific hypothesis:

- Proposed method of jet turbine engine's parameters degradation was not verified during real operation of an engine. Following actual knowledge, it should be verified scientifically. The easiest way is to use data from operation of a specific SO-3 engine.

- In Author's opinion, accuracy of such observer in proposed method is not an important matter, because symptom of engine's parameters degradation is not a value of difference between parameters measured directly and calculated with the observer, but expected value of increasing change of such differences.

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