PERFORMANCE OF THE ADVANCED AND SIMPLIFIED VARIANTS OF A NON-LINEAR OBSERVER OF A TURBOJET ENGINE, COMPARISON OF RESULTS

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Abstract

Non-linear observers have got great potentialities in the fields of turbojet engine control, monitoring and diagnosing. They may prove of particular suitability for measuring actual values of the so-called difficult-to-measure parameters, e.g. temperature of the working medium at the combustion chamber outlet, thrust, etc. For this reason, reliability and accuracy of results of the performance of observers should be given careful consideration. The paper has been intended to deliver comparison between results gained with two variants of a non-linear observer of the SO-3 engine. It has been assumed in the computational algorithm of the first variant that the working medium in the engine duct is a perfect gas. In the second variant, the working medium has been considered a semi-perfect gas. Both the variants of the observer have been tested using real data from tests of the SO-3 engine on a ground-based engine test bench.

Key words: *turbojet engine, mathematical modelling, non-linear observer*

Nomenclature

Cp_{12} - average specific heat of the working medium in the compressor duct
Cp_{23} - average specific heat of the working medium in the combustion chamber
Cp_{34} - average specific heat of the working medium in the turbine duct
D - convergent nozzle
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
G3t - reduced mass flow of the working medium through the turbine
I_o – polar moment of inertia of the spool of the turbine-compressor assembly
k_{12} – mean value of the isentropic exponent of the working medium in the compressor
k_{34} - mean value of the isentropic exponent of the working medium in the turbine
k_{45} - mean value of the isentropic exponent of the working medium in the nozzle
KS - combustion chamber
M - Mach number (here: air speed)
n - rotational speed of the spool
N_s - input power of the compressor
n_{sr} - reduced rotational speed of the compressor
n_{start} - initial rotational speed of the spool
N_t - turbine power
n_{tr} - reduced rotational speed of the turbine
Pi_1 – actual value of the ‘i’ parameter calculated with the non-linear observer no. 1

Pi_2 – actual value of the ‘i’ parameter calculated with the non-linear observer no. 2
P0 - total pressure of the working medium at the engine inlet
P1 - total pressure of the working medium in front of the compressor
$P2_{start}$ - initial average total pressure of the working medium behind the compressor
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
Pks_{start} - initial average total pressure of the working medium in the combustion chamber
Q - rate of fuel flow
Q_start - initial rate of fuel flow
R - engine thrust
Rg - gas constant
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
T3start - initial total temperature of the working medium at the combustion-chamber outlet
T4 - total temperature of the working medium behind the turbine
T4start - initial total temperature of the working medium in the nozzle
u_1, u_2, u_3, u_4, u_5 - errors of iteration
w_1, w_2, w_3, w_4, w_5 - factors of amplification of iterative loops
Wo - fuel calorific value
Wu - air bleed coefficient
ΔPi - percentage difference between actual values of the ‘i’ parameter, calculated by means of both versions of the observer
$\Delta T12$- increment of temperature of the working medium due to compression
Δt - interval of sampling the inputs and results of computations
Π - pressure ratio (of the compressor)
ε - pressure ratio of decompression of the working medium while flowing through the turbine
ϕ - rate-of-flow coefficient of a convergent nozzle
η_{ks} - efficiency of heat emission in the combustion chamber
η_{ms} - coefficient of mechanical efficiency of compressor
η_{mt} - coefficient of mechanical efficiency of the turbine
η_s - isentropic efficiency of the compressor
η_t - isentropic efficiency of the turbine
σ_{01} - the total-pressure-retention coefficient for the compressor flow
σ_{23} - the total-pressure-retention coefficient for the combustion-chamber flow

1. Introduction

The suggested variants of a non-linear observer of a one-spool turbojet engine [1, 2, 4, 6, 8] differ in their scopes of directly measured parameters. Among these variants one should be distinguished, i.e. one featured with that a minimum number of such parameters are required for the performance thereof [8]. These parameters are as follows: flight altitude (H), air speed (M), total temperature of air at the engine inlet (T0), rotational speed of the spool (n).

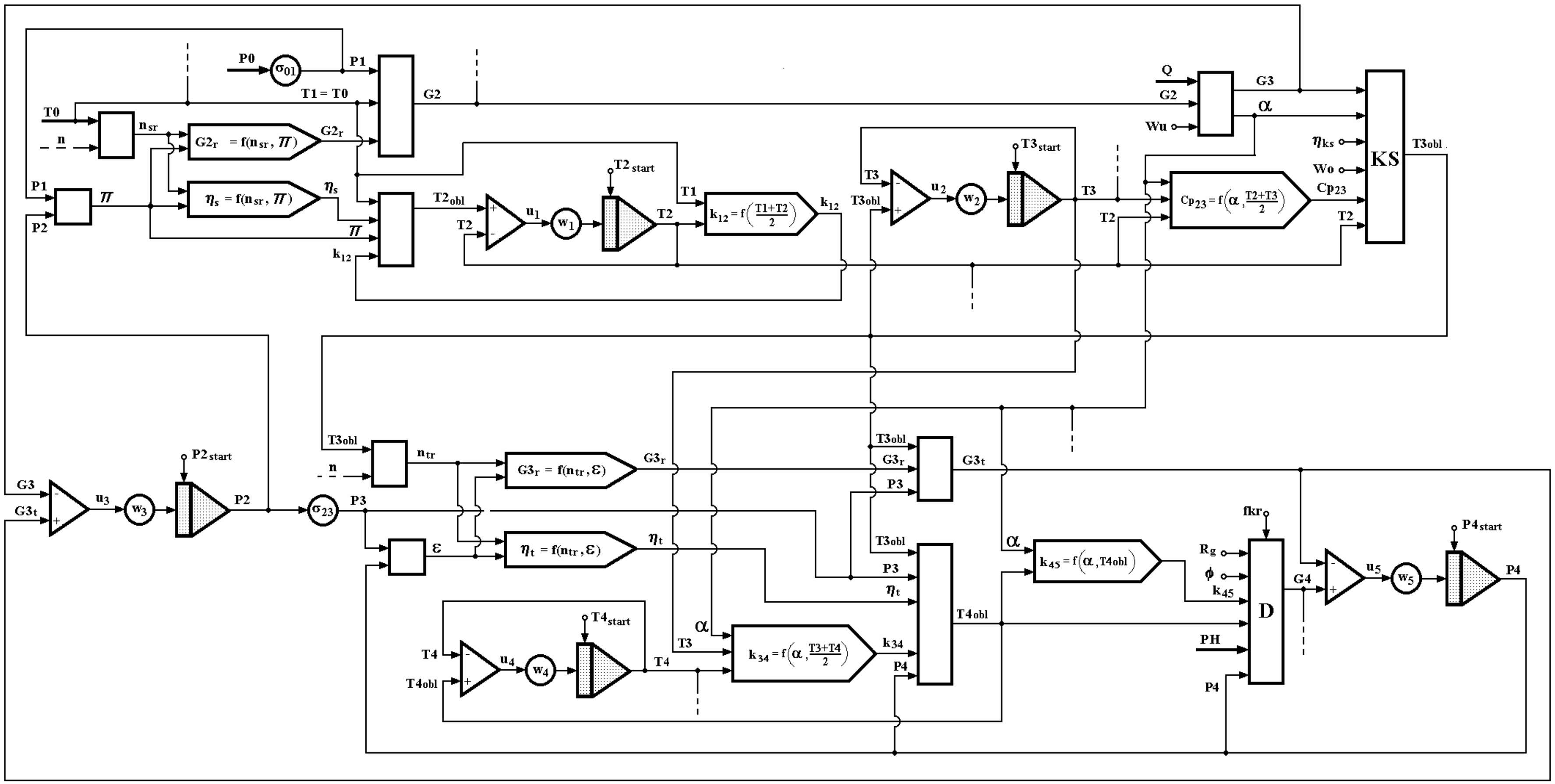

Fig. 1a. An analogue diagram of the observer no. 1. The block of the iteration-based solving of a system of non-linear algebraic equations that describe actual values of parameters of the working medium in the engine duct

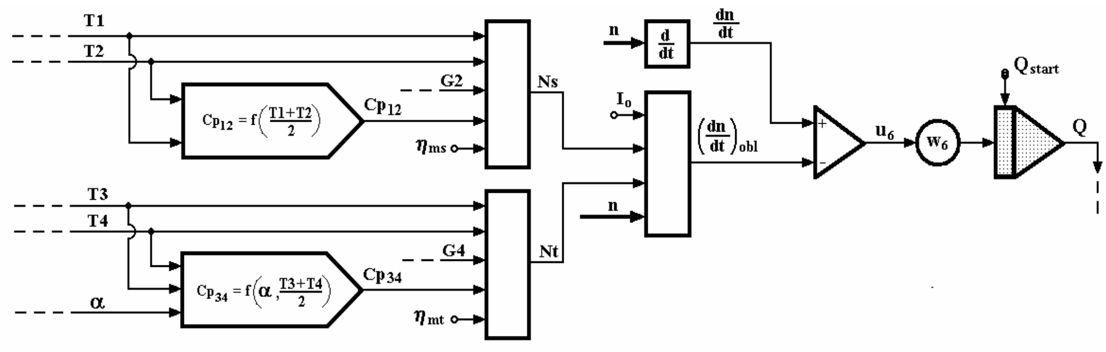

Fig. 1b. An analogue diagram of the observer no. 2. A block to calculate actual values of turbine power, compressor power, and the rate of fuel flow

In practice, there are a number of potential applications for this variant of the observer. Among other ones, the following should be mentioned:

- In procedures to monitor degradation of turbojet performance throughout the engine's operational use [5] – as the reference while evaluating the rate of degradation;
- In failure detection systems of sensors to control turbojet engine's operation – as comparative data to evaluate errors of measurements of engine parameters taken with digital electronic control systems of the FADEC class;
- In systems to automatically detect unstable operation of compressors of turbojets [4];
- In systems to detect other dangerous modes of turbojet's operation, e.g. uncontrolled flameout or incorrect shut-down.

The above-mentioned potentialities for practical applications of the observer generate demand for investigating into the accuracy of results gained with this observer. This paper has been intended to examine the effect of a simplifying assumption that the working medium in the engine duct is a perfect gas upon the observer's accuracy. Therefore, two versions of the observer have been developed for the same engine.

In version no. 1 it has been assumed that the working medium is a semi-perfect gas. In practice it means that variable values of specific heats (Cp) and isentropic exponents (k) have been assumed in equations which describe parameters of the working medium flow. Non-linear functions inserted in the observer's algorithm, which describe dependences of isentropic exponents and specific heats of the working medium on temperature and the excess-air coefficient have been shown in Figs 1a and 1b. Fig. 1a shows a diagram of the block intended for the iteration-based solving of a system of non-linear algebraic equations, which describe parameters of the working medium flow. Fig. 1b shows a diagram of the block intended to calculate an actual value of power generated by the turbine (Nt), input power of the compressor (Ns), and the rate of fuel flow (Q).

In version no. 2 isentropic exponents and specific heats of the working medium remain constant. The respective values are as follows: $k_{12} = 1.40$, $k_{34} = 1.33$, $k_{45} = 1.33$, $Cp_{12} = 1.0048$ kJ/(kg·K), $Cp_{23} = 1.0886$ kJ/(kg·K), $Cp_{34} = 1.1723$ kJ/(kg·K).

Simplifying assumptions made to satisfy the needs of a mathematical description of the observer are exactly the same as those made for the simulation-based model of the SO-3 engine [3]. To make this paper more consistent, it has been decided NOT to present all mathematical equations used to construct the algorithm. Instead, special attention has been paid to detailed presentation of analogue diagrams that illustrate the method of the iteration-based solving of the system of non-linear algebraic equations.

2. Results of the processing of data from the ground testing of the SO-3 engine

The intention was to compare results gained from the processing, with each of both versions of the observer, of exactly the same plot (Fig. 6) of how the rotational speed of the spool was changing.

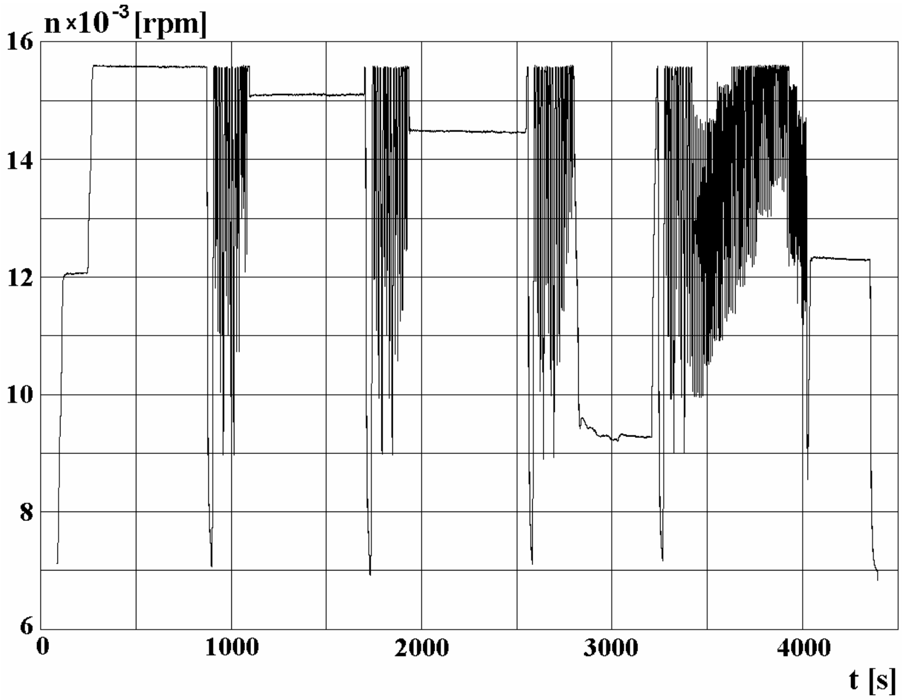

Fig. 2. Rotational speed of the spool changing in the course of ground testing of the SO-3 engine

Files with results of the processing carried out with each of both versions of the observer have been completed with actual values of thrust (R) and fuel consumption per unit (Cj). Not to be found in the diagrams, these values have been calculated in some obvious way using another values of parameters shown in Figs 1a and 1b.

Percentage differences between results gained with both versions of the observer ($\Delta Pi(t)$) have been calculated in the following way:

$$\Delta Pi(t)\ [\%] = 100\ [Pi_1(t) - Pi_2(t)]\ /\ Pi_1(t), \quad (1)$$

where:

$Pi_1(t)$ - an actual value of the 'i' parameter calculated with the observer no. 1;
$Pi_2(t)$ - an actual value of the 'i' parameter calculated with the observer no. 2.

Tab. 1. Times of the processing

Version of observer	Time of processing [s]	Time interval Δt [s]	Number of samples	Time of a real process [s]
No. 2	3245	0.02	215800	4316
No. 1	4865			
No. 2	2060	0.04	107900	
No. 1	2975			

The processing was carried out using a PC furnished with the Pentium processor (R), a system clock of 3.0 GHz and RAM of 1.0 GB. Table 1 shows times of the processing with each of both versions of the observer. Codes of computer programs have been written in Turbo-Pascal.

3. Results

Exemplary plots of actual values of parameters of engine performance, calculated with version no. 1 of the observer, have been shown as functions of a directly measured rotational speed of the engine (Figs 3 ÷ 6). The idea of directly presenting the actual values of parameters of the engine performance, calculated with version no. 2 of the observer, has been given up. Instead, two exemplary plots of percentage differences discussed in 2. have been shown in Figs 7 and 8.

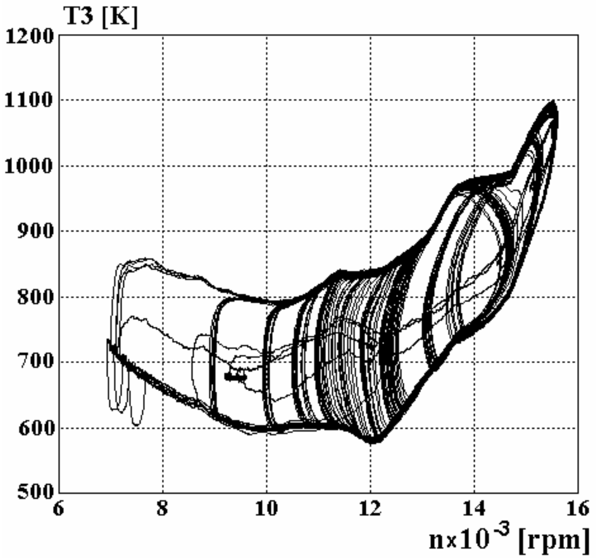

Fig. 3. An actual value of total temperature of the working medium at the combustion-chamber outlet, as calculated with the observer no. 2 – against rotational speed of the spool

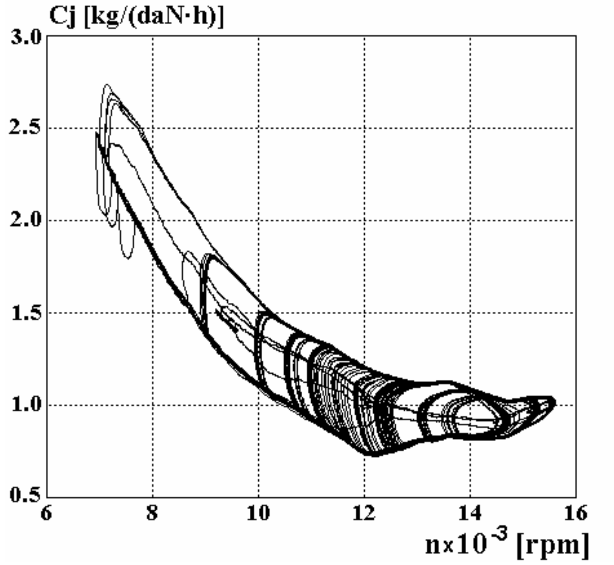

Fig. 4. An actual value of specific fuel consumption, as calculated with the observer no. 2 - against – rotational speed of the spool

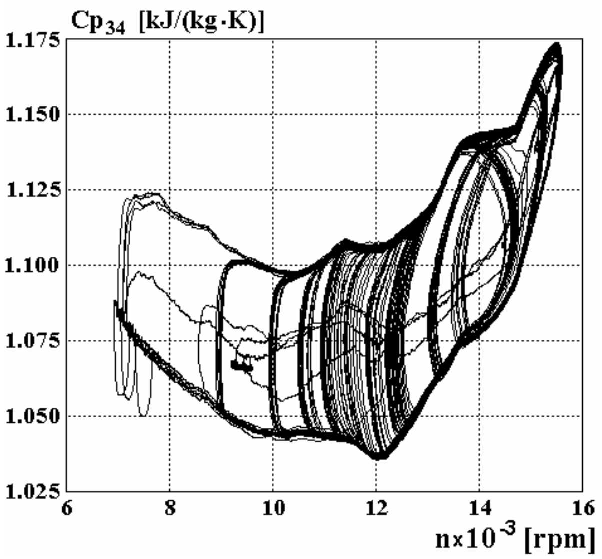

Fig. 5. An actual value of specific heat of the working medium in the turbine, as calculated with the observer no. 1 – against rotational speed of the spool

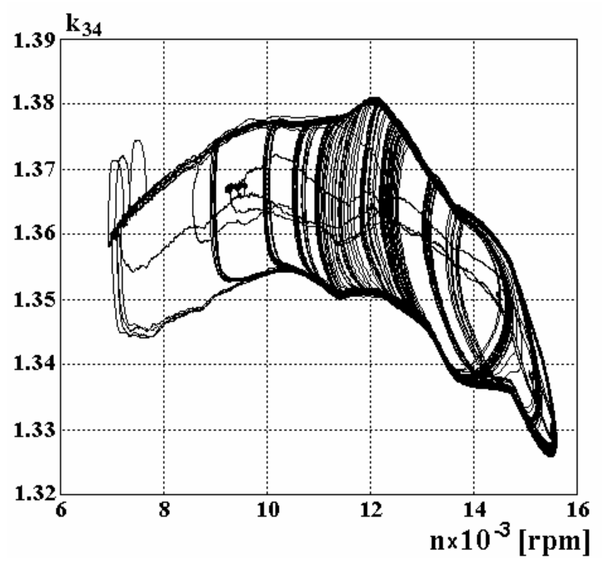

Fig. 6. An actual value of the isentropic exponent of the working medium in the turbine, as calculated with the observer no. 1 – against rotational speed of the spool

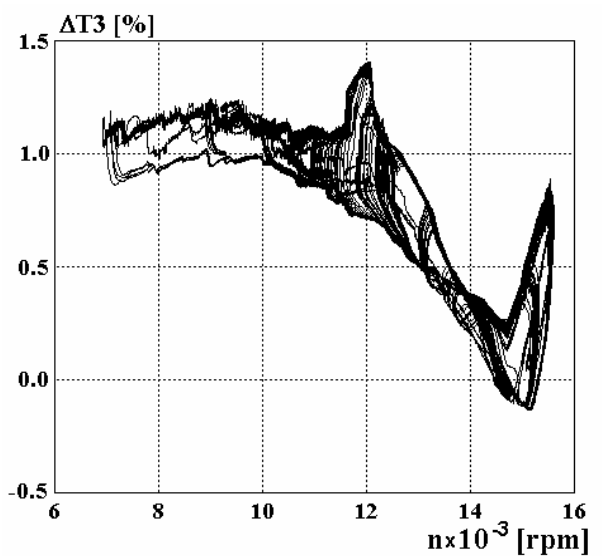

Fig. 7. How actual values (measured with both versions of the observer) of difference in the average total temperature of the working medium at the combustion-chamber outlet change - against rotational speed of the spool

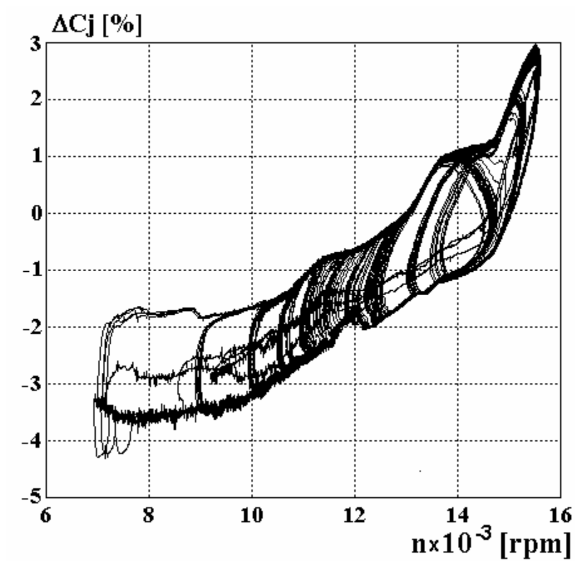

Fig. 8. How actual values (measured with both versions of the observer) of difference in the specific fuel consumption change - against rotational speed of the spool

4. Conclusions

Complete evaluation of the above-presented results needs comparison with similar values gained from some reliable measurements taken on a real engine. Unfortunately, at the time of preparing this paper the Authors had no digital records of the relevant data from tests of the SO-3 engine, where – apart from and in sync with actual values of the rotational speed of the spool (n) – also values of some other parameters would be recorded.

Variable scatter of differences between results of calculations carried out with both the versions of the observer is a real peculiarity of these differences. The scatter ranges depend in some particular way on the rotational speed of the spool.

Percentage values of these differences remain satisfactory low. Therefore, also the simplified version of the observer may take the part of a virtual sensor intended to measure difficult-to-measure parameters of the engine operation. After some modification and optimisation of program codes, both versions of the observer may be operative in the real-time mode.

5. References

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