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*WOJCIECH I. PAWLAK**)

A NON-LINEAR OBSERVER IN THE WARNING SYSTEM INDICATING FAULTY MODES OF OPERATION OF A TURBINE JET ENGINE

The present-day methods of supervising the operational use of jet engines are based, among other things, on computerised procedures of monitoring and recording various failure modes, including the surge. This dangerous mode of operation of a turbojet engine occurs quite commonly while operating it. In some cases, it could result even in the engine destruction. What has been presented in this study is the way of applying a non-linear observer of a one-spool single-flow turbojet to generate a computer algorithm to detect the surging. An exemplary application of such an algorithm to monitor the surging that occurs in the K-15 engine has also been shown.

NOMENCLATURE

BV – on/off indication of positions of compressor bleed valves (logical value),

CC – combustion chamber,

Cp_{23} – average specific heat of the working medium in the combustion chamber,

DSS – angular displacement of the engine control lever,

f – sampling frequency,

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,

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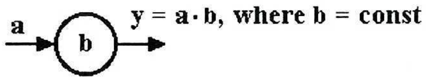
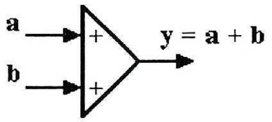
*) *Air Force Institute of Technology, Księcia Bolesława Str. 6, 01-494 Warsaw 46 PB. 96; E-mail: pawlakizydor.wojciech@acn.waw.pl*

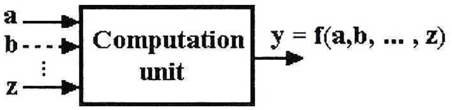
$G3_r$ – reduced mass flow of the working medium at the combustion chamber outlet,
$G3_t$ – mass flow of the working medium at the turbine inlet,
H – ambient air,
k_{34}, k_{45} – isentropic exponents,
N – convergent nozzle,
n – exponent,
n – rotational speed of the spool,
n_{sr} – reduced rotational 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,
$P2_{obs}$ – average total pressure of the working medium behind the compressor, calculated by means of the observer,
$P2_{start}$ – 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,
Q – rate of fuel flow,
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,
V – air speed,
w_1, w_2 – factors of amplification of iterative loops,
Wo – fuel calorific value,
WP – surge index,
Wu – air bleed coefficient,
$\Delta P2$ – difference between pressure values measured and calculated by means of the observer,
$\Delta T12$ – increment of total temperature of the working medium while flowing through the compressor,

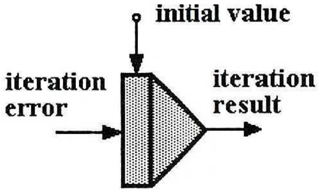
Π – pressure ratio (of the compressor),
ε – pressure ratio of the working medium while flowing through the turbine,
ϕ – rate-of-flow coefficient of a convergent jet nozzle,
η_{ks} – efficiency of the combustion chamber,
η_t – isentropic efficiency of the turbine,
σ_{23} – the total-pressure preservation coefficient for the combustion-chamber flow.

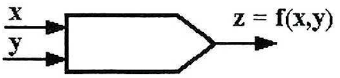
Graphic symbols



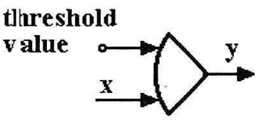




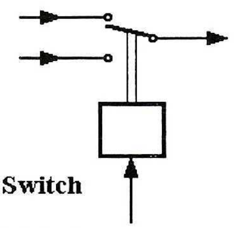




Generator of function with two variables



Comparator



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1. Introduction

It should be made clear: it is not difficult for a pilot to notice the surging phenomenon in the course of flight. The audibly obvious "rumble" and noticeable engine vibration are the cues. Also, careful observation and heuristic analysis of how the engine's performance characteristics change with time (both based on the records taken with flight data and/or maintenance/quick-look recorders) prove helpful. Problems arise when this procedure is expected to follow automatically, according to some computer algorithm.

The surge that occurs in gas turbines, in particular in turbojets, has been extensively described in the literature of the subject [1], [2], [3], [4], [5], [6], [7], [8], [9], [18], [19], [20], [21]; any detailed description thereof remains beyond the scope of this work. The most typical of this phenomenon are strong, high frequency oscillations of the working medium column of air and combustion gas along the engine duct. To put it in a colloquial way, any turbojet – while in the surge mode of operation – is similar to an improperly performing pulsejet, poor in design.

The surging is usually observed in the band of frequencies higher than those at which normal modes of engine operation are observed. Therefore, correct analysis of the surging process needs digital records to be taken with suitable, high frequency of sampling, e.g. f = 1000/s. However, observation of normal modes of engine operation requires much lower sampling frequencies (Tab.1).

Table 1.

Sampling frequencies for some selected parameters of the K-15 engine

Parameter	f [1/s]
n	16
Dp	16
P2	64
P4	8
T4	16
BV	8

It is very difficult to find a compromise between different requirements for sampling frequencies within one airborne digital-data-recording system. Therefore, to monitor phenomena observed within a band of higher frequencies (e.g. vibrations) separate recorders are used as well as special procedures to collect and process the measurements. These procedures are responsible, among other things, for the compression and aggregation of huge amounts of data effected by high-frequency sampling. All these efforts are essential because of the limited capacity of even the most advanced digital information carriers.

This study shows that detection of the turbojet surging is possible by means of a non-linear observer, using a measuring signal sampled with low frequencies suitable for normal modes of engine operation.

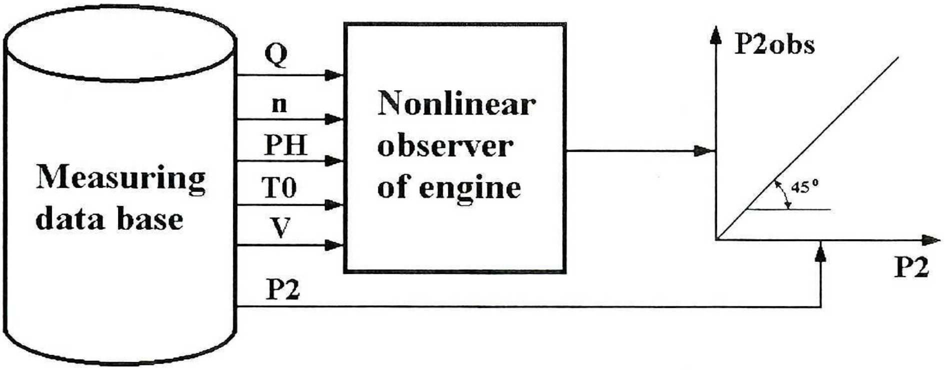

Fig. 1. The concept of detecting failure modes of engine operation with a non-linear observer

The automatic method of detection, proposed further on, consists in comparing the time courses of both a readily measurable value of the total pressure of air behind the compressor (P2) with a similar value calculated by means of a non-linear observer's algorithm (P2obs). The P2obs value can be easily obtained by means of transforming values of directly measured parameters of the engine operation. They can be as those shown in Fig. 1: the rate of fuel flow (Q), the rotational speed of the spool (n), the air speed (V), the ambient pressure (PH), and the total temperature of the air at the engine inlet (T0).

In the course of normal engine operation, discrepancies between the calculated and the directly measured values of pressure keep small. These differences decrease as the accuracy of the algorithm of the non-linear observer increases. In the case of a hypothetical ideal observer, the differences would equal zero, what is shown in Fig. 1 by means of a hypothetical straight line in the phase diagram: P2obs = f(P2). An observation of any rapid growth in the above-described discrepancies amounts to the detection of the engine surge, since the algorithm of the observer performs correctly only in the course of normal mode of engine operation. During the normal mode of operation, there is a high probability that the engine can be treated as a non-linear first-order inertial member [11], [13]. On the other hand, during the surge, the engine becomes a more complicated, inertial (oscillating) member of some higher order; hence, it is more difficult to describe it in a mathematical way. Therefore, in the course of the turbojet surging, the algorithm of the observer does not function correctly, because it describes a completely different dynamic object at the moment. Therefore, one should expect that the results obtained in this way will take the form of easily observable random disturbances.

2. A non-linear engine observer

A design configuration of a one-spool single-flow turbojet K-15, with computation sections of the engine's flow duct shown, is presented in Fig. 2.

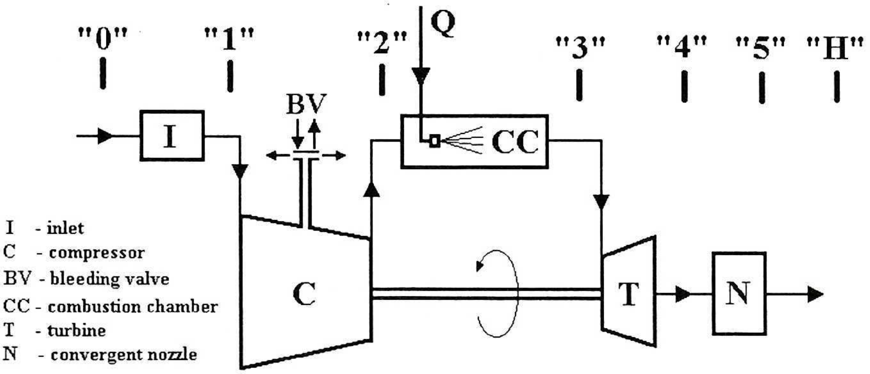

Fig. 2. A design configuration of the K-15 turbojet

The non-linear engine observer in the form of an analogue block diagram has been shown in Fig. 3. It consists of a set of two non-linear algebraic equations to be solved with the iterative method. The block diagram presents a complete set of casual connections (cause-effect interdependences) between all parameters of the engine operation, observed in the computation sections of the engine's flow duct. The block diagram also shows the way of solving the set of equations with the Euler iterative method. The iterated variables are as follows: the total air pressure behind the compressor (P2), and the total pressure of the exhaust gas in the convergent nozzle (P4).

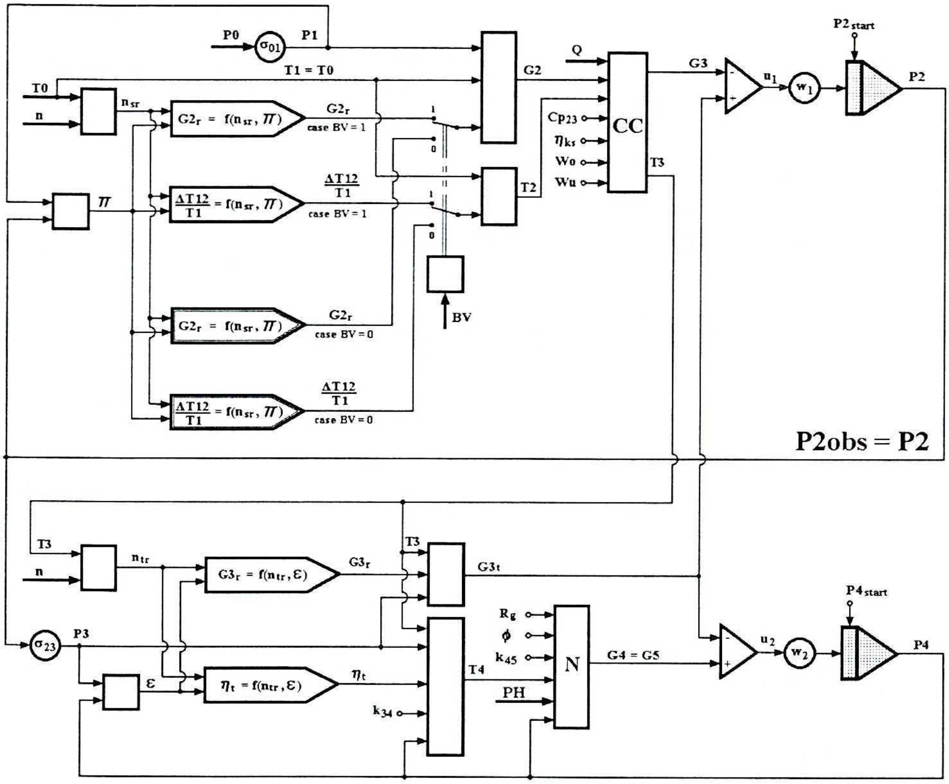

Fig. 3. An analogue block diagram of the non-linear observer of the K-15 engine

The most important components of the observer's algorithm shown in Fig. 3 comprise non-linear static characteristics of the compressor, separately for engine operation with opened (BV = 0) and closed (BV = 1) bleed valves:

$$G2_r = f(n_{sr}, \Pi); \tag{1}$$

$$(T2 - T1)/T1 = f(n_{sr}, \Pi); \tag{2}$$

and static characteristics of the turbine:

$$G3_r = f(n_{tr}, \varepsilon); \tag{3}$$

$$\eta_t = f(n_{tr}, \varepsilon). \tag{4}$$

In the present study, the observer has been used to process some sample data recorded during engine tests on a ground-based test stand. Therefore, the following parameters were chosen as the directly measured input:

total pressure and temperature of the air at the engine inlet (P0, T0 – respectively),
ambient pressure (PH),
rotational speed of the rotor impeller (n),
rate of fuel flow (Q).

All the remaining parameters shown in the block diagram could be the output of the observer. To detect the surge, the total pressure of the air behind the compressor (P2) was taken as the output parameter.

3. How the observer functions in the course of normal engine operation

For normal modes of engine operation, values of both directly measured parameters and those calculated by the observer should be similar, whereas in the case of an exact (ideal) observer – even equal. In practice, the observers accuracy depends most on the accuracy of static characteristics of the compressor and the turbine, which have been used to generate this observer.

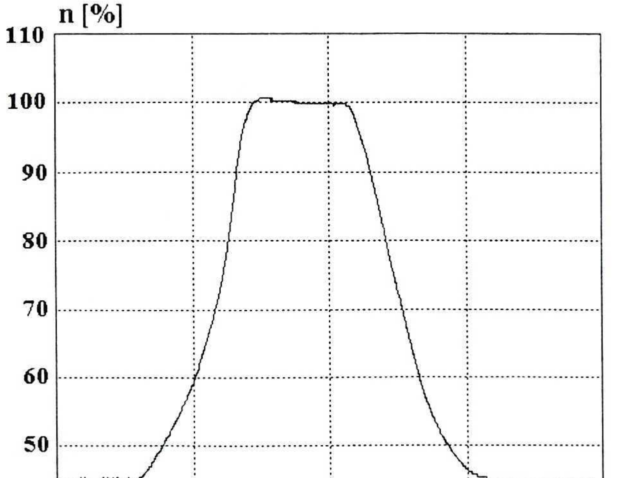

Fig. 4. The rotational speed in the course of a normal mode of engine operation

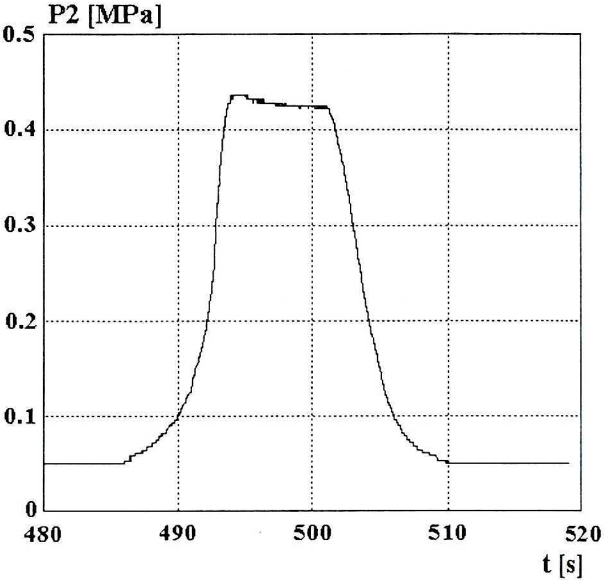

Fig. 5. The total pressure of air behind the compressor in the course of normal operation (P2 – overpressure)

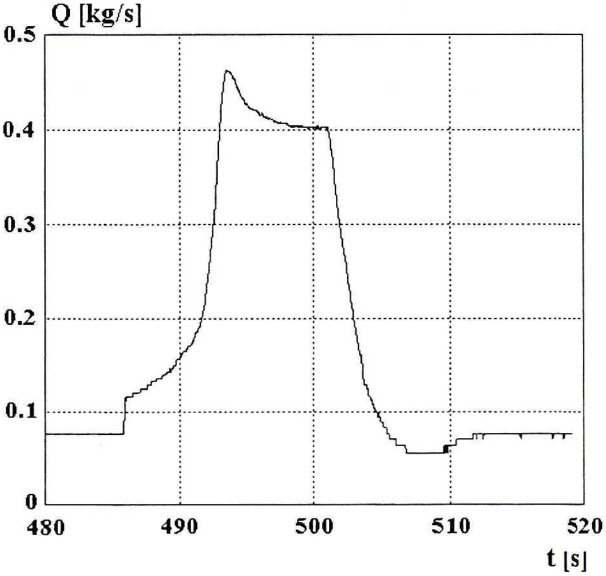

Fig. 6. The rate of fuel flow in the course of normal mode of engine operation

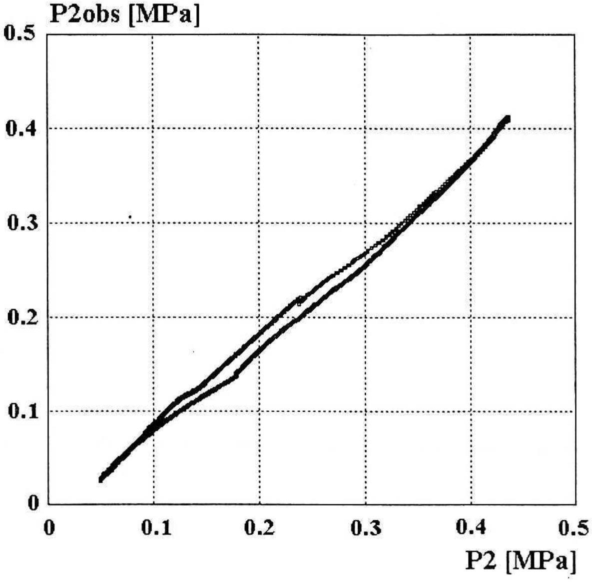

Fig. 7. A phase diagram of the total pressure of the air behind the compressor: calculated by means of the observer and measured directly – the normal mode of engine (P2, P2obs – overpressures)

Figs. 4 ÷ 6 show variations in time of actual performance characteristics of the K-15 engine (the rotational speed of the spool (n), the total pressure of the air behind the compressor (P2), and the rate of fuel flow (Q)) during full-acceleration and deceleration stages, recorded in the course of ground tests. No faulty mode of operation can be found in the above-presented diagrams. Therefore, the directly measured instantaneous values of air pressure behind the compressor and those calculated with the observer are expected to be similar. The for this purpose developed phase diagram P2 = f(P2obs) confirms this presumption (Fig. 7). If the ideal observer is used, the above-mentioned phase diagram should present a straight-line segment.

4. How the observer functions when the surging occurs

Fig. 8 shows a plot illustrating the total pressure of the air behind the compressor (P2), recorded during the engine acceleration when the surging occurred, the phenomenon manifesting itself with oscillations of relatively high frequency. The attendant synchronous variations with time of the rotational speed of the spool (n) and the rate of fuel flow (Q) have been shown in Figs. 9 and 10. On the grounds thereof, by means of the observer's algorithm, the total pressure of the air behind the compressor (P2obs) has been calculated and shown then in Fig. 11.

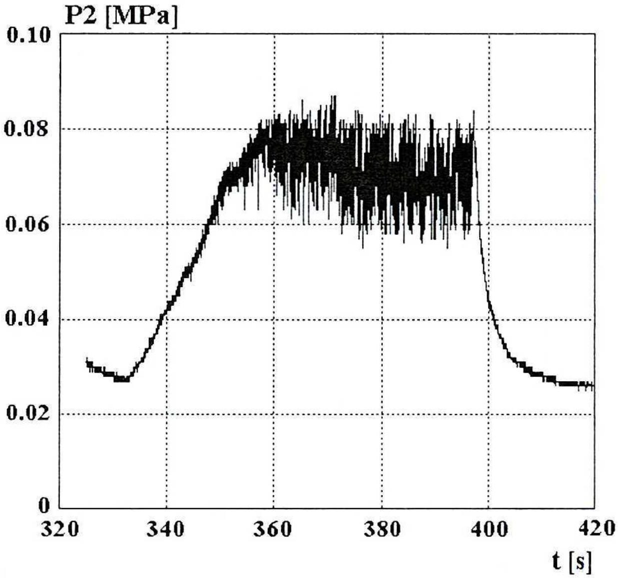

Fig. 8. The surge that occurred in the course of a ground acceleration test of the engine (P2 – overpressure)

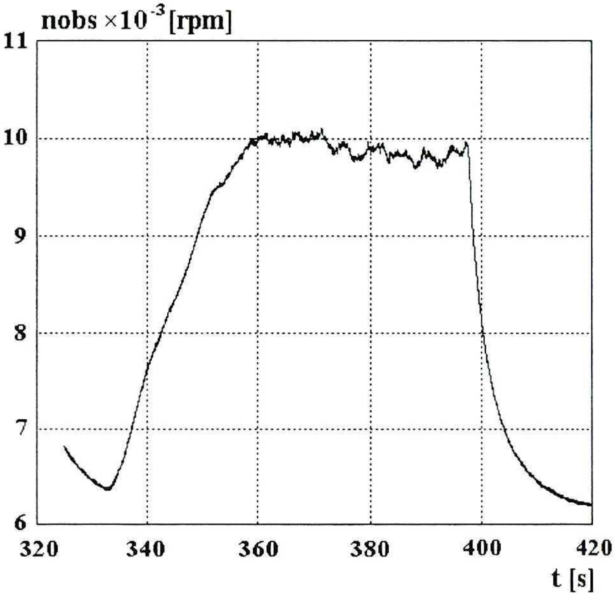

Fig. 9. The rotational speed of the engine for the case illustrated in Fig. 8

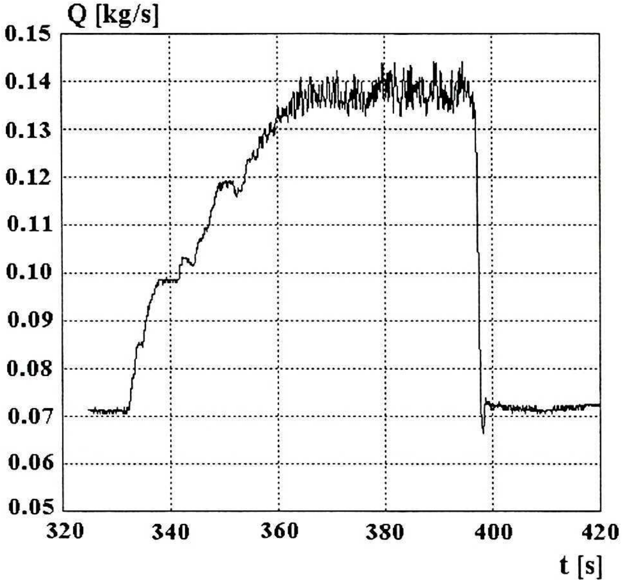

Fig. 10. The rate of fuel flow for the case illustrated in Fig. 8

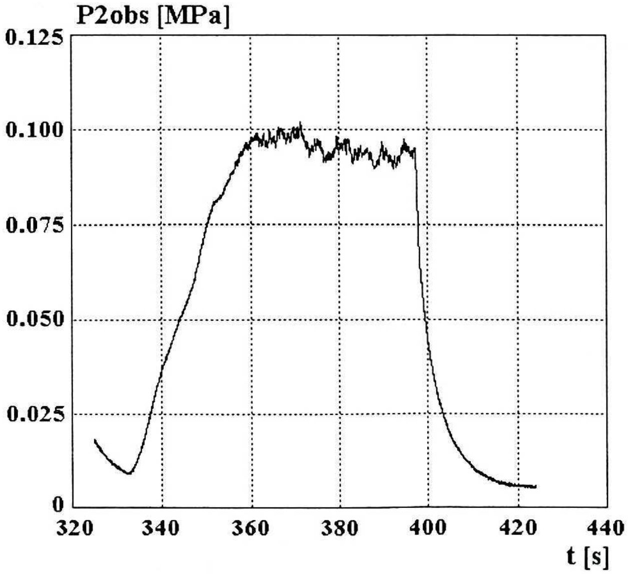

Fig. 11. The total pressure of the air behind the compressor as calculated by the observer, for the case illustrated in Fig. 8 (P2 – overpressure)

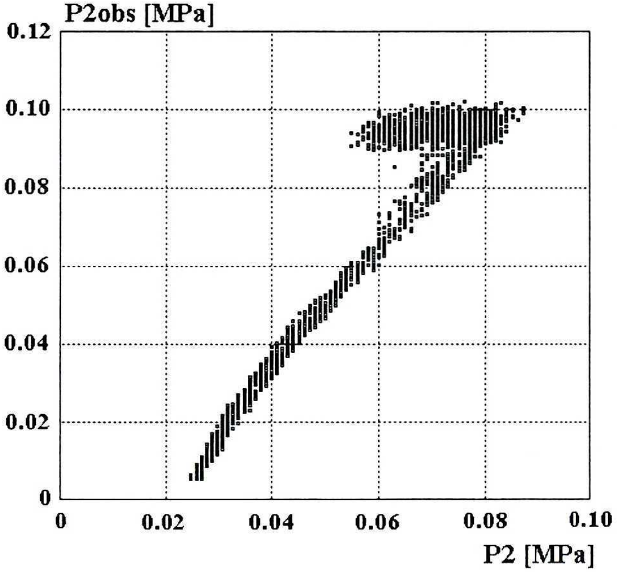

Fig. 12. A phase diagram of the total pressure of the air behind the compressor: (i) calculated by means of the observer, and (ii) directly measured, when the surge occurred (P2, P2obs – overpressures)

Comparison of plots of the directly measured (P2) and calculated (P2obs) air pressures shows some considerable differences, which become evident in the phase diagram: P2obs = f(P2) presented in Fig. 12. This proves the assumption formulated in Fig. 1 to be true and correct.

5. A non-linear observer in the system of detecting faulty modes of operation

A phase diagram shown in Fig. 12 proves helpful to quickly identify that a faulty mode of operation has occurred. It can also prove helpful to experts of the engineering supervision service responsible for routine maintenance, including the checks of records, of turbojets operated in both military and civil aviation. This capability of the observer could also be used to design and construct an automatic surge-detecting system. One of possible designs of the system has been outlined in Fig. 13. The principle of operation of the proposed system consists in setting off the difference (P2) between the directly measured values of air pressure behind the compressor and those calculated by the observer. This difference is raised to a power and then differentiated, according to the following equation (5):

$$\mathrm{WP} = \left| d[(\mathrm{P2} - \mathrm{P2obs})^n]/dt \right| \tag{5}$$

where: n – the natural-number exponent.

For an odd value of the exponent (*n*) in eq. (5), it is advisable to use an absolute value of the WP index.

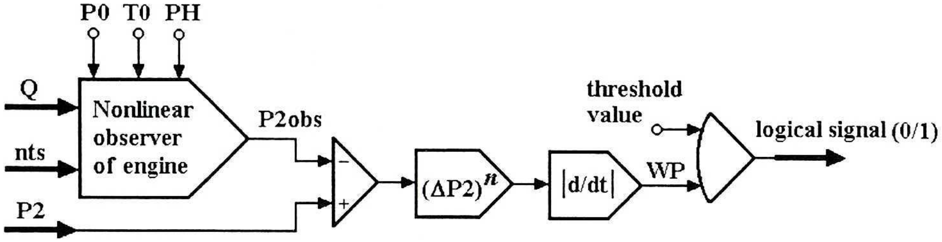

Fig. 13. A system to detect faulty modes of operation, developed with a non-linear observer employed

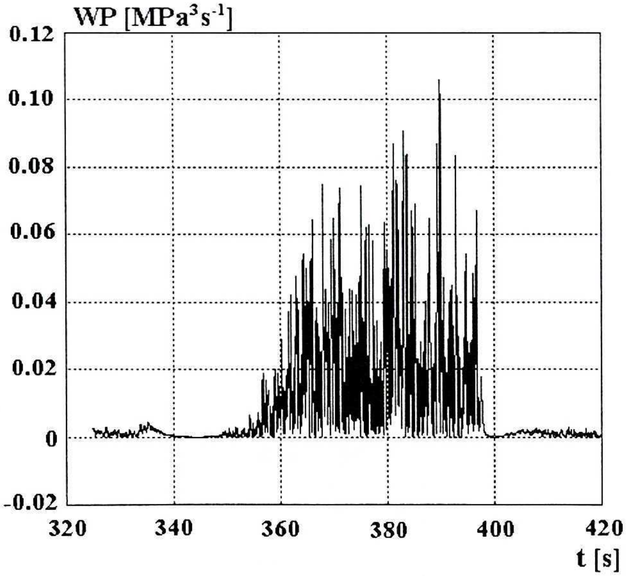

Fig. 14. Variations of the surge-index (WP) value, showing that the surge has occurred (for $n = 3$)

Fig. 13 shows the above-defined time-variant index (WP), for the specific instance presented earlier in Figs. $8 \div 12$. Having chosen the optimum threshold value of this index, one can easily and in an automatic way generate a logical signal in the comparator suggested in Fig. 13. This signal informs of the occurrence of a faulty mode of operation, in the case under discussion – the surge.

6. Conclusions

- A variant of the algorithm to detect faulty modes of operation, accomplished according to the idea presented in Fig. 13, is just one from among many other solutions.
- The capability to detect the surge in spite of applying relatively low sampling frequencies (here: f = 64/s) is the most prominent feature of the proposed algorithm.
- In the future, it seems advisable to test the system's capability to perform at even lower sampling frequencies typical of flight data recorders used in aviation.
- One can assume that an observer of an engine is accurate enough, if results of computations conducted by this observer differ from measurements taken directly on a real engine by not more than similar values of the same parameters measured under the same conditions on several engines the same type [13]. Furthermore, one can observe differences between the performance of the same engine at different stages of its installation life, which might be effected by natural wearing processes [10], [17]. Hence the conclusion: the aspiration to generate an exact observer of an engine remains utopian. The Author supposes, however, that the effectiveness of the proposed surge-detection system only slightly depends on the observer's accuracy. Nevertheless, the optimisation of the observer's accuracy remains an open question.
- Experience gained in the course of performing the K-15 testing program shows that this engine is featured with the peculiarity of difficult entering the deep-surge condition. Furthermore, unlike the well known to the Author instances of violent and deep surging observed on other engines (e.g. of the SO-3 type), the surging of the K-15 engine shows the nature of long-lasting oscillations of relatively low amplitude (Fig. 8). Therefore, the surge-detection system could probably be developed with a regular band filter employed.
- It is expected that the proposed algorithm proves as effective in the case of the uncontrolled engine shutdown.

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Nieliniowy obserwator w układzie sygnalizacji awaryjnych stanów pracy turbinowego silnika odrzutowego

Streszczenie

Współczesne metodyki nadzorowania procesu eksploatacji silników odrzutowych bazują, między innymi, na skomputeryzowanych procedurach monitorowania i ewidencjonowania różnych stanów awaryjnych, w tym również zjawiska pompażu. Jest ono pospolicie spotykanym w eksploatacji, niebezpiecznym stanem pracy turbinowego silnika odrzutowego. W niektórych przypadkach prowadzi nawet do jego zniszczenia. W referacie przedstawiono sposób wykorzystania nieliniowego obserwatora jednowirnikowego jednoprzepływowego turbinowego silnika odrzutowego do budowy komputerowego algorytmu detekcji pompażu. Pokazano przykład praktycznego zastosowania opisanego algorytmu do sygnalizowania zjawiska pompażu silnika K-15.