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Aims and Scope

Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 114, 2003, 3-4

Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery*. At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Condition-based maintenance of turbojet engines based on compressor blade vibration measuring method

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Abstract

The structure of a condition monitoring system to diagnose some turbojet engines has been discussed in the paper. System approach to the actual technical problem has been exemplified with the fatigue crack growth within the first-stage compressor blades. Results of statistical analysis of the process of blades fatigue cracking have issued and followed with a concept of solving the problem. An optimum measuring method has been suggested as well. The method of measuring precisely the engine rotational speed and the amplitude of vibration of the first-stage compressor blades has also been discussed. Results of numerical analysis of measurements have also been enclosed. The application of only one measuring line to complex, dynamic diagnostic of the engine technical condition of the engine fuel and bearing systems. The operational experience gained in the course of implementing the diagnostic system into the Air Force of the Republic of Poland is also presented.

Keywords: Blades fatigue crack; Expert analysis; Diagnostic system

Nomenclature

CV	–	condition vector
DOF	–	degree of freedom
f_s	–	sampling frequency, Hz
n	–	engine rotational speed, rpm
M_F	–	others assemblies rotational moment, Nm
m_{pal}	–	mass fuel consumption, kg/s

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m_{pow}	–	mass air consumption, kg/s
M_S	–	compressor rotational moment, Nm
M_T	–	turbine rotational moment, Nm
Par_i	–	simple signal
Q_{pal}	–	volumetric fuel consumption, m^3/s
t	–	time variable, s
TS	–	technical specifications

1 Introduction

There are many different technical engine failures we can face in turbine engine life and exploitation process. The rotor blade fatigue cracks propagation and as a consequence the blade breakaway, the excessive main engine fuel supply and bearing system getting out of order always as a rule cause a formidable danger for flight safety, engine life and reliability. A detailed analysis of each engine fault occurred during last years in Polish Air Force units showed that:

- there were some cases of fatigue blade breakaway in spite of an earlier check using blade ultrasonic and eddy current inspection and technology;
- there were some cases of bearing system damages in spite of complying with engine maintenance technical requirements;
- the engine fuel system getting out of order was observed as a result of fuel aggregates dynamic characteristics failure of their components as well as exploitation adjustment activities faults caused by deficient adjustment technology or methodology.

About 70% of all faults observed during turbine engine maintenance appeared to be located with fuel systems faults or strictly maintenance faults (combustion chamber and exhaust system, fuel system, turbine section).

Based on above there is of utmost interest the need of looking for a new method to recognise stochastic loads during engine operation, their influence on structural engine reliability and running engine technical condition. These methods should comply with present aviation trends i.e. should increase sensitive identification of engine technical condition and reduce the number and minimise the weight of control devices as well as reduce the quantity of measured parameters.

The paper presents non-interference technique of turbo-machine blade vibration phase method, one of the most interesting such complex jet engine diagnostic method as well as the tool for dynamic phenomena investigation of a running engine. The described method has been used in some units of Polish Air Force since 1993 as SNDŁ-1b/SPŁ-2b SO-3 jet engine diagnostic system.

2 Theoretical basis

2.1 Analysis of a turbine engine maintenance

The most popular, non-destructive testing methods and diagnostic systems of turbojet engine have been applied to structures in an effort to locate structural faults. They are based on MIN-MAX formulae identification (usually used in stationer machines) with the underlying idea:

"If all observed values of all observed parameters are in $<\mathrm{MIN}_i,\mathrm{MAX}_i>$ range complying with technical maintenance condition requirement it means that the engine is fit to fly".

Assumption to this formula is that all observed parameters have no any links and interference between them and controlled object is in continuous state of operation. In case of turbine engine with observed signals as depended variables such assumption has to be changed to the following shape:

"If all observed values of all observed parameters are in $<\mathrm{MIN}_i,\mathrm{MAX}_i>$ range complying with technical maintenance condition requirement it means the engine is with high probability fit to fly".

The deficiency of this method is not zero probability of hidden machine fault. These faults usually cause aircraft crashes.

2.2 Idea of the expert system SNDŁ-1b/SPŁ-2b

The consciousness of low plausibility of exiting diagnostic systems based on multi engine parameters MIN-MAX control formulae as well as repeated first stage compressor blades fatigue breakaway causes (damages) created the urgent need to elaborate more effective, sensitive system based on minimum quantity of measured and analysed parameters.

The major concept of expert analysis of engine technical condition is projection of momentary working object characteristics point (i.e. blade, fuel system or bearing system) on the phase plane, which equals an $3m$-vector of technical state (m – the number of analysed signals).

$$\forall \in (1,2,...,m) CV = \left(Par, \frac{dPar_i}{dt}, \frac{d^2 Par_i}{dt^2} \right) \in TS \Rightarrow \text{ENGINE OPERATIONAL} \tag{1}$$

It can happen that the signal Par_i can comply with technical requirement of the engine but first or second derivative will not comply with new widen technical requirement installed during object dynamic characteristics identification process by inverse operation. This case usually projects (the most frequently) the hidden *faults of the engine or disadjustment of the particular systems.*

In simplest case, having only one analysed signal, for example, the engine rotational speed, the working engine range is described in three-dimensional space. The momentary point of engine performance is monitored not only on the transient value of rotational speed but basing on the first and second derivative of rotational speed which project some trends of parameters changes (and accompanying excitations).

To solve this complicated problem a qualitative evaluation of applicability of non-contact blades vibration measuring method was done. A particular attention was drawn to the possibility of estimating the technical condition of a blade (crack initiation and propagation) on a running engine [1, 5, 6]. The measured blades vibration spectrum is analysed using the phase plane. It is worth noticing that such solution enables measurement of rotational speed of the engine rotor by frequency method and the basic difference rely on using the vibrating and rotating blades as phase marks. This enables to consider measured signal as a composition of two different signals:

- one is aperiodic signal of rotational speed (configured by average time value of consecutive rotation of engine rotor),
- second describes oscillation of the distance between two adjacent vibrating blades which is stroboscoped by rotational speed.

Basing on narrow band filtering of measured signal we are getting some signal components very useful to expert analysis of engine technical condition following assemblies and structure: I^{st} compressor stage blades, engine fuel system and bearing system [2-6].

2.3 Vibration analysis of turbine engines

In regard to vibration analysis turbo jet engines are non-linear, multi-frequency resonance systems. All kind of vibrations of this system is a combination of forced and natural resonant vibration. Forced vibration can arise due to:

- internally generated forces (e.g. combustion, power receiver);
- unbalances (e.g. compressor and turbine);
- external loads (e.g. inlet turbulence, flight loads);
- ambient excitation (e.g. temperature, pressure and humidity).

Resonant vibration typically amplifies the vibration response far beyond the acceptable stress and strain level deflection caused by static loading.

Mode (or resonances) are inherent properties of a structure. Resonances are determined by the material properties (mass, stiffness and damping), and boundary conditions of the structure. For each mode is defined a natural (modal or resonant) frequency, modal damping, and a mode shape. **If either the material properties or the boundary conditions of a structure change, its modes will change.** This fact is using in machine modal diagnostic.

2.4 Blade vibration

The object under scruting were the blades of compressor Ist stage (28 blades made of 18H2N4WA steel, length 100 mm, chord 37 mm, twisted with 38° angle). The frequencies of 4 following modes of blade vibrations were as follows: 350 Hz (transverse vibrations), 1380 Hz (transverse vibrations), 1890 Hz (torsional vibrations) and 3940 Hz (transverse vibrations).

During examinations with extensometer (not published materials) no evident symptoms of interconnections between disk and blades vibrations were observed – compressor stages are a compact design. However it was observed, that during the starting range of SO-3 engine ($n = 15600$ rpm) synchronization of blades vibrations with forces from II harmonic of rotational speed ($f_{1mode} = 520$ Hz) may occur. Such phenomena observed, i.e. during presence of foreign object (bird, ice) on a stator blade-ring, induces blades up to a dangerous level, where the yield point is reached and exceeded, and quick initiation and propagation of faigue crack occurs. Under such operating conditions of blades, time of safe operation of an aero-engine may be much shorter than one flight of an aircraft.

On the basis of a blade resonance characteristics (measurements with inducer without centrifugal forces) it was oberved, that the factor that increases the danger of blade vibrations' exceeding the allowable amplitude is a high value of amplification factor during resonance ($Q_s > 400$), resulting from a low value of logarithmic decrement of a blade damping ($\delta = 0.0065 \div 0.0075$). Low value of a damping decrement is simultaneously a positive factor – during operating range of an engine ($n = 6800 \div 15800$ rpm) exist only small zones of blades vibrations synchronization with kinematic forcing.

During bench testing of SO-3 jet engines, where moving blades are not packed, described below DOF model of a blade was verified:

$$y(t) = \sum_{i=1}^{k} A_i(t) \sin(\omega_i t + \varphi_i) \tag{2}$$

Because the blade resonance factor Q_s is more then 400 (e.g. first mode frequency $f_{min} = 320$ Hz, bandwidth $B = 5$ Hz) so we observe clear and "separate" modes in frequency domain. It enables solving blade vibration problem as a sum of narrow-band signals. Nyquist condition of minimal frequency sampling without aliasing is described as $f_{smin} > 2B$. As we can see this sampling frequency is much smaller than minimal sampling frequency of low-band signals ($f_s > 2_{fmax}$).

This fact enables sampling vibration signal e.g. compressor blade with frequency **much smaller then the first-mode frequency** (e.g. only one sampling per shaft revolution). After sampling with frequency $\omega_s(200 \div 1650 \text{ rad/s})$ blade's *DOF* is described as:

$$y(k) = \sum_{i=1}^{k} A_i(k) \sin\left(2\pi \frac{\omega_i}{\omega_s} k + \varphi_i\right). \tag{3}$$

Taking into account blade resonance characteristic in particular damping coefficient we can recognise and investigate different mode vibrations. Consequence of sampling is spectrum duplicate of every mode of vibration (ω_i/ω_s) with period 2π. This fact enables observing higher mode of blade vibration in $< 0 \div 0.5\omega_s >$ band frequency. In discrete signal spectrum doesn't step out aliasing if the following condition holds:

$$\frac{2f_c - B}{m} \geq f_s \geq \frac{2f_c + B}{m+1}. \tag{4}$$

If sampling frequency is equal engine rotation frequency (variable time sampling) then $2\pi\omega_i/\omega_s$ is order-tracking frequency as in Vold-Kalmann filter. During engine operating conditions rotor blades are excited by different sources. Therefore the resonance blades synchronizing phenomena can be used as sensitive detector of:

- flow disturbances in engine channel – Fig. 1;
- mass forces (for example created by dynamic rotor unbalance).

Blades vibrations are shown in the form of phase distributions as intercepting points of phase trajectory with the phase plane. Characteristic feature of the method is information lasting about a total number of the blade modal frequency periods between two subsequent crossing points of phase trajectory with phase plane with simultaneous preservation of basic blades modal parameters. This phenomena allows to detect blade fatigue cracks initiation and propagation during engine performance – Fig. 2.

After analysis of destructive testing results (controlled propagation of blade crack during normal operating conditions of SO-3 engine) it was observed that:

- during initiation of blade crack (no crack on the blade surface) – Fig. 2a, only change of B factor of dynamic increment of blade vibrations frequecy is seen – blade free vibrations frequency is constant;
- appearance of blade crack – Fig. 2b, decrease by 1000 rpm ($df = 16.6$ Hz) of the range of appearnce of forcing from rotational speed II harmonic was observed. At the moment blade free vibrations frequency was changed by less than 3 Hz;

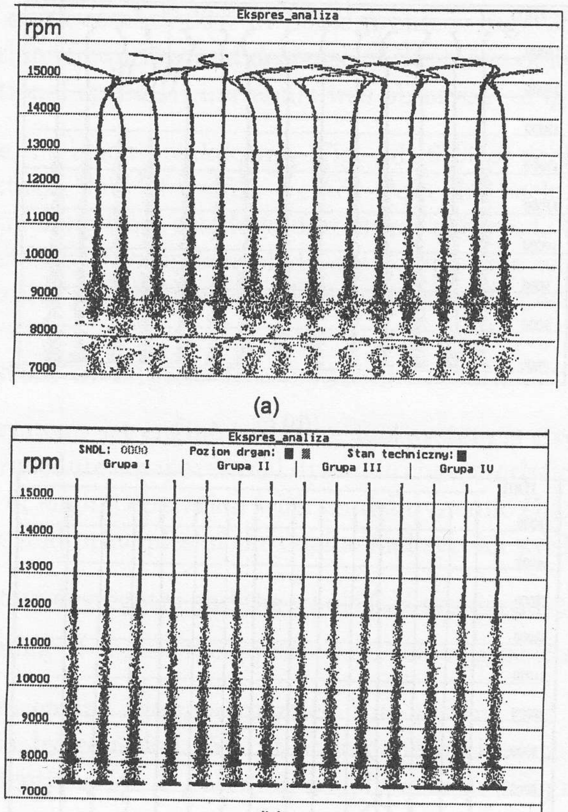


Figure 1. First stage amplitude-phase compressor blade vibration model spectra of SO-3 engine: a) standard spectrum; b) influence of foreign object dwelling in compressor first stage stator blades.

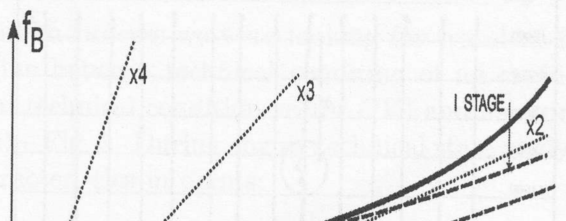


Figure 2. Projection of blade crack propagation process in blade phase vibration spectra: a) blade frequency on the Campbell diagram, $f_B = \sqrt{f_{Bst}^2 + Bf_R^2}$.

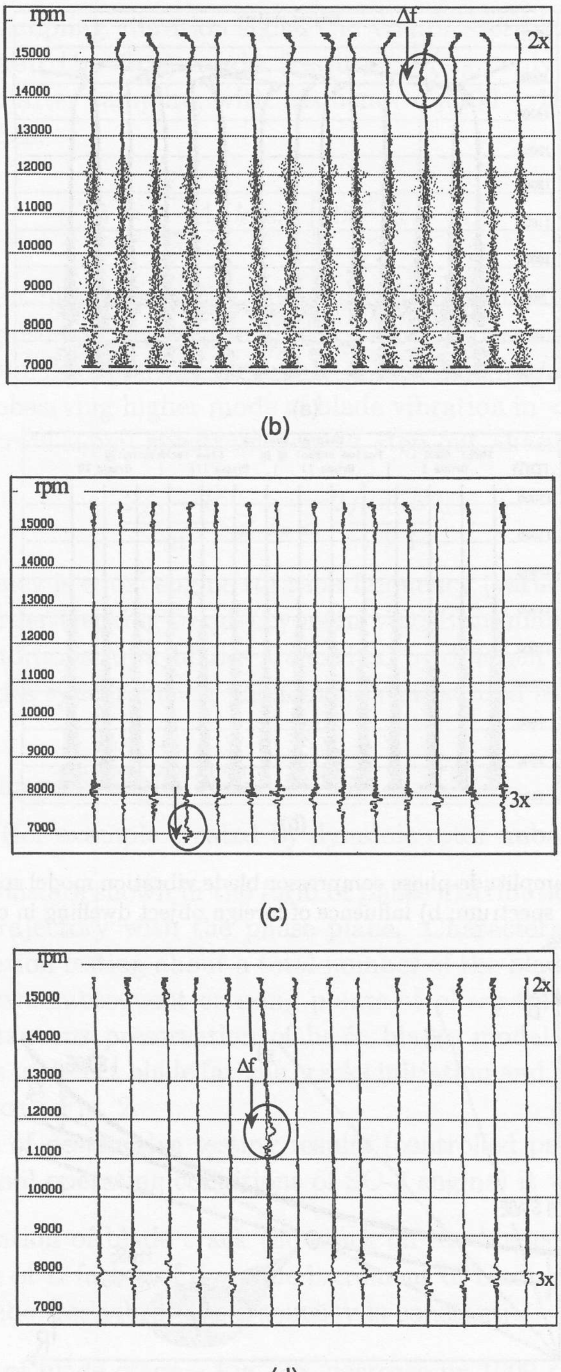


Figure 2. b) first stage of blade crack – change of B only; c) second stage of blade crack – change of f_{Bst} and B; d) final stage of blade crack – five minutes after the break.

- when the crack reaches 30% of blade profile – Fig. 2c, clear reduction of free vibrations frequency and decrease of the range of appearance of forcing from rotational speed III harmonic was observed – Fig. 2a;
- just before the blade breakdown – Fig. 2d (65% of profile – crack from the edge of attack, 95% of profile – crack from the back of the blade), clear effect of stiffening from cetrifugal forces was observed. Changes in dynamic scale inflicted by the broken blade are comparable with changes of other dynamic scales (the influence of engine rotational speed).

2.5 Diagnostics of engine fuel system

Dynamical system: jet engine turbine – fuel system is strongly non-linear inertial system. Procedure compares real dynamic characteristics taken during non-stabilized range of engine operation with model dynamic characteristics. Having in view structure and principles of the engine fuel system work, procedure allows:

- all fuel system aggregates and the whole fuel system adjustment and control;
- early revealing of engine fuel system and fuel aggregates failures.

The link between engine thermodynamics, fuel system and kinematics parameters is described by equation (5). It should be noticed that engine dynamic characteristics identification is based on simply measured signal.

$$\begin{aligned} &\tfrac{d^2n}{dt^2} + a(n)\tfrac{dn}{dt} + b(n)n = f(m_{pal}, m_{pow}) = f(Q_{pal}, Q_{pow}) \approx f(Q_{pal}) \\ &\tfrac{dn}{dt} = const\tfrac{M_T - M_S - M_F}{I} \end{aligned} \qquad (5)$$

During identification process we were looking for transient function, which was describing the line between technical condition of an engine (characterised by multidimensional technical condition vector CV) and measured rotational speed (residue method) – Fig. 3. During engine technical state analysis we employ finite set of phase characteristics m points:

$$\text{TECHNICAL CONDITION} = \left(CV, \frac{dCV}{dt}, \frac{d^2CV}{dt^2}\right) \approx \left(n, \frac{dn}{dt}, \frac{d^2n}{dt^2}\right)_m . \qquad (6)$$

Fig. 3 shows graphical visualisation of measuring data – relation $y(dn/dt) = f(n)$ with additional informations about:

- optimal track of engine transient states;
- dangerous zones localization (surge borders, high temperatures);

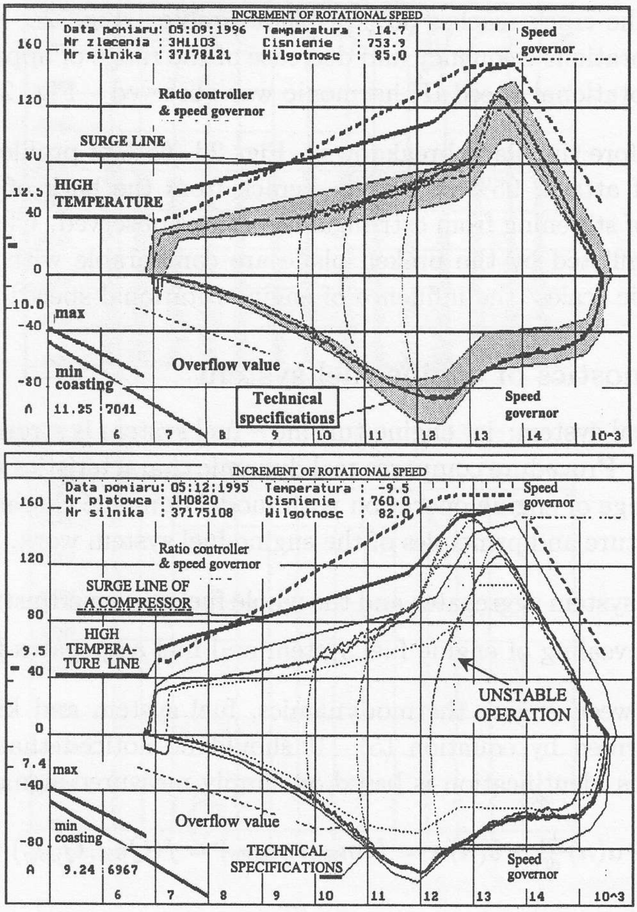


Figure 3. a) Model characteristic of engine fuel system during transient condition of SO-3; b) Control error of fuel system and surge threat.

- influence of main components of fuel system on the shape of phase trajectory (orbit) of rotational speed;
- technical specification for the time of engine acceleration;
- test conditions.

Example of an error of fuel system regulation, that led to short surge during acceleration in the range of 12500 rpm, is shown in Fig. 3b.

2.6 Diagnostics of engine bearing system

The idea of bearing technical condition estimation of SO-3 engine is based on correlation between rotor shift and measured blades vibration spectra changes.

Basic principle of this method is that blades of rotor are **independent generators**. Such phenomenon like blades flutter vibration or rotor shift are projected into blades vibration spectra (so called "apparent" blades vibration) – Fig. 4.

Fig. 4a shows dynamic phenomena observed sporadically in autumn and winter during deceleration of SO-3 engine rotational speed. Abnormal asynchronous blades vibrations in the range of 9500 rpm are strongly correlated with dominant frequency approximately $0.5 f_s$.

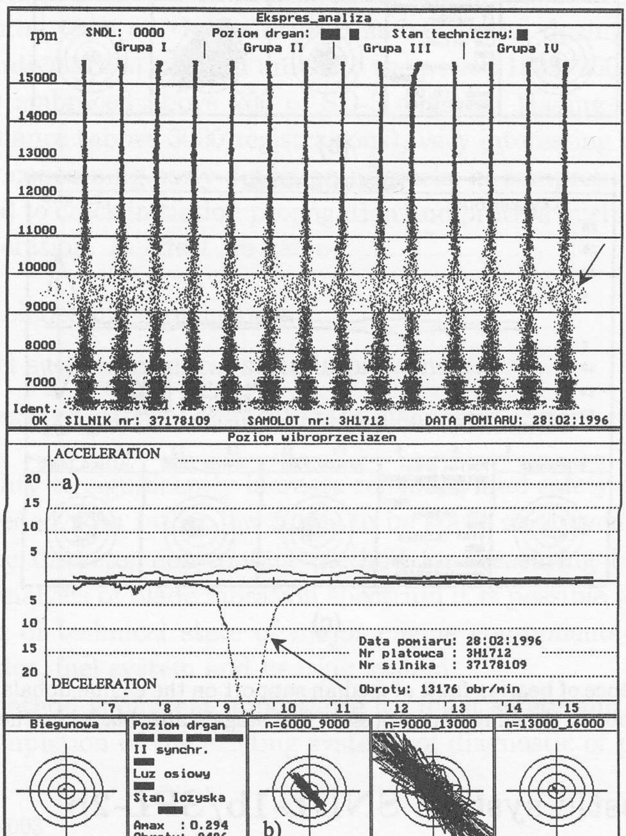
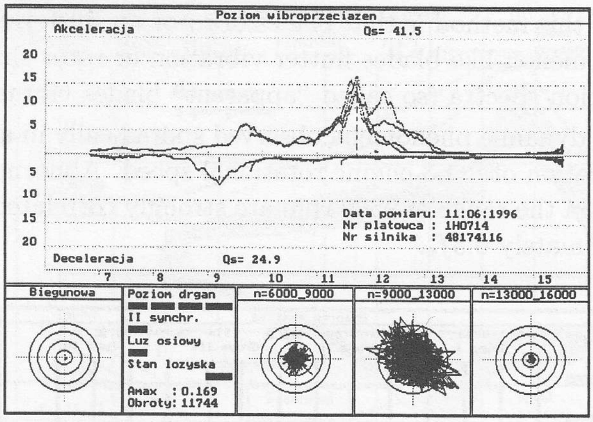


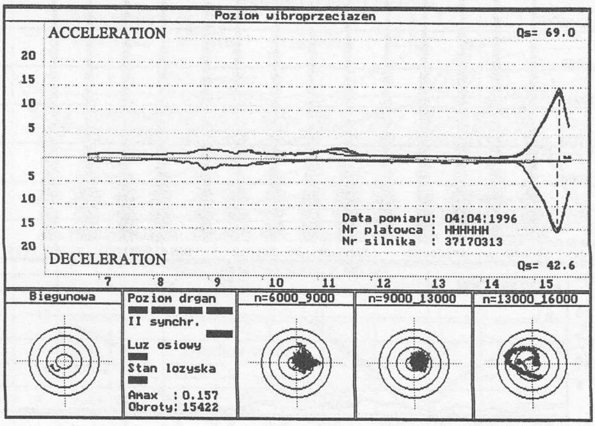
Figure 4. a) Display of blades vibration and the rotor dynamic conventional unbalance level.

Fig. 4b shows mapping of symptoms of main bearing damage – correlated blades vibrations in the range of 11500÷12500 rpm were caused by excessive run-out of compressor rotor.

Fig. 4c shows the influence of foreign object presence on a stator bladering on the level of vibrations correlation in the range of forcing from rotational speed II harmonic.



(b)



(c)

Figure 4. b) Influence of bearing fault of median support on the engine unbalance; c) Influence of foreign object dwelling in compressor first stage stator blades on the engine unbalance.

3 Diagnostic system SNDŁ-1b/SPŁ-2b

The diagnostic system SNDŁ-1b/SPŁ-2b consists of:

- blade excessive vibration signalling device SNDŁ-1b;
- ground control device SPŁ-2b for periodic:
  - recording and computer analysis of first compressor stage blade vibration spectrum;
  - SNDŁ-1b technical condition control performance without its disassembly;

– The engine rotational speed in I and II cabin indicator faults control without their disassembly;

- SPŁ-2b software.

4 Conclusions

The functional abilities of described measuring method were verified during some experimental tests on the Institute test bench and during system SNDŁ-1b/SPŁ-2b maintenance in aviation units. In the period 1993/2003 system SNDŁ-1b/SPŁ-2b has embraced above 200 of SO-3 engines. Having in view running aircraft maintenance (above 3000 registrations), very interesting results were collected specially concerning early detection of cracks in compressor blades of turbojet engine and to crack initiation propagation and process during engine normal condition of operation. In effect we gained:

- technical blades life prolongation;
- engine fuel system technical state improvement;
- simple bearing systems technical state diagnostic system creation.

Besides, capability to significantly increase reliability and safety of aircraft operation was succeeded with rather low funds to be spent on preventive activities.

By using the discrete, non-contact method for measuring blades vibration and numerical analysis of blade vibration spectrum it is possible to conduct complex monitoring of technical state of major engine components like: compressor/turbine blades, fuel system and bearing system.

Described method is of great importance for flight safety and may be recommended as a completion of the existing systems of diagnostic of power turbine.

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