

QUALITY ASSESSMENT OF DIAGNOSTIC WORTHINESS OF NON-INTERFERENCE DISCRETE-PHASE METHOD OF MEASURING COMPRESSOR BLADES VIBRATION

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The paper presents a qualitative evaluation of applicability of the non-contact vibration measuring methods in the diagnostics of turbine engine blades. A particular attention is drawn to the possibility of estimating the condition of a blade (crack initiation and propagation) on a running engine. Relevant theory has been included in the paper, to an indispensable extent. General approach to the issue, the concept of the diagnostics, the employed measuring method and a theoretical model have been presented. The qualitative evaluation makes use of experimental results obtained on a test bench (simulation) as well as of a verification (passive experiment in user's conditions) performed on a statistically representative population of jet-propulsion turbojet engines. The effect of conditions of engine operation upon long-term fatigue strength of the blade is emphasized. The results of an analysis of the process of crack propagation under conditions of normal engine operation have been given. In conclusion, a high reliability and sensitivity of the method in monitoring both the energy level of blade vibration and the physical condition of the blade has been pronounced.

Problem statement

Components of aviation equipment under operation are subjected to a process of continuous wear due to:

- working loads,
- ambient conditions (atmospheric corrosion),
- hidden design and manufacturing defects,
- natural ageing.

The wear process is reflected by a continuous stream of minute damages and an occasional equipment failure, like e.g. a blade brakeaway due to fatigue.

A blade failure usually stops the engine, due to flow disturbances and secondary damage to the compressor - Fig.1. According to an analysis, a periodic evaluation of the physical condition of the blades using the methods of non-destructive diagnostics (visual inspection, eddy-current, ultrasonic and colour defectoscopy) does not provide trouble-free operation between checks. This is mainly a consequence of the fact that no information is available on actual, stochastic loads on the blades under operation. Therefore, preference is given to monitoring blade energy level (vibration amplitude) and of blades condition, performed with the use of non-contact, discrete methods of measuring (DM) the amplitudes of blade vibration during engine run. This approach is now frequently applied, especially to engines with rotor blades having "increased susceptibility to cracking" (i.e., a reduced life-to-fatigue failure expectation).

Concept of Diagnostics

General Features

The effect of blade load upon its generalized displacement (elastic deformation) is analyzed by considering the blade as an appropriately shaped, beam fixed to the rotor disc. Due to working loads the beam is simultaneously subject to tension, bending and twisting. An actual stress level is evaluated by employing the linear

dependence of stresses upon generalized displacements of blade tip:

- deflection c ,
- angle of torsion α ,
- elongation h .

The following relationships hold for a given time instant:

$$\text{Normal stresses} \cong f(c, h) \quad (1)$$

$$\text{Shearing stresses} \cong f(\alpha) \quad (2)$$

The displacement of the centre of mass and of the leading edge of blade tip section may be described with formulae:

$$c(t) = c_s(t) + c_d(t) + \Delta c_\alpha(t) + \Delta c_h(t) \quad (3)$$

$$\alpha(t) = \alpha_s(t) + \alpha_d(t) + \Delta \alpha_c(t) + \Delta \alpha_h(t) \quad (4)$$

where,

- s - quasi-static component index,
- d - dynamic component index.

Measuring Method Description

In the DM method, the vibration level of a blade is estimated using the linear dependence between its vibration amplitude and the measured time intervals between pulses generated in a sensor.

If the sensor is located in the plane of the mass centre of blade tip section (which is one of the typical locations), the measured j -th time interval reflects the reference quantity - the *Amplitude*. The latter contains basic information on:

- instantaneous variations in deflection $c(t)$ - formula (3) for three subsequent blades: $j-1, j, j+1$,
- static pitch of blades L_j and the difference between adjacent pitches ΔL_j^{j+1} (constant component):

$$\text{Amplitude}(t) = \frac{\Delta L_j^{j+1} + \Delta c_{j-1}^j(t) - \Delta c_j^{j+1}(t)}{L_j + \Delta c_{j-1}^j(t)} \quad (5)$$

The generated sequence of pulses carries also the information on:

- engine rotational speed and its fluctuations,
- distance between the blade and the sensor.

The stochastic continuous signal *Amplitude*(t) is transformed into a discrete signal due to DM sampling action.

It is possible to prove, employing the analogy between mechanical and electric vibrations (modulation of the amplitude, frequency and position of pulse), that the discrete *Amplitude*(τ) signal contains information which is qualitatively comparable to that provided by strain gauge techniques, on condition that adequate resolution is secured.

Model of Blade Ring for Monitoring Purposes

A pseudo-deterministic model is imposed by the selected input parameters and method of measurement. It is described by the matrix relation:

$$X(t, \hat{r}) = \Phi[Y(t)] + \eta_x(t, \hat{r}) \quad (6)$$

The matrix operator Φ in the model represents a transformation of condition vector $Y(t)$ into symptom vector $X(t, \hat{r})$ dependent on the point of measurement \hat{r} and time of service t , in the presence of disturbances vector $\eta_x(t, \hat{r})$. Equation (6) is formally analyzed in the domain of time of service t :

$$X = \Phi(y) + \eta_x = \mu(t) + \eta(t) \quad (7)$$

With properly selected symptoms X , the functions $\mu(t)$ with superimposed disturbances $\eta_x(t)$ may be understood as the object "life" curves i.e., the functions describing the development of separate, independent damages. In case of rotor blades of the ring considered, it is purposeful to present relation (7) in form of a set of normalized functions $kz_i(t, n_{rpm})$:

$$kz_i(t, n_{rpm}) = \frac{N_i(t, n_{rpm})}{N_i(t=0, n_{rpm})} \quad (8)$$

where,

$N_i(t, n_{rpm})$ - current load capacity of blade, at a given rotational speed (determined by the composition of blade features defining the blade capability of bearing operational loads),

$N_i(t = 0, n_{rpm})$ -initial, theoretical load capacity of blade at a given engine speed (determining the allowable range of operational loads for which the blade has been designed).

The functions $kz_i(t, n_{rpm})$ reflect the variation of blade durability. They are monotonously decreasing functions and become equal to zero at the instant of blade failure. Allowing for the effect of differences in:

- technology and manufacturing of blades (dimensional tolerances, hardness and structure of material),
 - character and level of load during operation (vibration amplitude, level of component loads at various parts of frequency spectrum)
- the set of "life" curves for a group of N blades may be represented in form of a confidence range (function) of density determined by normal distribution of the set of function values $\{kz_i(t, n_{obr}), i = 1, 2, \dots, N\}$. In a statistical analysis of the function thus defined it should be noted, that the increase of standard deviation and amplitude level of blade vibration entails:
- an increase of the limit value of "life" curve, at which no symptoms of cracking are observed yet,
 - a shortening of the total time of safe blade operation,
 - a shortening of the time of crack propagation.

For this reason, while discussing the instant of onset and propagation of a crack in an element under load, it is necessary to take account not only of material destruction observed (number of micro- and macro-cracks), but also the capability of carrying operational loads by the damage-affected element.

In order to make practical use of the "life" curve in diagnosing the condition of blades in its energy (current level of flow disturbances) and technical (material structure) aspects, it is necessary to associate the mean "life" curve of a tested population of blades with those of their physical features which are most relevant in providing diagnostic information, as e.g.: flexural S_g and torsional S_s rigidity of blades, logarithmic decrement of damping δ , static natural vibra-

tion frequency f_s and dynamic forced vibration frequency f_d :

$$kz_i = \langle S_{g_i}, S_{s_i}, \delta_i, f_{s_i}, f_{d_i} \rangle \quad (9)$$

Forecasting of Blade Service Life

The process of service life forecasting consists in an appropriate extrapolation of the variation of blade durability to a space of time (employing the "life" curve values):

$$kz_i(t + \tau, n_{rpm}) = kz_i(t, n_{rpm}) - f \left[\text{Amplitude}_i(n_{rpm}), \frac{\delta^2 kz_i(t, n_{rpm})}{\delta \tau \delta \text{Amplitude}_i(n_{rpm})} \right] \quad (10)$$

Assessment of the method sensitivity and repeatability

A statistical analysis of the measurement results has been performed in order to determine the DM method sensitivity and repeatability. The following "zero" hypotheses have been put to test:

- H_0^I - the blade condition in its energy aspect and associated occurrences may be identified on the basis of a single measurement and a known characteristics of blade vibration spectrum
- H_0^{II} - the blade condition in its technical aspect, and consequently the initiation of a crack at its early stage, may be identified on the basis of a single measurement and knowledge of the characteristics of blade vibration spectrum.

Analysis of Measurement Results

Object of investigation

A qualitative analysis of the applicability of discrete methods of measuring blade vibration in diagnostics has been performed on the population of turbojet engines in service in Poland. In the course of the investigations, model characteristics of blade vibration spectrum have been determined for:

- normal conditions of operation - **Fig.2**;
- increased level of flow disturbances, caused by a reduction of the margins of:
 - a) compressor stability,
 - b) engine flameout limit;
- reduced dynamic strength of blade(with the exclusion of cracks), including:
 - a) reduced blade load capacity
 - b) excessive effect of blade manufacturing tolerances on the differences in blade material effort level and character;
- high and dangerous level of flow disturbances caused by:
 - a) unstable compressor operation,
 - b) foreign object dwelling on the inlet ring of guide vanes;
- crack propagation occurring at a low and high level of stress.

Effect of Engine Conditions of Operation on Blade Vibration Spectrum

Evidence provided by experimental results confirmed a very strong influence of the engine pattern of operation and the condition of its main functional systems, as e.g. the system of main bearings or fuel supply (remote as working environment for blades), on the long-term fatigue strength of blades. For the practice of diagnostics it is of utmost interest to have in the spectrum of blade vibration a reflection of the specific conditions of: engine operating with reduced margin of compressor stability and engine at flameout limit. The changes, observed in the both cases in the blade vibration spectrum, were generated by developed rotating stall zones (asynchronous resonance) - **Fig.3**. In case of a foreign body dwelling in the inlet guide vane ring it has been observed that:

- the amplitude of blade vibration increases in the area of strong influence of synchronous (resonance) forcing for the form I blade vibration - **Fig.4**.
- a synchronous vibration of rotor blade rings occurs.

In the both above recorded phenomena a strong influence of the type of blade vibration spectrum on the growth of rotor dynamic unbalance and dynamic load on bearings was also manifested - **Fig.5**.

Analysis of Blade Crack Initiation and Propagation

By correlating the changes in vibration amplitude spectrum of a cracking blade with the history of material effort (engine working conditions) and the structure of fracture - **Fig.6**, it has been possible to expand the knowledge of the actual mechanism of the phenomenon, and to determine the effect of engine conditions of service on the limits of crack propagation time. There were some regularities observed during the investigation, which may be linked to the history of blade strain, namely:

area A - the destruction proceeded in form of a volumetric damage (undetected for ultrasonic defectoscopy) during high material effort, caused by:

- a) repeated instability of compressor operation (low and high- temperature surging),
- b) blockage with a foreign body.

This phase, in spite of an earlier reduction of the level of load on the blade, ended up with an abrupt appearance and propagation of an open, flat crack at low stress. The rate of the crack propagation was related to the history of maximum blade material effort (accumulation effect).

The fracture examination has shown area A to cover about **23%** of the active blade cross-section.

area B - the progress of destruction was hindered, mainly due to a change from the flat to a three-dimensional form of cracking. The rate of propagation resulted from the current level of material effort; in favourable engine working conditions there were longer stops in the crack propagation.

In the fracture examined, the area B takes about **12%** of the active blade cross-section.

area C - the progress of the three-dimensional cracking was slow and uniform until a critical section was reached.

The propagation rate depended only on the current level of blade load (the reduction of active blade cross-section

produced no rate increase). There were no longer stops of propagation observed.

The examined fracture shows area C to be about **28%** of the active blade cross-section.

area D - an extemporary completion of the crack.

The time of a fatigue crack propagation from the onset to breakaway is closely related to the level and characteristics of flow disturbances. For the examined type of engine it amounted to:

- over **28 hours** - for a low level of disturbances,
- not longer than **20 min** - for a high level of disturbances.

Analysis of the measurement method sensitivity and repeatability

A detailed qualitative analysis of the results obtained from the active and passive experiment has shown that:

- the method is sufficiently sensitive to identify the dynamic processes occurring in a rotor blade ring and their causes;
- the probability of making a credible diagnosis with the zero hypotheses H_0^I and H_0^{II} being valid, for an appropriate selection of boundary conditions, is $p > 0.89$ at a confidence level of 0.96.

Conclusions

1. By using the discrete, non-contact method of measuring blades vibration it is possible to conduct an extended diagnostics of blade condition with little interference in the construction of an engine.
2. It is possible to diagnose the technical condition of the principal functional systems of an engine and also to reveal and locate dynamic processes dangerous for the engine, by correlating the blade vibration spectra with the structural layout of an engine.
3. The discrete methods of measuring blades vibration may be recommended as a complementation of the existing systems of diagnostics of turbine engines.

References

1. SZCZEPANIK, R., WITOS, M. (1987-1994) "Unpublished work on dynamic properties of blades and on a discrete/phase method of diagnosing their condition", ITWL Warszawa. (in Polish)
2. ZABLOCKI, I. E., KOROSTIELEW, J. A., SZIPOW, R. A. (1977) "Contactless measurements of turbomachinery blade vibration" Maszinostrjenije, Moskwa.

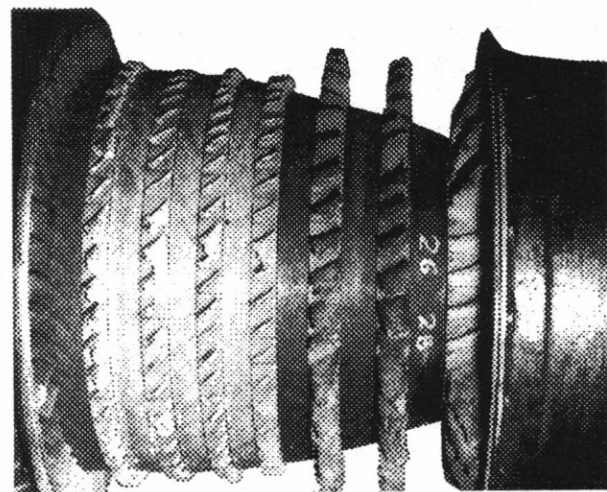


Fig.1. Compressor condition after damage caused by I-st stage rotor blade breakaway.

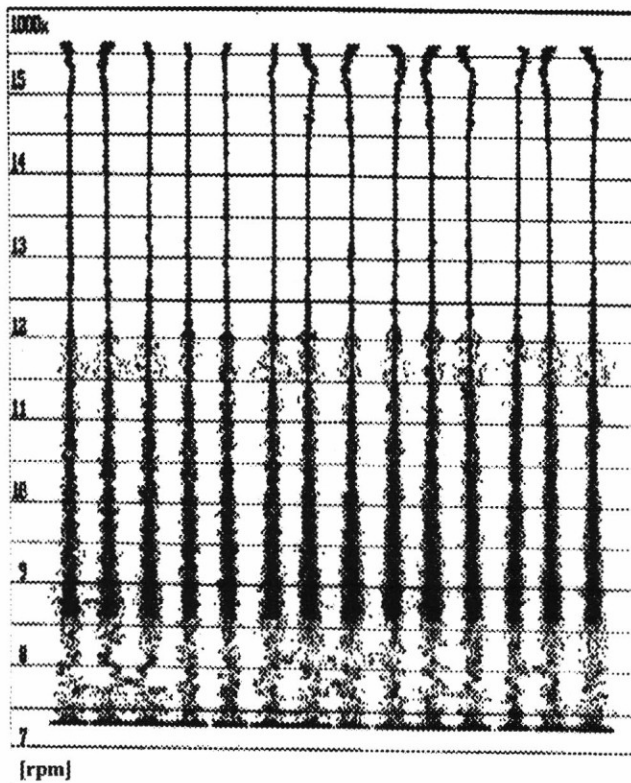


Fig.2. Spectrum of blade vibration amplitude during normal engine operation.

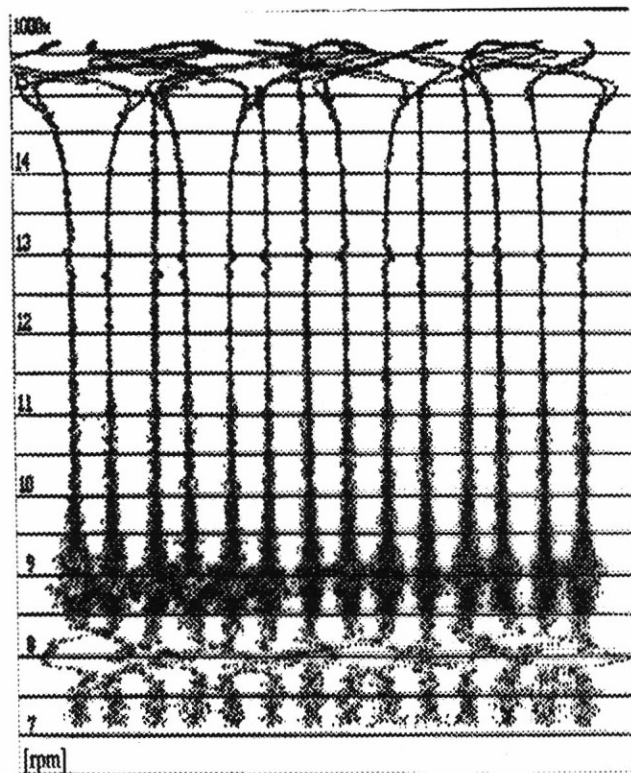


Fig.4. Spectrum of blade vibration amplitudes during synchronous resonance.

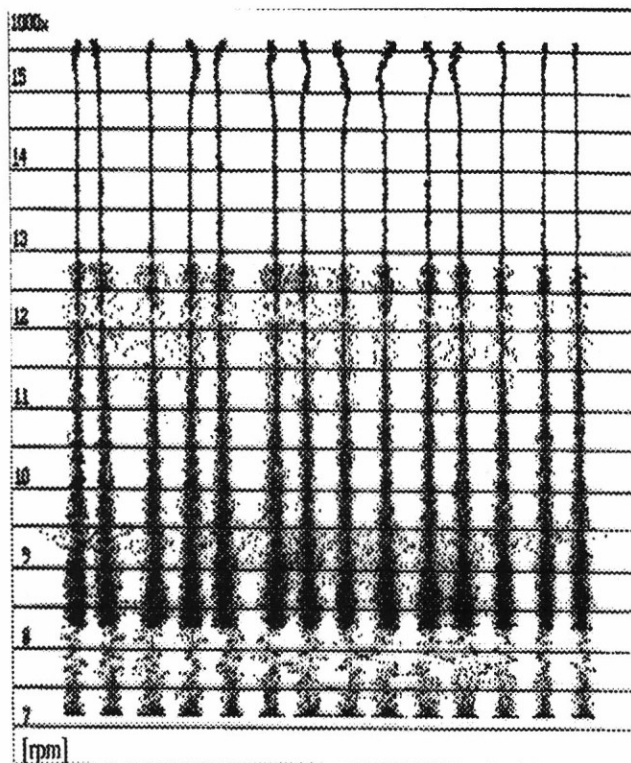


Fig.3. Spectrum of blade vibration amplitude during asynchronous resonance.

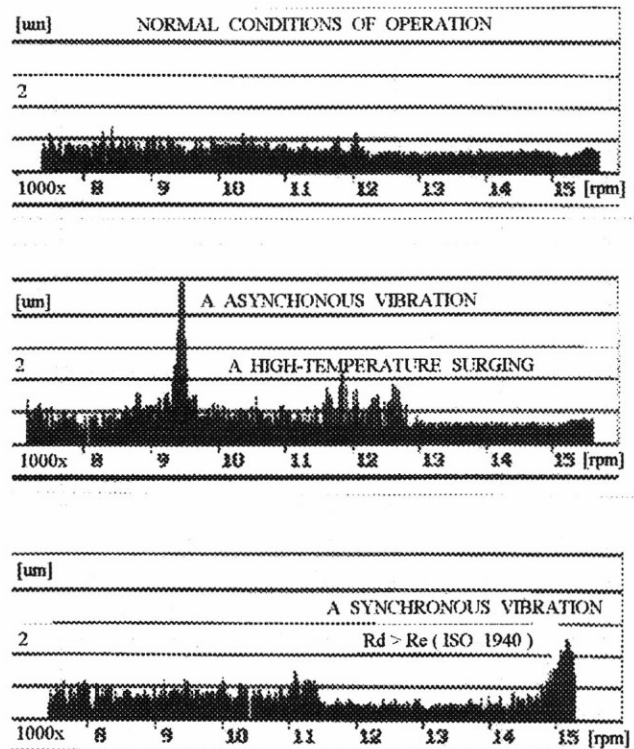


Fig.5. Effect of blade vibration type on the rotor dynamic disbalance.

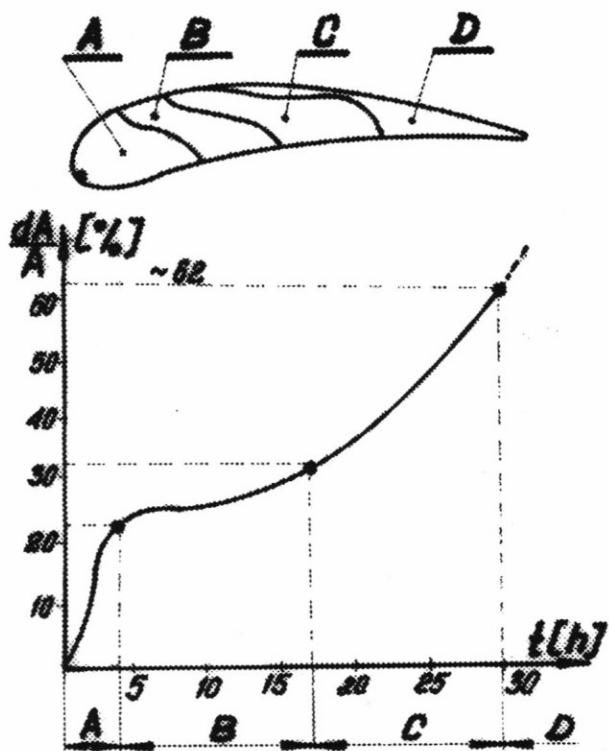
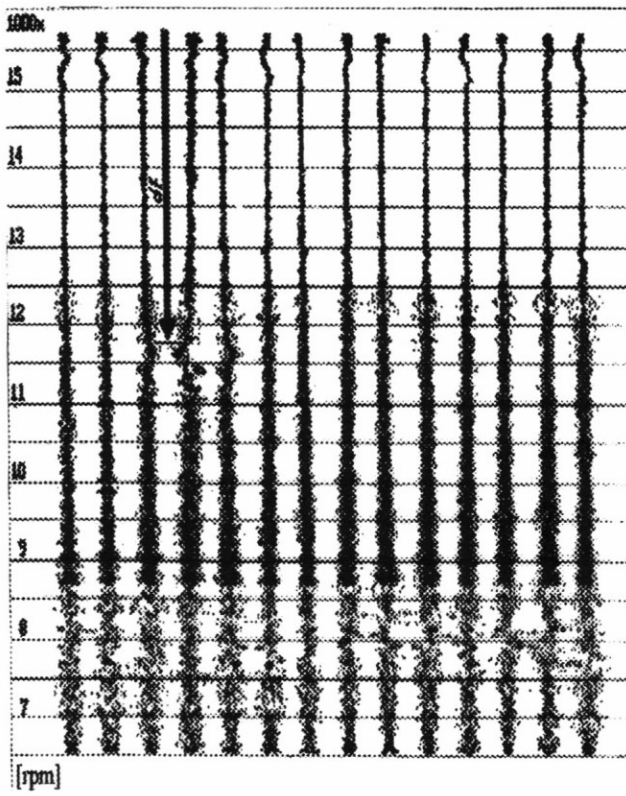


Fig.6. Analysis of the process of blade cracking.