HIGH SENSITIVE METHODS FOR FATIGUE DETECTION

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Summary

The diagnostic and research aspects of compressor blade fatigue detection are investigated in the paper. The authors review the characteristic of different modes of metal blade fatigue (LCF, HCF, VHCF). The polycrystalline defects and impurities influencing the fatigue, along with their related surface finish techniques, are taken into account. The experimental methods of structural health assessment are considered. The Tip Timing (TTM), Experimental Modal Analysis (EMA) and Metal Magnetic Memory (MMM) provide information on the damage of diagnosed object (compressor blade). It has been proven that the shape of resonance characteristic gives an ability to determinate if fatigue or a blade crack is concerned. Early damage symptoms, i.e. modal properties of material strengthening and weakening phases (structural and magnetic anisotropy) have been described.

Keywords: compressor blade, damage, fatigue, modal analysis, lattice-spin coupling.

WYSOKOCZUŁE METODY DETEKCJI ZMĘCZENIA

Streszczenie

W artykule przedstawiono doświadczenia z badań stoiskowych i diagnozowania zmęczenia łopatek sprężarki. Wskazano typowe przypadki zmęczenia metalowych łopatek (LCF, HCF i VHCF). W rozważaniach uwzględniono cechy rzeczywistego materiału konstrukcyjnego, w tym wpływ domieszek, defektów struktury polikrystalicznej i obróbki wykańczającej na zmęczenie materiału. Przedstawiono metody badawcze stosowane do monitorowania stanu technicznego. Wykazano, że metoda tip timing (TTM), eksperymentalna analiza modalna (EMA) i magnetyczna pamięć metalu (MMM) udostępniają informację o narastającym zmęczeniu diagnozowanego obiektu (łopatki sprężarki). M.in. wykazano, że kształt krzywej rezonansowej jest związany z poziomem zmęczenia struktury i pęknięciem pióra. Opisano wczesne symptomy zmęczenia, m.in. właściwości modalne fazy umocnienia i osłabienia (strukturalnej i magnetycznej anizotropii).

Słowa kluczowe: łopatka sprężarki, degradacja, zmęczenie analiza modalna, sprzężenie siatka krystaliczna-spin.

1. INTRODUCTION

Many different fatigue failures (LCF, HCF and VHCF) could occur throughout the turbine engine's life, Figure 1.

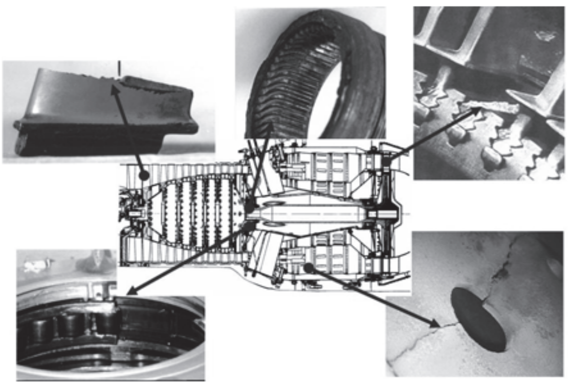

Fig. 1. Structural fatigue problems of turbine engines

Fatigue cracks propagating in rotor blades, the incorrect control of the engine's fuel system and the lack of knowledge on the loads affecting the bearing system generally cause a formidable hazard to flight safety, as well as to engine life and reliability. Therefore, the AFIT keeps looking for new methods of recognizing stochastic loads during the engine's running, and the effects thereof upon the engine's structural reliability. The paper presents three methods:

a) A non-contact blade-vibration measuring technique (tip timing method) [1-10], which is one of the most interesting methods of complex diagnosing of jet engines and a powerful tool to investigate dynamic phenomena in the running engine. The method has been used in the Polish Air Force since 1993 with the SNDŁ-1b/SPŁ-2b diagnosing system developed for the SO-3 engines. Since 1997, this method has been also used in the post-repair/post-overhaul acceptance tests.
b) An experimental modal analysis, which has been used as a sensitive NDT method during overhaul blade tests since 2008 [11].

c) A metal magnetic memory, which has been used as a sensitive observer of residual and applied stress, and continuous material damage [12-18].

These methods are source of information about blade quality (of design, production and overhaul) and real dynamics of phenomena (correlation by modal proper-ties), which have an effect on blades damage and fatigue differentiation. This information has been used to actively control fatigue of compressor blade and verify FEM model.

2. MOTIVATION

In the years 1975-91 as many as 25 first-stage compressor blades of ten SO-3 engines suffered fatigue-attributable break-offs, which caused two accidents. The metallographic examination of damaged blades made out of the 18H2N4WA steel has proved that the crack initiation centres were located either on the leading edges (55%) or on the blade-back surfaces (45%), in the areas of nodal lines of the first mode vibration. Crack propagation occurred at low-level stresses (HCF problem) or high-level stresses (LCF problem), Figure 2. Fatigue fracture covering as much as 95% of the blade's cross section was found in one of the blades. Furthermore, it has also been found that erosion and corrosion, both occurring on the blade's face surface, as well as fine mechanical damages on the leading edge are stress concentrators [2]. Fatigue problem was also observed in titanium blades (Ti5.8Al-3.7Mo) in the TW3-117 engines in the years 2005-2007.

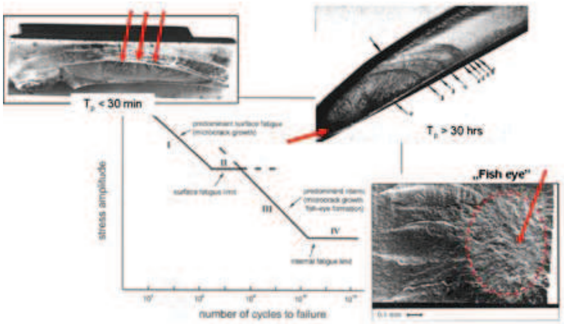

Fig. 2. Fatigue problems (LCF, HCF, VHCF) of compressor blades

The gigacycle fatigue problem (VHCF with "fish eye" symptoms) of compressor blade has been observed at foreign users, e.g. in Russia [19,20], Figure 2. Compressor blades run a risk of VHCF problem because they count more then $3\cdot10^9$ cycles for 1st flexible mode and more then $1\cdot10^{10}$ cycles for 1st torsional mode during time between overhaul (TBO). High risk of VHCF problem, with crack nucleation under the blade surface and stresses level below fatigue life stresses, concerns of high resistant material and blades made with surface finish techniques [21-23].

Uncontrolled blade over fatigue:

- is a threat for service safety;
- limits aero-engine life time;
- increases maintenance costs.

It is also a great challenge for a diagnostics engineer.

If blade fatigue is found, who is responsible for the problem?

Classical NDT (eddy current, ultrasound, magnetic and fluorescent methods) are very low effective to diagnose blade crack before damage, because of:

- crack gap closing during engine standstill (about 50% of crack area after 12 hrs);
- lack of reliable information about real operating conditions;
- lack of knowledge about early cracking symp-toms and mechanisms;
- difficult access to tested blades (because of inlet stator vane).

An other disadvantage of the NDT methods in use (during overhaul and service) is no possibility of fatigue prognosis. This disadvantage is very impor-tant for the 1st compressor blades of the SO-3 engine. The blades have design errors - too low the first-mode mistuning form the 2nd rotational harmonic excitation. There for, too high stress and fast fatigue crack initiation can occur during operation. These conditions take place during the take-off phase when there is a foreign object lying in the inlet or the inlet icing occurs. Under such conditions time between crack initiation and blade damage can be shorter than time of a single flight.

An intuitive diagnostic symptom of a blade crack is a change its modes frequency. The cracking propagation and blade break off occur at limiting decrease in frequency, the value of which depends on the crack centre's position and the loading. Blades' frequency check offers too short prognosis horizon. It is sufficient in the system monitoring only; for example, in the tip-timing method.

3. THE TIP TIMING METHOD

The tip timing idea consists in observing displacement of loaded component part. In our case, it will be a rotating and vibrating blade. The observer is built onto a fixed part of machinery. The measured signal contains:

- Aperiodic part *A(t)* – average instantaneous rotational speed of perfect stiff rotor.
- Oscillating part *P(t)* – resultant from: pitch errors, blade, rotor and disk vibration and instantaneous rotational speed perturbations (from the engine control system, flow, g-force, clearance in a kinematic system, and torsional vibration).
- Noise and weak oscillating components *I*(t)

$$S(t) = A(t) + P(t) + I(t) \quad (1)$$

so it is possible to design a general-purpose observer for real operating conditions of rotating parts and have a complex view on:

- Disadvantageous dynamic phenomena (flutter, stall, surge, resonance, load coupling);
- The influence of production, overhaul and maintenance real conditions on the level of malfunctioning and fatigue prognosis.

Blade vibration and deflection are a source of a time-interval (measured) change between flexible key phases. Time period signal would be measured with a frequency method [10].

Analyzed data (discrete time of signal $S(k)$) – a number of pulses $Code_i$ with clock frequency counting between key phases includes three groups of variables to be identified in effect of further numerical signal analysis

$$S(k) = Code_i = K_{i,i+1} Trunc\left(\frac{\Delta T_{i,i+1}}{t_{clock}}\right) = \left(\frac{(1+\zeta_B)}{(1+\zeta_R)}\frac{2\pi / N_B}{\omega}\right)_{i,i+1} \quad i \in \langle 1, 2, ..., N_B \rangle \tag{2}$$

where, k – discrete time, N_B – number of blades, $\Delta T_{i,i+1}$ – time interval between two blade passes; t_{clock} – time period of generator pulses; $K_{i,i+1}$ – error and disturbance factor ($K_{i,i+1}$ = 1 for data without error), ζ_B – jitter of blades group components, ζ_R – jitter of rotor group components, ω – angular velo-city of ideal rotor.

Every component of S(k) is used to diagnose. An oscillating part $P(k)$ is a main carrier of diagnostic information about blades damage and danger dynamics phenomena. An aperiodic part $A(k)$ and part $I(k)$ give the capability to compare new diagnostic symptoms to the health of machinery. The scope of interest of TTM data processing includes [1-10]:

- Vibration level of all blades at the same time.
- Disadvantageous dynamic phenomena.
- Blade stress and health.
- Disk health,.
- Engine health.

The tip timing method is not intended to direct measure: load, local displacement (strain) and local stresses in the blade. This can be estimated by using TTM data and other numerical methods (GPA – Gas Path Analysis; FEM – Finite Element Method; CFD – Computational Fluid Dynamics, statistical ones) and knowledge about blade modal properties. Characteristic features of the TTM are:

- getting information about vibration and quasi-static blade deflection only once during 360 degrees rotation;
- irregular signal sampling rate, affected by vibration parameters (like amplitude, frequency and phase). The Nyquist-Landau law describes discrete-time information;
- periodic measurement data structure – data can be illustrated with matrix with N_B columns (number of blades) and rows that represent each full 360 degrees cycle of a rotor;
- the inherent in a signal oscillating parts that are not connected with blade vibration. There are two groups of oscillating parts of a signal: synchronized and non-synchronized with rotor rotational frequency;
- observation of effects of coincident amplitude modulation (AM), frequency modulation (FM) and phase modulation (PM) if there are oscillating parts in a signal.

To develop the expert analysis on compressor blade and engine health, the qualitative evaluation of applicability of the tip timing method was done in 1987-1993. The possibility of estimating the blade health (crack initiation and propagation) on a running engine was taken into consideration [2]. Signal components are obtained with the narrow-band filtering and AM/FM demodulation. They are very useful to expert analysis of health of the engine itself and to the 1st stage compressor blades, the engine fuel system and the bearing system [6].

Blade vibrations are shown in the form of phase distributions as points of phase trajectory crossing the phase plane [2], Figures 3 i 4. A characteristic feature of the method is information that lasts about a total number of modal frequency periods between two subsequent points of phase trajectory crossing the phase plane, with basic modal parameters of the blades preserved. This phenomenon enables detec-tion of the LCF and HCF crack initiation and propagation in the blade during the engine operation.

3.1. Examples

The object under scrutiny has been the 1st stage compressor blade (28 blades made out of the 18H2N4WA steel, each 100 mm long, chord 37 mm, twisted by the angle of 38°). Frequencies of three subsequent modes of blade vibration were as follows (average values): 350 Hz and 1380 Hz (bending vibration), 1890 Hz (torsional vibration).

Synchronous resonance

During examination with a strain gauge no evident symptoms of interrelationships between the disk and blade vibrations were observed – compressor stages are of compact design. However, it was observed that within the take-off range of the SO-3 engine operation (n = 15600 rpm), synchroni-sation of blade vibration with forces from the 2nd harmonic of the rotational speed (f_{1mode} = 520 Hz) may occur, Figure 3. Such phenomena observed, e.g. after some foreign object (bird, ice) has been deposited on the stator blade-ring, induce blade vibration up to some dangerous level where the material yield point is reached and exceeded, and quick initiation and propagation of the LCF and HCF crack occurs. Under such conditions of blade operation, time of safe operation of any turbojet engine may be <u>much shorter</u> than one flight/mission of an aircraft.

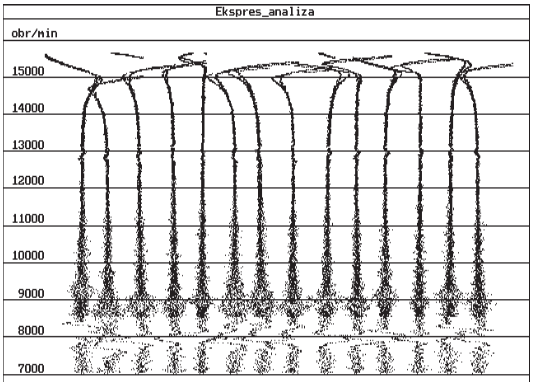

Fig. 3. How foreign-matter deposi-tions may affect the level of stress in the SO-3's 1st stage compressor blades - effect of foreign matter in compres-sor inlet [2]

The blade cracking

After an analysis of destructive testing results (controlled propagation of blade cracking under normal conditions of operating the SO-3 engine) it was found that:

- during the blade cracking initiation (no open crack visible on the blade surface) only change in the *B* factor of dynamic increment of blade vibration frequency is seen, Figure 4.a) – frequency of the blade's free vibration $f_B(0)$ is constant

$$f_B(n) \approx \sqrt{f_B(0)^2 + B n^2} \quad (3)$$

- the occurrence of a blade crack decrease in the range of excitations from the rotational-speed II harmonic by 1000 rpm (Δf = 16.6 Hz), Figure 4.b). At the moment, frequency (the 1st mode) of the blade's free vibration changed by less than 3 Hz;
- when the crack reaches about 30% of the blade profile evident reduction in frequency of free vibration and decrease in the range of excitations from the rotational-speed III harmonic (n ≅ 8000 rpm) was observed;
- just before the blade break-off (about 65% of profile for the crack from the leading edge, 95% of profile for the crack from the back of the blade), an evident effect of stiffening due to centrifugal forces was observed, Figure 4.c). Changes in the dynamic scale inflicted by the broken blade are comparable with those in other dynamic scales (the influence of the engine's rotational speed).

The representative one-hour profile of the engine mission used for the bench test has comprised:

- starting of the engine,
- engine warm-up,
- ground idle running (3x 4.5 min),
- running the engine within take-off range of speed (4.5 min)
- running the engine within cruising range of speed (4.5 min)
- eleven full acceleration/deceleration cycles (ground idle - take-off range of speeds – ground idle),
- half-way accelerations/decelerations within the range: idle - 12000 rpm (3x4.5min, 5 cycles/min),
- half-way accelerations/decelerations within the range: 12000 rpm - take-off range (3x4.5min, 5 cycles/min),
- engine cooling,
- stopping the engine.

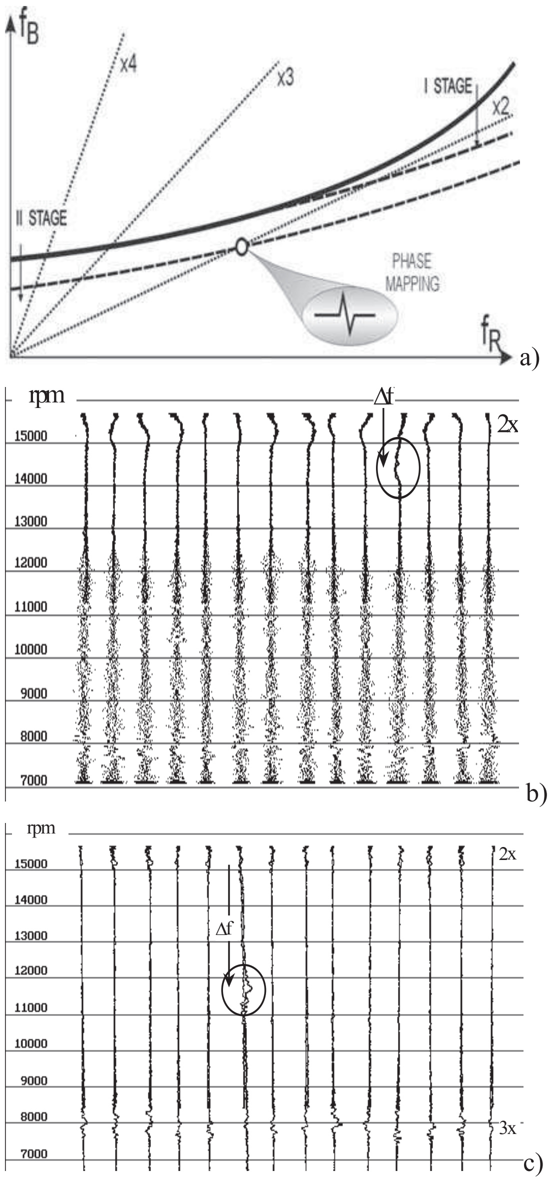

Fig. 4. The effect of blade cracking as phase representation of blade vibration [2]: a) blade frequency plotted in the Campbell diagram; b) the first stage of blade cracking – changes only B; c) final stage of blade cracking – 5 minutes before break (LPF)

In such a mission profile, the blade crack propagation from the crack initiation down to the blade break-off took more than 30 hrs for the normal level of excitations. On the other hand, it didn't take more than 20 minutes (about $6{,}2\cdot10^3$ blade cycles with the 1st mode frequency) of the engine running within the take-off range of speed and at high level of stress (deposition of some foreign object in the inlet). It has been proven that the TTM gives credible prognosis for 50 engine work hours (over $9\cdot10^7$ HCF and 100 LCF cycles, 1/8 TBO). It has been also proven [11] that TTM symptoms of the cracking are closely related to:

- the strengthening phase – the quality factor of the resonance system increases together with the friction mode frequency;
- the weakening phase – growth in the resonance curve asymmetry and growth in nonlinearity.

Nowadays, these symptoms are not used in the SNDŁ-1b/SPŁ-2b system. They provide a capability of broadening prognosis horizon.

4. THE EXPERIMENTAL MODAL ANAYSIS METHOD

Experimental modal analysis is an effective aid in solving blades' fatigue problems. It allows of finding an answer to the question: "Why does a blade crack?", not only: "Is it cracked?". The modal parameters of all the analysis modes (within the frequency range of interest) constitute a complete dynamic description of the blade structure [11,24]:

- ✍ blade material,
- ✍ blade geometry,
- ✍ the influence of surface treatment and adding protection coating;
- ✍ technical health (structural heterogeneity, crack and fatigue).

The characteristic feature of blade vibration measurement on a modal excitation system is knowledge of both a force level and a blade response on it. That's why it is possible to identify blade modal properties for following modes.

The broadband identification (up to 20 kHz) of modal properties of a compressor blade made of 18H2N4WA steel and Ti5.8Al-3.7Mo titanium alloy, has been made on the PSV-400 Polytec scanning vibrometer and low power PZT exciter.

The identification of early fatigue and cracking symptoms of these blades has been made on the B&K electro-dynamic exciter 4802T. The experimental stand, used during the SO-3 and TW3-117 engine overhauls, included:

- the MTI Instrument laser measurement system MicroTrack™II with CMOS measurement head LTC-120-40 [25];
- the Vibration Research Corporation VR-8500 controller that includes 24 bit A/D and D/A converters, and RISC processor [26];
- the Vibration Research Corporation Vibration View software to control the exciter, data acquisition and analysis [26].

The sensitivity of measurement system is 100 mV/mm.

Experiments have been performed in four stages in which:

- the measurement method has been verified,
- blade cracking symptoms have been identified,
- early symptoms of fatigue have been identified,
- new diagnostic symptoms have been verified for titanium blade.

It has been proven that used measurement technique (MTI laser head) guarantees reliable modal results when vibration amplitude is higher 2 μm. Reliable resonance curve shape during sine test has been got for force frequency: 2.5 Hz/min for 1st flexible mode (1F, Q_s >350) and 1.0 Hz/min for 1st torsion mode (1T, Q_s > 1000). Such a stand gives an ability to make precise measurements with an exact test profile and frequency step. The measurement system gives almost laboratory accuracy. That's why it let [11]:

- Precise identification of blade modal properties in measured frequency range.
- Metrological factors influence analysis on recorded resonance characteristics.
- Modal parameters trends analysis observed during fatigue tests.

The modal properties identification (sine test) was based on the transition function

$$G(\omega) = \frac{Y(\omega)}{X(\omega)} \quad \left[\frac{m}{m}\right] \tag{4}$$

where $X(\omega)$ – displacement of an exciter head (blade root); $Y(\omega)$ – displacement of a blade tip.

4.1. Modal properties of a defect-free (non-cracked) blade

In the case of a defect-free blade (health) resonance characteristics of particular modes were gained, ones that could be well described with a model of a **s**ingle-**d**egree-**o**f-**f**reedom linear system (SDOF) – of mass m suspended on a spring with spring rate K and viscous damping C [27]. For sine test SDOF model describe

$$\begin{aligned} & m\frac{d^2y(t)}{dt^2} + C\frac{dy(t)}{dt} + Ky(t) = F(t) \\ & F(t) = A(\omega)\sin(\omega t) \\ & y(t) = B(\omega)\sin[\omega t + \varphi(\omega)] \end{aligned} \tag{5}$$

Characteristics of subsequent modes remain continuous under resonance conditions and exhibit good symmetry around the resonance frequency (within the band-width of 3 dB), Figure 6. The blade displacement at the measuring point can be described with:

- vibration amplitude

$$b(\omega)=\frac{y_{st}}{\sqrt{\left[1-\left(\frac{\omega}{\omega_o}\right)^2\right]^2+\left(\frac{\delta}{\pi}\frac{\omega}{\omega_o}\right)^2}} \qquad (6)$$

- vibration phase angle

$$\varphi(\omega)=\arctan\left(\frac{\frac{\delta}{\pi}\frac{\omega}{\omega_o}}{1-\left(\frac{\omega}{\omega_o}\right)^2}\right) \qquad (7)$$

where, ω_0 – a free vibration frequency, δ – a logarithmic damping decrement.

4.2. Diagnostic symptoms of a cracked blade

When analyzing resonance curve shape we can observe how different it is for cracked blade. The blade has all nonlinear properties [11,29] which describe a nonlinear 2DOF model, Figure 5.

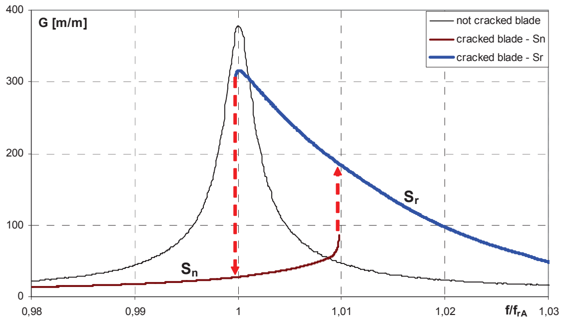

Fig. 5. The effect of a crack on the 1st mode characteristics shape (steel blade, a = 19.62 m/s^2, f_{rA} – frequency of amplitude resonance)

Close to the resonance frequency it is possible to observe two branches of characteristics: resonance attractor – S_r, and non-resonance attractor - S_n, and jumps between them. The shape of a cracked-blade's resonant curve is affected by the blade's material and conditions existing on the edge of the crack gap. The characteristic curve is sloped to the left (towards lower frequencies) for the crack with material weakening. On the other hand, for the gap with material hardening, the curve is sloped to the right (towards higher frequencies). The knowledge of resonant curve inclination is essential for correct interpretation of measurements, including correct identification of the resonant and non-resonant branches. During one-sided test we observe "asymmetry" resonance curve with seeming quality factor decreases. Resonance frequency and characteristics are functions a blade amplitude. They were not asymmetry symptom for:

- small loads that don't develop an open crack. Asymmetry is growing with a load increase;
- a notch on a blade, which was used as a simplified crack model (no friction at a notch hole). No friction in notch modeled blade is a source of other differences in modal properties, Table 1, and fatigue (JCF phenomena).

Table 1. Blade with 11 mm length damage (*starting from TE*) placed 20 mm from lock

Blade	Frequency change (Hz)		
	1st mode	2nd mode	3rd mode
Cracked	-12	+7	-27
Notched (*no friction*)	-13	-5	-80
Difference (%)	**-0.28**	**-0.86**	**-2.73**

The obtained characteristics of the cracked blade cannot be described with a SDOF linear model. The blade crack forms a two-degrees-of-freedom (2DOF) non-linear system for any form of blade vibration. The equivalent linear equation that satisfies the non-linear equation with accuracy ε takes the following form:

$$\frac{d^2y}{dt^2}+2h_\varepsilon(b)\frac{dy}{dt}+\alpha_\varepsilon^2(b)y=\varepsilon\, p\cos(\omega t) \qquad (8)$$

where: ε – small parameter, p – amplitude of the exciting force, b – steady-state vibration amplitude, $\alpha_\varepsilon(b)$ – equivalent natural (free-vibration) frequency, $h_\varepsilon(b)$ – equivalent elementary damping coefficient.

The measured and analyzed parameters of the blade are described with the following relationships:

- vibration amplitude

$$b(\omega)=\frac{\varepsilon\, p}{\sqrt{\left(\alpha_\varepsilon^2(b)-\omega^2\right)^2+4h_\varepsilon^2(b)\omega^2}} \qquad (9)$$

- resonance frequency

$$\omega=\sqrt{\left(\alpha_\varepsilon^2(b)-2h_\varepsilon^2(b)\right)\pm d}$$
$$d=\sqrt{4h_\varepsilon^2(b)\left(h_\varepsilon^2(b)-\alpha_\varepsilon^2(b)\right)+\left(\frac{\varepsilon\, p}{b}\right)^2} \qquad (10)$$

- vibration phase angle

$$\varphi(\omega)=\arctan\left[\frac{-2h_\varepsilon(b)\omega}{\alpha_\varepsilon^2(b)-\omega^2}\right] \qquad (11)$$

4.3. Early fatigue identification

The LCF and HCF data analysis showed that blade modal properties could be used to observe the material strengthening phase [11,29,30]. Increase in the 1st mode resonance frequency of approx 0.4% is a symptom of the initial resonance system quality factor growth (correlation with structural and magnetic anisotropy), Figure 6. This phase can be described with linear SDOF model. The orientation indicator of maximum cyclic material strengthening is $R_m/R_{e0.2}$ (like as for metal magnetic memory NDT according to ISO-15242).

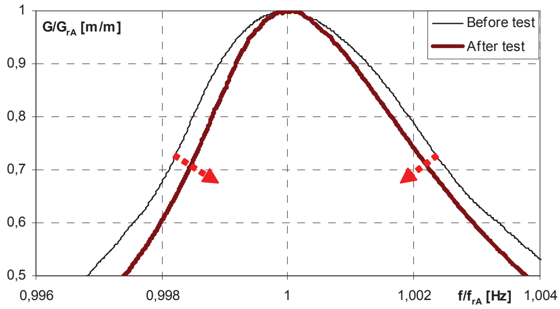

Fig. 6. Changes in modal parameters during material strengthening phase

The growing asymmetry of the resonance curve was observed only in the final fatigue phase; it preceded the 1st mode frequency decrease, Figure 7.

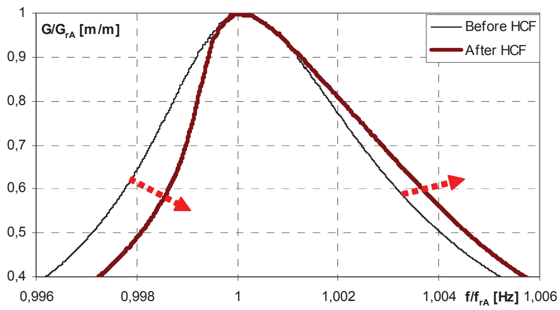

Fig. 7. Changes in modal parameters during material weakening phase (δf_{rA} = -0.5 Hz)

4.3. JCF phenomena

Influence of the cracked blade's resonant curve discontinuity on the propagation rate was investi-ated for blades made from titanium alloy. It was found that in the case of constant frequency input (HCF tests without fine tuning to current resonant frequency), characteristic curve sloping to right and resonant curve discontinuity helps stopping the crack propagation.

The speed rate of its development was conditioned by the load history of a blade. The asymmetry is a symptom of the material weakening phase [11,29,30]. The speed rate of the resonance curve asymmetry development, from the very first symptom of an open crack, is determined by the blade loading history.

Discontinuity of the resonant curve (blade pulse input discharge and load even for constant external load) is a source of very fast crack propagation during frequency transient phase – the phenomenon is called **J**ump **C**ycle **F**atigue (JCF), Figure 8.

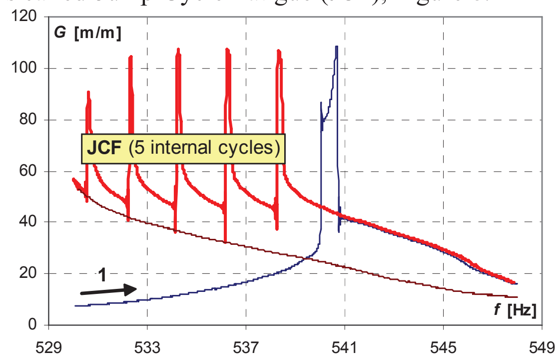

Fig.8. JCF phenomenon for a cracking blade with Ti5.8Al-3.7Mo (sine sweep 4 Hz/min with constant external load)

The JCF is a reason for the serial material tearing during the decrease in excitations frequency, observed in the unstable phase of cracking. Those observations are fundamental for the prognosis of crack propagation velocity and determination safe prognosis horizon for blade operation and fatigue reverse engineering - correct interpretation of fracture structure (answer on the question "How many load cycles took place during crack propagation?"). Arrest lines of fatigue strap map only a number of cycles for internal loads. Their values could be bigger several times than a number of cycles for external loads, which result from a flight mission profile.

5. THE METAL MAGNETIC MEMORY METHOD

Modal properties of compressor blade (*K*, *C*) are correlation with local and global magnetic properties of its material by grain-lattice and lattice-spin coupling (magneto-mechanical effects i.e. Villari effect, ΔE effect, stress magnetization and spontaneous magnetization of ferromagnetic in the Earth field) [12,31-33]. Zones RSC of local residual stress concentration, plastic, material anisotropy (mechanical and magnetic) and dislocation concen-tration are potential place of cracking nucleation and local magnetic anomaly [31].

The RSC are searched by passive observer - the metal magnetic memory method (MMM). Stress, strain (elastic and plastic) and dislocation density (sources of structural anisotropy) change material magnetization ***M*** and external magnetic field ***B*** in the vicinity of blade surface (magnetic permeability μ and electrical conductance ρ of polycrystalline material) [18,34]. The Earth's magnetic field and electro-magnetic noise are natural external source of magnetic field.

For small elastic deflection (strain) of the blade, the magneto-mechanical effects are described by reversible thermodynamic relation [35]:

$$\mu_0\left(\frac{\partial \mathbf{M}}{\partial \boldsymbol{\sigma}}\right)_{\mathbf{H}} = \left(\frac{\partial \mathbf{B}}{\partial \boldsymbol{\sigma}}\right)_{\mathbf{H}} = \left(\frac{\partial \boldsymbol{\lambda}}{\partial \mathbf{H}}\right)_{\boldsymbol{\sigma}} \qquad (12)$$

where, μ_0 - magnetic permeability of free space, $\left(\frac{\partial \mathbf{M}}{\partial \boldsymbol{\sigma}}\right)_{\mathbf{H}}$, $\left(\frac{\partial \mathbf{B}}{\partial \boldsymbol{\sigma}}\right)_{\mathbf{H}}$ - reversible isofield magneto-mechanical coefficients, $\left(\frac{\partial \boldsymbol{\lambda}}{\partial \mathbf{H}}\right)_{\boldsymbol{\sigma}}$ - reversible isostress magnetostrictive coefficient. The magnetostrictive phenomena $\boldsymbol{\lambda} = \lfloor \lambda_{\|}, \lambda_{\perp}, \lambda_n \rfloor$ describes properties of material surface in parallel and perpendicular to load direction and material magnetic properties in orthogonal to surface.

The magneto-mechanical effects are partially irreversible for elastic strain and RSC (source of stress magnetization and local magnetic anomaly).

Potential possibilities of MMM were tested during active and passive experimental with used of compass (simple magnetometer), GM-04 magnetometer with Hall sensor, and IKN-1M-4 stress concentration recorder. Very good relation has been observed between the MMM results and blade node lines after LCF tests [18]. Local magnetic anomaly has been also observed near the close crack gap after HCF tests. Nevertheless, the most interesting phenomena is non-destructive detect of stress prehistory (a change of remanent magnetization), Figure 9.

On the base of former research absolutely, that exist the circumstances of use MMM to diagnosis the VHCF problems.

5.1. Magneto-mechanical damping

Applying a stress to a ferromagnetic blade causes a variation of magnetization due to the magneto-elastic coupling, which results in the so-called "ΔE effect" (i.e. an apparent reduction of Young's modulus below the purely elastic value found in the magnetically saturated state) and also in a related dissipation of mechanical during loading/ unloading or in case of vibration. The latter effect can give rise to a strong magneto-mechanical damping with stress-dependent and stress-independent components (a small change of K in Equation 5) [36] .

Experiments show that ferromagnetic have a higher internal friction than other metals because of phenomena of an electro-magnetic nature resulting from the application of elastic fields. Considering five main contributions to the total energy of a ferromagnetic without an external field (exchange energy W_{ex}, magnetocrystalline anisotropy energy W_k, magneto-elastic (or magnetostrictive) energy W_λ, magnetostatic energy W_m, energy of magnetic domain walls W_w), four main mechanisms of magneto-mechanical damping may be defined [36]:

- magnetoelastic hysteresis damping, Q_h^{-1}
- macroeddy-current damping, Q_a^{-1}
- microeddy-current damping Q_u^{-1}
- damping at magnetic transformation Q_{PhT}^{-1}

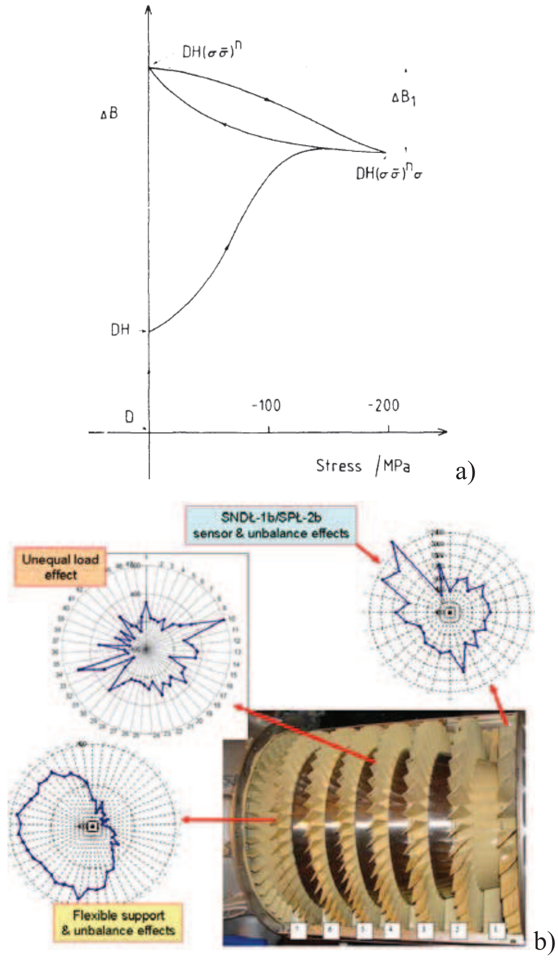

Fig. 9. Detect of stress prehistory:
a) irreversible process of stress magnetization [34]; b) identification of blade fatigue risk [28]

Therefore, the total magneto-mechanical damping Q_m^{-1} in ferromagnetic blade can be considered as sum of these components:

$$Q_m^{-1}(\varepsilon,\omega,T) = Q_h^{-1}(\varepsilon,\omega,T) + Q_a^{-1}(\omega,T) + \\ + Q_\mu^{-1}(\omega,T) + Q_{Ph.T} \qquad (13)$$

where contrary to Q_a^{-1} and Q_u^{-1}, the hysteretic contribution Q_h^{-1} depends on the strain amplitude. The damping Q_m^{-1} is also dependent on the load frequency, material temperature, and initial conditions (micro- and macrostructure, magnetization, residual stress) – the Q_m^{-1} is nonlinear [37], so damping coefficient C in Equation 5 and the FEM model of damage blade is nonlinear too.

6. CONCLUSION

1. During 15 years of using the tip timing method in the Armed Forces of Poland, the following things have occurred:
   - The statistical mean time between fatigue break-offs of blades has been increased (nine times for calendar-based data, and five times on the hourly basis). Since 1991 no fatigue crack of any compressor blade in the SO-3 engines has been found;
   - The surge as a result of maladjustment of the fuel system and latent defects of subsystems has been eliminated (fatigue problems results from maintenance);
   - Five SO-3 engines have been taken out of service due to excessive errors in shapes of the blades.
2. The shape of cracked blade resonant curve is described by blade's material and conditions existing on the edge of the crack gap. The characteristic curve is sloped into left for the crack with material weakening. On the other hand, for the gap with material hardening, the curve is sloped into right. Asymmetry of resonant curve wasn't found on the blade with notched – a simple crack simulation model, often found in the literature.
3. The mode frequency of cracked blade depends on the condition of the crack edge. For the titanium blade with 12 mm crack and hardening stiffness characteristic, a vibration frequency of the first mode was considered as efficient under technical specification conditions!
4. Nonlinear properties of a crack blade are fundamental for the prognosis of the crack propagation rate and for the determining safe prognosis horizon. These modal symptoms of material damage are correlated with magnetic symptoms.
5. Diagnostic symptoms of the material weakening occur before:
   - the 1st mode frequency decrease by 3 Hz, the symptom of airfoil crack according to current technical and overhaul requirements;
   - an open crack, identified during the engine overhaul with a classical NDT method.
6. MMM method is developed in cooperation with The Faculty of Automotive and Construction Machinery Engineering (Warsaw University of Technology) during project "MONIT".

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