Health Monitoring of Turbomachinery

Based on Blade Tip-Timing and Tip-Clearance

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ABSTRACT

Eddy-current sensors, mounted in a gas turbine engine casing, can reliably measure blade time-of-arrival and tip clearance during flight and ground operation. Gathered data are used to estimate parameters characterizing blade and rotor vibrations. The technique employs numerical models of rotating components to assess engine response.

This paper describes development of a new monitoring system for turbomachinery, based on tip-timing technology and adapted to operation in harsh environment of combat aircraft. Prototypes are manufactured for TS-11 Iskra and Mig-29 Fulcrum. The system includes software, which checks for abnormal engine responses to detect failures, including detection of fatigue cracks in blades, health assessment of rotor bearings and engine fuel supply system. In-flight blade and rotor vibration monitoring, combined with ground-based fleet usage and fault database, offers a great potential to reduce high maintenance costs of aging aircraft while increasing reliability and safety level.

INTRODUCTION

Effective engine health monitoring is crucial for the aircraft safety, especially for aging machines. ITWL developed SNDŁ-1b/SPŁ-2b diagnosing system for TS-11 Iskra jet-trainer, which has been used successfully in the Polish Air Force since 1993 [1, 2]. The system has diagnostic functionality balanced with necessary technician participation. Numerous benefits in aircraft maintenance and safety encouraged MoD to support development of a new engine health monitoring system, also based on tip-timing technology. It was intended to be much more than upgrade of the successor and should use new technologies available on the market. Two versions of the system were ordered, for SO-3 turbojet (TS-11) and RD-33 turbofan (Mig-29).

Most of contemporary tip-timing measurement systems are designed for laboratory conditions and used during HCF spin tests or in ground engine runs to verify blade design or to investigate self excited vibrations [3, 4, 5]. They offer micrometer accuracy, high channel count and sophisticated tools for analysing bladed disk response [6].

The objective of the new ITWL system is to detect and record abnormal blade and rotor vibration and warn the crew and ground personnel about impeding serious risk of failure. It uses a limited number of sensors to bring diagnostic functions unavailable in existing systems and flight data recorders for these aircraft.

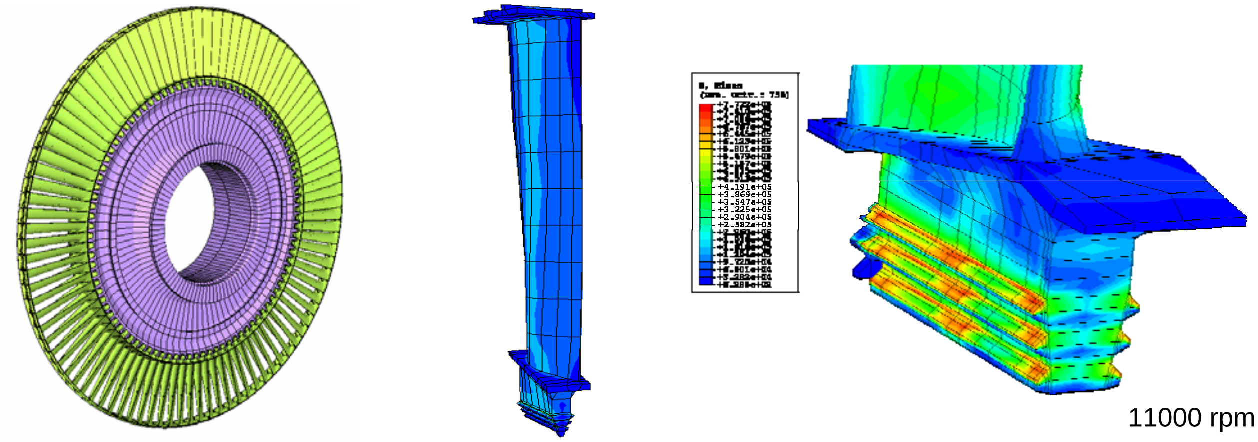
The system is expected to identify the following dangers:

- Excessive blade vibration caused by foreign object damage or icing in the inlet section of the engine;
- Change in vibration frequency due to fatigue crack development;
- High non-synchronous vibration due to rotating stall, flutter or surge, caused by the blocked inlet or fuel system failure;
- Free vibration of a single turbine blade caused by shroud wear;
- Excessive vibration of turbine blades caused by combustion problems (deficient fuel, faulty nozzles or vanes);
- High rotor vibration due to bearing failure or rotor bow;
- Improper dynamics of engine start and rundown due to bearing failure;
- Other symptoms and problems identified during system tests and implementation.

Probability of listed events rise with engine aging, imperfect pilotage, maintenance or overhaul, low quality spare parts etc. In these cases extended engine monitoring is more than necessary and effective.

SYSTEM DEVELOPMENT

The research program started with the system definition, concept and gathering information about the engine structure and material parameters. Accessible engine documentation was incomplete and geometry models were unavailable. Reverse engineering was performed for selected stages, including 3D airfoil scan and development of a bladed disk and rotor 3D FEM model (fig. 1). Experimental results from vibration exciter and engine test-runs were used to calibrate models and estimate blade loads. Engine field history was analyzed to identify weak structural points, which was the basis for development of fault detection algorithms.



a) bladed disk model b) blade model c) von Misses kinematic stress

Fig. 1. FEM model of LPT bladed disk (RD-33 engine)

The next phase of the project included designing of system components (fig. 2) and manufacturing of prototypes. Development of completely new sensors, embedded computer and software was necessary due to untypical application and extended environmental requirements. Another important aspect of the project was the development of ground-based database containing fleet usage and fault information. Finally, the system implementation and usage procedures should be defined.

Assumptions and requirements:

- All onboard equipment adapted to extended temperature and vibration range and DC powered;
- First stages of fan, compressor and turbines monitored (fig. 2);
- Minimal interference to engine structure: 1-2 sensors per stage;
- Onboard computer responsible for processing and recording up to 8 measurement channels, able to warn against serious risk of failure.

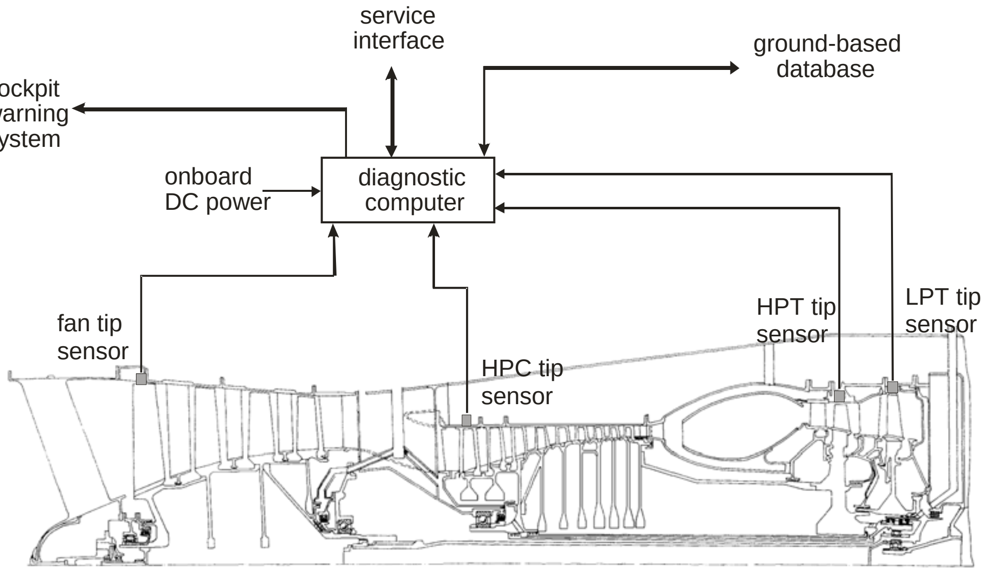


Fig. 2. Health monitoring system for RD-33 turbofan

Sensors

Tip-timing sensors, installed in compressor and turbine casing, should function reliably in adverse engine environment during flight and ground operation. Typically they cannot be replaced in the time between engine overhauls, so only robust materials and sensor technologies can be considered. For example optical probes, ensuring highest tip-timing resolution, cannot be used due to their sensitivity to contamination and lack of space for optical hardware in the aircraft.

Fan and compressor blade tip sensors

Inexpensive and reliable inductive sensors (based on Variable Reluctance effect - VR) has been used by ITWL for about twenty years to measure vibration of steel-made compressor blades (fig. 3a). They typically survive more than five years in fan environment and generate falling-slope pulses, convenient to trigger digital counters. They cannot sense blades made of paramagnetic materials like titanium alloys, which is serious drawback.

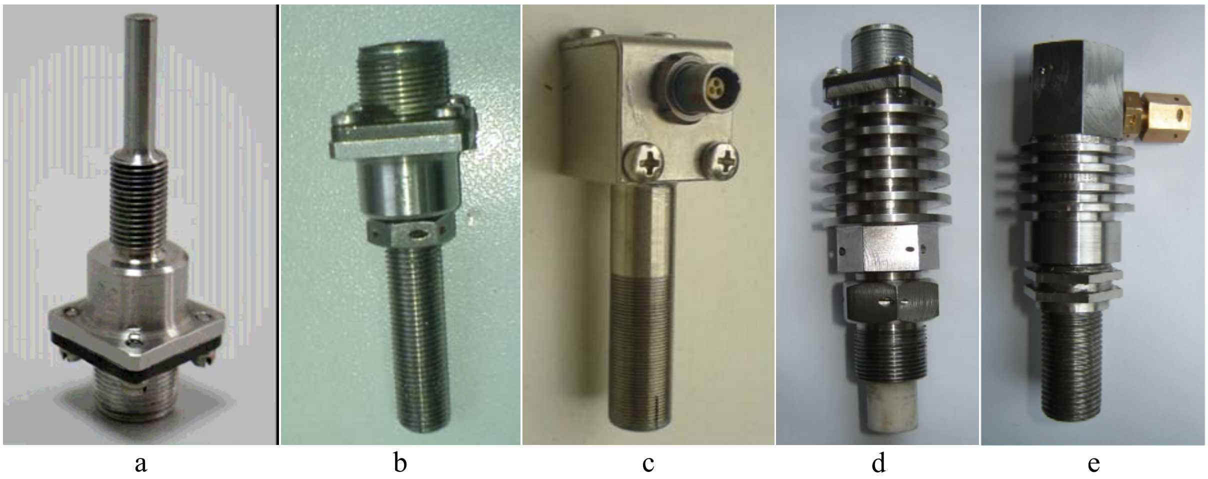


Fig. 3. Tip-timing sensors developed and tested in ITWL: a) inductive (VR) for steel SO-3 fan blades, b) passive EC for titanium K-15 fan blades, c) passive EC for titanium RD-33 fan blades, d) passive EC for SO-3 turbine, e) microwave for SO-3 turbine

Efforts focused on adequate materials selection, magnetic field modeling and amplifier design optimization, resulted with improved VR sensor signal in low speed range or with high tip clearance. Sensors developed afterwards (fig. 3b,c) were able to sense weak eddy currents (EC) fields, generated on the tip of titanium blade. These sensors were tested in a laboratory test rig and also during bench test of RD-33 engine with satisfactory results. Passive EC sensors are optimal for fan and compressor stages, where air temperature is below 200°C. The sensor design is customized to the planned installation location.

Signal from passive EC sensors is similar to that generated by inductive speed pickups. Circumferential and radial tip position is described by the phase and amplitude of blade-related pulse, respectively. Signal amplitude of passive EC sensor is speed dependant and has to be dynamically calibrated to measure absolute tip clearance. Amplifier characteristic is adjusted to get preferred working range, defined by maximum clearance and rotor speed.

Turbine blade tip sensors

Gas turbine is extremely harsh environment for any kind of measurements and requires sensors manufactured with the use of materials and technologies, resistant to high temperature. For a few years ITWL was involved in development of microwave tip-timing sensor [7, 8]. Several prototypes were manufactured (e.g. fig.3e) and tested in the laboratory and during engine runs. Metal-ceramic probe structure was optimal for gas temperatures exceeding even 1000°C. The sensor performance was acceptable but it was difficult to guarantee stable operation of the integrated electronics in flight condition.

Accumulated experience with temperature-resistant materials, especially ceramics, was used to develop passive EC sensor (fig. 3d), resistant to the turbine environment. The prototype with integrated passive cooling (radiator) successfully passed tests on SO-3 turbine (800°C). They are plans to test the sensor on low-pressure turbine (LPT) of RD-33 engine (1000°C). In case of unstable operation in these conditions, air-cooling will be considered.

It is very difficult to reach and measure tip deflection of high pressure RD-33 turbine (HPT), not only due to extreme temperature (>1200°C), but also there is no access to the blade tip. The expected tip deflections are quite low, requiring high-resolution sensors (optical). Most probably HPT blade deflection will be not measured in the final version of the system.

Onboard computer

Real-time blade vibration monitoring requires efficient signal processing procedures, both in flight and during on-ground operation. The task is performed by a specialized on-board diagnostic computer (fig. 4), which handles data from all monitored compressor and turbine stages. Device design is determined by required computational power, memory and bit-rate of generated data. These parameters increase with channel count, which is defined by a number of used sensors. Bit-rate depends on rotational speed and blade-count, so it could be different for specific channels.

According to our experience, it is possible to get sufficient parameters from the tip-timing system using desktop PC components designed to operate in office/laboratory conditions. Typical dataflow (fig. 5) is several hundred kilowords per second, which could be handled by modern processors and hard disks in real-time. But it is quite challenging to design similar hardware for extended temperature range, based on embedded technology components.

Another problem is limited space in combat aircraft. Our electronics should fit into a tiny box (fig. 4), which can fit no more than 3-4 PC104 boards. Different computer architectures were considered (DSP, ARM, PC). The current design, based on a FPGA chip and some auxiliary processors, will be tested shortly.

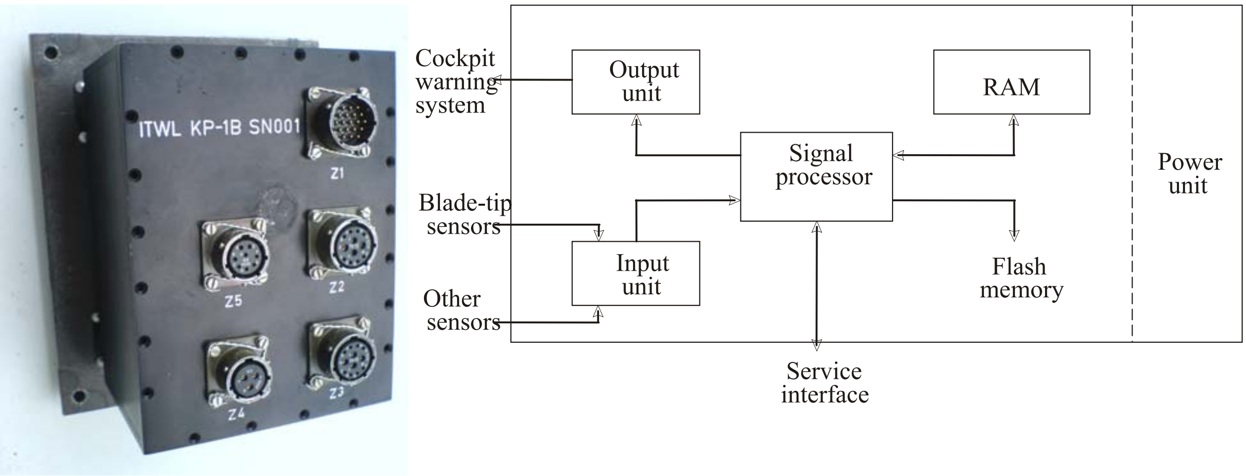


Fig. 4. Onboard diagnostic computer

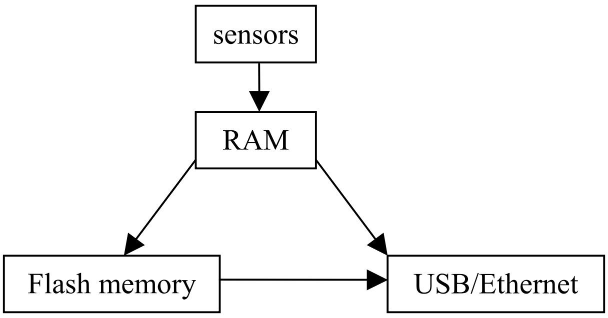


Fig. 5. Main directions of data flow

Blade deflection

The diagnostic computer uses constant clock to record time-stamp for each blade-tip pass, which represents the classic approach to tip-timing [4]. The higher the clock frequency the better, as absolute resolution of deflection measurement decreases proportionally with increasing rotational speed. The clock frequency higher than 100 MHz in practice offers redundant resolution for typical setup, often exceeding sensor and electronics noise level. Electronics is also able to sample peak pulse amplitude, which is used to estimate tip clearance.

Monitoring of blade vibration level is the primary function of the onboard computer, but it is also able to detect low-order synchronous resonances. Estimated parameters like vibration frequency and amplitude are used to assess blade health. Correlation of blade spacing pattern is used to assign pulses to particular blades, as there is no one-per-rev sensor.

In regard to the low pressure RD-33 turbine, the system is expected to detect discontinuity of the shroud. Numerical calculations have shown that a faulty shroud can lead to resonance vibration of loose blades which can be dangerous for the structure [9].

The onboard computer also uses blade-related pulses to perform precise measurement of rotor speed and disk angular position, which is a kind of encoder. Speed signal is used for fatigue cycles counting, fueling system health assessment [1] and analysis of engine start and rundown dynamics. Signals from different stages are used to measure relative disk angle, which helps to estimate shaft twist and torque.

Disk integrity

Various techniques for disk crack detection are in development, especially in the USA [10]. ITWL system is expected to identify blade lean by monitoring average circumferential and radial blade position.

Rotor vibration

Typically rotor response is measured with accelerometers installed on the engine casing. This method is indirect and the gathered vibration spectrum is influenced by modal casing properties. Direct access to the rotor using proximity sensors is unpractical in gas turbine engine.

The method applied in the system assumes that the modulation depth of the sensor signal is proportional to amplitude of shaft vibration. The rotor-related component is extracted from pulse peak amplitudes after correction of characteristic differences in blade tip clearance and cross-section. Results are used for rotor unbalance estimation and non-integral shaft vibration monitoring.

Usage and Fault Database

Selected data from all flights of the whole fleet are transferred to the ground database system. It handles comprehensive health and usage engine-related information, which can be searched and analyzed. The software automatically looks for suspicious trends and advises maintenance actions. Only a few duties are added to ground personnel. The system is open architecture for implementing new diagnostic algorithms and functions.

CONCLUSION

Diagnostic system is supposed to have a positive impact on aircraft availability. ITWL system monitors health of crucial engine components, which decreases the risk of engine failure, shortens service time and extends available fleet operation hours. The onboard computer does not generate false alarms, which could cause redundant service actions. Engine health and usage information is used to extend time between overhauls, increasing the number of available engine work-hours. Comprehensive diagnostics is especially necessary for engines designed 3-5 decades ago, which cannot be replaced in the near future.

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