Aircraft Turboprop Engine Vibration Monitoring Module

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Abstract – **The paper describes electronic vibration monitoring module (EVM) that can be used as standalone diagnostic system or as a part of a complex modular concept of engine electronic control (EEC/ FADEC) with aircraft health monitoring system. We present a new generation of EVM for modern small turboprop engines and their vibration diagnostics which has been developed by Unis, a.s. in cooperation with Brno University of Technology and Tomas Bata University in Zlin.**

Keywords- In Flight Vibration Monitoring, Turboprop Engine Vibrations, Vibration Monitoring System, Signal Processing Algorithm

I. Introduction

Components and methods that are generally used and implemented in an aircraft engine vibration measurement equipment are well known. Technical requirements are described in SAE technical standard [1]. EVM systems for transport category aircrafts should be employed for achieving compliance with CS-25 [2] / Part 25 ESASA/FAA standards [3] and CS-E [4] / Part 33 [5] in case of engines. The EVM is interfacing to cockpit and it displays eventual engine imbalance related to vibration. The EVM monitors vibrations of engine sub-systems as gears, bearings, transmissions, propellers, afterburners and engine accessories. Modern high-speed digital signal processors (DSP) are well suited for more sophisticated vibration analysis techniques (as time/frequency domain analysis, etc.). Prediction and identification of rotor and propeller unbalance can minimize engine degradation. The EVM brings in an improvement of engine prognostics and diagnostics, operational cost reduction and safety especially when it is integrated with advanced aircraft/engine health usage monitoring systems.

Detailed description of vibration diagnostic methods goes beyond the framework of this paper. The relevant topics are described in many publications. For example, the paper [6] describes aircraft gas turbine engine vibration recording and diagnostics during the ground tests. Papers [7, 11] provide exhaustive description of vibration signals processing, while the physical methods are well described in [8] and [9]. In [12], rotating machinery analysis is described in an exhaustive way. Although the idea of in-flight measurement of vibrations is rather old [10], a real-time, in-flight digital signal processing of aircraft engine vibration signals is not published very often.

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II. System Description

The EVM is intended for monitoring the engine – the gas turbine (GT), power turbine (PT) and propeller rotor vibrations in real time and within all operational power ratings of the engine. Standard setup of two vibration sensors and two rotation speed sensors is used. The vibration sensors are special high-temperature piezoelectric accelerometers located on the front and rear part of the engine.

The system has been designed to replace an older solution that was implemented using a bank of programmable analog narrowband filters. The aim was to replace the analog system with a digital system. It was required to monitor the vibration amplitude only at the frequency corresponding to the current speed of the gas turbine (GT) and the power turbine (PT). This requirement can only be met with a narrowband tunable filter. In the literature, this method of signal filtering is referred to as a tracking filter [14]. When designing a tracking filter, the goal is to find a compromise between the quality factor Q of the filter and its rise time.

Various methods of tracking signal filtering with variable center frequency and selectable shape and bandwidth were tested. The IIR filter, peak filter, coherent demodulation method, Vold-Kalman filter and FFT-based methods were simulated [15]. Based on the performed simulations, a coherent demodulation method was selected for implementation. It represents a reasonable compromise between the demands on computing power and the achieved parameters of the tracking filter. The new EVM is based on a digital signal processor that implements a lock-in/coherent demodulation method based on Direct Fourier Transform (DFT) with variable-width sliding window.

A. Advantages

The advantages of the hereby presented solution are as follows:

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1. Variability. The parameters of signal processing may be changed by updating the software or adjusting the signal processing parameters according to the customer's requirements.

2. High resolution. 32-bit signal processor with 16-bit inbuilt A/D converters offers great flexibility of the HW system.

3. Robustness. Most of the signal processing is executed on single DSP CPU.

4. Real time processing. The data are processed in real time during the flight.

B. System Specifications

The EVM system provides the following features:

- Input, acquisition and conditioning of vibration signals from two piezoelectric accelerometers.
- Input, acquisition and conditioning of rotation speed signals from two tachogenerator sensors.
- CANaerospace/ARINC 825 communication interface / data bus for connection with the Engine Control Unit (ECU) [13].
- Communication port for on-ground service and maintenance purposes, e.g. flashing a firmware update, setting initialization values and monitoring the system functions on the engine test stand.
- On-board alarm signals activation (state processing and signaling): Excessive / Dangerous vibration / Fault
- Continuous vibration measurement.
- Buffered broadband analog signals from accelerometers to on-ground service and maintenance port.
- Built-In self-Test (BIT) diagnostics for detecting the most critical system failures.
- 28 V DC input power supply.

III. Detailed System Description

A. Application Requirements

The system must operate within the following range of values:

· Vibration sensors / Accelerometers:
Charge sensitivity: 20 pC/g to 50 pC/g.
Amplitude range: 0 to 200 g.
Frequency range: 10 Hz to 10 kHz.
Sensor Front / A: sensing radial vibration of propeller shaft, radial vibration of compressor (GG) and power turbine (PT). Maximum thermal stress up to 250°C.
Sensor Rear / B: sensing vibration of GG and PT. Maximum thermal stress up to 400 °C.

· Tachogenerators:
GG and PT rotation speed sensor: pulse frequency range 100 to 3000 Hz.

· Power supply:
Compliance with RTCA/DO-160G Category B.
Nominal Voltage +28 V DC.
Withstands abnormal voltage range 18 - 32 V DC.
Max. overvoltage surge pulse: 60 V DC / 100 ms.
Undervoltage 15 V DC / 7 s.
Power interrupt 20 ms.

· Communication interfaces:
CANaerospace/ARINC 825 [13], RS485.

B. System Interface

As depicted in Fig. 1, the EVM unit has several inputs and outputs. There are two analog channels for two accelerometers placed at the front and rear part of the engine. Since the accelerometers are capacitive in nature, charge amplifiers are used at these inputs. For service purposes, the unfiltered analog signal from the accelerometers is available at the Analog vibration monitoring port. The gain of the monitor channel is set at the fixed value of 1.
There are also two input channels for rotation speed sensors of GG and PT shafts. As tachogenerators are induction-based devices, the frequency and amplitude of their output is dependent on the rotation speed. Therefore a pulse shaping analog circuit must be used for converting the tachogenerators signals to digital domain. This circuit implements also diagnostics of the sensor states and possible faults.

The data from vibration sensors are sampled by the CPU A/D converters and processed by digital signal processing algorithms. The results are provided in several ways. The output data from the signal processing are sent to the CANaerospace and RS485 communication interfaces. Moreover, there is an Alarm State channel that is directly activated when pre-programmed vibration values are exceeded. This channel can directly turn on the appropriate warning light in the cockpit.

The computed vibration data are also stored in a non-volatile MRAM memory and can be downloaded for service purposes once the aircraft landed.

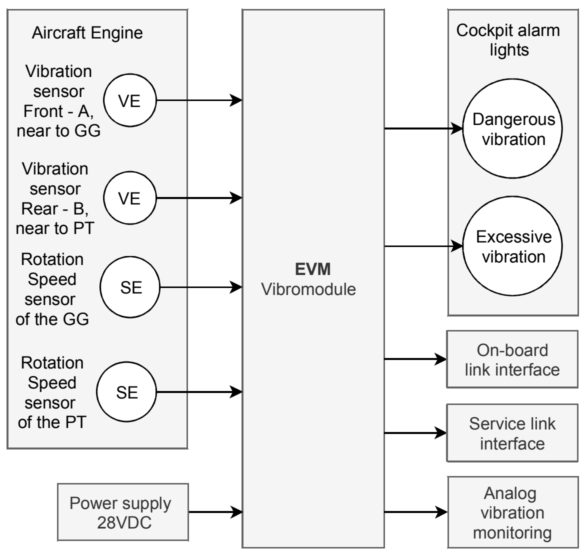

Fig. 1 Top level EVM block diagram

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C. Fault Detection

The following faults are detected at analog input interfaces: disconnected sensors, short-circuited sensors and sensor signals out of expected ranges. All sensor fault states are recorded and reported to the parent/supervising system.

Most critical internal circuits faults are also detected, recorded and reported.

spectrum and $c_k(n)$ are samples of a complex sinusoid at frequency k/N, defined by:

$$c_k(n) = e^{-jk\frac{2\pi}{N}n} = \cos(k\frac{2\pi}{N}n) - j.\sin(k\frac{2\pi}{N}n) \qquad (2)$$

In our application, the engine manufacturer requested to analyze only two spectral components:

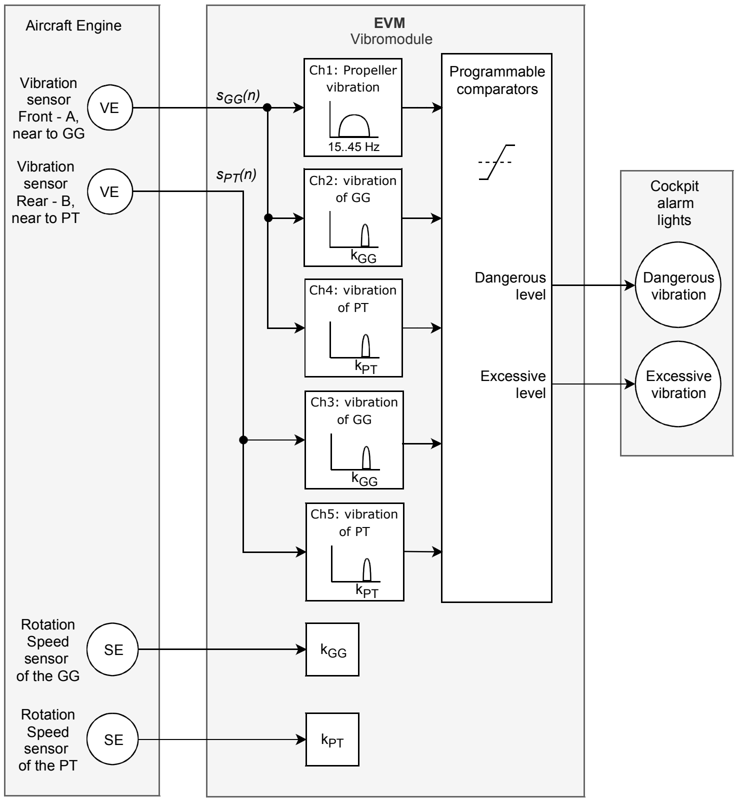

Fig. 2 Dataflow block diagram

D. Data processing

The dataflow diagram is shown in Fig. 2. The diagram illustrates flow of data in our digital signal processing algorithms on the global system level.

The algorithms are explained in more details in the following chapter.

E. DSP Algorithm core

The digital signal processing algorithm core is based on Discrete Fourier Transform (DFT), which is defined by:

$$S(k) = \sum_{n=0}^{N-1} s(n) \, . \, c_k(n) \qquad (1)$$

where $s(n)$ is the n-th sample of the input signal, $S(k)$ is the k-th point in the input signal frequency

1. $S(k_{GG})$ – the 1st harmonic of Gas Generator shaft vibration,
2. $S(k_{PT})$ – the 1st harmonic of Power Turbine shaft vibration.

The computing of these two spectrum components on a digital signal processor (DSP) can be done very efficiently – see Fig. 3.

As can be seen on the block diagram, the computation core can utilize the „Multiply and accumulate" (MAC) instruction available on most modern DSPs. The two complex sinusoids $c_{kGG}(n)$ and $c_{kPT}(n)$ are generated from single pre-generated table. The specialty of our implementation is that the frequency of each sinusoid (k_{GG}/N and k_{PT}/N) is a variable directly derived from the GG and PT shaft rotation sensor signals.

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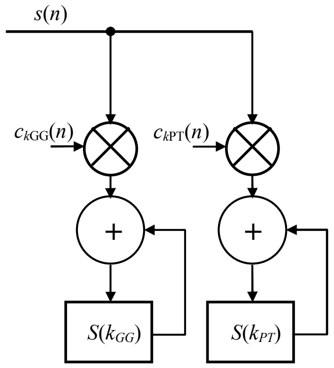

Fig. 3 Block diagram of the DFT computing core

To maximize the efficiency of MAC instruction, the computation core runs on buffered input signal. The length of the buffer is given by a customizable parameter, which can be changed in real time by CANaersopace protocol commands.

The buffer size is known as DFT window length, which defines the width of each DFT frequency bin:

$$DFT_{bin\_width} = \frac{sampling\_frequency}{window\_length} \qquad (3)$$

As the DSP has limited RAM and the engine manufacturer requires the DFT_{bin_width} to be ≤ 1 Hz, we had to implement two-level buffering hierarchy, where the 2nd level buffers (L2) hold the results of MAC computation core running over 1st level buffer. This way, we are able to compute spectrum equivalent to order of magnitude longer DFT windows.

The engine manufacturer requirement was to compute vibration levels from two independent vibration sensors. For each sensor, both GG and PT vibration frequencies should be computed. The results are sent to the communication interface as 4 "channels" – see the block diagram in Fig. 2.

The 5[th] channel monitors the propeller vibration, which is measured using a band-pass filter from 15 to 45 Hz with output integrators. As DFT results can be interpreted as matched filters with output integrators, the whole computation is depicted as a bank of matched filters in Fig. 2.

For mitigating system faults, the Built-In self-Test (BIT) HW provides continuous diagnostics for detecting abnormal conditions of the most important HW components – power supplies, sensors and their input interfaces. The faults are logged in the non-volatile memory and reported to the engine control system. Redundancy was not required and was not implemented because the vibration monitoring module was not identified as potentially safety-critical component of an aircraft.

IV. Conclusion

Within the framework of this paper, the new generation of vibration monitoring system for turboprop engines is described. The system, developed by Unis, a.s in cooperation with Brno University of Technology and Tomas Bata University in Zlin, employs advanced signal processing methods and enables real-time monitoring of the engine during the flight. Moreover, the data are stored for further service purposes. Although the system was tailored according to requirements of a specific customer, great emphasis was placed on the universality of the architecture. Therefore, its functionalities can be widely modified by changing the SW implementation.

Acknowledgement

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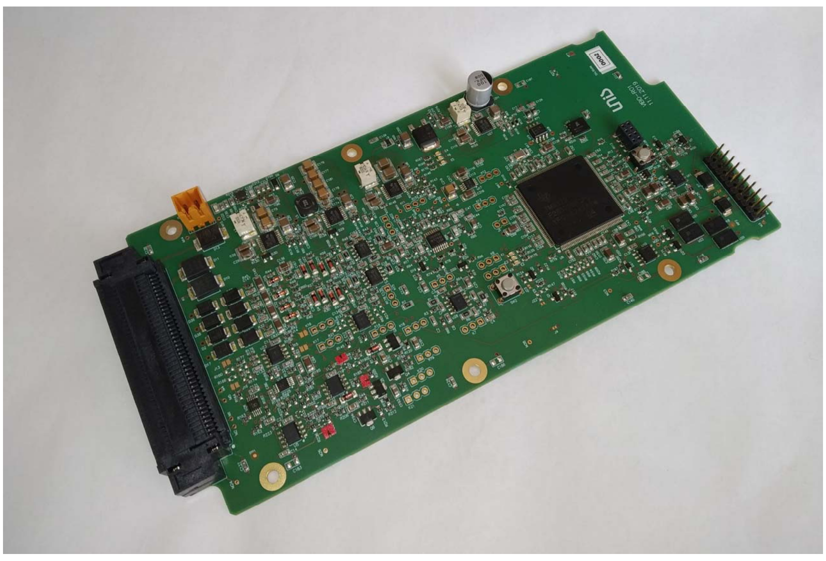

Fig. 4 Physical realization of the EVM: the printed circuit board

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