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Engine Vibration Monitoring and Diagnosis Based on On-Board Captured Data

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ABSTRACT

An advanced vibration monitoring system (VMS) consisting of on-board and on-ground tasks is presented in this paper. The on-board part of the VMS includes the detection of vibration incidents by monitoring of defined vibration amplitude values and comparison with prescribed absolute and relative vibration limits, where the relative vibration limits are specific for each particular engine. Exceedence of defined vibration alarm limits trigger a cockpit warning. The processing and acquisition of different vibration data sets using several algorithms are additional tasks of the on-board vibration monitoring function. The on-ground part of the VMS comprises the trend analysis of vibration signals as well as sophisticated methods based on artificial intelligence for the diagnosis of vibration events which includes data generated on wing, test-bed and the results of numerical simulations performed using extensive structural Finite Element whole engine models.

In this paper the vibration data sets which are necessary to carry out the vibration monitoring function are described in detail. Finally experience gained during the application of the presented VMS to EJ200, the engine of the Eurofighter EF2000, are reported and discussed.

Key words: vibration, signal processing, trend analysis, incident detection, mechanical diagnosis

1 LIST OF ABBREVIATIONS

BSD	Bulk Storage Device	LP	Low pressure (rotor/system)
CSMU	Crash Survivable Memory Unit	MAS	Vibration Maximal Amplitudes Store
DECU	Digital Engine Control Unit	MDP	Maintenance Data Panel
ECMS	Engine Condition Monitoring System	MPR	Vibration Max Per Run
EF	Eurofighter	OOB	Out of balance
EF2000	European Fighter Aircraft	PMDS	Portable Maintenance Data Store
EHM	Engine Health Monitoring	RMS	Root Mean Square
EJ-PC	Eurojet Partner Company	RPM	Revolutions Per Minute
EMS	Engine Monitoring System	RVE	Residual Vibration Energy
EMU	Engine Monitoring Unit	THS	Vibration Time History Store
EO	Engine Order (spool speed harmonic frequency)	VMS	Vibration Monitoring System
GSS	Ground Support System		
HP	High pressure (rotor/system)		
IPU	Interface Processor Unit		

2 INTRODUCTION

One of the most sensitive parameters for continuous monitoring of the condition of aero-engines are engine vibrations. These vibrations are captured by one or more accelerometers mounted at carefully selected casing positions. With these in-service gained signals and additional operational parameters, used for aircraft and engine control, it is possible to reliably monitor engine health and, if necessary, to diagnose the reason for the engine malfunction.

The main objectives of engine vibration monitoring can be summarised as:

- increased safety through identification of dangerous vibration conditions at all engine speeds and thrusts, including steady state and transient operation, and through generation of the corresponding cockpit warning,
- avoidance of major secondary damage by way of early failure identification,
- reduction of maintenance expenditure through isolation, localisation and diagnosis of the vibration causes and
- optimisation of maintenance by means of consideration of the current engine condition.

In the current paper an advanced vibration monitoring system will be presented which aims to satisfy the above requirements.

3 DATA ACQUISITION AND PROCESSING

Vibration monitoring is a substantial part of the Engine Monitoring System (EMS) of EJ200, the engine of the EF2000. The tasks of the vibration monitoring function are distributed over airborne and ground equipment, where the airborne equipment comprises vibration transducers and the Engine Monitoring Unit (EMU) and the ground equipment comprises the Engine Health Monitoring system (EHM) as an element of the Ground Support System (GSS).

As shown in Figure 1, this data is transferred to GSS using several devices - Interface Processor Unit (IPU), the Bulk Storage Device (BSD) and the Portable Maintenance Data Store (PMDS) - and stored in the corresponding data base within the GSS.

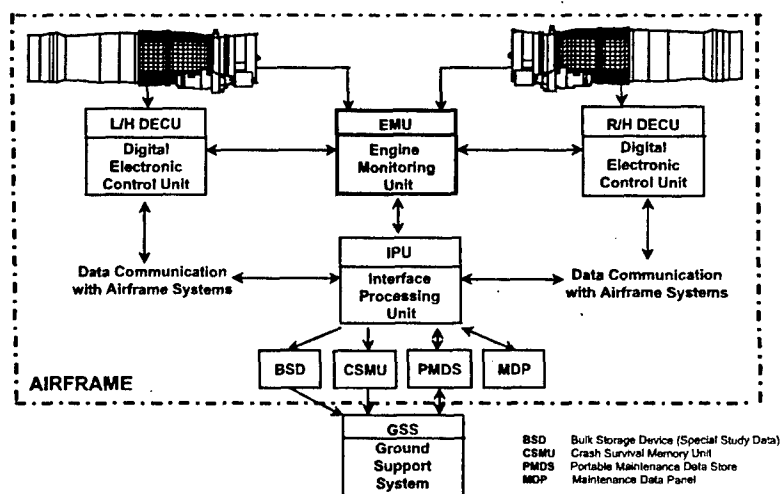


Figure 1: Data flow of the engine monitoring system

The location of the two engine vibration transducers is shown in Figure 2. The transducers are attached to the engine casings at carefully selected positions which allow monitoring of the dynamics of the rotors in the frequency range below 1 kHz. The vibration transducers are hardwired to the EMU and also positioned to ensure simple maintenance.

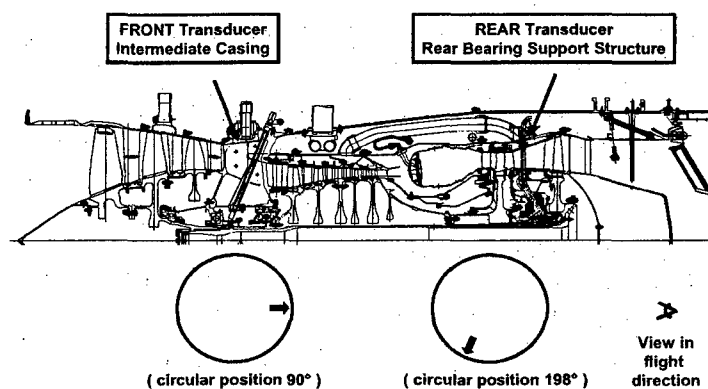


Figure 2: Vibration transducers attached to the EJ200 engine

The transducer signals are conditioned by the EMU to produce filtered velocity analogue signals. The health of the vibration transducers and of the EMU signal conditioning interfaces is continuously monitored and status information is stored together with the sampled and derived data. The resulting velocity signals are continuously sampled by EMU for analysis and storage.

Additionally, hardwired engine speed signals are provided from the Digital Engine Control Unit (DECU) to the EMU, see Figure 1. They are also conditioned by the EMU hardware. A number of values, like the current time for one revolution of the different spools, are generated, describing the rotor dynamics characteristics of the low pressure spool (NL) and the high pressure spool (NH). These values are then used for the generation of the vibration monitoring parameters.

The analysis of vibration related data is performed by the EMU during engine operation based upon a periodic time cycle of 0.5 s to collect and analyse the data. During each of these cycles two vibration sample sets in time domain are produced simultaneously, one for each vibration transducer. These vibration sample sets correspond to individual speed bands (SB), characterised by defined NL speeds and NL speed changes with respect to the time, and are the basis of the vibration monitoring function as illustrated in Figure 3. There are 100 SB which are derived from the NL spool speed. SB 0 covers NL spool speeds up to 30% of the nominal NL speed, SB 99 covers NL spool speeds higher than 103% of the nominal NL speed, SB 1 to 98 are evenly distributed between these two limits. The SB corresponding to acceleration and deceleration conditions are processed and stored separately.

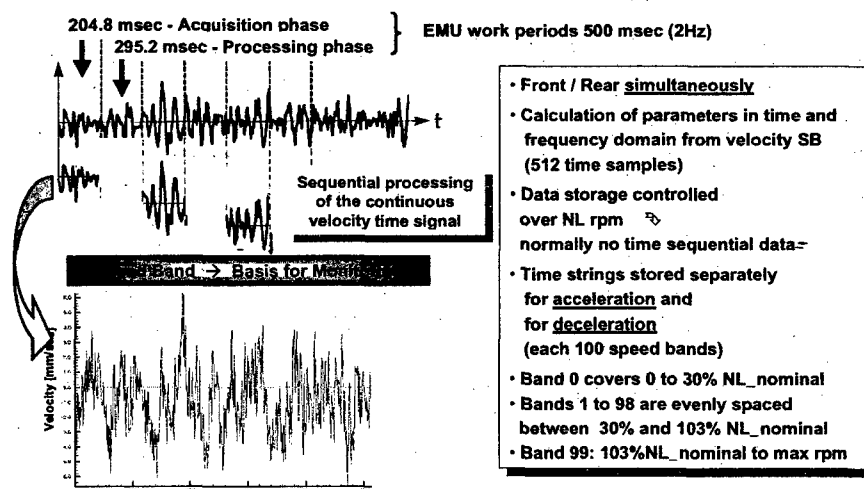


Figure 3: EMU work periods and data capture

The following vibration monitoring parameters (**derived amplitude values**) are generated from these sample sets for the FRONT and REAR transducers:

- Amplitude values corresponding to the first order of the NL fundamental spool frequency, identified as **1EO NL**. The amplitude values are derived via Discrete Fourier transform (DFT) using a subset of the sample sets that corresponds to 10 complete revolutions of the NL spool.
- Amplitude values corresponding to the first order of the NH fundamental spool frequency, identified as **1EO NH**. The amplitude values are derived via DFT using a subset of the sample sets that corresponds to the number of completed revolutions of the NH spool for 10 NL spool revolutions during the recording of the sample set.
- Amplitude values corresponding to a programmable frequency, that is calculated from a programmable order of the NL spool frequency plus a programmable order of the NH spool frequency plus a fixed frequency, identified as **PROG**. The amplitudes are derived via DFT using the same subset as used for the calculation of the amplitude value for 1 EO NL.
- Overall broadband energy amplitudes for the front and rear transducers are calculated via a Root Mean Square (**RMS**) extraction algorithm using the complete sample set.
- Residual Vibration Energy (**RVE**) amplitudes are calculated by subtracting the DFT amplitudes for 1 EO NH, 1 EO NL and PROG from the corresponding RMS amplitudes (separately for FRONT and REAR). This amplitude describes the energy content of the vibration signal in the observed time interval excluding the contribution of the 1 EO NL, 1 EO NH and PROG vibration components.

The measured and derived vibration data are continuously monitored and cumulatively stored to different data set stores for download to the Ground Support System.

Using these monitoring parameters and associated data, the following tasks can be performed within the vibration monitoring system:

- vibration incident detection with subsequent indications and warnings
- vibration trend analysis and
- vibration diagnosis.

The following data sets are available within the EMU for the vibration monitoring functions:

- **Vibration Datum store (Datum)**
This data set contains the reference vibration signature of the engine, describing the reference vibration characteristics of the engine captured, for instance, during the corresponding pass-off test. It consists of all derived amplitude values (1 EO NL, 1 EO NH, PROG, RVE and RMS) for both FRONT/REAR transducers and for each speed band under ACCEL/DECEL conditions. This data set is used for the generation of relative limits for vibration incident detection.
- **Vibration Maximum Amplitude Per Run store (MPR)**
The MPR store contains the derived amplitude values for FRONT and REAR transducers for acceleration and deceleration for all speed bands that have been detected during a single engine run. This data set includes the following additional parameters -Ambient static pressure, aircraft acceleration along normal axis (g_z), aircraft angular velocity about normal axis (r), Mach number (Ma) and intake temperature (T_2)- which describe the corresponding operational conditions. The structure of this data set is illustrated in Figure 4. The store is reset at the start of each engine run. During engine operation, the data for the different speed bands are overwritten and the MPR store records the highest achieved vibration levels for each speed band.

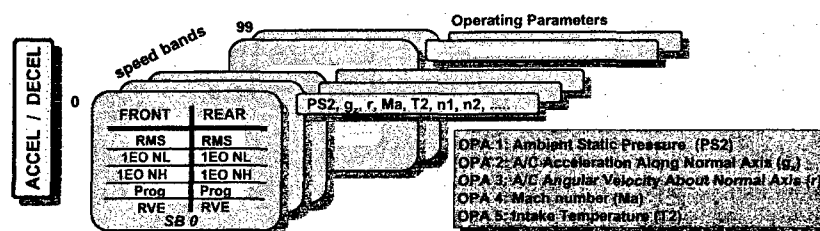


Figure 4: Max Per Run (MPR) → Incident detection and trend analysis

- Vibration **Maximum Amplitude Store (MAS)** in conjunction with Vibration **Time History Store (THS)**.

The MAS data set contains the maximal amplitudes of the different derived vibration parameters for the time interval since last EMU reset (data generated over several engine runs). The data for the different speed bands are overwritten, if no data have already been recorded for the corresponding speed band or if a weighting algorithm for the different amplitudes stored in the MAS indicates a higher vibration level for the new data than the previously stored data. Additional conditions for data overwrite are, that no surge is detected simultaneously and that the changing rate of the spool speeds related to the time ($\%NL/s$) is within a defined range. This data set will be stored separately for accelerating and decelerating conditions.

The THS contain measured velocity data sample sets for FRONT and REAR transducers in time domain for the different speed bands. The overwrite of these data sets is controlled by the overwrite criterion of the MAS data sets as described above. Figure 5 shows the structure of these data sets including the corresponding operational parameters.

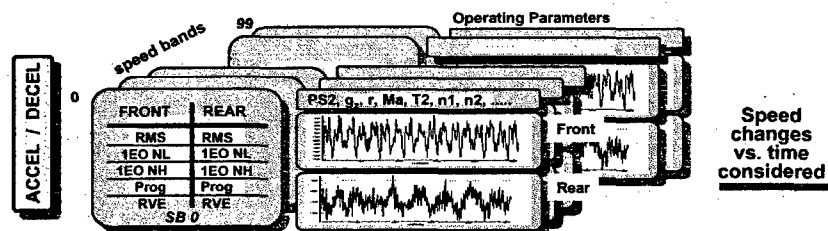


Figure 5: Max Amplitude Store (MAS) + Time Histories Store (THS) → Diagnosis

- **Vibration Incident Time History Store (VITHS)**
VITHS contains continuously sampled, time based vibration velocity data for a specified period of time before and after a vibration incident has been detected. There are two VITHS in the data set. VITHS 1 is overwritten after the first vibration incident has been detected during engine operation. VITHS 2 is overwritten if a subsequent vibration incident has been detected, that is more severe than the first vibration incident and either the VITHS 2 is empty or the detected vibration incident is more severe than the incident already stored in VITHS 2.
- **Vibration Special Study Data (SSD)**
SSD contains all the derived vibration parameters for the FRONT and REAR transducers stored continuously with respect to time at a frequency of 2 Hz. The corresponding operational parameters, stored partially with frequencies higher as 2 Hz, are also included in this data set.

With exception of VITHS and SSD, each of these data sets contains areas to store data for 100 speed bands separately for front and rear transducer data measured during acceleration and deceleration of the engine. A complete store therefore consists of data for 400 speed bands.

All of the data sets are tagged with status information (store status, transducer status, status of signal conditioning interfaces) and with operational parameters.

Vibration incident detection

In order to detect vibration incidents, each of the derived amplitude values is compared with a set of predetermined limits as shown in Figure 6. Incidents of different types are generated, depending on the limit exceeded:

- Cockpit warning (warning to the pilot due to exceedance of an absolute vibration limit)
- Maintenance warning (warning to the ground crew due to exceedance of an absolute vibration limit, which is lower than the cockpit limit)
- Relative maintenance warning (warning to the ground crew because the ratio between current vibration amplitudes and the Datum store engine vibration signature (specific current engine) exceeds a defined limit)

Each of these warnings can be generated according to its duration in two different types:

- steady state warning (limit exceedance longer than a defined time interval)
- transient warning (limit exceedance shorter than a defined time interval).

Different limit values are used for both, transient and steady state warnings. Additionally, each vibration warning (incident) is classified according to the actual flight manoeuvres (normal flight conditions or high g and/or gyro-loads). The cockpit warning signals are relayed via the DECU to the aircraft systems.

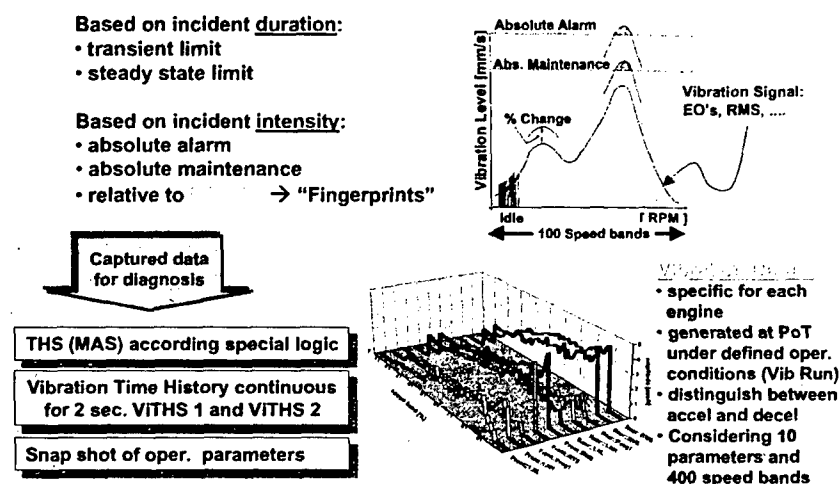


Figure 6: Concept for incident detection → Exceedence of vibration limits

Vibration trend analysis

Trend evaluations are performed to predict problems, preventing engine failure. The purpose of this analysis is to derive prognoses from downloaded data sets from a number of engine runs. The trending is carried out based on the observation of an overall increase or decrease of engine vibration levels. The data sets on which vibration trending is based are the Max Per Run (MPR), Maximum Amplitude Store (MAS) and Time History Store (THS). The current data is compared with the reference data and deviations are evaluated. A trending curve can be generated with regression techniques to predict when the engine will exceed allowable limits. The consideration of the associate operational parameters which describe the flight conditions is mandatory for vibration trend analysis, as the corresponding amplitudes depend on these parameters.

Vibration diagnosis

The vibration data are transfer into the frequency domain using Discrete Fourier Transform, for tracked orders of engine spool speeds, and Fast Fourier Transform to obtain amplitude spectra in the frequency domain. For diagnosis purposes the use of waterfall plots is very useful. These diagrams are generated by arrangement of the different spectra with respect to the spool speed as shown in Figure 7.

Selected indicators, as for example changing of the engine orders, sub-harmonics, side-bands, fixed frequencies, resonances, jump ups / kick downs and noise floor, will be generated based on waterfall diagrams in order to create vibration patterns.

These vibration patterns are compared with a library of known vibration induced patterns obtained from typical engine fault situations. Therefore, identification of the cause of certain engine vibrations (i.e. a defect source) is supported.

Semi-automatic analysis is provided for pattern recognition by the vibration monitoring function presented here. This means, that the current vibration characteristics (pattern) is derived automatically from download data. A correlation analysis between the current pattern and the patterns in the library is performed, leading to a proposal of the most probable matching pattern.

The vibration data necessary for generation of patterns library are collected mainly on wing, at the different operating flight test centres, but also on the test-beds of the diverse companies of the EuroJet consortium (EJ-PC). 3D simulations of the mechanical engine response due to different excitations are also a substantial source of data for generation of vibration patterns, in particular by extreme or catastrophic situations.

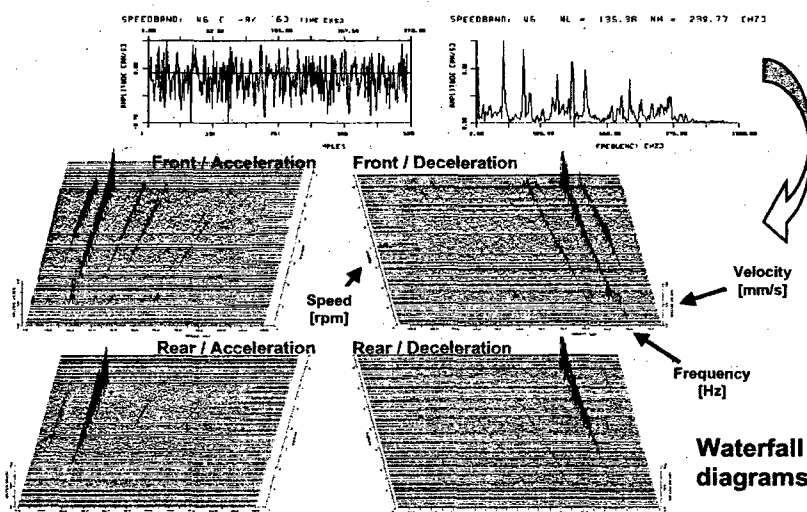


Figure 7: Transformation of the THS in the Frequency Domain Using FFT

Some mechanical faults which can be detected and diagnosed by this vibration monitoring system are:

- increased out of balance due to "normal" deterioration
- ice build up LP compressor blades under icing conditions
- high pressure rotor bow
- aircraft buffeting
- excessive out of balance due to FOD, bird strike, blade loss
- instabilities due to malfunction of squeeze-films, rub, loose joints
- low bearing thrust
- misalignment due to internal distortions broken bearing support / mounting links

In particular the vibration monitoring system combined with an extensive 3D structural Finite Element Model of the whole engine is a very powerful tool for the evaluation and interpretation of the impact of vibration events on the mechanical integrity of the engine.

4 APPLICATIONS

In this section experience gained during the application of the presented vibration monitoring system on the EF2000 engine EJ200 will be presented and discussed. Only a sample of selected cases will be reported giving an impression of the flexibility and reliability of the system.

The initial set of three examples concentrates investigations related to the high pressure turbine (HPT). That means, it can be expected that high vibration parameters amplitudes mainly associated with the HPT (1.EO NH / REAR and RMS / REAR) will be detected, the remaining vibration parameters amplitudes will be within the usual boundaries.

For the first two investigations the evolution of the vibration amplitudes signals with respect to time were analysed. Using this representation it was possible to identify and diagnose the vibration causes considering continuous changes of the amplitudes after reaching defined operational conditions.

Figure 8 shows an out of balance (OOB) occurrence on the HP turbine which can be identified by an increase of the amplitudes of the vibration parameters 1 EO NH and RMS captured with the rear transducer. It was noted that the vibration level started to increase at about 80% NH during acceleration from idle to max dry. At max dry the amplitude of the 1 EO NH is approx. 10 mm/s and increases continuously to a maximum value of 18 mm/s during an engine stabilisation period of 1-2 min. This cycle was repeated two times.

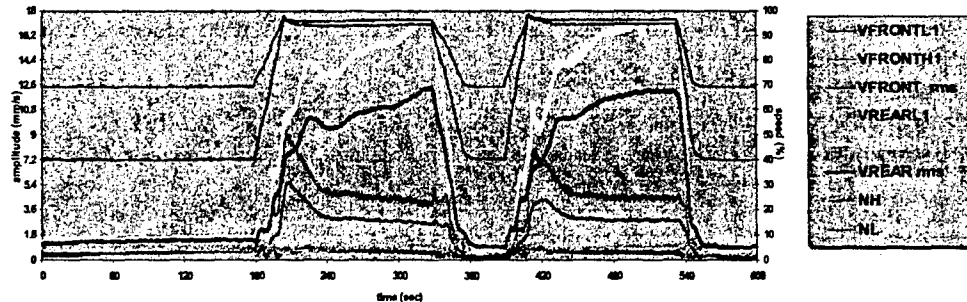


Figure 8: HPT out of balance – Case (a)

Analysis of the manufactured tolerances of the involved parts, shown in Figure 9, identified the cause of the vibrations to be as follows:

A heavy interference (top limit) on pos. 1 combined with a loose interference on pos. 2 (bottom limit) leads to loss of interference on pos. 2 during engine operation causing high unbalance, which increases with time at constant speed.

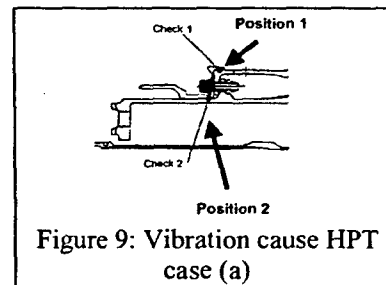


Figure 9: Vibration cause HPT case (a)

A similar investigation, case (b), was performed using a modified design of the involved parts shown in Figure 9 in order to compensate out of balance effects. The signals of the relevant vibration parameters in Figure 10 show also an increasing of the amplitudes. Reaching the rotor speed of about 80%NH the amplitudes of the 1 EO NH are about 7 mm/s in the first run and about 9 mm/s in the second run. The vibration level increases continuously up to max dry, 1 EO NH amplitudes of about 29 mm/s and 34 mm/s for the first respectively second run were achieved. A vibration step change is visible, the maximal amplitudes difference is approx. 17%. After reaching max dry the vibration level decreases continuously in contrast to the case above, and reaches values of about 18 mm/s respectively 21 mm/s after about 2 minutes of engine stabilisation.

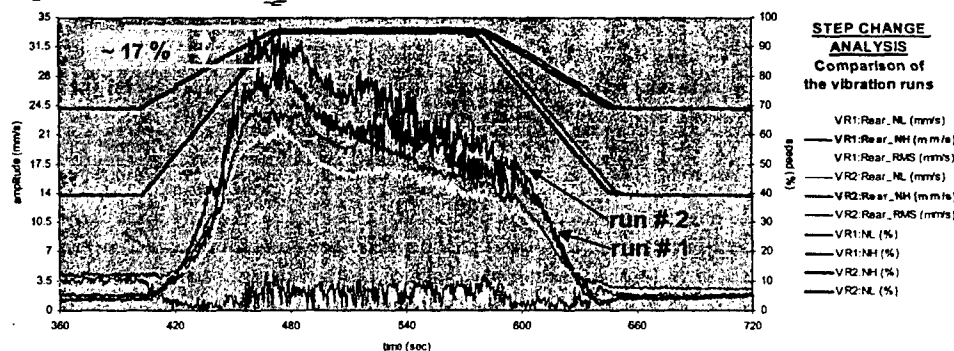


Figure 10: HPT out of balance – Case (b)

In this situation the cause of high vibration was identified as follows:

Similar to case (a), high unbalance resulting of loss of interference on pos. 2 is detected, but here other thermal effects related to additional masses (resulting of a balancing procedure) according to Figure 11 are identified. These effects compensate the high unbalance resulting of the loss of interference after some seconds of engine operation and the vibration level decreases continuously at constant speed.

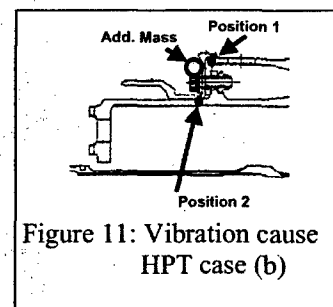


Figure 11: Vibration cause
HPT case (b)

HP turbine blade deterioration also has a significant effect on vibration levels. Figure 12 shows max per run (MPR) data stored during vibration runs (slow acceleration – stabilisation – slow deceleration) over several engine runs. During early runs the amplitudes of the 1 EO NH / REAR reach maximum values of approx. 26 mm/s. During later runs the maximum amplitudes achieve approx. 37 mm/s, showing a vibration level increase of some 40%.

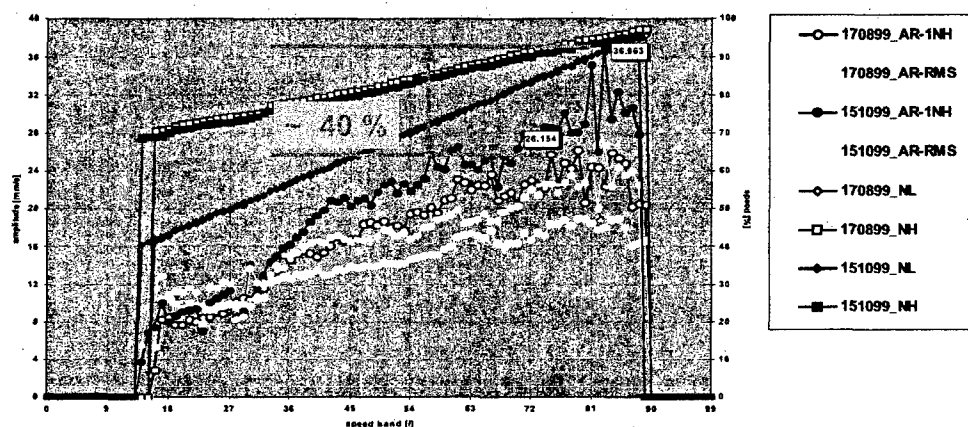


Figure 12: HPT out of balance – Case (c)

In this case the cause of high vibration levels was identified as follows:

Incremental deterioration of the tip of HPT blades due to a malfunction of the blade cooling system progressively increasing out of balance (and consequently vibration amplitudes) with time, see Figure 13.

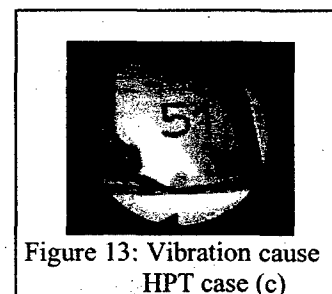


Figure 13: Vibration cause
HPT case (c)

Vibration monitoring and investigation during icing tests showed high out of balance effects on the LP compressor rotor.

Figure 14 shows waterfall diagrams generated from the acceleration and deceleration vibration signals recorded during icing tests. The corresponding four first engine orders (EO) associated with the LP rotor are exposed in the right hand part of the figure.

The amplitudes of the 1 EO NL near idle reach abnormally high values for both acceleration and deceleration conditions. These dominating amplitudes can be easily identified in the waterfall diagrams.

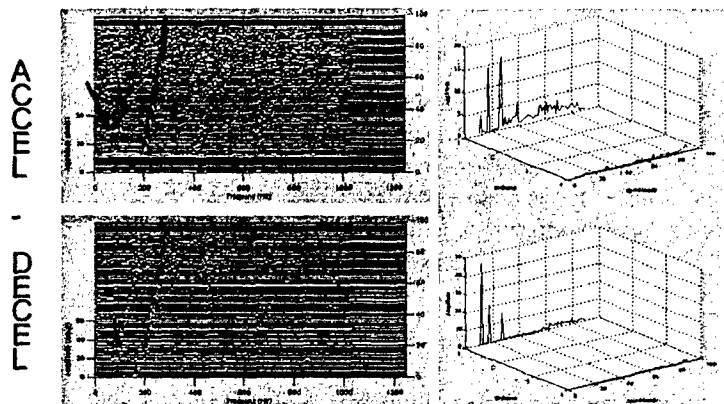


Figure 14: LPC out of balance due to ice build up

The THS corresponding to a selected acceleration speed band captured simultaneously for the FRONT and REAR transducers are plotted in Figure 15. The left hand side of the figure in the time domain and the right hand side in frequency domain.

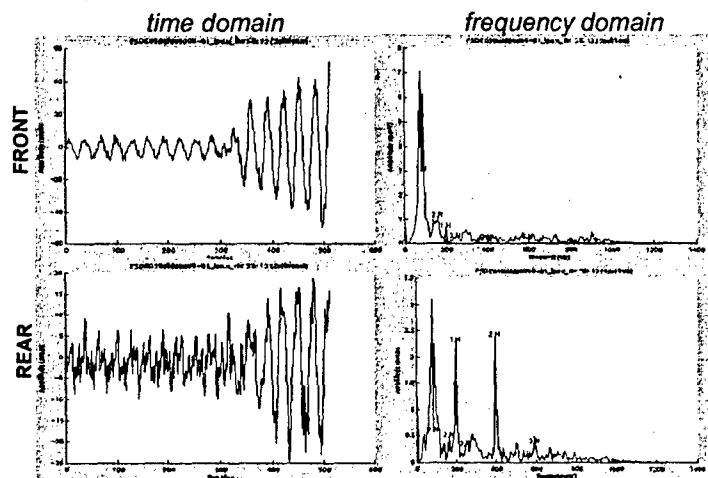


Figure 15: THS acceleration speed band 11 / FRONT and REAR transducers

The increase of the vibration level at a certain time results from the build up of a non-symmetric ice layer in the front stages of the LP rotor and consequently generates a high level of unbalance. After shedding of the ice layer the engine resumes a stable condition and the vibration levels of engine return to normal values.

Another significant application of the vibration monitoring system is for the identification of high vibration levels due to thermal rotor bow. This temporary deformation of the HP rotor can generate very high vibration amplitudes due to the excitation of different primary modes of the rotor. As a consequence of these high vibration levels, significant damage to HP compressor blading and seals can occur causing considerable premature engine deterioration.

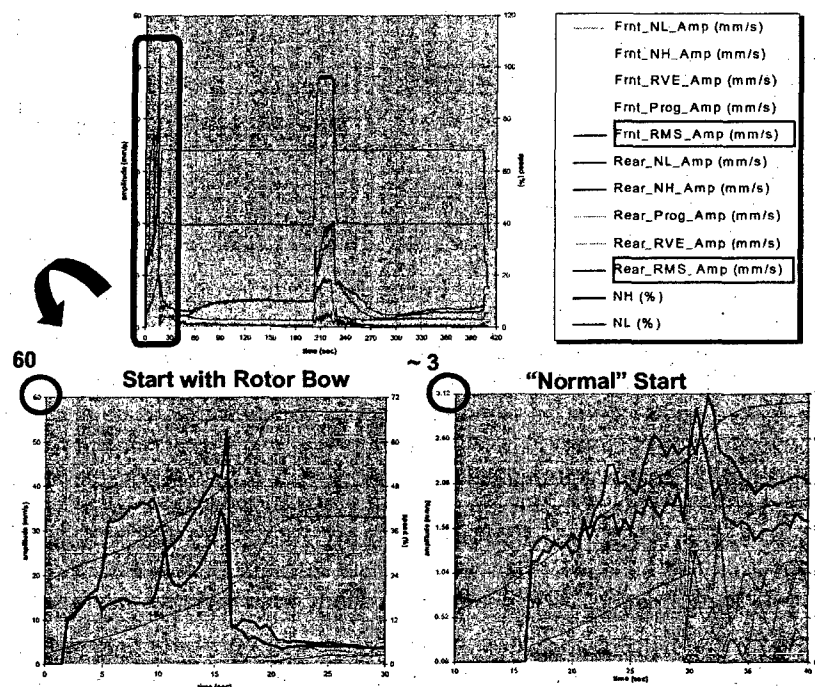


Figure 16: Engine start with HP rotor bow

The upper part of Figure 16 shows a typical engine run including the start phase to idle. The amplitudes of the different vibration parameters are related to the left hand axis whereas the rotor speeds in % of the nominal speeds are related to the right hand axis. Maximum vibration levels up to 55 mm/s for RMS/FRONT were reached. After a short time period the rotor returns to the nominal shape and the high vibrations resume normal levels. In the left hand lower part of Figure 16 an expansion of the vibration signals during the start phase is shown, including the rapid decline of vibration amplitudes to normal values. The start phase of a normal start is shown on the right hand lower part of the figure to compare the amplitudes with the amplitudes of the start with rotor bow. The ratio of the maximal amplitudes is approx. 20.

To illustrate the use of the vibration time histories (VITHS) an example of surge investigation is shown. Figure 17 shows different parameters versus time. At a selected operational condition (constant spool speeds), the nozzle throat area is continuously reduced in order to generate an engine surge with the corresponding increase of the vibration level and subsequent vibration incident detection.

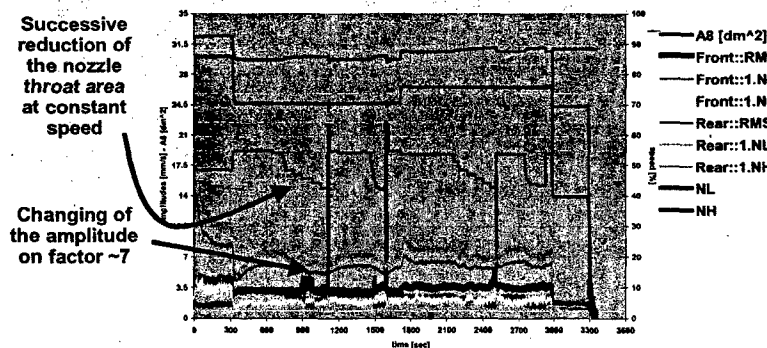


Figure 17: Engine surge due to continuous reduction of the nozzle throat area

The evaluation of the VITHS in Figure 18 shows maximal vibration velocities of approx. 95 mm/s p-p at the FRONT transducer. Moreover in a time period shorter then 1 second three events can be clearly identified.

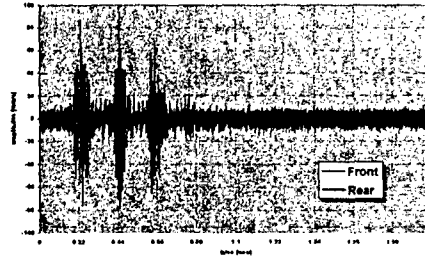


Figure 18: Surge analysis / Vibration Time History

The vibration monitoring system presented in this report also enables engine external excitations to be detected and analysed. The Aircraft buffeting resulting of the application of the air brake is one such case. The engines are excited with a vibration component with a constant frequency of about 35 Hz independent on the speed of the rotors. The upper part of Figure 19 shows a waterfall diagram generated using the vibration time histories captured at the REAR transducer during decelerating conditions. In particular the first two EO of the HP rotor can be identified as well as high vibration amplitudes at a constant frequency band between 30 and 40 Hz. The same conclusions can be observed using an order analysis as shown in the left hand lower part of Figure 19 for the LP orders and in the right hand lower part of the figure for the HP orders. Also here the constant vibration components are readily identifiable.

Due to air brake buffeting in the rear section of the core engine, high vibrations with amplitudes up to 3 mm p-p can be induced which, depending on the duration of the excitation, can be detrimental to the engine or to its parts.

The use of the vibration monitoring system presented in this report in combination with an extensive 3D structural Finite Element Model of the whole engine represents a powerful tool for a detailed analysis and evaluation of the mechanical impact of vibrations to the condition of the engine and its components in terms of displacements and stresses as well as for diagnosis of the causes of vibration.

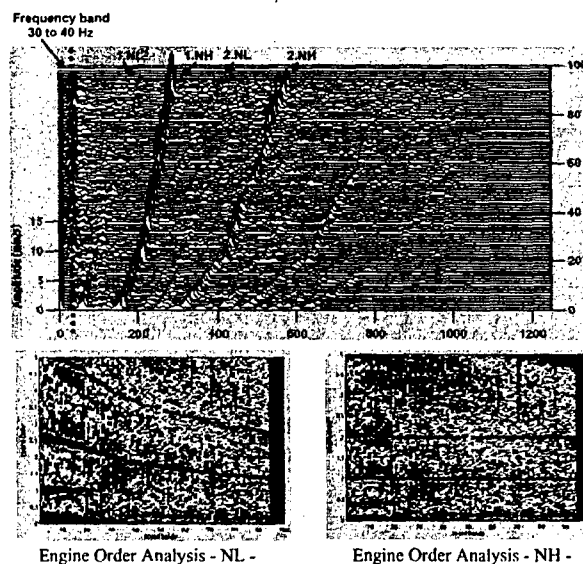


Figure 19: Waterfall diagrams – Excitation due to air brake buffeting

5 CONCLUSIONS AND OUTLOOK

The capabilities of the vibration monitoring and diagnosis system presented in this report to satisfy the requirements:

- increased safety by identification of dangerous vibration conditions at all engine speeds and thrusts, including steady state and transient operation and through the generation of the corresponding cockpit warning,

- avoidance of major secondary damage by way of early failure identification,
- reduction of maintenance expenditure through isolation, localisation and diagnosis of the vibration causes and
- optimisation of maintenance by means of consideration of the current engine condition.

are being demonstrated during the first phase of application.

The initial findings are favourable with respect to the quality of the signals, the philosophy for vibration incidents detection and the logic for storage of the different vibration data sets. The diagnostics and prognostics facilities currently developed will be extended, improved and automated by the use of artificial intelligence for pattern recognition. Additional data will be collected during further applications of the VMS to continue these efforts and to determine the cost and performance benefits.

Paper 7: Discussion

Question from H Pfoertner – MTU, Germany

Why is the vibration not measured in the axial direction when, with respect to gas turbines, this may be more relevant to bearing defects?

Presenter's Reply

All vibration measurements will be captured using accelerometers on the casing of the engine. As the bearing support structures, upon which the accelerometers are located, are very stiff in the radial direction, it can be assumed that the rotor vibrations will be transmitted, unchanged, to the sensors.

In the case of vibration in the axial direction, measurements are only reliable if the sensors are located directly in contact with the bearing chambers. Such locations are generally not considered for accelerometers due to the maintenance implications and, moreover, because of confidence in detecting bearing defects from vibration measurements in the radial direction.

Question from Dr R Szczepanik – Instytut Techniczny Wojsk Lotniczych, Poland

What was the reason for the increased level of engine vibration during the engine icing test?

Presenter's Reply

The vibration was due to a non-symmetrical ice layer that developed on part of the first stage of the fan.