# Investigations into engine transient response due to internal and external dynamic excitations

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**ABSTRACT:** In the current report applications of an advanced vibration monitoring system used on EJ200, the engine for EuroFighter EF2000 Typhoon, in combination with an extensive 3D Finite Element model of the whole engine for vibration monitoring and diagnosis are presented.

A description of the measurement system on wing and the methods used for vibration monitoring is given. In order to reach a high level of consistency, the flying monitoring system is also used on the test-bed in addition to the usual test-bed equipment. Therefore a common database with common file formats is created which guarantees reliable comparison of the measurements from the test-bed and on wing.

Extensive 3D Finite Element models of the whole engine and of single components are explained. Different techniques for processing of the models are discussed.

The combination of the whole engine Finite Element model and the vibration monitoring system of the real engine represents a very powerful tool to evaluate the impact of the measured vibrations on the mechanical condition of the engine.

For selected cases of internal excitations, such as unbalance on the different shafts, and external excitations, such as airbrake buffeting and icing conditions, engine response is analysed based on the measured transient signals. The displacements and stresses on particular areas of the engine due to one of these load cases are evaluated in detail.

Conclusions and an outlook of future activities in the field of the vibration monitoring and diagnosis complete the report.

**KEYWORDS:** Aero engines, Finite Element models, transient engine response, on-board vibration monitoring, vibration analysis, model based vibration diagnosis

## INTRODUCTION

Modern aero engines such as the EJ200, the engine for the Eurofighter EF2000 Typhoon, shown in Figure 1, demand an increasing thrust to weight ratio with simultaneously higher energy density. This involves a careful balance between requirements related to the efficient operation of the propulsion system, and the necessity to incorporate sufficient safety margins to ensure the structural integrity of the system under all conditions.

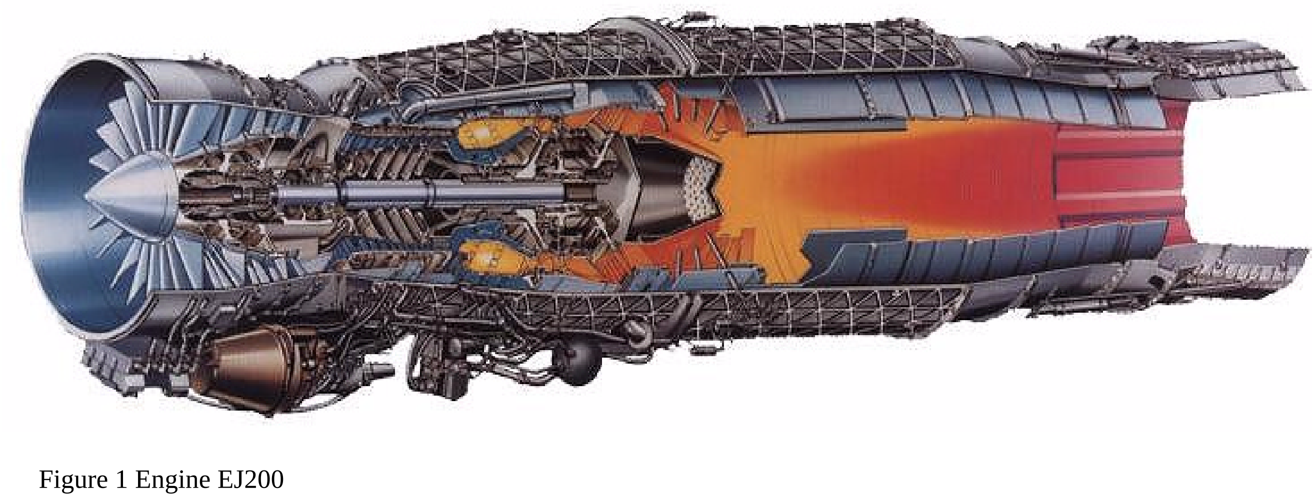


Figure 1 Engine EJ200

Such complex structures are normally designed in modular form amongst other reasons for efficient maintenance. That means, there are different components of the engines which have a defined function for various disciplines such as structural mechanics, aerodynamics, etc. These components can be manufactured by several partners in line with a defined work-share.

For the prediction and analysis of the mechanical response of the engine and their components due to different loads resulting from the engine operation, Finite Element (FE) models are normally generated in an early design phase of the project. The resulting FE models are carefully validated using several techniques through correlation of the engine or component response due to selected loads with the corresponding measurements.

According to several current regulations in force for aero engines, as for instance FAR 25.1305, ref. /1/, aero engines shall be monitored continuously with respect to engine vibrations, at least an indicator to point out rotor systems unbalance is required. It follows that vibration monitoring systems are standard devices on modern aero engines.

In view of these two different facilities for engine analysis, which are usually considered separately, the idea is to combine both tools for an extensive evaluation of the engine response.

## FINITE ELEMENT WHOLE ENGINE MODEL (WEM)

For the mechanical analysis of EJ200 the 3D FE Whole Engine Model illustrated in Figure 2 is used.

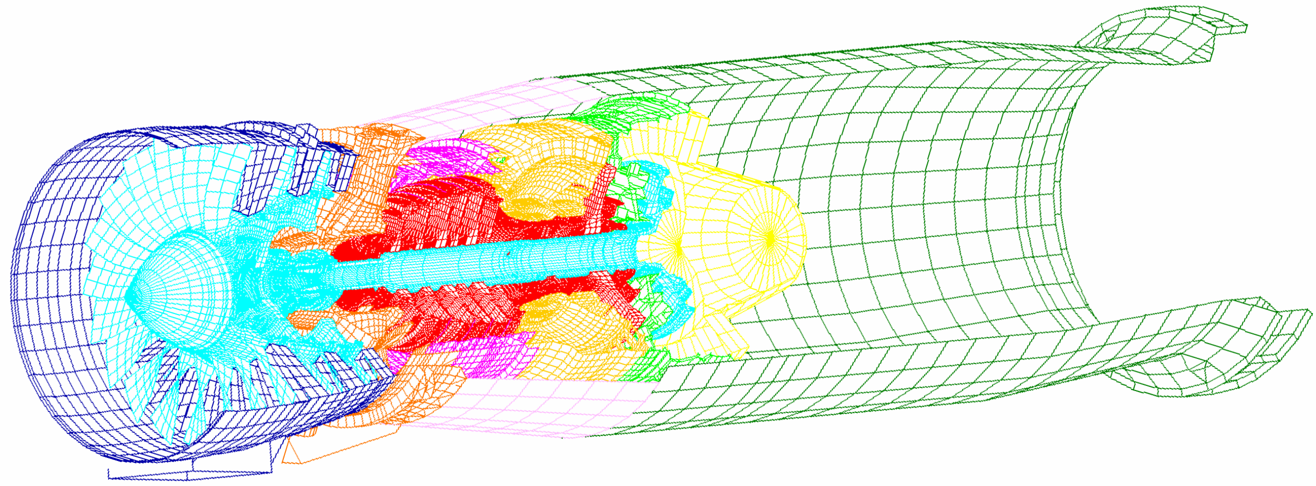


Figure 2 Engine EJ200 – FE whole engine model

This model consists of the following main groups:

- Low pressure (LP) rotor
- High pressure (HP) rotor
- Non-rotating components

The main group of non-rotating parts includes the following two sub-groups of models of the single components:

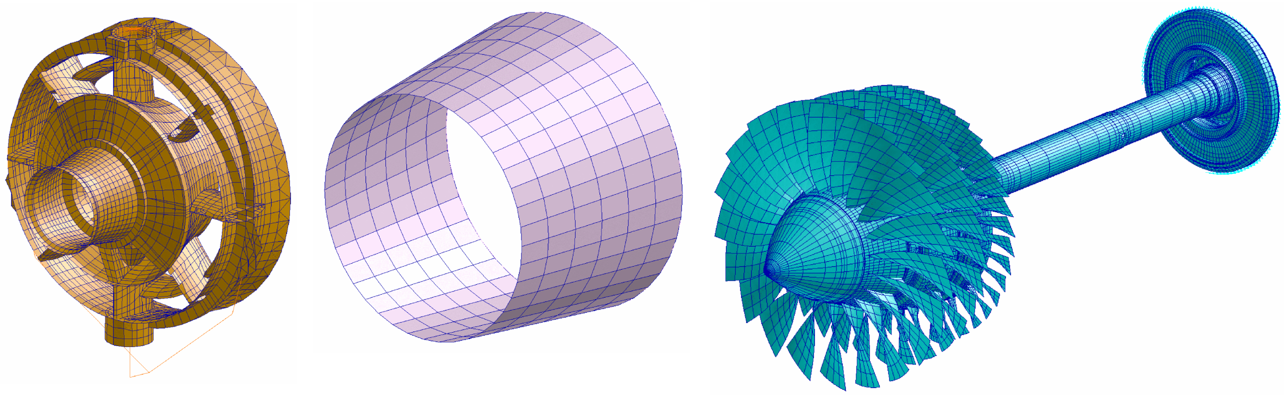
- engine casings: fan casing, by-pass duct, jet pipe, high pressure compressor casing, combustion chamber outer casing and turbine exhaust casing
- bearing support structures: intermediate casing and rear bearing support structure.

Accessories and dressings are considered either as non-structural or evenly distributed masses.

For the generation of the models of the diverse single components which are integrated into WEM, different mesh densities depending on the structural function of the single component within the whole system are used. In case of structural critical components, ref. /2/, as for instance the bearing support structures, that is the intermediate casing (IC) in the front part of the engine and the rear bearing support structure (RBSS), FE meshes with a high density are preferred for appropriate idealisation of the expected high stress gradients. Similar high density meshes are used for the idealisation of the rotors. On the other hand, for the modelling of single components which are more relevant for the aerodynamics than for the structural behaviour of the engine, as for instance the by-pass duct or the jet-pipe, coarser meshes are used. For comparison of these modelling techniques the models of the single components intermediate casing, by-pass duct and LP rotor are illustrated in Figure 3.

The FE models of the single components, of sub-assemblies consisting of two or more single components and of the whole engine model are validated very carefully using selected measurements and appropriate techniques.

For simulations of the dynamic response of the whole engine in the transient time domain the models of the different single components are processed using different methods in order to generate a compressed model with appropriate accuracy and size. According to the usual MSC/NASTRAN terminology this model is called the residual model.



Intermediate casing By-pass duct Low pressure rotor

Figure 3 Models of single components

The compression of the whole engine model is performed in two phases:

In the first phase of the process the models of the non-rotating single components were reduced using standard techniques, as for instance the component mode synthesis. For this Craig-Bampton reduction, ref. 3, basically all the degrees of freedom (DOF) of the nodes of the connecting flanges between the single components and the DOF of nodes at selected locations, for example positions for further introduction of non-linear connecting elements or for the direct output of the engine response, are selected as physical co-ordinates in the residual structure. The displacements at all the other DOF of the structure are approximated using modal co-ordinates considering the full excitation frequency range. In this way the physical engine response at the selected locations can be evaluated directly without a transformation of the results to the whole engine.

The 3D models of the rotors are transformed into equivalent beam and generalised models keeping unchanged the mechanical characteristics in the considered frequency range. The nodes and elements of these models are located on the engine centreline. Blades are not included as structural parts but the mass, c. g. and mass moments of inertia properties were considered using rigid concentrated masses on the centreline nodes. The deviation in frequency between solid and beam rotor models is below 3% for the first five eigenmodes (free-free and fixed-fixed). Gyroscopic effects, caused by the rotors precession in conditions such as take-off, are modelled by applying suitable moments to the centreline nodes of the rotor for static and dynamic analyses. A significant advantage of this technique compared with the standard static reduction is that the resulting models have more physics significance, in particular at areas which are approximated with usual beam elements.

In a second phase of the condensation the model resulting from the first phase is again reduced using the Craig-Bampton reduction. In this case only a part of the DOF at the connecting flanges and a reduced number of the additional, internal DOF are considered as physical DOF which together with a number of selected modal DOF result in a very compact model with a total number of DOF below 1000. This model is then completed with special non-linear elements for the connection of several systems which are (a) non-rotating, (b) low pressure and (c) high pressure systems and can be used for iterative calculation of the transient response of the engine in the time domain.

For prediction of the engine response due to steady-state and static loads full size models of the non-rotating components and equivalent models of the rotors are used.

## VIBRATION MONITORING SYSTEM (VMS)

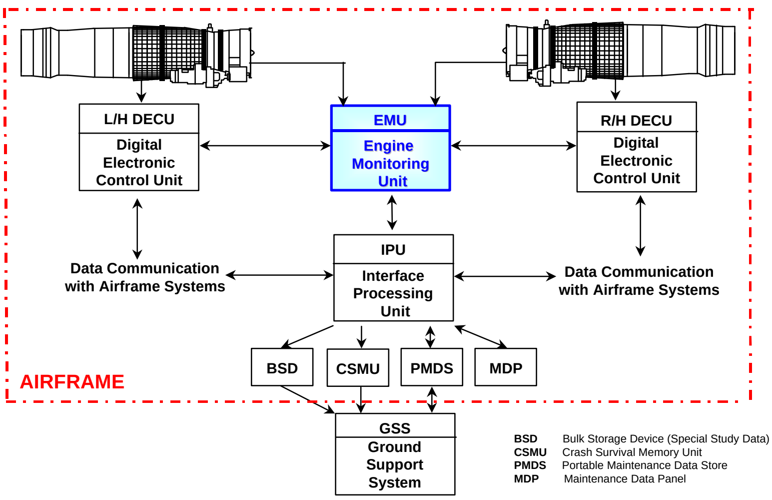



Figure 4 Vibration monitoring system – Data flow

The schematic description of the vibration monitoring and diagnosis system using for EJ200 is illustrated in Figure 4. The tasks of the vibration monitoring function are distributed over airborne and ground equipment.

The airborne equipment comprises basically vibration transducers (accelerometers) and a flying computer, the Engine Monitoring Unit (EMU), and the ground equipment comprises the Engine Health Monitoring system as an element of the Ground Support System (GSS) dedicated to the detailed evaluation of the in flight captured signals.

The location of the two engine vibration transducers used for continuous engine monitoring is shown in Figure 5. 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.

An extensive description of the different data sets and the methods used for vibration monitoring as well as of the corresponding strategy for vibration incident detection is given in ref. 4.

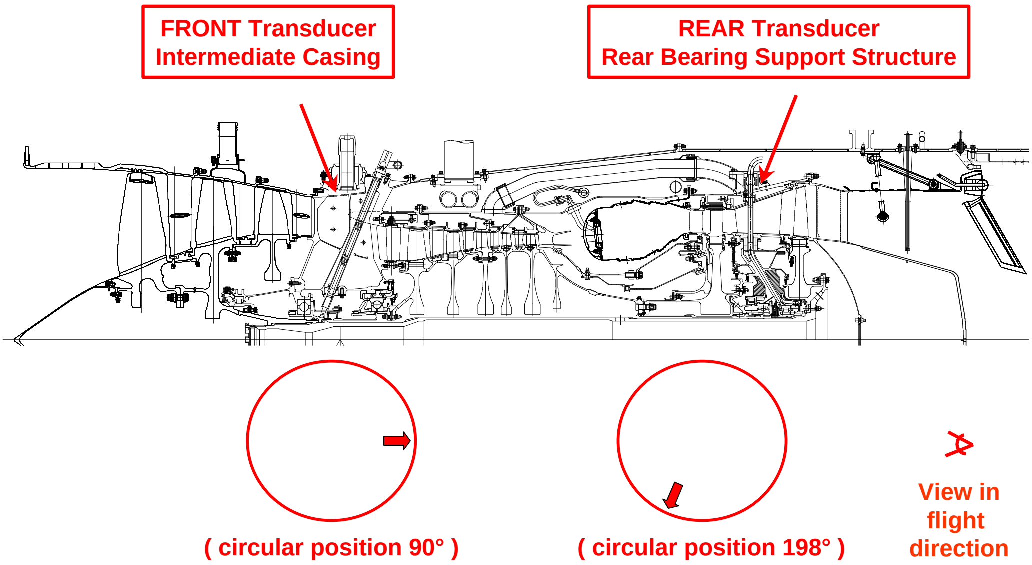



Figure 5  Vibration transducers attached to the EJ200 engine

The vibration monitoring system of EJ200 is not only applied on wing but also at diverse development and production test-beds of the different Eurojet Partner Companies having a total experience of more than 19000 engine run hours. The same flying monitoring system is also used on ground in addition to the usual test-bed equipment to reach a high level of data and analysis consistency. This allows the generation of a common vibration data base including certification and pass-of tests as well as vibration events occurring in flight, especially under the influence of extreme manoeuvre loads which are typical for modern fighter aircraft.

From a large number of investigations performed in the last few years only the following cases have been selected in order to demonstrate the capability of the vibration monitoring system presented here.

a) External excitation: Icing test

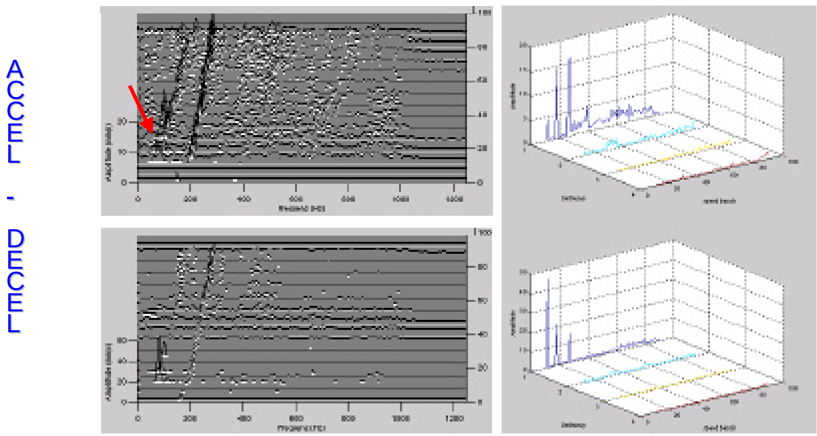



Figure 6  LPC out of balance due to ice build up

Vibration monitoring and investigation during icing tests showed high out of balance effects on the LP compressor (LPC) rotor. Figure 6 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 1st EO NL near idle reach abnormally high values for both acceleration and deceleration conditions. These dominating amplitudes can be identified easily in the waterfall diagrams.

The velocity signals at a selected spool speed captured simultaneously for the FRONT and REAR transducers are plotted in Figure 7. The left hand side of the figure shows the signals in the time domain and the right hand side the signals in the frequency domain.

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.

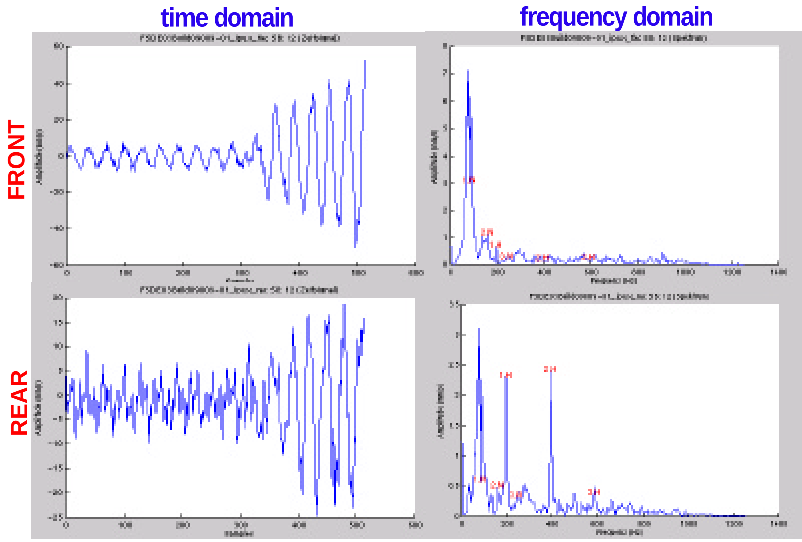



Figure 7 Selected vibration signals / FRONT and REAR transducers.

b) Internal excitation: High out of balance due to HP turbine (HPT) blade deterioration

HP turbine blade deterioration has a significant effect also on vibration levels. Maximal vibration amplitudes at 100 defined spool speed bands derived from the LP rotor speed in rpm are recorded at each of several engine runs including a slow acceleration, a stabilisation and a slow deceleration. Figure 8 shows these maximal vibration values over several engine runs. During early runs the amplitudes of the 1st EO of the high pressure rotor at the REAR sensor reach maximum values of approx. 26 mm/s. During later runs the maximum amplitudes achieved were approx. 37 mm/s, showing a vibration level increase of some 40%.

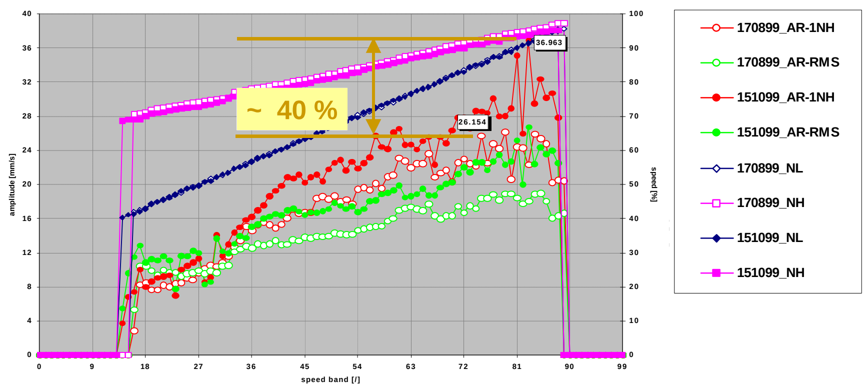




Figure 8 HPT out of balance

Figure 9 Vibration cause HPT blade deterioration

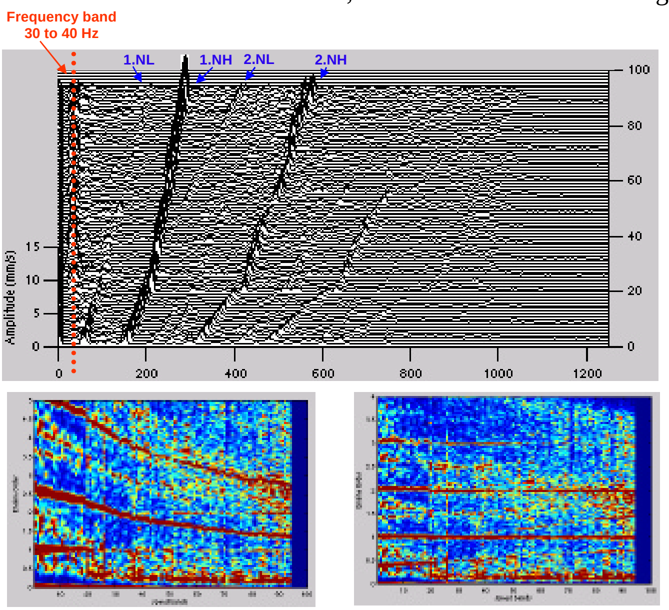
In this case the cause of high vibration levels was identified as follows:

Incremental deterioration of the tip of HPT blades due to a malfunction of the blade cooling system progressively increased out of balance (and consequently vibration amplitudes) with time, see Figure 9.

c) Mounting excitation: Air brake buffeting

The vibration monitoring system presented in this report also enables engine external excitations to be detected and analysed. The aircraft buffeting resulting from the application of the air brake is such a case. The engines are excited with a vibration component having a constant frequency of about 35 Hz independent of the speed of the rotors. The upper part of Figure 10 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 pattern can be observed using an order analysis as shown in the left hand lower part of Figure 10 for the LP orders and in the right hand lower part of the figure for the HP orders. The constant vibration components are also 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.




Engine Order Analysis - NL - Engine Order Analysis - NH -

Figure 10 Waterfall diagrams – Excitation due to air brake buffeting

## INTERACTION BETWEEN THE *VMS* AND THE *WEM* ANALYSIS OF SELECTED LOAD CASES

The main objective of this report is to present the application of the finite element model of an aero engine described in the previous section in combination with the monitoring and recording system for vibration monitoring and diagnosis explained above. The combination of both these facilities represents a very powerful tool to evaluate the impact of the measured vibrations on the mechanical condition of the engine.

Within this report only one of the load cases mentioned in the preceding section is discussed exemplary in detail, the icing test. Similar analyses for the other presented load cases are also possible.

The first step of the investigation includes the transformation of the on-operation recorded velocity signals in displacements. The resulting displacement signals for the locations of the FRONT and REAR vibration transducers versus time for the considered spool speed band are shown Figure 11. A significant increment of the amplitudes at the time of the build-up of a non-symmetric ice layer at the front stages of the LPC is clearly noticeable.

After that, the time dependent equivalent loads can be determined which cause similar displacements as the measured ones at the locations and directions (DOF) of the finite element model which correspond with those of vibration sensors.

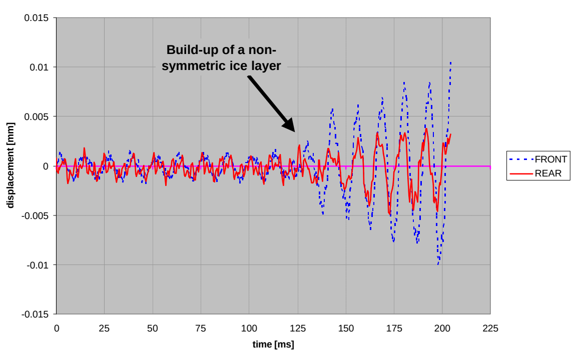



Figure 11 Icing test: Transient displacements at DOF corresponding to the sensors for a selected speed band

A direct imposition of the measured displacements on the whole engine model at the position and direction of the sensors is normally not suitable for investigation of the loads and stress distribution on the engine. The reason is that only local effects at the considered positions can be observed which are not representative for the real engine response due to the investigated cases, in particular in locations at internal areas of the engine. Therefore the use of equivalent load arrangements for investigation of the mechanical impact of the measured conditions on the whole engine is mandatory.

In particular the investigation of the static response corresponding to the maximum displacement values scaled with an appropriate factor to consider the dynamic behaviour of the event yields to significant findings with respect to displacements, loads and stresses on the whole engine giving an indication of the most sensitive areas for the considered load configuration.

Figure 12 shows the deformation of the whole engine due to static loads applied on the front part, that is the 1$^{st}$ stage blades, of the low pressure compressor. This configuration of loads is very similar to the observed one during the experimental investigation. The loads applied in the horizontal and in the vertical direction at the chosen location were determined using static transfer functions between the loaded and the measurement points, that is, between the 1$^{st}$ stage of the LPC and the location of the vibration sensors.

Large displacements at the front part of the LP rotor are included in the deformation of the whole engine simulating the real measured conditions.

The corresponding stress distribution is plotted in Figure 13, where red tones show high and blue tones low stress levels. As already expected, high stress concentrations are visible in the area of the front bearing support structure, in particular in the region of the front bearing, and in a low degree at the by-pass duct and jet pipe due to the engine mounting configuration also.

An investigation in detail of the stress distribution at the high load areas as shown in Figure 14 allows the engine design at extreme conditions to also be validated.

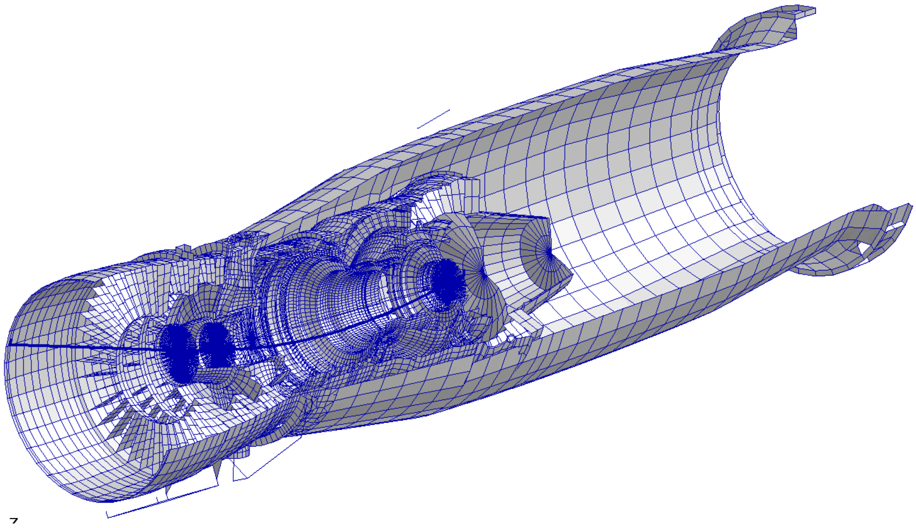


Figure 12  WEM maximal deformation

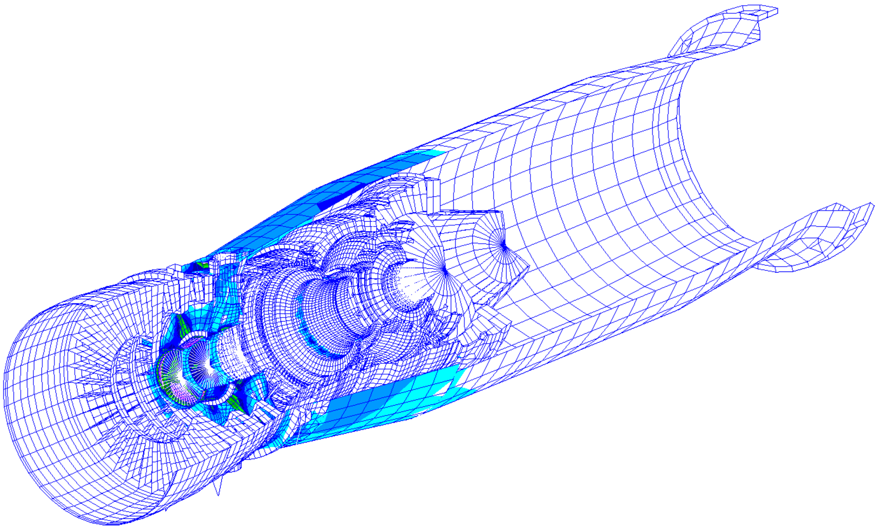


Figure 13  WEM Stress distribution

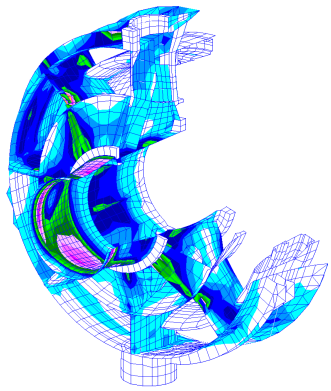


Figure 14 IC stress distribution

In the instance that the rotation speed of the LP rotor at the time of the load application corresponds to the eigen-frequency of the fundamental 1$^{st}$ bending mode of the LP rotor integrated in the whole engine, it is possible to use another alternative for the evaluation of the loads and stresses resulting from the considered load case. In this situation a scaling factor resulting from comparison of the calculated amplitudes, which are arbitrary, and measured, fixed amplitudes on the vibration transducer locations can be determined. The identified factor can then also be used for scaling of the calculated stress levels to analyse the real loads. This assumption is exact only in the case that the engine vibrates nearly to the 1st bending mode of the LP rotor.

## SUMMARY AND CONCLUSIONS

In the first part of this report two different instruments for analysis of vibrations on a high power aero engine are presented.

The first one is an extensive 3D finite element whole engine model having more than half a million of degrees of freedom. The whole engine model is assembled from models of single components which can have different mesh characteristics conditional on the structural function of the single components in the whole assembly. The model is processed using different techniques depending on the load cases which are investigated.

The second instrument is a sophisticated vibration monitoring system capable to process and to record transient vibration signals in flight. The vibration signals are captured with a high sampling rate in order to allow the spectral analysis of the vibration signals in a frequency domain up to the 3rd harmonic of the high pressure system.

The main objective of this report is to present the combination of the two facilities mentioned above as a very powerful tool for model based vibration diagnosis. With this combination it is possible to analyse the vibration signals acquired during real applications of the engine on wing considering effects related to extreme flight manoeuvres which are typical for modern fighter aircraft. This tool is essential for effective interpretation of signals captured during vibration events and for the evaluation of their impact with respect to the structural integrity of the engine.

The vibration monitoring and diagnosis system presented here satisfies the requirements of:

- 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.

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 based on operational and simulated data 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 vibration monitoring system to continue these efforts and to determine the cost and performance benefits.

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