An innovative Prognostic Health Management system for turbojet

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INTRODUCTION

Turbine engine failures are the leading cause of class-A mechanical failures (loss of aircraft). The cost of these incidents is astounding: increasingly, commercial air maintainers are turning to Prognostic Health Management (PHM) systems to prevent these losses and to reduce maintenance costs. For this reason, the development of PHM systems is advancing rapidly.

Taking into account the previous scenario, an innovative PHM system should develop and validate a turbojet Health Management System (HMS) able to process operational data acquired from sensor-equipped turbojet. The most common health monitoring parameter in the aerospace engine industry is vibration, making vibration monitoring a crucial component of any PHM system. The vibration measure can offer important information only if the data is obtained in correspondence of sensible points of the engine critical components: the choice of the sensor application points can be made only by means of a punctual dynamical model of the entire engine. Moreover, the validation and verification of detection/diagnostic/prognostic capabilities requires access to high quality data for both healthy and faulty systems. While generic data are often readily available, more specific values for healthy or faulty systems are much more difficult to obtain. In particular, seeded fault tests are time consuming, expensive, and are not always representative of operational condition.

The development of the HMS should be carried out through the deployment of high-fidelity Vibration Validation Tool (VVT) able to supplement physical testing. Currently, physical testing is the only avenue to validate diagnostic/prognostic systems. However these tests have high costs and duration, and are therefore conducted on a very limited basis. As a result, the need for faulty data is great but their availability is limited. The VVT fills this need by generating realistic vibration data for faulty scenarios, data that can complement any available data from operation or test bed data.

The VVT would reduce the costs and time required for the development of a HMS system providing simulated, yet realistic, vibration data for healthy and unhealthy critical components. Physics-based, data driven and hybrid vibration source models for the critical components can be merged to emulate the entire engine. VVT can then be used to generate realistic vibration signals for engine in different combinations of fault states and operating parameters. These results can be used to accomplish many difficult tasks, such as evaluating new technologies, assessing the most effective location for sensors, and determining the ability to detect a specific fault minimizing the false alarms and missed detections.

The main aim of this article is therefore to illustrate the concept, objectives and relevance of this novel PHM system VVT based showing architecture and approaches. In addition, the development of a tool for prognostic/diagnostic based on vibrations can be extended to several domains.

1 CONCEPT AND OBJECTIVES

Mechanical failures (loss of aircraft) originated from turbine engine failures are the main cause of aircraft disasters. The cost of these incidents is astounding: for example, the carrier-based F-35 CV is estimated to cost $38 million, and the loss of crew is unacceptable. By avoiding only fatigue failures in the US civil and military aviation, the potential savings could approach $1 billion per year. Increasingly, commercial air maintainers are turning to Prognostic Health Management (PHM) systems to prevent these losses and to reduce maintenance costs. For this reason, the development of PHM systems is advancing rapidly.

According to the concept stated in the introduction, the development and validation of an Engine Health Management System (EHMS) able to process vibration data is a key objective. Such system will be able to operate in the following way:

a) Acquiring and recording at appropriate rate all vibration engine data, speed data and operational data (e.g. loads, etc.) during flight. Vibration sensors distributed throughout the engine collect data on the condition of components and subsystems, while speed and "operational" sensors collect data related to UAS regimes.

b) On flight diagnostic/prognostic analysis to provide near real-time fault isolation and early warning of engine faults. On-board processor assesses engine health and predicts possible deterioration and remaining useful life.

c) On ground diagnostic/prognostic analysis by in-depth processing of all data acquired during flights, so that all stressed engine events can be encompassed in this analysis. The resulting information can be used to improve maintenance, extend the life of both the whole engine and individual critical components, improve UAS readiness and availability, and reduce operating costs.

The development of the EHMS will be carried out through the deployment of high-fidelity Vibration Validation Tool (VVT) able to support physical testing. This is a key and innovative approach in the actual scenario. The VVT will reduce the costs and time required for the development of a EHMS system providing simulated, yet realistic, vibration data for healthy and unhealthy critical components. These results can be used to accomplish many difficult tasks, such as evaluating new technologies, assessing the most effective location for sensors, and determining the ability to detect a specific fault minimizing the false alarms and missed detections.

2 STATE OF THE ART AND PROGRESS BEYOND

The current state of the art is well represented by 2 systems, namely ADMS (Aircraft Diagnostic Maintenance System) and PHM (Prognostic Health Management) developed for the Joint Strike Fighter program (JSF). JSF in particular has incorporated PHM functions, information management and reasoning systems. Working on area correlations, generated analysing purpose built sensors data links transmit vehicle health data to ground based systems, directly linked with the JSF supply chain.
The emerging research themes most relevant are focused mainly in modelling, advanced analytics and complex system articulated in the stages (layers) of fault detection, fault diagnosis and prognosis.

The PHM should be designed and developed on the basis of open system architecture-condition based maintenance (OSA-CBM) approach [1-7] including development of the following six layers:

- **Data acquisition (DA)**: collection converting and recording of sensor data and information;

- **Adaptive data manipulation (DM)**: signal processing, diagnostic/prognostic feature extraction and transformation. Engine environment is *highly noisy*: therefore, the purpose of pre-processing is noise elimination performed by novel de-noising based on the modified wavelets and adaptive filters.

- **Adaptive state detection (SD, i.e. fault detection)**: feature comparison against baselines or operational limits, generation of enumerated condition indicators, determination to which abnormality zone the data belong, generation of alerts. Engine environment is highly dense. Therefore, identification and tracking of engine critical component should be performed primarily by novel model based, *non-stationary* time frequency linear and non-linear second order signal processing techniques.

- **Adaptive health assessment (HA, i.e. fault diagnosis)**: determination of the health of components; if the health is degraded, generation of diagnostic information that proposes possible fault conditions with an associated confidence;

- **Adaptive prognostic assessment (PA, i.e. prognosis)**: health projections of components, including Remaining Useful Life estimation;

- **Advisory generation (AG)**: provision of actionable information regarding maintenance or operational changes required.

As previous stated, the development of the EHMS can be carried out through the deployment of high-fidelity Vibration Validation Tool (VVT) able to supplement physical testing. The VVT can reduce the costs and time required for the development of a EHMS system providing simulated, yet realistic, vibration data for healthy and unhealthy critical components. Physics-based, data driven and hybrid vibration source models for the critical components are combined to emulate the entire engine. VVT can then be used to generate realistic vibration signals for engine in different combinations of fault states and operating parameters. These results can be used to accomplish many difficult tasks, such as evaluating new technologies, assessing the most effective location for sensors, and determining the ability to detect a specific fault minimizing the false alarms and missed detections.
Currently, physical testing is the most useful method to confirm diagnostic/prognostic systems. As alternative, in the **simulated test case**, the engine vibration, speed and operational data are generated by VVT, introducing the fault sources along the mechanical paths and analyzing the EHMS outputs to measure the performance and reliability of the diagnostics/prognostics on the basis of probabilities of missed detections and false alarms, probability errors of diagnosis and accuracy of prognosis (i.e. accuracy of the remaining useful life estimation). In the **real test case**, the engine vibration, speed and operational data are collected by vibration, speed and "operational" sensors deployed along the mechanical paths of the engines. The EHMS digitalizes and records these signals during the flight.

Physics-based, data driven and hybrid vibration source models for bearings, gears, shafts and other critical components are combined to emulate the entire engine. VVT can then be used to generate realistic vibration signals for engine in different combinations of fault states and operating parameters. These results can be used to accomplish many difficult tasks, such as evaluating new technologies, assessing the most effective location for sensors, and determining the ability to detect a specific fault minimizing the false alarms and missed detections, Figure 1.

3 VVT ARCHITECTURE

In virtue of above considerations, the VVT architecture is composed by the following blocks, Figure 1:

- **Vibration Paths Simulator,** the core of VVT, can simulate individual component vibrations and the transmission paths of these vibrations to the sensor locations, thereby generating representative vibration signals at each sensor location. This block implements also dynamical models for the sensors, and outputs signals which are close to the sensor outputs in real operation. Such signals are input to the EHMS.

- **PHM Algorithms Analyzer** can collect and analyze the outputs of EHMS, in order to evaluate and validate their performance.

- **Data Logger & Report Generation** is able to store the results and produce the relevant test analysis and statistics.

- **Graphic User Interface (GUI)** can be developed for entering the simulation parameters, the relevant data of critical mechanical components (engine shafts, gearbox, bearings, couplings, etc.), and displaying the relevant results and statistics.

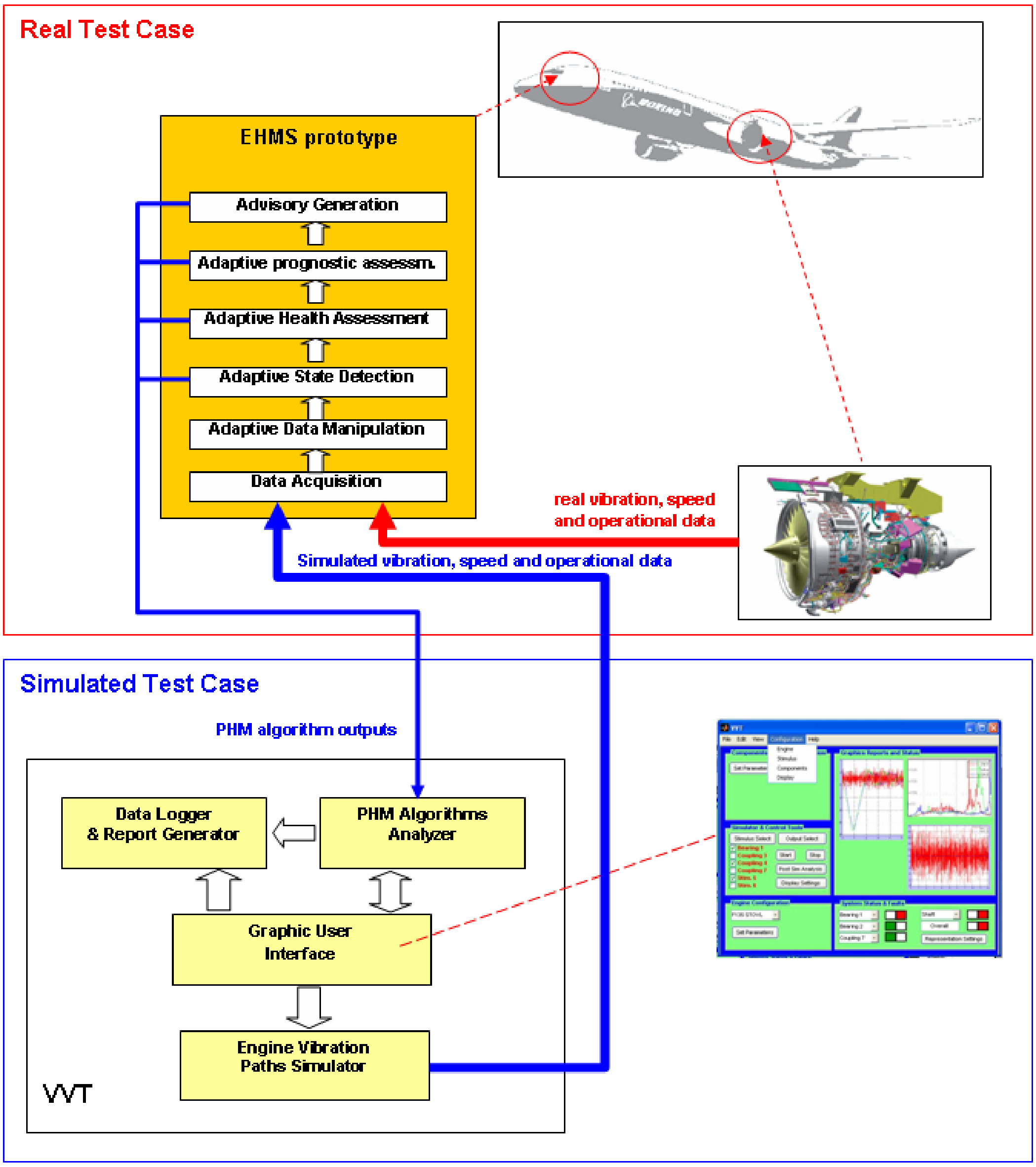

Figure 1. Simulated and real test case

There are three main approaches which can be pursued for system modelling:

1. **Physics-based**: it is based on writing down the dynamical equations governing the separate components as well as the physical conservation laws governing their interaction, to obtain the dynamical behaviour of the engine system.

2. **Black-box (i.e. data driven)**: it uses the real measurement data. At the first stage a candidate model with tuneable parameters is identified. Then, its parameters are selected (*parameter identification*) in order to achieve a close matching between the model response and the measurements. Finally, a *model refining* should be performed.

3. **Hybrid:** it is useful when some physical parameters are uncertain, which may occur for many reasons. The candidate model is derived according to physics based modelling, and its uncertain parameters are set via parameter identification techniques using measured data. In order to derive the vibration paths models, the best approach case by case can be considered.

Assuming to have a full set of measurements only for normal operating conditions (and not for faulty conditions), it can be expected that the physics-based and hybrid approaches should play a major role for modelling the components and transmission paths. Nevertheless some part of, at least, the nominal model could be constructed via black-box modelling as well. It is also expected that some faults could be mapped onto some parameter variation with respect to the set of nominal parameters. Sensor modelling would be heavily based on the sensors' data sheets and, possibly, on an experiments-based model refinement.

The dynamic modelling of the engine requires the use of a complex approach which considers the single component behaviour in normal and faulty conditions and the interaction between single parts to obtain the system dynamic modelling.

The models should be targeted on capturing the mechanical interconnections of the components, the vibrations caused by the faults and the way the vibrations would propagate among the components of the engine and towards the sensor locations. Also the sensor type and position can be defined on the basis of the dynamic model, with the aim to obtain more representative data not much sensitive on external variable parameters.

This is the core part of VVT implementation and would require the development of accurate dynamical models for the:

- Vibrations of components in normal and faulty conditions.
- Components interaction and links for a complete knowledge of the engine vibrations.
- Transmission path from components locations to sensors locations.
- Real behaviour of sensors (e.g., finite bandwidth and realistic level of noise).

The dynamics of the overall components and transmission paths entails complex multi-body interaction and vibration phenomena. Before this, a dynamic characterization of the single component in healthy and faulted condition must be made; the Finite Element (FE) Analysis now is one of the most reliable and careful method used.

As a viable approach that would speed up significantly the VVT, the use of automatic model-generation software available on the market (SimMechanics Matlab Toolbox, Simulink, Adams, etc.) can be considered. These software are very flexible and fit to model complex systems; for example, a SimMechanics simulation file is built by interconnecting elementary blocks representing mechanical entities such as masses, actuators, transmissions, gearboxes, moving parts. It allows to include motion constraints, any dynamical or static nonlinearity, and provides built-in vibration analysis tools. The dynamic characterization from FE analysis could be used inside this automatic model generation software in order to consider the contribution of the components both in the healthy and faulted condition with good accuracy. This allows to simulate the dynamic behaviour in presence of mechanical faults, for example a crack propagation, and to optimize the choice of the right sensors (and their position) in all the conditions.

The numerical integration of the system model, typically a system of nonlinear DAEs, is performed **automatically** via efficient built-in solvers.

Faults include common conditions such as bearing spall, pits, gear tooth chips, etc. Detailed descriptions of the faults should be supplied by the Fault Scenarios Analysis. Faulty conditions could be modelled either by appropriate exogenous "disturbance" oscillation inputs, by parameter variations, or by considering a "mechanical equivalence" of the faulty behavior, and representing it with multibody software. Actual and measured components vibrations in faulty conditions can be predicted via the use of such models.

Sensor modelling should done case by case looking at the relevant literature. For instance, the characteristics of typical accelerometers signals have been widely studied in the literature relevant to inertial navigation. The presence of a significant, yet predictable with good accuracy, drift of sensed acceleration due to sensor heating was highlighted.

The inertial and static model parameters should be derived from engine technical drawings and documentation. Dynamical parameters such as the friction ones could be tuned by means of identification techniques using field measured data. This phase is especially crucial for obtaining affordable models of the transmission paths. The VVT should be validated against all field measurements.

4 CONCLUSIONS

The EHMS system fitted with VTT approach should provide a novel solution for efficient aircraft maintenance by researching and developing an aircraft orientated service. This service could offer both real time maintenance analysis on board an aircraft as well as a more advanced analysis on the ground. The EHMS system should

therefore help to reduce the number of late aircraft departures as a result from last minute and major maintenance issues.
Research presented to the International Air Transportation Association (IATA) in 1995 concluded that 50% of flight delays are caused by engine problems resulting from maintenance issues and 50% of flight cancellations are due to engine problems. Although we will not be able to completely remove all of these flights delayed by maintenance issues, we estimate that the EHMS system will greatly reduce these by enabling ground maintenance crews to analyse the whole of an aircraft's engine in detail. Presently aircraft maintenance technology is limited to analysing each of these components individually and not evaluating their combined impact/result.
A short-medium term perspective of this innovative Prognostic Health Management system for turbojet is aimed at developing novelty technologies, methodologies and recommendations able to directly impact on MRO, in particular CBM, as well as on-flight safety. The goal is to reduce maintenance time and improve system availability by getting the right information to correct problems before they occur or become serious. Prognostics algorithms can be used to increase operational availability and reduce cost, as well as to increase the on-flight safety. This EHMS system involves the possibility to attach digital data collection devices to aircraft to collect all the pertinent data coming from the various engine sensors. After a flight, maintainers can download data from these devices into a ground station with a larger data base that contains comprehensive maintenance information about the aircraft and fleet. Maintainers can use the EHMS system to analyze the vibration data to help isolate faults in the aircraft engines much more quickly, get reliable information to predict parts failures, and make the appropriate repairs. For example, if the EHMS indicates that an engine component is nearing the end of its service life, the component will be scheduled for replacement. CBM takes advantage of this EHMS technology that tells what's actually going on with a particular system (jet-engine), so that maintainers can perform work based on the known effective condition of a specific component, rather than relying on statistical history or worst-case estimates. Knowledge of the components condition can be used to eliminate scheduled maintenance that is insensitive to the actual component's condition. This reduces unnecessary maintenance and inspections. The increased reliability is also beneficially due to fewer unexpected failures that can result in gate delays, cancellations and partial mission aborts or re-routing.
Furthermore, the EHMS system supports concepts to provide health status information at near real-time levels: the on-board EHMS continuously feeds data into its database and performs the prognostic analysis for enabling pilots to perform corrective operations in flight. Consequently, this increases the on-flight safety.
A medium-long term time perspective, aimed at:

a. Dramatically reducing the post-flight MRO and consequently the travel delays and inconvenient by enforcing the on-line prognostics. In fact, the MRO ground centre will be able to download in real-time the input data (vibration data) and the outputs data (results of the prognostics) of the EHMS before landing: as a result, maintainer don't have to wait for a data download after landing to determine an aircraft's condition related to the engines. This involve a dramatically speedup of the MRO process and the reduction of the travel delays related to this operations.

b. Enabling adaptive control to modify the system controls to achieve optimal performance also in presence of failures and degradations, exploiting the current vehicle capabilities.

The proposed method could be cost-effective and relevant to many applications (gas and steam turbines, compressors, pumps, fans, etc.) of high benefit across a number of markets: not only aerospace but also power, oil, gas, mechanical, chemical and civil engineering. However, helicopter gearbox monitoring can take a direct advantage from this system. Finally, a dedicated Gearbox Health Management System (GHMS) could be implemented directly and monitor the whole helicopter power transmission line.

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