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A REVIEW OF APPLICATIONS FOR ADVANCED ENGINE HEALTH MONITORING IN CIVIL AIRCRAFT ENGINES

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Abstract

Rolls-Royce has developed TotalCare™, an innovative approach to serving gas turbine operators' needs. A key element of making these services effective is the ability to minimise unplanned equipment downtime, and a major component of this capability is the provision of diagnostic and prognostic tools through advanced health monitoring.

The field of condition and health monitoring is developing at a rapid pace. As computing power increases, novel complex signal processing techniques, augmented with state-of-the-art pattern recognition methods, are now being applied to on-line monitoring systems and operated in real-time. In some cases these new methods are able to extract valuable diagnostic indicators from existing measured signals, and hence avoid costly system upgrades. This paper considers a number of emerging monitoring techniques, with respect to their detection ability in the context of past aviation events, that are likely to be incorporated into future products.

INTRODUCTION

During the design stage of any high-integrity complex machinery, significant analysis effort is applied to the understanding of potential failure mechanisms. Depending on assessed levels of the probability of failure and the estimated severity of impact, the considered failure mode will either be designed out of the physical product, or the risk mitigated by in-service monitoring. This approach is adopted by many industrial sectors and is known as Failure Mode Effect and Criticality Analysis (FMECA) [5,10]. Part of this analysis depends on the operational history of similar products already in service in the form of probability distributions. A useful reference when looking at a history of the aviation industry failures is the Technical Report on Propulsion System & Auxiliary Power Unit (APU) related Aircraft Safety Hazards, written in October 1999 and updated in January 2005 by a joint committee of the FAA and the Aerospace Industries Association [2]. This report is more commonly referred to as the CAAM (Continued Airworthiness Assessment Methodologies) report. This database can be used to underwrite the need for diagnostics based upon the consequences and the criticality of detectable failures. A more useful "database" is that of the Manufacturer's own products operational service history as this embeds the design heritage within the data. In the case of the aero gas-turbine, key areas of focus will be possible bearing failure mechanisms; fatigue induced cracks in mechanical systems such as combustors, compressor/turbine blades and rotating assemblies; potential secondary effects arising from foreign object damage (e.g. bird strike); and aero-dynamic instabilities such as fan flutter.

The primary function of TotalCare™ is to ensure availability of the product for all operational requirements. Clearly the ability to guarantee this level of service availability requires a robust method of health monitoring. In addition, the prize of this service is not with correct and accurate diagnostics of events as they occur, but rather in the ability to detect incipient signs of problems, such as those listed above, long enough in advance, such that serious outages are avoided and cost of disruption minimised.

REVIEW OF AVAILABLE MONITORING TECHNIQUES

Modern aero engines are designed to be extremely reliable and robust, typically operating for many thousands of hours before requiring major overhaul. This poses a significant challenge in the implementation of dependable health monitoring systems where design assumptions are made in the context of an abundance of normal data. The approach of novelty detection in this field is regarded as an established technique [4,12] and is now incorporated as part of the on-line monitoring capability of the latest Trent family of engines. The implemented system utilises a range of feature detector modules each focusing on a specific aspect of the acquired data. These detectors are based on a range of methods for detecting novel behaviour. We have utilised neural network and linear predictor models for detecting sudden variations in the amplitude of a tracked order. In addition, assessment of the significance of fractional and multiple tracked order components, often using simple rules, can provide useful indicators of blade rubs, defects in support structures and other changes in engine characteristics. Following this approach, a library of feature detectors can be implemented to cover a range of anomalous conditions whilst ensuring growth capability as new detection methods become available.

The following sub-sections provide a brief overview of some of the anomaly detection methods currently being reviewed.

Combustor temperature profile monitoring

A typical combustion system within a gas-turbine consists of a single flame tube, completely in annular form, with a series of fuel-spray nozzles equi-spaced around the tube. Temperatures of the resulting hot gases from the combustion process are monitored using an array of thermocouple devices. Combustion instabilities, for example arising from the effect of fatigue induced cracks in casings, are likely to be observed as variations in the temperature profile of the thermocouple array. Similar effects have been observed in Industrial gas-turbines, used for pumping gas, where blocked fuel injectors can result in pressure/thermal cycling of turbine blades, potentially leading to blade failure and ultimately secondary damage to turbine and engine. Such blockages can occur as a result of contaminants in the fuel supply, which is often taken from the gas being pumped. Condition monitoring within the combustion system of the industrial turbine is limited to 17 thermocouple readings from the gas generator exhaust of the low-pressure turbine. When an individual injector is partially blocked, there will be fall in the temperature measured over a small group of contiguous thermocouples downstream of the affected injector. The remaining thermocouple measurements are likely to show a slight increase in temperature as the combustor system attempts to compensate for the blockage. Previous work in this area [11] has demonstrated that a neural network, using a group of thermocouple readings from one side of the engine annulus to predict a temperature from a thermocouple on the opposite side, can be used as an effective functional estimator from which large prediction errors highlight abnormalities in the combustion system. This conclusion is supported by assessment of seeded fault data where blockages, at 5% and 10% levels, were deliberately introduced into a fuel injector of an Industrial RB211 gas turbine. The ability of the neural network to separate each level of blockage is shown in figure 1 below.

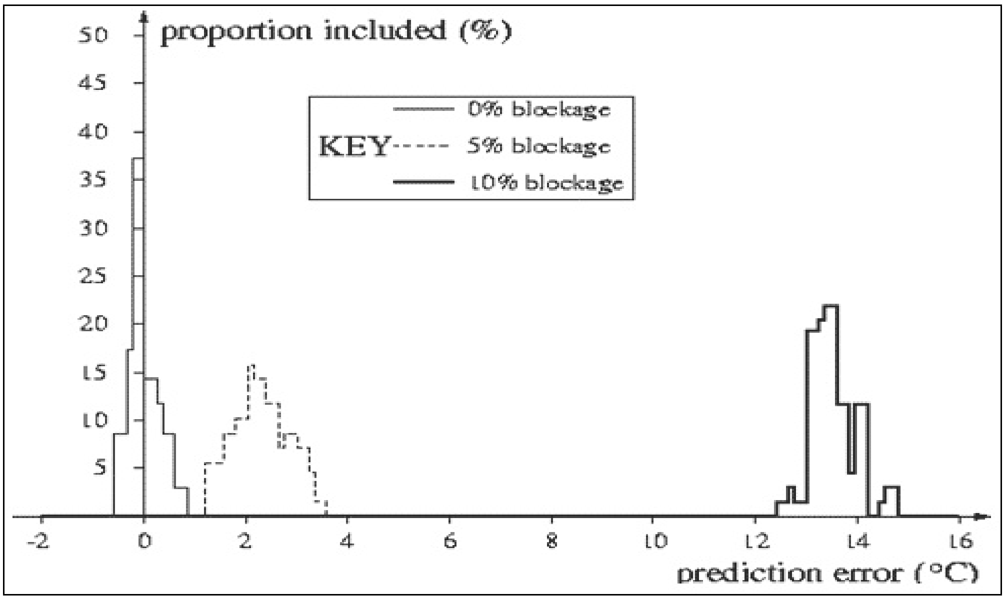

Figure 1 – Histogram of Prediction errors over different levels of injector blockage

Foreign Object Damage and Fan Flutter detection by Microphone

Experience has shown that foreign object damage (FOD) is easily detected within the vibration spectrum by monitoring for sudden excursions within the tracked order amplitude responses of a given shaft system. Clearly the most exposed component likely to experience FOD is the fan where effects such as bird-strike, ice shedding and runway debris during take-off, can lead to damage and eventual failure if undetected. For example, ice formation can occur on static structures and eventually shed into the path of rotating components. The resulting force of impact has the potential to deform blade profiles and even initiate small cracks. Obviously foreign objects (e.g. runway debris and birds) being drawn into the engine will have similar effects. As part of the Trent 900 flight trials Rolls-Royce has demonstrated the detection capability of an airborne microphone. Figure 2 shows the ability of a microphone to detect the effect of a deliberate flight test manoeuvre designed to build-up ice on the fan, which is then dislodged during a subsequent engine acceleration manoeuvre. The x-axis, in the left-hand image, represents time and the y-axis frequency. At any given point on the x-axis, a vertical slice through the image corresponds to an instantaneous frequency spectrum, the amplitude having being converted to a colour representation. The example also indicates that a small proportion of the ice entered the IP compressor. Both these effects can be detected by monitoring the fundamental shaft orders for a step change in amplitude, as indicated in the right-hand plot of the figure. Other examples from the same flight test have indicated the ability of the microphone to detect ice impact damage on other engines mounted on the airframe.

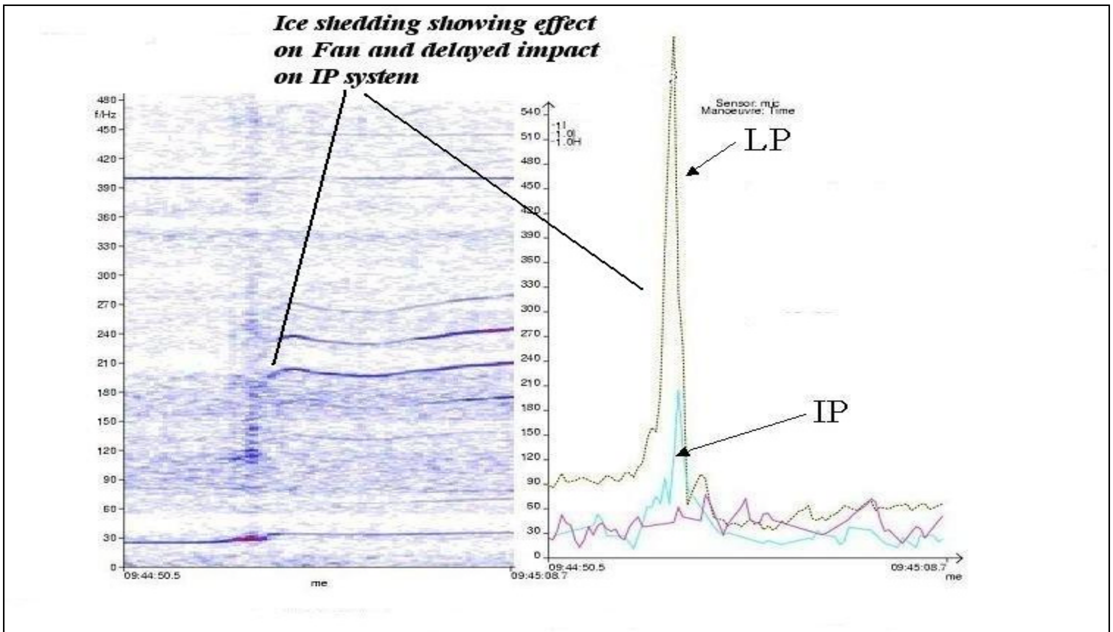

Figure 2 – Microphone Response to Ice Shedding Manoeuvre

Although the standard carcase vibration monitoring unit is able to detect changes of vibration characteristics in the rotating components, through bearing support structures and other mechanical interfaces, there are a number of indicators that cannot easily be detected using this mechanism. Specifically fan flutter, which is a self-excited dynamic instability, is manifested as an acoustic phenomenon and therefore its effect may not propagate through the engines structure. The instability may arise from cracked or damaged blades, or even incorrect handling of the engine, and can result in very high vibration levels. Once initiated, the flutter instability acts on the entire fan assembly and can occur in a 2, 3, 4 or 5th diameter travelling mode. A static microphone will observe the travelling wave of flutter at the frequency of 1st flap resonance, of the blade, plus an offset related to the speed of the engine (see figure 3 below).

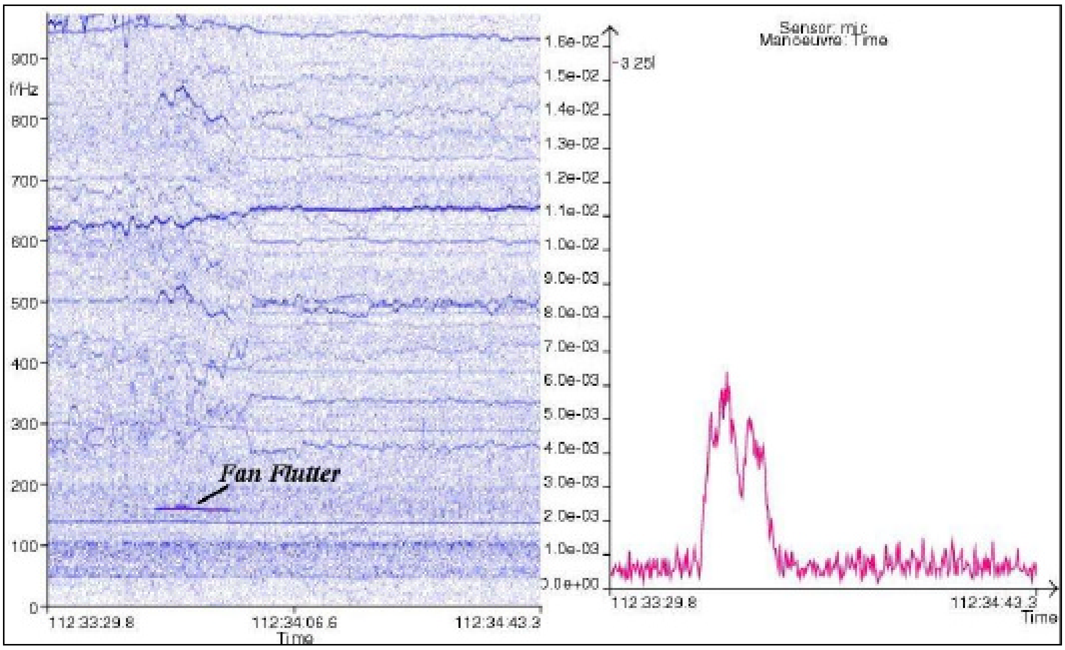

Figure 3 – Example Microphone Response of Fan Flutter

Tracked Order Phase Amplitude Information

Airborne vibration monitoring systems have traditionally focused on just the amplitude information corresponding to excitation from the main engine shafts. The benefits of utilising information from the full vibration spectrum are already known [1,6,9]. However, incorporating phase information, from the tracked order response, provides additional valuable diagnostic indicators. Experience has shown that apparent reductions in vibration magnitude may actually represent an increase in vibration levels within the structure due to the way the vibration response is measured. Hence, combining phase with tracked order amplitude response and monitoring for sudden step-changes in this derived vector is a key indicator for detecting anomalies within the engine [6,7]. However, it is also important to monitor for slow gradual changes in this vector response over time. Figure 4 shows how a model of normality could be represented for a given engine shaft order. It can be seen that the phase/amplitude response changes with engine speed as a result of change in frequency of shaft excitation. The model consist of derived error bands over the entire speed range of the shaft, but which vary in width according to the measure of normal deviation expected at different points of speed.

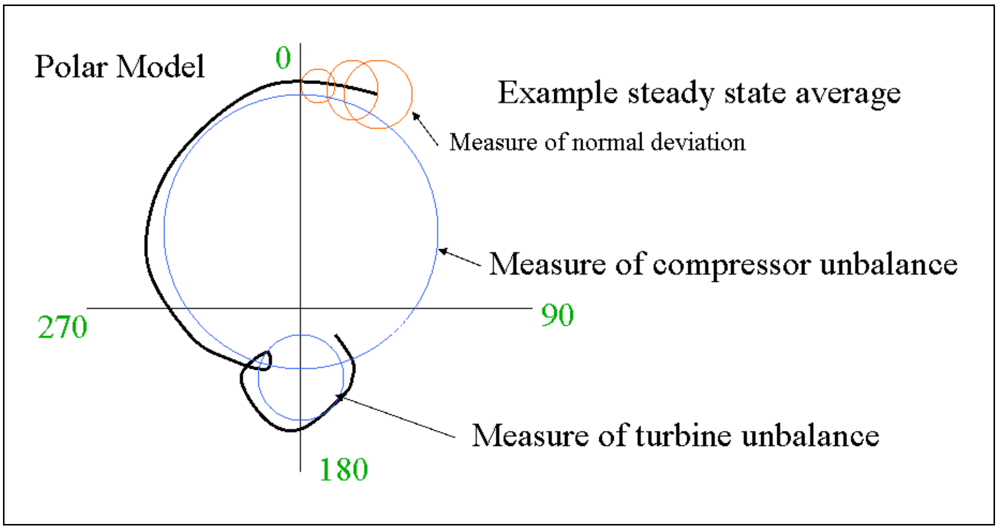

Figure 4 – Expected Phase/Amplitude Response over engine operating speed range

Novelty can then be determined when a measured vibration point falls outside a given set of error bars for a particular engine speed condition (see figure 5 below).

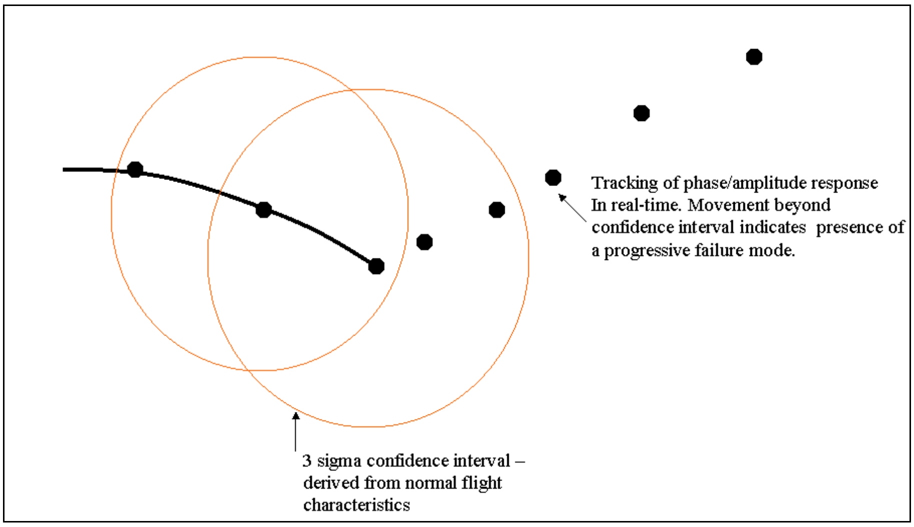

Figure 5 – Monitoring for gradual change in Phase/Amplitude Response

This approach therefore allows early detection of a progressive failure mode, such as the development of a crack in a fan blade.

CONCLUSIONS

This paper has discussed a range of advanced real-time monitoring techniques that can provide early warning of in-service events. The use of combustor temperature profile monitoring is considered a useful method for providing early warning of problems within the combustion system (e.g. injector blockage or cracks in combustor casing) and is therefore directly applicable for health monitoring of aero engines. The ability to detect changes in tracked-order amplitude/phase (sudden and gradual) is known to serve as a reliable indicator for foreign object damage and crack propagation in fan blades. Innovative utilisation of time-frequency analysis techniques applied to the carcass vibration signal have also demonstrated the ability of detecting on-set of cracks, and subsequent propagation, in rotor assemblies of the compressor systems [3] and is currently being evaluated for implementation on future engine products. Aerodynamic instabilities, such as fan flutter, can be detected using an airborne microphone and monitoring for novel features in the region of 1st flap vibration mode. Potentially, these same features may be detected within the dynamic pressure signal already available on certain engines. Previous work in this field [6,7] has also demonstrated our ability to detect bearing defects and other vibration phenomena using a combination of robust empirical modelling methods and embedded engineering rules.

In addition to developing techniques for real-time airborne monitoring, a number of novel data analysis methods have been utilised for processing data within an off-line environment. Methods such as principal component analysis have already been demonstrated [11] as a mechanism for providing effective two-dimensional visualisation of complex engineering data. We have also exploited neuroscale models [8] as a simplified mechanism for tracking changes in tracked order vibration characteristics of gas-turbine gearbox accessory components during service operation.

Current developments are focusing on incorporating a range of novel detection methods within the latest Trent family of engines. The design philosophy of this system is to fuse information from disparate domains (i.e. Fourier transformed vibration signals as previously discussed) with the temporal performance signal and hence provide an additional level of robustness to the monitoring system. Utilising engine performance signals, for the purpose of health monitoring, can be accomplished in several ways. Standard off-line analysis involves the use of exchange rate information which expresses the predicted percentage change of value in certain engine performance metrics (e.g. HP Compressor efficiency, IP Capacity, etc) that will give rise to expected changes in a set of actual engine performance measurements. Comparison of measured deltas between successive flights, at similar operating conditions, can then be used to explore the underlying causes of any large delta values (e.g. natural deterioration, flow leakage within the gas path, etc). Work is currently in progress to develop mechanisms for performing such analysis within the on-board monitoring unit, continuously in real-time, so that results can be fused with novelty scores from other feature detector modules, such as those described above, and hence provide in-flight prognostic capability.

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