INVITED PAPER

THE DEVELOPING FIELD OF INTEGRATED VEHICLE HEALTH MANAGEMENT

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Abstract

The goals that are being set for aviation growth in the near future, combined with the growth in service provision, are unattainable without active health management of airplanes. Numbers associated with door to door travel time and accident rates, coupled with availability demands to provide cost-effective transport, simply do not allow time for unscheduled maintenance. We are therefore going to experience a step jump in the take up of Integrated Vehicle Health Management (IVHM) on these platforms in order to give accurate warning of sub-system and component degradation, allowing for maintenance to be carried out in a timely, scheduled, manner.

This paper describes the development of IVHM, covering emerging services, standards, technology and IVHM as used in various industry sectors. This will lead to the commercial picture of today with the top level goals that are being set, providing the business push for technology and its adoption. Examples of research being conducted in the field will be shown, to support the claim that real progress is being made, with implementation of this technology on the horizon.

Introduction

To many the name Integrated Vehicle Health Management (IVHM) may be new but the concepts surrounding it are probably very familiar. From the automobile world, car oil is regularly checked for deterioration and metal chips, tyres monitored for correct inflation and radiator fluid checked to avoid overheating. These steps are taken to prevent unexpected failures, activate timely maintenance, and reduce the cost of ownership. IVHM applies the same logic to complex assets, producing an integrated view across the vehicle, for it is of no value to rigorously maintain one part of a vehicle only to have another fail.

Various definitions of IVHM exist. The one used in the SAE HM-1 committee (Jennions ed. 2011) is: The unified capability of a system of systems to assess the current or future state of the member system health and integrate that picture of system health within a framework of available resource and operational demand.

This, while scientifically accurate, is rather a lot to take in at first reading. The definition used at the IVHM Centre focusses on practical use and is: IVHM is an end to end capability that transforms system data into information to support operational decisions that results in:

- Minimized maintenance actions
- Improved readiness and availability
- Reduced redundancies
- Product life extension
- Improved vehicle safety and reliability
- Reduced environmental impact

hence creating real business benefit.

Either way, the intention is the same, to have an integrated view of system health in order that informed action can be taken.

Defined in this way, IVHM encompasses the fields of SHM (Structural Health Monitoring), NDT (Non-Destructive Test), and condition monitoring; more about this under the discussion of an IVHM framework later. It (IVHM) enables services such as CBM (Condition Based

Maintenance), Performance Based Logistics (PBL) and ALS (Autonomic Logistic Systems). While the concepts behind these service provisions are quite simple, their widespread uptake has proved quite elusive. CBM is aimed at monitoring the condition of all parts of a complex asset and maintaining the asset based on the information collected. In PBL, rather than specify that the asset should be maintained to a certain level, maintenance is delivered to attain a level of performance, usually expressed thought performance indicators. ALS takes these concepts to a new level through an analogy with the autonomic nervous system of the human body, which senses, controls and actions response to external stimulus. Here the airplane is monitored, diagnostics and prognostics run, and this information is (seamlessly) fed into service support for spares and maintenance provision. Currently the JSF (Joint Strike Fighter) is the only plane maintained in this way.

From this interplay of service offering and IVHM capability it can be seen that IVHM is an emerging and disruptive technology. Disruptive, as this new technology can enable a new service offering and create business value without changing the underlying product. It covers a very broad subject area, with very few experts and hence room for skill development as its industrial use grows.

There has been much progress in IVHM in the last 10 years: standards (SAE's IVHM Steering and HM-1 groups), books (Jennions, editor, 2011 and 2012), business modeling and technology; the latter two will be touched upon, and explored, in this paper. MacConnell (2006) conducted a review, along with a team from industry and academia in the USA, looking at the barriers to the take up of health management and its associated technologies in aerospace. It took a broad view ranging from mission availability to design and concluded that changing the culture was key in almost all of the areas studied. This may seem to be obvious as companies struggle with the shift from selling a product to selling a service, but should not be underestimated. Keller et al. (2012) report on a program, sponsored by the FAA and Boeing, to evaluate IVHM design in commercial airplanes. They present a number of conclusions, one of which is that IVHM is gradually being viewed as part of an overall, multi-use data and information system that supports the aircraft through its life cycle. To present a balanced picture, Esperon-Miguez et al. (2012a) discuss, in some detail, the problems associated with providing IVHM cover on a legacy military platform. They articulate the interplay between regulations and processes and the aspiration of optimal financial performance on a complex asset. Finally reference has to be made to the excellent Indo-US Workshop on IVHM and Aviation Safety held in Bangalore in Jan 2012 (see reference). The workshop outlined several promising ways in which to work together for mutual benefit over the coming years.

By the nature of the topic, and the fact that the IVHM Centre was set up in 2008 to advance this subject for its industrial collaborators, this paper is a view from the Centre. Most of the references are to work done in the Centre over the last four years, the references then leading the curious reader to a broader review of this subject area. The paper starts by examining the drivers for IVHM in some detail. A suggested framework for IVHM is then discussed and a number of examples from current research then given. The paper finishes with some concluding remarks.

Drivers: Why IVHM?

There are three separate ways to consider the drivers for IVHM. These are for safety, operational and economic needs. Each of these will be briefly visited in order to create the overall case for IVHM.

Table-1 shows a five year picture (1998-2003) of events, including SCFM (System / Component Failure / Malfunction) events, the events that are thought to be avoidable using IVHM, from Reveley et al. (2010). Part 121 operation refers to major airlines and cargo carriers, while Part 135 refers to commuters (greater than 10 seats). This latter category is further split into either scheduled or nonscheduled (time negotiated with customer). Accidents refer to those events in which a person suffers death or serious harm, or where the aircraft is substantially damaged, while incidents refer to events that affect, or could affect, safety of operation. Examining the Part 121 column, the total number of accidents seems remarkably small compared to the miles flown. However 36% of fatalities and 66% of incidents could have been addressed by IVHM. This is the safety standard currently demanded by the flying public and any further increase in air miles would result in a growing number of events and the publicity surrounding them. Therefore, in a world of increasing thirst for air travel, the actual percentage of events has to be reduced and, given the above, one way of addressing this is IVHM. This line of thought gave rise to the NASA IVHM program (Srivastava et al, 2009).

Recent Airbus figures, from AeroTech 2011, predicted a 4.8% growth per year in civil aerospace for the next 20

Table-1 : Summary of SCFM Events by Operation Category

Type of Event	Operation		
	Part 121	Scheduled Part 135	Non-scheduled Part 135
Total flight hours	232,868,640	25,050,928	46,350,000
Total accidents	600	213	1070
Accidents with SCFM	109 (18.2%)	33 (15.5%)	228 (21.3%)
SCFM accidents per million flight hours	0.468	1.317	4.919
Fatal accidents	60	49	278
Fatal accidents with SCFM	16 (26.7%)	5 (10.2%)	47 (16.9%)
Total fatalities	2151	328	664
Fatalities in accidents with SCFM	777 (36.1%)	52 (15.9%)	109 (16.4%)
Total incidents	7497	2218	2081
Incidents with SCFM	4957 (66.1%)	1557 (70.2%)	1218 (58.5%)
SCFM incidents per million flight hours	21.29	62.15	26.28

years. Considering that the 9/11 tragedy is only just over 10 years ago, and that resulted in an over capacity of 1,000 aircraft in the world in 2002, in 2012 it's expected to be 1,000 under capacity, emphasising the remarkable growth in the sector. It is predicted that some 4,500 aircraft will be replaced in the next 20 years. The targets set by Flightpath 2050 (see reference) reflect an equally positive view of the market:

- 90% of travellers, door to door, anywhere in Europe in less than 4 hours
- Fewer than 1 accident per 10M flights. This figure is one third of the accident rate observed by Reveley et al. (2010), see above.
- Air Traffic Management will need to handle 25M flights/year

Against these operational demands, the necessity for IVHM is overwhelming. To achieve the door to door time it will not be acceptable for a plane to be delayed at a gate because the cause of a problem is not known. The situation will demand the unequivocal location of a faulty LRU (Line Replaceable Unit) so that it can be replaced and the aircraft get underway. It will also demand a movement from accurate diagnosis of a fault, with fault forwarding so that the aircraft can be repaired on the ground, to prognostics where the required repair is known for some time in advance and maintenance booked when convenient for the operator and maintainer.

The last class of requirements for IVHM stems from the need to run an airline in the most economical way possible. With the push on all airlines to meet KPIs (Key Performance Indicators) for on time departure and arrival there has been the tendency to insert a small amount of reserve time into each scheduled flight in order that the flight achieves its KPIs. The problem is that if a plane is used on a number of short haul runs during a day, this extra time adds up and can amount to the time for another flight in the same day. Delta estimated the cost incurred in this way to be $385M per year. In order to remove such added time from the schedule, accurate information must be available about the aircraft's state so that swift action can be taken to catch any potential failure before it occurs; IVHM is necessary to inform this process.

Framework for IVHM

In order to express the breadth of IVHM, the taxonomy used in Figure 1 was devised when the IVHM Centre was started in 2008. It has proved extremely useful in explaining what this new field covers and what it does not cover. Under IVHM are a number of themes (Business, etc), eight in total. Moving from left to right, the impetus for IVHM is firmly seated in the move to provide services, with those examples shown. For a product company to consider IVHM is hard to imagine. They would be giving away the means by which to access the assets behavior in service and hence the ability to maintain it, with the associated revenue. Next there is a creation phase. Here the overall business case for IVHM is formulated, and examined against legislative and regulatory requirements. The overall architecture and system are designed.

The next themes are in technology. One observation is that we have a lot of technology on the shelf, but to bring it to market in the services shown, those areas under the creation phase require work, both to articulate the technology benefit and package it in a suitable end to end system. Finally there is a need to support those systems in operation. Demonstrators also play a role in the overall picture. Small scale demonstrators are a good way of understanding the fundamental problem and working up a solution. This provides a good understanding of the underlying physics, that can be challenged as the solution is exposed to industrial rigs or real world assets.

The Centre has worked in most of these areas over the last four years. Some examples are given in the following references:

- Business case development: Fan et al, 2011a
- Esperon-Miguez et al, 2012b.
- Systems design: Fan et al, 2011b.
- Architecture: Sreenuch et al, 2011, 2012.
- Diagnostics: Gelman et al, 2011.
- Prognostics: Eker et al, 2012.
- Electronics: Bhambra et al, 2011.
- Energy Harvesting: Giuliano et al, 2012.
- SHM: Gagar et al, 2011.
- Demonstrators: Niculita et al, 2012.

In order to illustrate this work a few selected examples are illustrated in the next section.

Research Examples

Simulating Warrior Armoured Vehicle Logistics

Logistics is a significant function in any organization, focusing on two main goals: maximizing availability and minimizing cost. Logistics management controls many important aspects in a business such as inventory level, delivery period, due date, reliability and high capability utilization. Applying this concept to the defence sector, military logistics management is considered by defence to be the key to success in many situations. Therefore, a number of methods have been applied to support operational and strategic decisions to achieve the optimum balance between availability and cost. One of these methods, called agent base simulation (Matar, 2012), is demonstrated here.

This simulation concerns the Warrior IFV (Infantry Fighting Vehicle), Fig.2. The main role of the IFV is to carry troops, under protection, to the objective and then give firepower support when they have disembarked (The British Army, 2009). Fig.3 illustrates the division of 400 Warriors divided into 4 fleets (each containing 100 Warriors) through a period of 25 years. While the numbers used in this simulation are taken from available public data, the overall scenario and results are thought to be quite close to a real business evaluation.

This work was done in conjunction with Aerogility (see reference), a company that has produced a specialised agent platform which they further customized for this scenario. The overall logistics viewpoint taken is shown in Fig.4, in which the IFV is considered to have 4 master parts (each of 2 types). These produce a configuration that forms an asset in one of the four fleets. Each fleet is then operated and maintained from its assigned base, a warehouse existing in each of the deployed countries. Each entity in Fig. 4 is modeled as an agent, having a set of rules to obey during the simulation.

The models are populated with realistic data, the complexity of which is chosen to match the questions being asked of the simulation. In this way the simulation behaves in a very intuitive way and is easily checked for validity and extra rules added if needed. The simulation can be run in a number of different ways. Here it was used to examine two key questions: i) with a given level of stock how should it be distributed across the different warehouses, and: ii) for a given level of availability what stock is needed. Particularly the second of these two questions is not an easy task to answer but, with agent modeling, it is relatively straightforward.

There were many outcomes from this work but, just to show one, Fig.5 shows the costs incurred at each warehouse during the 25 year scenario. Initially the Afghanistan warehouse is consuming more parts, and higher cost, with respect to the training operations going on in the UK. The Middle East deployment then shows high cost for the next 10 years, before a training period that uses parts from the UK warehouse. Scenarios such as those shown here can provide a very rich background against which to make operational decisions. What ifs are straightforward and modeling the behavior of any entity in the simulation, by adjusting the rules, is seen as a major future area when cultural changes are needed in an organization.

Localising Unbalance Faults in Rotating Machinery

Unbalance is one of the most commonly occurring faults in gas turbines. The localization of such faults is a relatively little studied topic, with industry often resorting to 'rules of thumb' in order to identify the position of unbalance in complex systems. A system capable of accurately localizing faults in rotating machinery has the potential to reduce machine downtime, along with the associated costs. In this work, the localisation of unbalance faults is detailed through the use of high-fidelity, and reduced order, simulations. Alongside this, an Artificial Neural Network (ANN) has been trained to localise unbalance in a rotordynamic test rig.

Recent research into unbalance faults in rotating machinery (Walker et al, 2012) has taken place in both simulation and data-driven forms. Whilst both approaches have clear advantages, the continual need for experimental validation and verification combined with the power of modern simulation packages results in the need for a synergy between both domains when considering such problems. With this in mind, the localization studies in this research are based upon a Machine Fault Simulator (MFS) from Spectraquest. This enables a wide range of rotordynamic faults, including inbalance, to be studied in a lab-based environment.

The subject rig for this research can be seen in Fig.6, along with a high-fidelity FEA model of the disk-shaft-bearing arrangement. Validation of the FEA model was performed through industry-standard impact testing.

The FEA model has been used in order to predict the performance of the MFS, through the use of Campbell diagrams and transient analysis, amongst other simulations. Building upon the research conducted for this, reduced order Matlab / Simulink models have been constructed and analysed in the time domain, with the intention to simulate the effect of unbalance position on the sidebands of the system. Model order reduction was performed in this case through the application of Craig-Bampton reduction using Structural Dynamics Toolbox. An example transient (run-up) analysis can be seen in Fig.7, alongside a portion of the reduced order model.

At time of writing, simulation work is on-going, with the intention of using the simulations for the purposes of adapting the ANN observed experimentally on the MFS for use in other machinery as this approach enables flexibility in the adoption of such a localisation technique.

Experimental studies have been based upon a four-rotor MFS, with localisation performed between these four unbalance conditions. An ANN has been trained in order to classify between these unbalance conditions, through the study of 1/3 (subsyncronous) features in the frequency domain. This can be observed as the first peak occurring in Fig.8.

This phenomenon is believed to occur due to the three-phase electric motor used in the MFS. However, such nonlinearities are known to appear through other machine characteristics, including from bearing points. This knowledge potentially enables the localisation of unbalance through sub-synchronous feature study for a variety of rotating machines. The resulting ANN displays a high level of accuracy for the case of the MFS, as displayed in Fig.9.

Future work in this area will be concentrated on adapting the system successfully developed for the case of the MFS to other rotating machines. Initially alternate rotordynamic test rigs will be examined followed, potentially, by gas turbine testing. The indications from the study to date are that sub-synchronous features in the frequency domain enable accurate unbalance localisation for the purposes of improved maintenance procedures.

Investigation of AE Generation from Fatigue Cracks for SHM in 2014 Aluminium Alloy

Acoustic Emission (AE) generation in 2014 aluminium coupon sheets with a Single Edge Notch (SEN) and under constant amplitude loading was investigated by Gagar et el. (2012). The rates of AE signal generated during fatigue crack propagation were monitored and 3 stages were observed as illustrated in Fig.10. Stage 1 is characterised by increasing and then decreasing rates of AE activity at crack lengths of 12-19 mm, followed by small almost constant rates of AE emission in the next stage (Stage 2) and an increase in AE just prior to failure in the final stage (Stage 3). The proportions of these three stages observed in other identical tests are shown in Fig.11 with Stage 2 occupying a significant duration of the samples fatigue life.

The recorded AE data during the tests were correlated with applied load and the results for one of the tests is illustrated in Fig.12. It was observed that the vast majority of emissions at early crack lengths occurred at about the middle and lower portions of the loading range which suggests that they may be associated with crack closure.

The implications of these results on the use of the AE technique for continuous health monitoring applications are that there appears to be periods of reduced opportunity to detect the fatigue crack. The greatest opportunity for detection lies in Stage 1 where the highest hit rates were observed. Also, the reappearance of the emissions in Stage 3, after a prolonged absence in Stage 2, was for a very short period of the samples fatigue life and fatigue crack detection in such instances may not be useful as it most likely would not allow for sufficient time to react in terms of maintenance actions.

Concluding Remarks

The major conclusions drawn from the paper are given below.

- Given the challenging goals that the aerospace business is facing, IVHM will be both an enabler and, continue to be, a disruptive technology. This paper has demonstrated the value of IVHM on safety, operational and economic grounds.
- There now exist standards bodies that are addressing IVHM. This will move the field forward and, as it does so, certification will be addressed.
- Striving for a business case may prove to be an excuse for inactivity. It can already be seen that those that embrace this technology, aligned to growth in service provision, have been amply rewarded.
- This paper examined three specific research areas. One demonstrated the use of simulation to construct usable business models, while the other two demonstrated areas of technology. Localisation inbalance in a rotating machine is both complicated and rewarding, in that the resultant vibration can be reduced once the source is known. The final example of SHM shows part of the research being conducted into the detection of acoustic emission for crack growth. There is still a long way to go with this research until it is used to on a commercial airplane but the rewards will be high.

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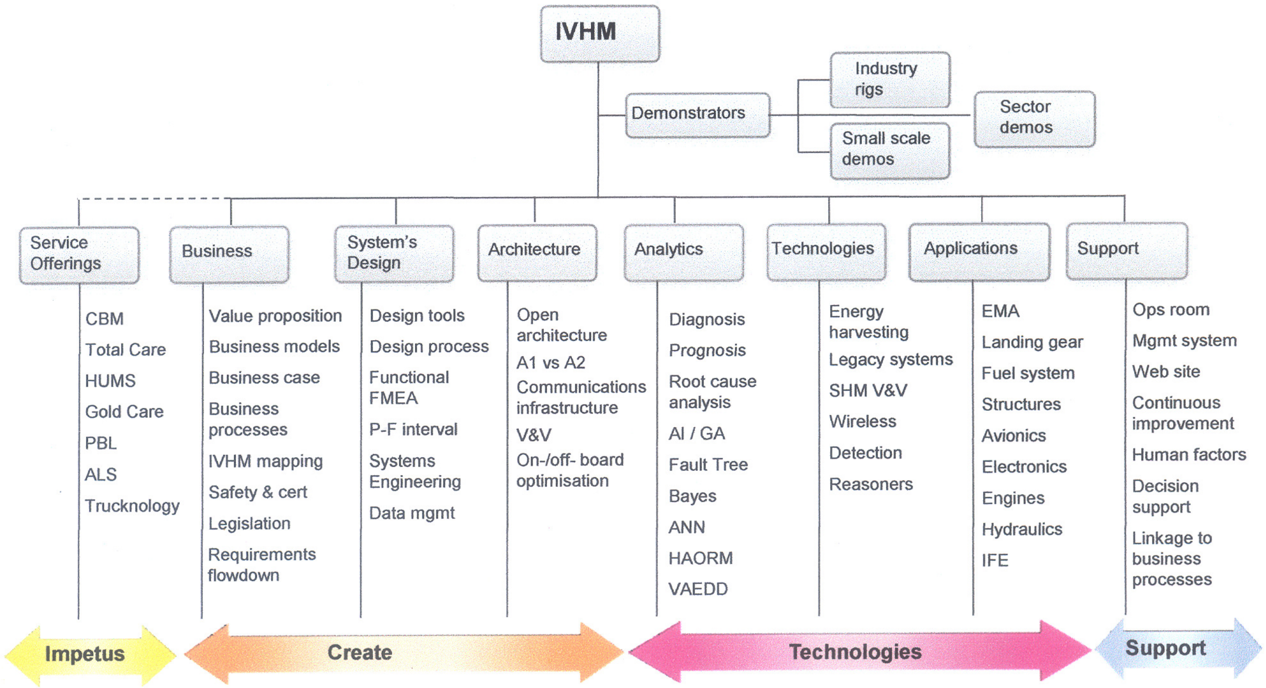

Fig.1 IVHM Centre Taxonomy

Fig.2 Warrior Armoured Vehicle

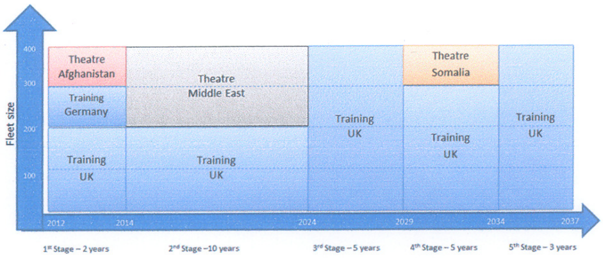

Fig.3 Warrior - Scope Considered

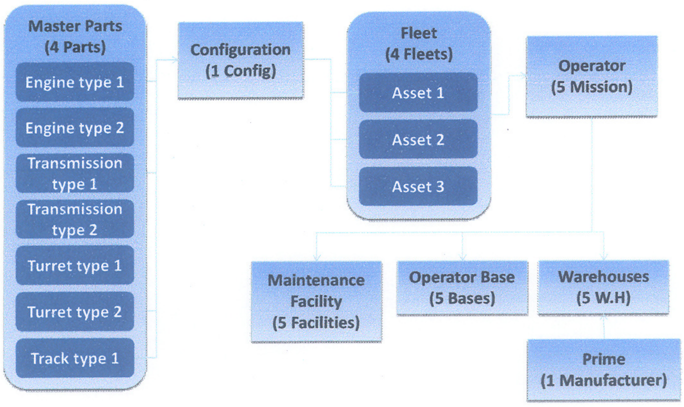

Fig.4 Logistics Viewpoint for the Warrior Simulation

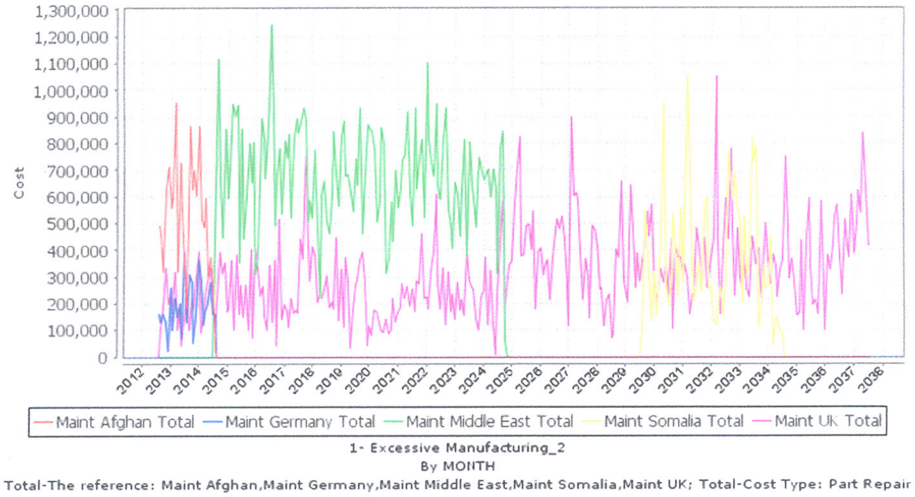

Fig.5 Cost Incurred Across the Overhaul Bases

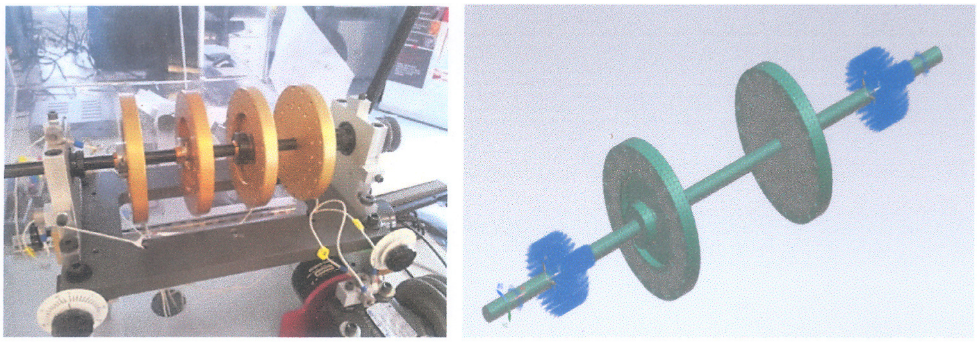

Fig.6 Spectraquest MFS and Nastran NX FEA Model

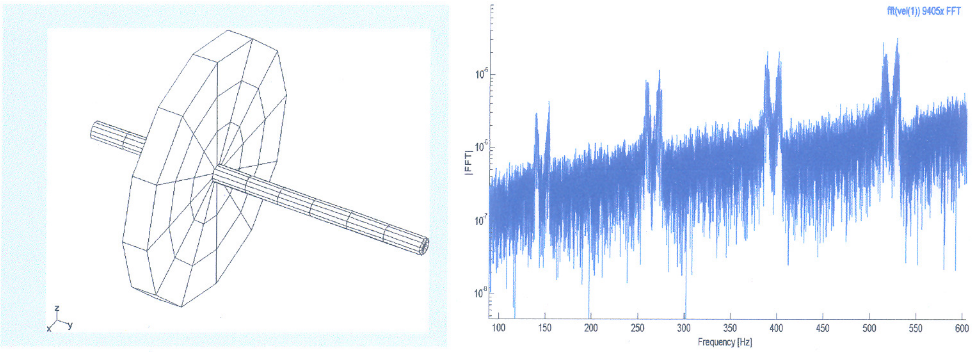

Fig.7 Reduced Order Model and Transient FFT

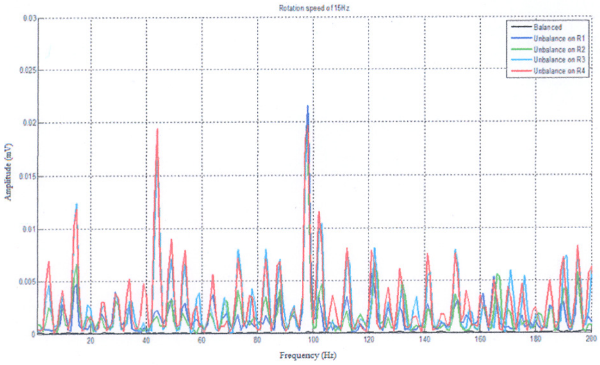

Fig.8 Frequency Spectrum for Unbalance Localisation Cases

Rotor Condition	Rotor 1	Rotor 2	Rotor 3	Rotor 4
5.0g (Minimum)	45%	45%	50%	55%
7.0g (Light	90%	100%	100%	100%
8.3g (Standard)	100%	100%	100%	100%
10.1g (Heavy)	100%	100%	100%	100%

Fig.9 Accuracy of ANN for Unbalance Localisation at 15 Hz

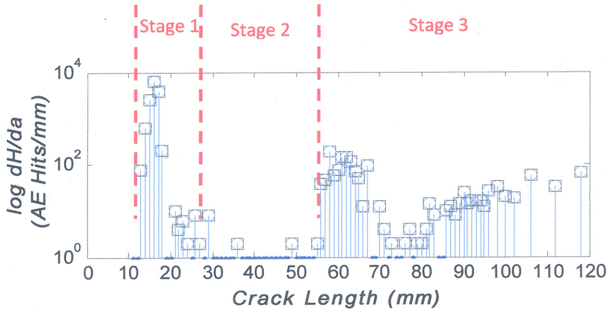

Fig.10 AE Hit Rates per mm of Crack Growth for SEN Coupon Sample

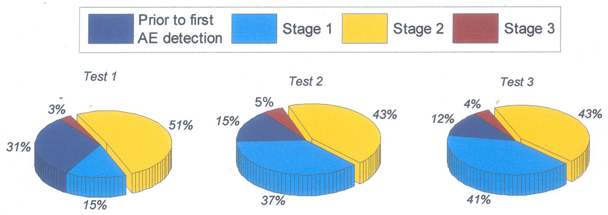

Fig.11 Proportions of Fatigue Lives for Observed Trend in AE Generation from Fatigue Crack

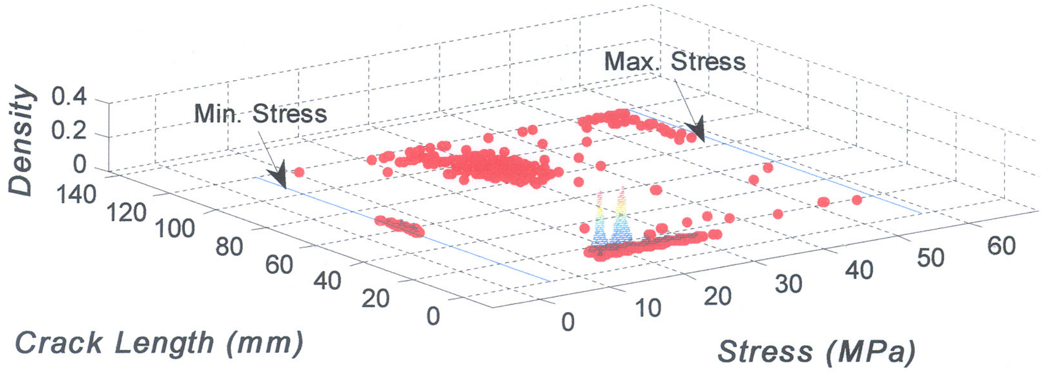

Fig.12 AE Hits Distribution with Applied Stress Over Increasing Crack Lengths