

**DSTO International Conference on
Health and Usage Monitoring,
February 19-20, 2001**

Editor: Graham F. Forsyth

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DSTO International Conference on Health and Usage Monitoring, Melbourne, February 19-20, 2001

Editor: Graham F. Forsyth

**Airframes and Engines Division
Aeronautical and Maritime Research Laboratory**

DSTO-GD-0262

ABSTRACT

The concept of On-Condition Maintenance implies the need for Condition Monitoring to close the loop. Condition monitoring may be implemented at many levels requiring various degree of complication.

As relatively fragile machines with catastrophic outcomes possible for many failure types, aircraft have always used some degree on monitoring. Recently, engines, mechanical sytems and airframes on both fixed-wing aircraft and helicopters are being fitted with permanent monitoring systems. These systems are also becoming more integrated to the extent that some are now called "Health and Usage Monitoring Systems" or HUMS.

Following a successful conference in February 1999, DSTO have again sponsored an International Conference on Conference on Health and Usage Monitoring in conjunction with the Australian International Airshow in February, 2001.

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1. Introduction

The maintenance of critical production machinery can follow a number of paradigms. Over the last twenty years, the concept often called "on-condition maintenance" has become widely used. OCM involves using some degree of monitoring to predict when maintenance is needed rather than simply performing maintenance at fixed time intervals. The savings arise from reduced and more targeted maintenance, reduced in-service failures and a reduction in stored spare parts. The costs are inherent in the monitoring used.

Machinery used in large industrial plants will often use a combination of timed maintenance and OCM, where annual or biennial timed maintenance occurs during seasonal plant shutdowns and the plant is maintained between these major overhauls using OCM.

As relatively fragile machines with catastrophic outcomes possible for many failure types, aircraft have always used some degree on monitoring. However, that monitoring was seldom fully integrated into the maintenance support program. That situation is changing with engines, mechanical systems and airframes on both fixed-wing aircraft and helicopters now more likely to be fitted with permanent monitoring systems. These systems are also becoming more integrated to the extent that some are now called "Health and Usage Monitoring Systems" or HUMS.

During 1996, the concept of a workshop to discuss application of this HUMS technology to military helicopters was proposed. After discussions with possible participants, the scope was widened to include application to fixed-wing aircraft of interest to the Australian defence Force (ADF) and to civil helicopters where the technology was likely to flow on to military helicopters in due course. As well, the event was scheduled to co-incide with the Australian International Airshow at Avalon.

In February 1999, that conference, still referred to by the name "HUMS Workshop" attracted over 140 participants with 40 of those from overseas including 18 overseas speakers. The two-volume proceedings of that event, "Workshop on Helicopter Health and Usage Monitoring Systems, Melbourne, Australia, February 1999", Graham F Forsyth (Editor), DSTO-GD-0197, February 1999, have been widely distributed as well as being reprinted, published electronically and produced as a CD-ROM.

The success of the 1999 event has led directly to the conference for which these are the Proceedings. HUMS 2001, the DSTO International Conference on Health and Usage Monitoring will be held at the Duxton Hotel, 328 Flinders Street, Melbourne, on the 19th and 20th February 2001. It will be affiliated with the Australian International Airshow to be held from the 13th to 18th February at Avalon.

As well as those formal papers appearing herein, a copy of this document and of conference presentations will also be published and supplied to attendees as a CDROM.

2. Acknowledgments

HUMS 2001, the February 2001 DSTO International Conference on Health and Usage Monitoring, has been organised by a committee comprising:-

Graham Forsyth	Convenor
Neil Kennedy	Representing RAAF Williams
Brian Rebecchi	Machine Dynamics
Ben Parmington	Applied Combustion
Joanna Kappas	Mechanical Integrity
George Karvounis	Engine Performance
Soon-Aik Gan	Helicopter Structural Integrity

As well, a number of other people (including Lisa Torrance and Barry Browne on the financial side, Jane Babbage and Karina Clement for the webpage) contributed directly.

A number of firms were contracted to assist; this included the conference venue, Duxton Hotel Melbourne, the dinner venue at the Melbourne Zoo and ICMS Ltd who were contracted to perform the registration process.

3. Conference Sponsors

In practise, it becomes extremely difficult to run a conference without sponsors. Sponsors provide the money which allows venues to be booked and arrangements to be made months before conference participants have registered and paid. We are fortunate to have seven sponsors whose involvement made this conference possible.

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4. PARTICIPANT PAPERS

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Not all papers presented at the conference are included in this document. Those included are in the order in which the papers became available rather than any indication of timetable placement, priority or preference.

The Development of an Expert System for Wear Debris Analysis

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ABSTRACT

Oil analysis technique has been viewed as an effective means to monitor the condition of a machine in some industries. However, wear particle analysis, the key component in oil analysis, has not been extensively applied in practice with its maximum economic benefit due to the requirements of extensive analyst's experience and time involvement of current techniques. It has been widely recognised that application of computer assisted analysis techniques and artificial intelligence technologies in wear debris analysis can significantly overcome the limitations. On the basis of the previous development of automated particle analysis and identification systems using numerical descriptors this project is a further work to develop an expert system. The aim of this project is to develop an artificial intelligence system to interpret comprehensive data obtained from the developed particle analysis system for machine condition monitoring. This paper presents the developing procedure, system functions and advantages of the expert system.

INTRODUCTION

Since 1983, the year when wear particle analysis was practically applied in industry in UK, especially in aircraft and marine industries, the techniques have been further developed and recognised as a valuable means to assess wear condition of operational equipment [1]. More and more commercial instruments have been advanced to provide a more objective and reliable assessment of particle number, size, colour and other characteristics to indicate the condition of a machine. The process is, however, cumbersome and time consuming especially when individual wear particle needs to be examined to reveal wear modes and severity of wearing condition. To speed up the process and also to reduce the analysis cost new generation techniques to study wear debris are been developing with the amazing development of computer technologies [2,3].

Computer assisted particle analysis is, no doubt, a current trend of wear debris analysis for machine condition monitoring and fault diagnosis [3,4,5]. Four major steps are normally involved in the particle analysis using this technique. They are: (i) particle separation and preparation, (ii) digital image acquisition, (iii) particle characterisation, and (iv) particle identification.

Among them, acquisition of an appropriate digital image of a particle is a crucial process. It is worthwhile to mention laser scanning confocal microscopy (LSCM) here as the technique makes it possible to obtain appropriate digital images for three-dimensional (3D) study [6]. Another advantage of the system is that, compared to scanning confocal microscopy, it requires an easy and economic sample preparation procedure [6,7]. The LSCM technique has been used in this study to obtain 3D images of wear debris. A group of numerical criteria

have been developed to characterise distinct features of six major types of wear debris, i.e., rubbing, cutting, spherical, laminar, fatigue and severe sliding particles [8]. As a result of the project, the boundary and surface morphologies of a particle can be examined using the developed 3D image analysis system called Tribologica. The numerical result is generated and displayed on a spreadsheet or a text file in less than one minute [9]. The next step, logically, is to develop an automatic debris classification system based on the previous analysis results [10]. A neural network, multi-layer perceptron, has been successfully applied to perform the task [11].

How to interpret the analysis data to assist machine condition monitoring is the main focus of this paper. An expert system appears to be the best choice because it can simulate human experts to conduct certain complicated tasks [12]. This technique has been successfully applied in many areas including fault diagnosis for mining machinery [13], aircraft condition monitoring [14] and other applications in engineering [15, 16]. This paper presents the development of an expert system to detect the condition of gearboxes using wear particle analysis results.

EXPERT SYSTEMS

What is an expert system and its advantages

"An expert system is a computer system which emulates the decision-making ability of a human expert" [12]. From this definition it is clear that an expert system has great potential in many applications. Compared to human experts, an expert system often has outstanding advantages, such as reduced cost, permanence, multiple expertise and increased reliability. Basic components of an expert system are shown in Fig. 1 and also listed out in the following texts.

- Knowledge acquisition facility to allow the user to enter knowledge in the system;
- User interface through which the user and the expert system communicate;
- Knowledge base which are rules with conditions and conclusions;
- Inference engine to make inferences by deciding which rules are satisfied based on facts;
- Database or facts to store analysis data.

Development procedure

For utilisation of the expert system technology in a real world application it is common to develop an expert system using a commercial expert system shell. An expert

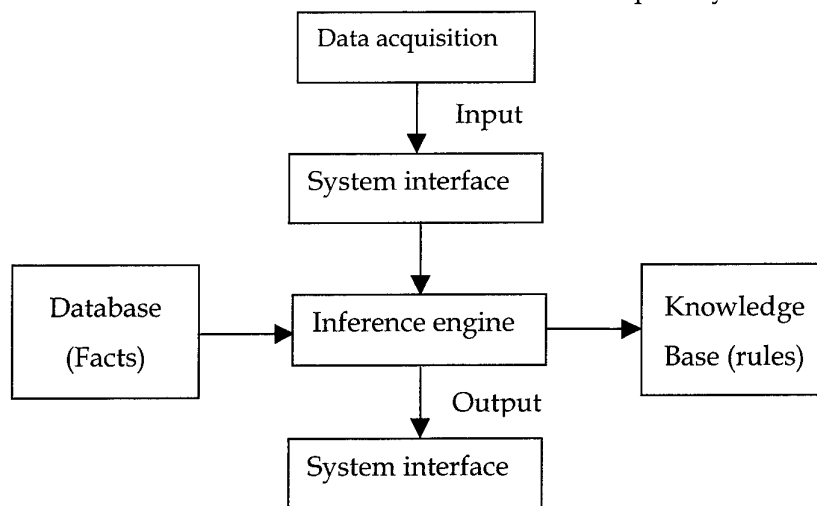


Fig. 1 The schematic diagram of an expert system.

system shell normally provides a platform for the users to develop their particular application system. There are four main steps in developing expert systems after a suitable expert system shell or platform is selected.

Step 1: The development of a knowledge base based on expert experience. This step is the key phase in the development of the expert system as the accuracy of the system's performance depends on the quality of the knowledge base. Therefore, a large amount of survey and interview work needs to be conducted to make sure the information collected for the development of the knowledge base is accurate and reliable.

Step 2: The development of a database to store facts used by the rules.

Step 3: The development of an interface to communicate between the user and the system. This might be the most time-consuming work in the whole system development when a sophisticated high-resolution, bit mapped interface needs to be developed. The development involves the design of the interface and programming to accomplish the design in the expert system shell or other computer languages which the expert system shell can be embedded into. After the interface is properly developed, the user can "tell" the system current conditions or analysis results of wear debris through the interface, and "ask" the system to draw conclusions of machine condition and explain how results are derived.

Step 4: Trial and modification. After a prototype is designed and completed, it is always necessary to test the system with sufficient examples and certain known outcomes. If the system has to be further developed or modified, the developer may need to go back to Step 1 and redevelop the system until it is tested to be functional and reliable for the application.

Applications of expert systems

As it mentioned before expert systems have been widely applied in many areas such as medicine, business, agriculture and engineering. Focusing on engineering application, Prof. Kuhnell with his colleagues in the Centre of Machine Condition Monitoring (CMCM), Monash University has successfully developed expert systems to diagnose turbo-machinery faults and automobile engine faults [15,16]. Expert system technique has also been proposed to use or has been used in oil analysis [17], debris analysis for machine condition and fault diagnosis [14,18]. The overview of current application of expert systems in machine condition monitoring can be referred to Basu's paper [13].

The application of expert systems in wear debris analysis for machine condition monitoring and fault diagnosis will eventually result in extensive and efficient utilisation of wear debris analysis technique in industry as it will significantly reduce capital cost of condition monitoring and maintenance management. However, the existing systems are, so far, not mature to be popularly applied in industry. The systems often need human analysts to examine wear particles manually and to provide wear particle analysis information to the systems using oral descriptions. Hence, the existing expert systems may suffer the same problems, that is, they are subjective, costly and time consuming, as the current analysis methods because the procedure of wear debris analysis still heavily relies on human involvement and experience. This project is therefore to develop an expert system on the basis of the automatic particle analysis and identification systems developed in the previous projects to significantly and effectively reduce the requirements of human involvement and expertise in wear debris analysis.

THE EXPERT SYSTEM FOR WEAR PARTICLE ANALYSIS

As it was stated before, the foundation of the expert system is the automatic particle analysis system advanced in the previous studies [8, 10]. Figure 2 shows the essential components of the expert system, and the relationship between the analysis system and the expert system. The expert system consists of a database storing particle analysis data, a rule/knowledge base to contain analyst's and maintenance personnel's knowledge, an inference engine to perform the task (usually using IF-THEN structure), and an interface to obtain input data and display results of the system.

Wear debris analysis - Database

The current version of the expert system uses the following particle analysis information to detect the wear state and the condition of machinery:

- Group information on particle analysis. This includes a total number of particles presented in the oil samples and percentages of particles in four size ranges, i.e., less than 10 μm , between 10 μm and 20 μm , between 20 μm and 100 μm , and greater than 100 μm . The information indicates the general particle condition. The large number of particles presented in oil and high percentage of

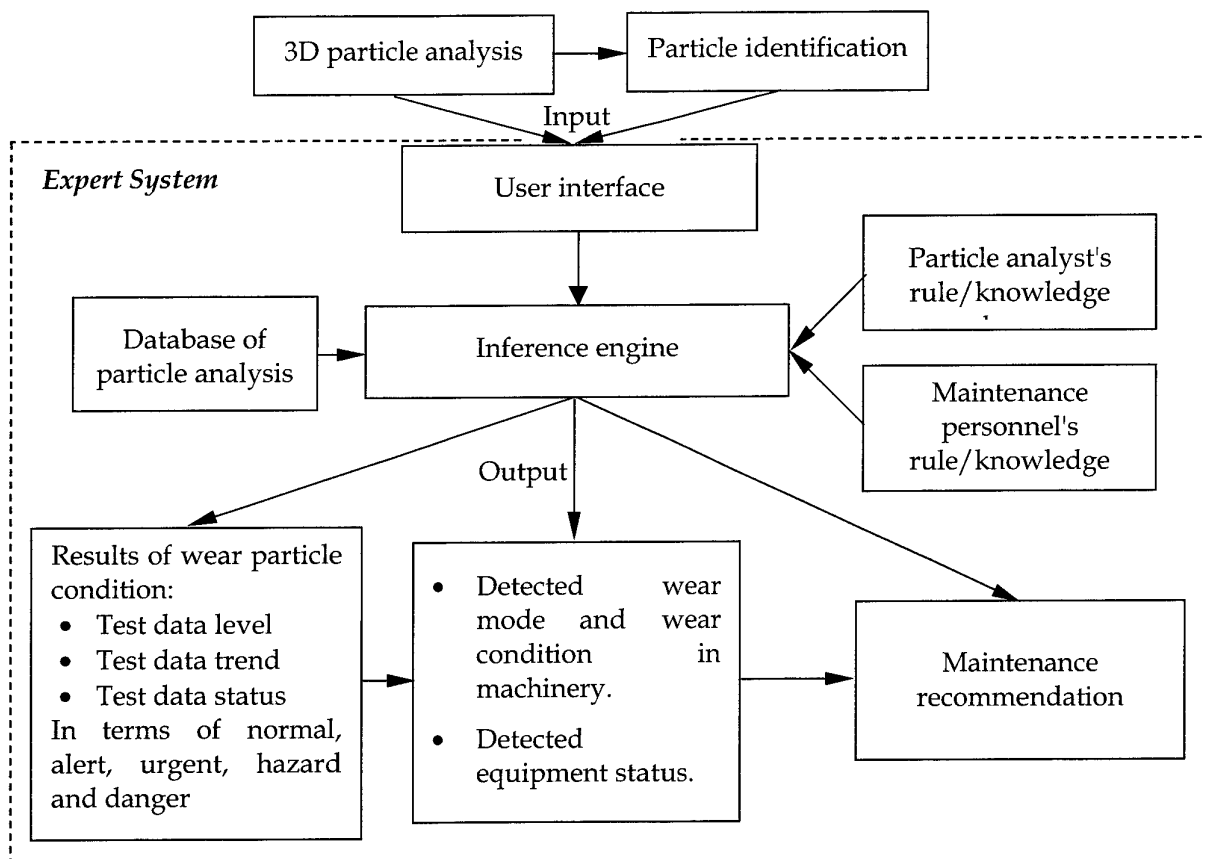


Fig. 2. The diagram of the expert system using wear particle analysis for machine condition monitoring.

particles in large sizes reveal a severe particle condition and may further expose abnormal wear condition undergoing inside the machinery.

- Individual particle analysis data. The data acquired in this part is composed of types of particles detected from lubricants, total number of particles in each type, percentage and size distribution of particles in each type. This information is in practice usually obtained by examining wear debris under a microscope by a trained person, which makes the process costly and very slow. Here a fully computerised particle analysis and identification system is applied to acquire this data [8,11].

First, a series of appropriate 2D digital images of a wear particle are acquired from a laser scanning confocal microscope after the solid particle is separated from lubricating fluids. 3D image of the debris is reconstructed for the analysis. The analysis system further developed in Optimas is then used to isolate the particle from the background, enhance the image and perform analysis to characterise the boundary and surface characteristics. Finally the analysis results are exported to a spreadsheet or a data file for particle classification [9]. The numerical parameters which have been developed in the previous study to describe distinguishing features of the six types of wear debris are: Area, Length in major dimension, Roundness, Fibre ratio, Fractal dimension, R_a , R_q , Height aspect ratio and the spectral moment [8]. The values of the parameters are then imported into the neural network trained to classify an unknown particle into the six types (rubbing, cutting, spherical, laminar, fatigue and severe sliding particles) [11]. After particles in the oil sample are classified, further statistic

analysis is conducted to count a total number of particles, to measure particle size distributions and to calculate percentage of particles in each type.

- Other information. In this version of the system visual inspection of any dark oxides and dust presented in the oil samples are used in the system to assess degraded levels and dust contamination levels of the lubricant. Meanwhile, the comparison between the current particle analysis data with the results of history analyses is also conducted to assist to track a wearing trend.

Particle analysis data and the condition of a machine

Four distinct wear conditions and machine conditions are considered in the system.

Condition 1: Being in a normal particle and machines condition when small amount of particles presented in small sizes. In this case, majority particles are usually rubbing particles resulted from flaking of pieces from mixed shear layer [3].

Condition 2: Starting to wear out with elevation of medium size particles. Further examination on particle types and size distributions may help to identify wear modes and sources, e.g., from contamination or lubricant degradation. Sub-conditions can be catalogued accordingly.

Condition 3: Being in a severe wear out condition with rapidly increasing large amount of particles or large sizes of particles in the oil. Usually the number of wear metals and the size of particles rises sharply when the condition of a machine becomes worse. The particle condition is abnormal in this case. Spectrometer analysis may help to locate a worn position. It is often recommended to conduct urgent inspection of machinery to identify and rectify problem followed by an oil change and complete

system clean if the wear out phase is identified using wear debris analysis.

Condition 4: Oil contamination while particle and machine are in normal condition. Examination of the level of oxides and oil colour can reveal oil contamination. Oil change is often necessary to avoid any second damage to machinery.

Knowledge base (Rules)

The expert system uses rules to simulate the thinking process of an expert. Here the IF-THEN structure is used to allow for execution of a set of actions based on certain conditional. The syntax is:

```
(if <condition>
    then
        <action>
    [else
        <action>])
```

The <condition> on IF side is the examined particle conditions which have been outlined in the above section. The <action> on THEN and ELSE sides is the detected condition related to wear state and machinery or/and maintenance suggestion. Below is one example of the rules.

Example

```
If
    Machine-type = Gearbox;
    Major types of wear debris = rubbing
    & cutting particles;
    Percentage of cutting particles in solid
    particles >20%;
    Size range of cutting particle = 10 µm
    ~ 50 µm;
    Particle contamination level = None.
Then
    Machine condition: Machine is in an
    abnormal condition with a possibility
    of misaligned parts.
    Possible problem: Large amount of
    cutting particles is likely due to the
    misaligned components.
```

Recommendation: Inspection is highly recommended as soon as possible to rectify the problem.

The interface of the expert system

The expert system has been developed in CLIPS which was advanced by NASA, Johnson Space Centre [12]. The advantages of using CLIPS are portable, quick and low cost. The limitation of CLIPS is that it doesn't support a graphics interface. The first interface developed in this project is a plain text input/output in DOS environment. In order to develop a user-friendly interface for this application, CLIPS has been embedded into C++ so that the powerful functions of C++ can be utilised to develop an interface for the user to communicate with the system easily. An graphics window based interface is being developed for the expert system.

DISCUSSION

There are certain distinctive advantages of the expert system for wear particle analysis.

- (1) The foundations of the expert system are fully computerised particle analysis and identification systems. Therefore, from the starting point, the system has overcome the limitations of the existing expert systems which are based on human inspection.
- (2) The system can provide more objective and reliable results than human analysts once it is well-developed. Furthermore, the system can be used as a general training system for a new particle analyst to interpret wear debris analysis results.

Like other systems developed in a laboratory, the expert system needs to be further developed for practical application. Future work includes: (i) to fully test the expert system using industrial examples, and modify the system if necessary, and (ii) to

develop the interface to communicate the expert system with the 3D wear particle analysis and identification systems.

CONCLUSION

The expert system has been developed to evaluate wear rates and the condition of a machine by the interpretation of analysis data obtained from the 3D particle analysis and automatic particle identification systems. The system is a useful tool to perform machine condition monitoring and fault diagnosis especially when the human expert is not available or too expensive to use. The further development of an integrated system to implement 3D particle analysis, automatic particle identification and machine condition examination in a single package is being under way.

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Application of LaserNet Fines to Mechanical Wear and Hydraulic Monitoring

J. Reintjes ¹, J. E. Tucker ¹, A. V. Schultz ¹, L. L Tankersley ², C. Lu ³,
P. L. Howard ⁴, T. Sebok ⁵ and C. Holloway ⁵

ABSTRACT

We describe the application of LaserNet Fines to the detection of mechanical wear in diesel engines and hydraulic contamination in a variety of systems. The ability to relate LaserNet Fines results to specific types of faults and the use of LaserNet Fines results for root cause analysis and recommendation of remedial action is discussed.

Key words: wear debris, diesel engine, hydraulics, shape analysis, fault identification, contamination

Introduction

The analysis of wear debris that is shed from in-service machinery and is contained in lubricating or hydraulic fluid has proven to be a useful indicator of machinery health[1-7]. The types of analyses that are used include measurements of the size, shape, amount and composition of the debris.

LaserNet is an optically based debris monitoring technology that determines the existence, type, severity and rate of progression of mechanical faults by measuring the size distribution, shape characteristics and rate of production of debris particles[8-11]. It is applicable to detection and early warning of faults in oil wetted systems such as reciprocating and rotating engines, drive trains, and gearboxes and in hydraulic systems.

LaserNet Fines Technology

LaserNet Fines (LNF), which is the technology described in this paper, measures the size distribution of particles from 5 micrometers to more than 100 micrometers, and provides wear classification based on shape features for particles larger than 20 micrometers. The analysis of particles in this size range is useful for the early detection of mechanical faults in diesel and turbine engines, turbochargers, and gearboxes. Additionally, it is useful for measuring particulate and water contamination in hydraulic and fuel systems.

LNF can be implemented in either a batch processor or on line configuration. The on-line configuration is suitable for the continuous, autonomous monitoring of a single machine. The batch processor configuration is suitable for the analysis of many types of machinery by one instrument, as well as for lubrication

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² US Naval Academy, Annapolis MD USA

³ Towson University, Towson, MD

⁴ PL Howard Enterprises, Newmarket, NH, USA

⁵ Lockheed Martin, Akron, OH, USA

systems which do not have flow loops, such as splash lubricated gearboxes.

Analysis by the LNF instrument involves imaging a magnified sampled portion of the fluid supply from the mechanical system under study. The on line implementation is illustrated in Fig. 1. In this case, a section is inserted into a sampled portion of the main flow with optical windows to constrain the fluid to a 100-micrometer-thick flow channel. A small volume of the fluid sample, and any particles that may be in the fluid is frozen in their motion by a backlighting pulsed diode laser light source. The image frame is captured by a CCD camera that is coupled to a frame grabber in a computer system. Each image frame is then analyzed for particles and, if they are found, size and shape information is collected. The resultant mage is analyzed with an image-processing algorithm as to identify objects and identify them as to their origin. Classification is done with an artificial neural network that was developed specifically for the LNF system. Shape features were chosen to give optimal distinction between the assigned classes of fatigue flakes, cutting wear, severe sliding wear, abrasive contaminants such as oxides, fibers, water bubbles, and air bubbles. An extensive library of particles, which were identified by human experts, was used to train the artificial neural network. Several thousand frames are examined to complete a LNF sample analysis.

Under a program on condition based maintenance sponsored by the Office of Naval Research, several prototype batch processor instruments were built by Lockheed Martin NESS in Akron, Ohio. These instruments are capable of operating with fluids having viscosities up to 350 cst at room temperature and particle concentrations greater than 1,000,000 particles/ml. It is compatible with synthetic and mineral-based lubricants, hydraulic,

and gearbox oils. The unit automatically compensates for each fluid's darkness and soot levels.

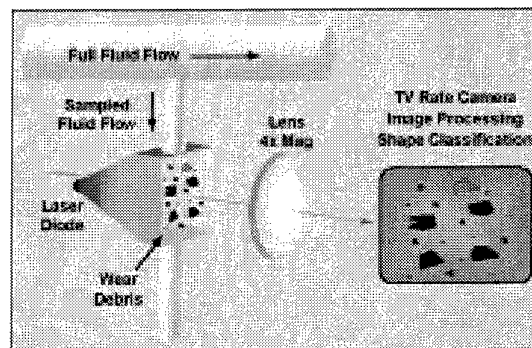


Fig. 1. Schematic illustration of LaserNet Fines operation

Mechanical Wear

In this section we describe the application of the LaserNet Fines technology to a class survey of 18 medium speed diesel engines. Wear debris assessment for equipment health usually involves the analysis of a time series of samples to detect an increasing rate of debris production, which is associated with the presence of mechanical faults. Similar information can be obtained from a class survey of equivalent pieces of equipment, all of which have been subjected to similar use profiles, but are in different stages of useful life.

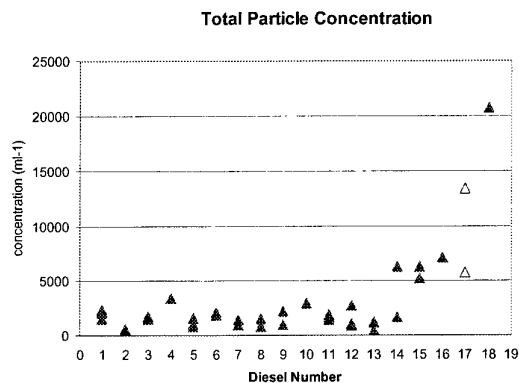


Fig. 2. Total particle distributions for medium speed diesel study

In this situation it is expected that most of the equipment will exhibit similar behavior, allowing a baseline for normal operation to be established. Deviations from the norm can then be associated with the presence of faults.

Oil samples were taken from the lube systems of each of the engines. The distribution of total particle concentrations for the entire class are shown in Fig. 2. Multiple points for a given diesel indicate samples taken at different times. Thirteen of the eighteen diesels show a consistent level of particle concentrations, which can be taken to represent the average total particle concentration for normal operation within the class. The remaining five engines show elevated total particle concentration and require additional analysis.

The wear particle distributions for particle larger than 20 micrometers for the 18 engines are shown in Fig. 3. One of the engines (#17) that had elevated total particle concentration shows no elevated counts in any of the wear classes, while the remaining four with elevated total particle concentration also show elevated levels of large particles. This indicates that the underlying fault process responsible for the particle production in that engine is different than for the remaining four.

The wear particle distribution for the four diesels with elevated large-particle counts show elevated counts in all of the classified categories, with one, diesel #18, having significantly higher readings than the rest.

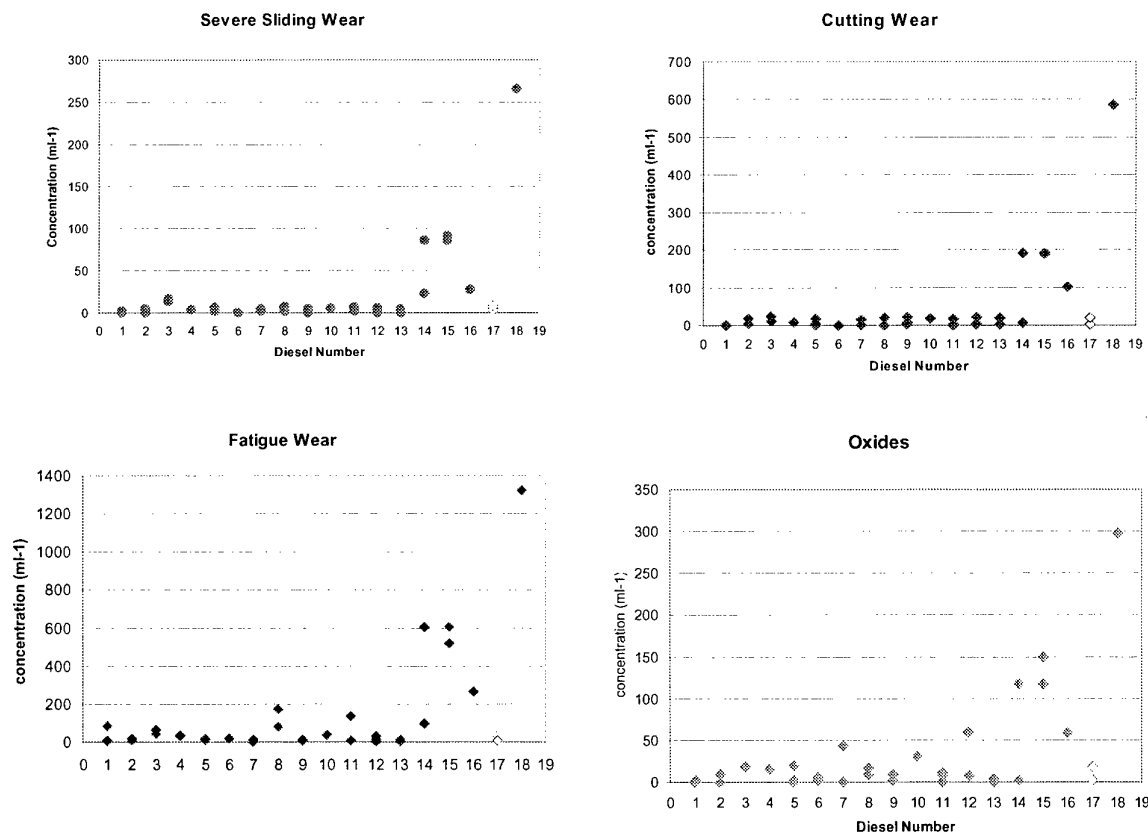
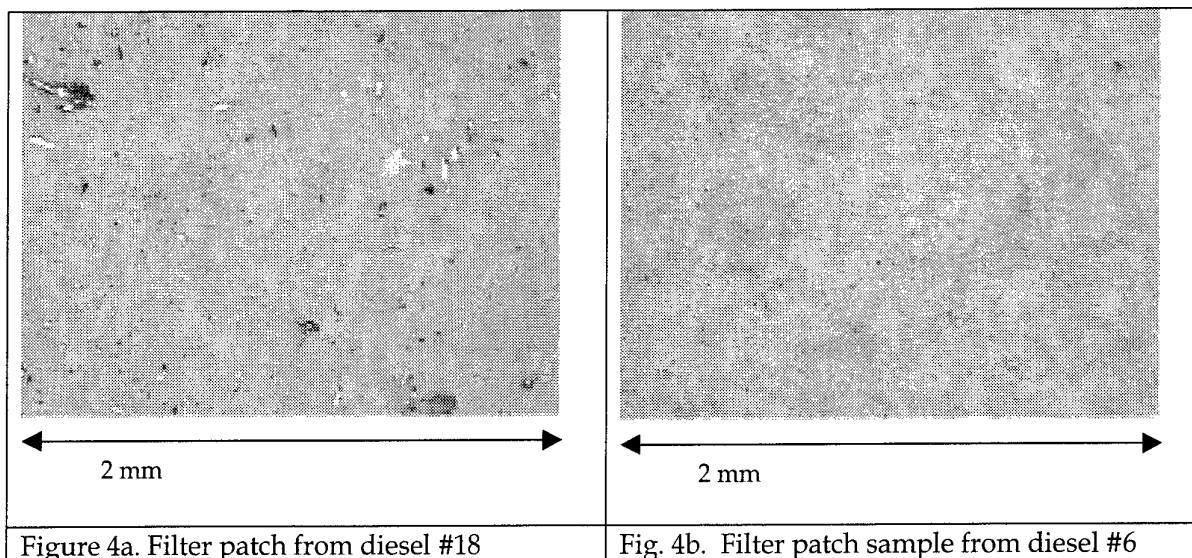


Fig. 3. Wear debris distributions from medium speed diesel study.



Microscopic analysis of the debris from diesel #18 is shown in Fig. 4a. A portion of the oil sample from diesel #18 was poured through a filter patch, which was subsequently analyzed under an optical microscope. A section of the filter patch from diesel #18 is compared with a similar section from diesel #6 (Fig. 4b.) which was one of the cleanest in the survey. The patch from diesel #18 shows numerous shiny particles consistent with wear metal. The similar image from diesel #6 shows only 1 detectable metal particle.

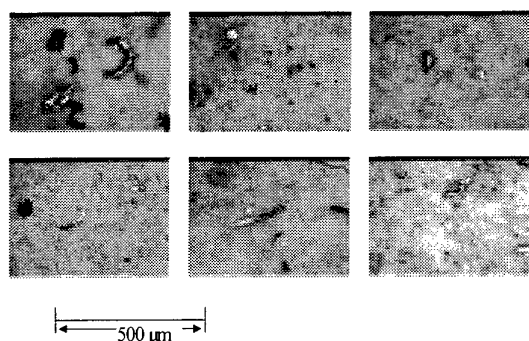


Fig. 5. Magnified images of wear debris particles from diesel #18

Magnified images of debris from diesel #18, shown in Fig. 5, show particles characteristic of flakes, slivers characteristic of sliding wear and curls characteristic of cutting wear. Some of the particles show evidence of overheating. The condition of the particles are consistent with a condition related to inadequate lubrication as might happen for example with inadequate or interrupted oil supply.

Scanning electron microscope energy dispersive x-ray (SEMEDX) analysis is shown in Fig. 6 for the debris from samples from diesels #18 and #14 along with similar analysis of debris from a wrist pin and wrist pin bearing insert that was taken from a teardown analysis of a failed wrist pin assembly. The X-ray spectra from the debris samples from each of the engines match only the spectra from the bearing insert, while debris from the teardown has components that match both the bearing insert and the wrist pin.

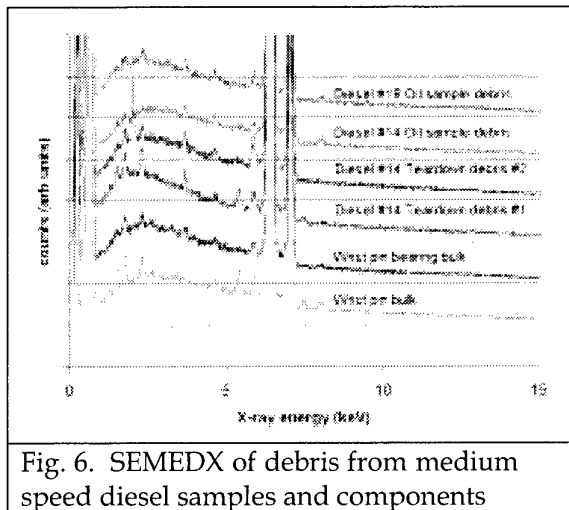


Fig. 6. SEMEDX of debris from medium speed diesel samples and components

The LaserNet Fines particle distributions for the fatigue, cutting and sliding wear are shown in Fig. 7. The fatigue particles are seen to decrease with increasing size range. This is consistent with expected distributions, except that the ratio of larger

to smaller particles is normally much smaller than in this distribution. The distribution for sliding wear is different, with the middle size range showing the highest concentration. A similar distribution is seen for cutting wear. The characteristic distributions of cutting and sliding wear and their relative amounts are consistent with a fault mode that involves inadequate oil supply in a low alloy steel bearing in which flakes are produced initially, sliding wear as the oil film collapses and cutting wear as the debris particles are trapped in the bearing clearance and cause secondary damage. These distributions can be used as a signature for faults of this type, providing the capability for fault identification and root cause analysis directly from the LaserNet readings without requiring extensive laboratory analysis.

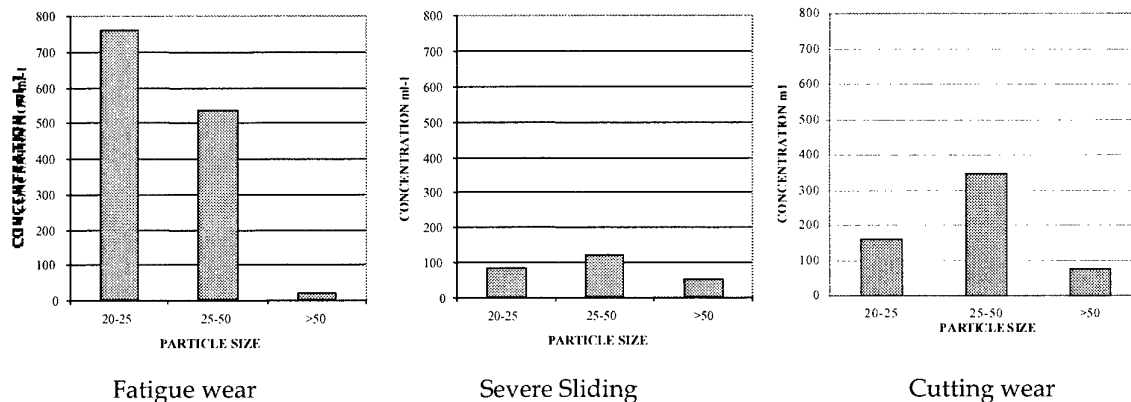


Fig. 7. Wear particle distributions from diesel #18.

Hydraulic Monitoring

LaserNet Fines is ideally suited to monitoring of particulate contamination in hydraulic systems. The size range of detection overlaps completely with sizes of interest for hydraulic cleanliness measurements. The fact that LNF measures actual particle dimensions makes it directly compatible with the new ISO 4406 standard. Added advantages are that LNF can identify free water, quantify its concentration and characterize the contaminant particles as to type of particle and linear dimensions. The ability to detect free water allows LNF to give a measure of water concentration in addition to particulate concentration without requiring a separate measurement, and to measure particulate contamination in the presence of water without requiring a separate measurement, and to measure particulate contamination in the presence of water without requiring dewatering or other sample preparation. The ability to characterize the type of particle and detect its largest linear dimension provides LNF with the ability to assess the significance of particulate contamination on hydraulic function and to provide root cause analysis and recommend suitable remedial action.

A hydraulic screen has been added to the LNF instrument display, an example of which is shown in Fig. 8. Here, in addition to the particle size histogram, cleanliness classes are given for various standards, including ISO 4406 (1998), ISO 4406 (1999), NAS and NAVAIR and CHA(RN). The cleanliness classes for the various size ranges for NAS, NAVAIR and CHA(RN) in addition to the overall class, and water concentration in ppm are also given.

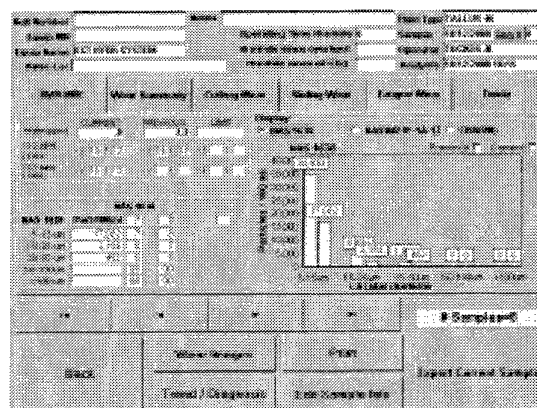


Fig. 8 LNF Hydraulic Display Screen

The absolute counting accuracy of LNF is indicated in Fig. 9, where LNF measurements are compared with NIST certified results for hydraulic calibration fluid SRM2806. The agreement between the LNF results and the NIST certified values is excellent over the entire range for which NIST certification exists. These measurements are done without calibration of the LNF instrument or other adjustment of the measurements. This means that LNF does not have to be calibrated in each size range, and that periodic recalibration with expensive reference calibration fluids is not necessary.

Free water is identified by LNF by the appearance of the water bubbles in the hydraulic fluid. LNF measurements of water concentration are shown in Fig. 10 as a function of a known amount of water introduced into a sample of Mobil Jet II. Within experimental error the measured concentration agrees excellently with the known amount.

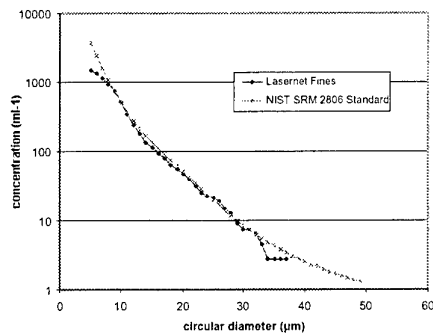


Fig. 9. Comparison of LNF results with NIST hydraulic calibration standard SRM 2806

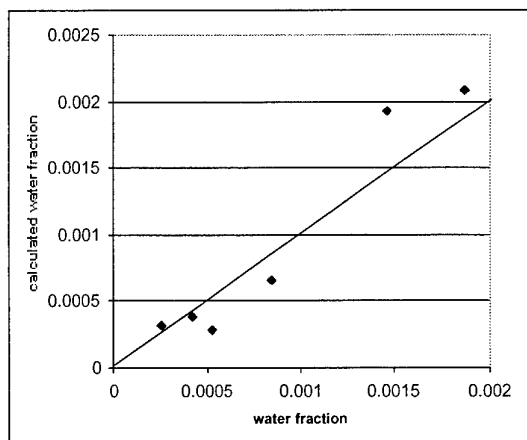


Fig. 10. Free water concentration measured by LNF compared to known water fraction

LNF has been used to monitor hydraulic systems such as helicopter flight controls and shipboard hydraulic systems. Examples of particle images obtained from these systems are shown in Fig. 11, 12 and 13.

In the helicopter hydraulic application, particle concentrations were measured that were in excess of the allowable contamination levels. The added value of LNF analysis is illustrated in Fig. 11, which shows images of particles larger than 20 micrometers. The particle images show a high concentration of abrasive oxides with particle sizes up to and above 100 micrometers. These images indicate that

not only is binding of flight controls likely, but damage to actuators and motors due to abrasion, which was confirmed on subsequent inspection, is also probable. LNF can thus provide not only a measure of particulate contamination, but also an assessment of the consequences of whatever contamination is present.

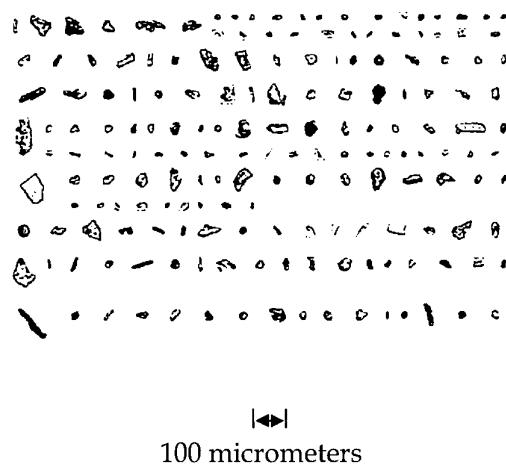


Fig. 11. Record of particles larger than 20 micrometers detected in helicopter flight control hydraulics

Similar image maps of particle from submarine external hydraulics and aircraft elevator hydraulics are shown in Fig. 12 and 13. The submarine hydraulic measurement shows the presence of water, wear metal flakes and rust. Here, in addition to simple contamination levels, LNF indicates the presence of water, from a possible leaking seal, and its consequences for degradation of hydraulic components. The elevator measurement, on the other hand, shows a high concentration of fiber, identified by the characteristic uniform width of high aspect ratio particles and confirmed in microscope analysis. Again, in addition to simple contamination measurements, LNF can identify the source

of the problem as being connected with deteriorating filters.

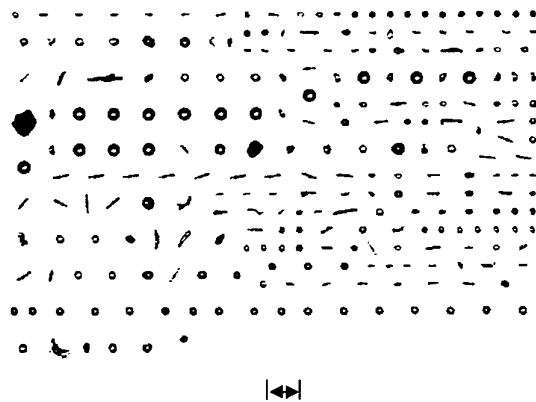


Fig. 12. Record of particle images from submarine hydraulic system

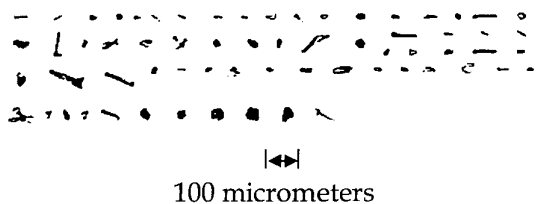


Fig. 13. Record of particles from aircraft elevator hydraulics

Summary

LaserNet Fines has been applied to the detection of mechanical wear in diesel engines and particulate contamination in hydraulic systems. The ability of LNF to identify and quantify particle types allows its results to be used for fault identification, root cause analysis and recommendation of remedial action.

Acknowledgement

The authors acknowledge the support of the Office of Naval Research.

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Static Balancing Rotor Blades to Maintain Interchangeability and Facilitate Rapid Track and Balance

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ABSTRACT

The extract data displayed in this paper was collected over a two-year time frame. Most of the data were obtained in the presence of government and contractor personnel. Complete data sets that support the data reflected can be made available.

The authors would like to thank the many AMCOM, CCAD, Dyncorp, Lockheed Support Services and Camber Corporation employees that supported this effort. Boeing, Sikorsky and Composite Structures for granting access to master blades.

The USBF development was partially funded by a Manufacturing Technology program spearheaded by the Corpus Christi Army Depot. Government funding, private funding, soldier involvement, and corporate cooperation facilitated the development of a good piece of equipment at great benefit to Army Aviation.

I. Blade History

Early helicopter rotor blades were fabricated from wood, dope and fabric. These blades were sufficient to take flight loads when new, but deteriorated within a relatively short time. Environmental weathering of these structures and dry rotting of the wood were prevalent. A common joke was, "You are OK as long as the termites continue to hold hands!"

Metal blades were the next technology iteration that solved the wood blade problems. Common design features included an extruded aluminum spar, aluminum honeycomb covered by aluminum skin after bodies. Stainless steels were utilized at the leading edge for erosion control. These blades were superior to the wood blades in most all respects. Eventually corrosion

became the primary reason for removal from service. Unfortunately there were some in-flight fatigue failures, due to manufacturing anomalies and environmental effects. During the Vietnam War, these blades served admirably. The blades were capable of sustaining damage and still getting the crew home. The one critical area where damage tolerance needed improvement was in the spar area. Damage here propagated very quickly and some losses were suffered.

As a partial result of the Vietnam experience, so called composite blades were developed during the 70's. Use of composite materials technology allowed for redundant load path structures and tailoring of blade layout, allowing for new aerodynamic shapes and airfoils. All blades have been, by strict definition, composite blades but the term

today refers to those blades made at least partially from fiberglass epoxy type materials. Blades of this type utilize either glass fiber or titanium for spar construction with a Nomex Honeycomb (Trademark) core after-body with glass skins. These blades are damage tolerant and very repairable in the field. It is this last fact, the reparability that has lead to much of the field's track and balance problems.

The Manufacturers Balance Process

Typically, after a rotor blade is manufactured, the blade is statically balanced span-wise. Some manufacturers balance both span-wise and chord-wise. The objective of span balancing is to get the span moment (the product of blade weight times the distance from the mast center of rotation to the blade center of gravity) to be equal to the specification target. Blade designers always document this value, although historically, have not used the numerical value for balance purposes. Generally, manufacturers select a blade that is used as a master blade. The master blade span moment gets measured as closely as possible and it is this value that is documented.

The master blade is used to comparatively balance production blades. When overhaul sites are established, a master blade is required. Usually the prime contractor is paid to make a duplicate(s) of the master for the new sites. Some manufacturers go an extra step in their process of producing blades. After static balancing, some manufacturers utilize a whirl tower and a whirl tower master to further refine blade track and balance characteristics. Blades that go to a tower do not have weight added or subtracted at the tower. The static span balance assures the lateral balance. The purpose of the tower is to set trim tabs and dynamic chord. Weights, generally at the tip

of the blade, are moved forward or aft, to dynamically tune the blade to the referenced master whirl blade.

During evolution of rotor blade design, whirl towers were found to be useful in the development process.

Out in the field, blade track and balance evolved from tracking by using a "flag" (a long pole with bunting at the top that had to be stuck into the blades rotating path) and guessing which blade was light, to dynamic tracking and balance computers.

Span Moment Tolerances

Span moment tolerances required by the blade manufacturers vary between $\pm 1/4$ in-lbs in span-wise moment on old UH-1 blades to ± 10 in-lbs on newer OH-58D blades. The tight tolerances are believed to be essentially the stated repeatability of the then in vogue, comparative balance available. The looser tolerances are probably recognition of what is achievable in a digital world.

If a comparative balance is good to $\pm 1/4$ in-lbs. and the working master is developed from the golden master using the comparative tool, is the working master accurate to a $\pm 1/4$ or a $\pm 1/2$ in-lb? Working masters for depot use are even more removed. How much do they vary during the year or two before mandatory recalibration?

With the advent of the Avion digital machine, insights into these numbers are now available. Figures 1-4 reflect requirements versus measured values on various master blades and new production or overhauled blades. Many variations from the expected are observed. These variations have probably been with us forever and have not always been a real problem in the past. On less repairable blades, the dynamic authority was sufficient and variation was easily handled. Now the variation in blade span moments is

such that the dynamic authority is not sufficient and the field is forced into swapping rotor blades until blades with similar span moments are, by chance, paired opposite each other. As many units in the field can now attest to, the other solution is to statically balance the blades using the Avion USBF (Universal Static Balance Fixture).

Master Blades

The AH-64 Apache

During the development / qualification process, the Avion USBF was taken to the various prime contractors facilities to "calibrate" with their masters. The first visit was made to the MDH (McDonnell Douglas Helicopter - now Boeing) facility in Mesa, Arizona. The master blade (serial number RBM-196) was used to obtain numerous data points. The readings varied from the 24,300 in.-lb. requirement by 13 to 19 in.-lbs. on the light side. The 13 was one reading with the other data points clustered at the 18 and 19

end of the spectrum.

The manufacturer of the Apache blade for the Prime Contractor is Composite Structures of Monrovia, California. Three master blades were made available at their facility. Figure 1. below reflects the data for each of these master blades. Figure 1 also incorporates the master blade data from MDH and CTI.

The MDH master blade agrees very favorably with the CSD (Composite Structures) master blades. CSD provided the master blade and calibration service to MDH. The total range in figure 1 above reflects a 11 in.-lb delta between the lowest Avion reading on the lowest span moment blade versus the highest span moment reading on the highest span moment blade. The average difference in these four CSD produce master blades is 4.2 in.-lbs. These blades are very close to each other; however, they seem to be "lighter" than specification requirements (24,300) by approximately 20 in.-lbs.

The CTI master blade was developed independently of CSD. Without access to the CSD standard, CTI had to develop their master blade to the specification! The CTI master blade was measured at much closer to spec values, but was on the high side.

It is clear (Fig. 1) that the Avion USBF machine is measuring to a repeatability of plus or minus three in.-lbs on any given Apache blade. With regards to answering the question; "Is the USBF accurate in evaluating the Apache blade?" the following reasoning helps! The fact that two sets of independently developed master blades were measured to either side of target value brings one to logically conclude that the Avion USBF might be closer to the target than either set of master blades.

More importantly, if blades balanced from either set of master blades are adequate, then blades balanced with the

SPAN MOMENT SPECIFICATION 24,300 in.-lbs			
	LOW	AVG	HIGH
CSD			
GRAND MASTER	24280	24281.6	24285
WORKING MASTER	24276	24278.8	24281
CONTROL MASTER	24278	24279.8	24281
MDH			
MASTER	24281	24283	24287
DELTA'S	5	4.2	6
TOTAL RANGE	24287	-24276	11
CTI			
MASTER	24304	24307	24309

Figure 1

Avion USBF will be somewhere in-between and will also be adequate.

Boeing Master Blades

The CH-47D master blade was measured at Boeing's facility in Ridley Park, Pennsylvania. The master blade was found to be about 10 in-lbs low. The USBF was shown to be capable of repeating Chinook blade readings to within ± 6 in-lbs.

The Avion USBF was used by Boeing to check Boeing production blades. Boeing, using their current pivot balance and master blade technology had balanced these blades. Their balance process produced new production and newly overhauled blades that varied as much as ± 72 in-lbs. Boeing's conclusion after using the Avion equipment was that the USBF was accurate and repeatable. Figure 2 below reflects the Chinook master blade findings.

scales were used to resolve the difference. The two point scales provided a third set of values. This data was in closer agreement to the USBF values. Boeing concluded that there was a problem with their master blades. Boeing volunteered that production blades should be evaluated as they were balanced on the pivot balance and should be good. In fact, new production blades were found to be within 23 in-lbs of specification.

Sikorsky Master / Production Blades

Sikorsky master blades for the UH-60, SH-60, and CH-53E were evaluated at the Sikorsky blade balance shop. All of the master blades were found to be under the specification targets. When you look at the specifications, especially for the SH-60 and CH-53E, you might conclude that the values are approximate values. These values are used by other engineering disciplines for

CH-47D	SPAN MOM	LOW	AVG	HIGH
	SPEC			
MASTER	65369	65353.6	65359.4	65364.6
DELTA FROM SPEC		15.4	9.6	4.4
CH46	SPAN MOM	LOW	AVG	HIGH
	SPEC			
MASTER	26605	26694.1	26694.6	26695
GOLD MASTER	26605	26688.5	26690.4	26692.2
DELTA BETWEEN MASTERS		5.6	4.2	2.8
DELTA FROM SPEC (AVG)		86.3	87.5	88.6
PRODUCTION BLADES	26605	26626	26628	26630
DELTA FROM SPEC (AVG)		21	23	25

Figure 2

When the CH-46 fiberglass rotor blade masters were evaluated, they were found to be 80 plus in-lbs over spec value. After checking key USBF data files and dimensions and finding no errors, Boeings two point

their calculations, but are not very precise for digital balance purposes. When master blades are used, exact span moment values are not necessary. What is necessary, is that all blades be close to each other in actual span

moment. Master blades accommodate this requirement. This same argument is supported by the Apache data above. CTI's master blade was developed independently and without benefit of existing master blades. Faced with developing a master blade to a digital specification, CTI used standards

found condition of these blades. Two contractor overhauled blades and the new production blade would have flown together, but the CCAD (Corpus Christi Army Depot) overhauled blade would most likely have been a problem. Interestingly, the CCAD blade was closer to specification than the other three. In the field however, this CCAD blade would have been

UH-60	SPAN MOM SPEC	LOW	AVG	HIGH
MASTER	35,418	35,384.30	35,387.50	35,391.90
DELTA FROM SPEC	-6	33.7	30.5	26.1

UH-60 Production Blades	SPAN MOM SPEC	LOW	AVG	HIGH
Overhaul (IAI)	35,418	35,361	35,361	35,361
Overhaul (IAI)	35,418	35,345	35,345	35,345
Overhaul CCAD	35,418	35,440	35,442.50	35,445
New Sikorsky	35,418	35,361	35,361.50	35,362
Delta's	-6	95	97.5	100

SH-60	SPAN MOM SPEC	LOW	AVG	HIGH
MASTER	35,800	35,778	35,780.40	35,784
DELTA FROM SPEC	-6	22	19.6	16

CH-53E	SPAN MOM SPEC	LOW	AVG	HIGH
MASTER	103,050	102,994	102,998.30	103,001.70
DELTA FROM SPEC	-6	56	51.7	48.3

Figure 3

other than an existing master blade and consequentially developed a blade much closer to the specification value. If given a master blade as the standard, rest assured that CTI's developed master blade would have been statistically equivalent.

A new production blade and three newly overhauled, never flown blades were obtained for evaluation. The span moments were analyzed and it was concluded that the four blades would probably not dynamically balance properly with each other. Figure 3 above documents the as

seen as the "bad" blade. (The reasoning that produced the above conclusion is provided later on in this document; in the paragraph labeled "Dynamic Authority".)

Bell Helicopter Blades

The only master blades available for Bell Helicopter aircraft were the master blades at CCAD, shown below. Again, there is significant deviation from specification. An overhauled blade balanced by processes

AH-1W	SPAN MOM SPEC	LOW	AVG	HIGH
MASTER (CCAD)	59,664.18	59,740.10	59,743.20	59,746.40
DELTA FROM SPEC		75.9	79	82.22
PRODUCTION	59,664.18	59,721.30	59,727.40	59,730.30
DELTA FROM SPEC		57.1	63.2	66.1

UH-1N	SPAN MOM SPEC	LOW	AVG	HIGH
MASTER BLADE (CCAD)	32,158.60	32,018.00	32,018.60	32,019.10
DELTA FROM SPEC		140.6	140	139.5

UH-1H	SPAN MOM SPEC	LOW	AVG	HIGH
MASTER BLADE (CCAD) 2522	28,866	28,847.60	28,849.40	28,851.60
DELTA FROM SPEC	-0.5	18.4	16.6	14.4

Figure 4

utilizing the master blade produced, not surprisingly, a similar blade. The AH-1W production blade was found to be 14 in-lbs closer to the specification than the master blade. Although the comparative balance tool is quoted to be accurate enough to maintain a plus or minus 1/2 in-lb tolerance, the fact is, the process in this case produce a product with a much wider tolerance. It should be emphasized that the above blade would have flown with similarly balanced blades and may have been "good enough".

V. Dynamic Authority

When statically balance blades are installed on a rotor hub, the whole spinning mass is again balanced using computerized dynamic balance tools. In the old days before the dynamic tools became available, tight blade specs and very little blade repair allowed the field to fix a lateral vibration by guessing which blade was at fault and then adding mass. If the lateral got worse, you deduced that you had guessed wrong. If it got better, you might have added additional

mass, with a flight test after every move. It was an art! Today, the Army uses the AVA (Aviation Vibration Analyzer) tool that tells the user how much weight to add where, as well as predicting track and vibration solutions.

Figure 5 depicts the span moment weight authority available to the field for dynamic balance of the rotor hub and blades. For instance, the 117 inch-pounds for the UH-60 means that if you had a perfectly balanced hub with four perfectly balanced blades installed on it and then were to add the maximum allowed weight to one blade, you would have a 117 inch pound unbalanced moment. The 117 inch-pound adjustment is

Dynamic Authority inch pounds	
Uh-60	117
AH-64	105
CH-47D	380
OH-58D	48.5

Figure 5

provided to the field to make up for the hub, blades, and eventual blade mass properties changes that happen over time.

One of the reasons the field has track and balance problems is because the new composite blades are so repairable; repairs are being accomplished that would have otherwise gone to depot. Economic pressures have forced the field commanders to attempt repair versus sending in to depot, which has exacerbated this problem. The weights authorized to be adjusted for dynamic balance purposes are just not large enough to counter act the factors that are changing the span moments of the blades. These factors include large repairs, moisture, erosion and painting. At depot, tip caps are removed and larger weight packages are revealed, that allow greater control than normally allowed in the field.

Another reason for some of the problems resides in the depots. Multiple overhaul sites, using master blade technology require precise master blade duplication and maintenance! For a multiple number of reasons, this has not always been happening. The table in figure 3 shows four blades with zero time since overhaul and / or since new. All of these blades were required to be statically balanced using master blades. All of these blades were balanced to the same specification. All of these blades were shown to be significantly out of tolerance. If the CCAD blade were to be installed opposite the second Israeli Aircraft Industries blade, there would be a 105 in-lb difference between them. On an UH-60 Blackhawk, you can add weights to the lighter span moment blade to counteract the other blade. The UH-60 blade accommodates enough weight during dynamic balancing to generate a 117 in-lb moment (Figure 5 above). If the hub were perfectly balanced this example hub and blade combination would dynamically balance acceptably. However, perusing hub

drawing tolerances reveal that the hub may consume about 30 in-lbs. of the 117 in-lb. capability. It's obvious that this hub, although well within engineering tolerances, when paired with the referenced blades, would probably not be adequately balanced dynamically.

VI. Field Operating Limitations

There are no real limitations to what can operate in the field! Blackhawk blades are operating at 400 inch-pounds over specifications. The way this is accomplished is, span moment heavy blades get matched up with other span moment heavy blades. The cost to this approach is high. The actual blade span moments of blades are unknown, so matching blades is a process of random chance. A number of blades might be tried before a suitable match is found. Maintenance test flights are required for each trial before a determination of suitability can be made.

The older the fleet of blades and the more repairable the blades the wider the variation in span moments. The wider the variation in the population of blades, the harder and more costly the search for a suitable match becomes. The Chinook is a good example. The Chinook meets all of the criteria for being hard to match up. Chinook blades on operating aircraft have been found to have span moment deviations to specs as large as the equivalent of plus and minus two pounds at the tip. Plus or minus 700 plus in-lbs. of imbalance on an aircraft rotor system is attention getting to say the least.

If a Chinook were successfully flying with blades at one end of this extreme and a single blade had to be replaced with a brand new blade, the aircraft could not be tracked and balanced within limits. There is not enough dynamic balance weight authority to make up for this situation. When this type of

situation occurs, the Army's dynamic balance tool will look at the data and then try and make corrections to the one blade that is not flying like the rest. The only blade meeting span moment specifications is the one that is deemed to be bad. The field gets unfairly so, but nevertheless, irate with the Boeing product.

With the advent of the fielding of the Avion USBF, this kind of problem has been largely eliminated, at least in those locations where the machine is available.

The tightness of span moment at depot is important, but the maintenance of that span moment in the field is critical. Coming out of depot there is considerable leeway available if the span moment is maintained over time. For instance, going back to the UH-60 example again, the field acceptable span moment using the USBF is set at 35,418 plus or minus 30 in-lbs. The UH-60 has a dynamic authority of 117 in-lbs. so if one blade is 30 in-lbs low and the opposing blade were 30 in-lbs high, there would still be 57 in-lbs of excess dynamic authority left to make up for any hub imbalance. There is a high probability that all of a population of blades meeting these criteria would be interchangeable and successfully balanced. Setting this higher field limits attempts to keep Blackhawk tip caps from being removed more than necessary. Getting tip caps off is a tough job. If the blade exceeds the plus or minus 30 in-lbs, then the tip cap comes off and the blade is re-balanced back to specification.

This field procedure and attendant tolerance is in recognition of what is really important. Dynamic balance and low vibration is important! Static span moment values are important only when they go out side of the tolerances that start making the dynamic balance process difficult or impossible.

VII. Dynamic Chord Problem

Both Boeing and Sikorsky utilize whirl towers at their respective facilities. The typical procedure is for the blades to first be statically balanced and then they go to the tower. At the tower, the objective is to make the production blades fly with the whirl tower master blade. Mass is generally not added nor subtracted from the blade. The span moments are assumed to be on specification so the only adjustments made to the blade is the bending of trim tabs and the moving of weight forward and aft to affect dynamic chord balance. Trim tabs allow for slight aerodynamic differences in blades. Moving weights chord-wise change the chordal response to moment of inertia changes with changes in lift.

For instance, a blade at the tower is flat tracked to the master using pitch links and trim tabs. Then pitch is increased and weights are moved to keep the production blades tracking with the master. If, for instance the production blade climbed above the master with the application of pitch, weight would be moved forward to try and bring that blade down. This is an oversimplified explanation of the procedure, but detailed enough for our purpose here. The over all goal is to try and get equal lift produced by the master and production blades at equal angles of attack.

This is all well and good. However, in real life this is what happens. The newly accepted rotor blade is sent out to the field as a replacement blade. The first thing that happens after installing the new blade is the aircraft is run up and flat pitch track checked. If this blade that simulates the whirl tower master does not track with the other two on the Chinook, the pitch links and possibly trim tabs get adjusted. When pitch is pulled and the aircraft leaves the ground, the AVA looks at track, lateral and vertical vibration levels and attempts to solve the dynamic situation.

The blade that changes the most is usually the blade just off the whirl tower. Remember that it's easier to change one blade than the two that have been successfully flying together. If all looks good or is made good during hover, then forward flight airspeed sweeps are made. Additional adjustments can be directed by the AVA to further fine-tune the blades to fly harmoniously with changes in airspeed. The bottom line is, after all of this commotion, there is little chance that the new blade still emulates the whirl tower master blade.

Occasionally, after span balancing a Chinook blade in the field, the aircraft goes from ground to a hover condition, and sees a split in blade track. One blade climbs or dives compared to the others. This may be a dynamic chord problem. The technical solution would call for moving weights chord-wise, just like on the whirl tower, until the split is resolved. There are some legitimate concerns that the AVA may not have the required resolution in track to make a small adjustment in the field. On the other hand, if the track is large enough in deviation that it is noticed, then at least an improvement may be possible with chord weight movement. The adjustment might not be as fine-tuned an adjustment as possible on a tower, but an adjustment is at least possible to push the blade in the right direction.

The relationship of static chord to dynamic chord was addressed by a recent Boeing study. Boeing utilized an Avion USBF to address whether or not there was a correlation between static chord center-of-gravity and the dynamic chord. The USBF was used to get static chord center of gravity data, both before and after whirl tower. Although Boeing has not delivered their official findings, Avion analysis of the data did not detect a correlation. There has been hope by some that the Avion USBF could somehow take the place of the whirl tower.

Whirl towers are very expensive and represent a funnel through which all production must flow, which also adds to the overhaul cost.

Unfortunately, static chord measurements do not predict dynamic chord reactions.

A case can still be made however, for doing away with whirling blades for field use. By recognizing that with the USBF in the field (taking care of the static span balance portion of the process) and with the AVA in the field, all aircraft become whirl towers. You lose very little in terms of not having a whirl tower master blade model when, as it has already been shown, the master blade imitation is not maintained after installation anyway.

It should be noted that for production, a whirl tower is invaluable due to the fact that all of the blades that are installed on the production aircraft come from the whirl tower. When all blades that are installed come from the whirl tower, their dynamic characteristics are very similar which will reduce the time for track and balance in the production facility.

Field Experience

The field experience with the USBF has been outstanding. Complete populations of CH-47 blades at locations such as Ft. Rucker and Ft. Campbell have been made, once again, interchangeable. Maintenance flight time for track and balance has been cut dramatically. AH-64 units are starting to reap similar benefits as a result of fielding 20 USBFs to Apache units in 1999. Where contractor personnel control USBFs, UH-60s and OH-58Ds are being balanced with excellent results and savings.

There is a required paradigm change, but tremendous savings are the reward!

Conclusions

No matter how tight depots control production span moments, maintaining span moments in the field is critical.

If span moments are maintained in the field, extremely tight depot tolerances are unnecessary.

A virtual master blade can maintain span moment tolerances better than comparative

balance / master blade technology. This is especially true when managing multiple depots for any given blade.

The Avion USBF is quite adequate for depot use.

It may be possible to adjust chord weights in the field to affect the dynamic chord of a blade.

Distributed Modular HUMS

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ABSTRACT

There has been a great deal of time and effort spent on the development of HUMS technology, the quest to produce a systems that is generic enough to be all things to all users has proven a difficult goal. Thoughts have gradually turned to towards modular technology that can be reconfigured to meet varying requirements of the end user. Distributed modular thinking will take this process a stage further by utilising existing technology as discrete modules. Each module can work independently or an integral part of a HUMS. The use of cost benefit and analysis tools can be effective in identifying the best value for money options dependent upon aircraft type and operation. Use of such tools can show that 70% of saving can be achieved by installing 4/5 modules at a cost of 25% of full HUMS system. This methodology will give the operator a choice to fit modules that will best suit their requirements, whilst the equipment manufacturer will be under pressure to deliver terms of price and support or risk being replaced. A day of pick and mix technology is coming to the market and should be welcomed by all, as benefits can be quantified and real to all concerned.

HUMS came to prominence in the late 1980's and early 1990's when promoted as the answer to all the operators' problems. It was expected the technology would be quickly developed and adopted. Sadly this has not been the case and after huge investment in terms of manpower and money HUMS technology is still not the universally accepted saviour it was expected to be.

There are only two major military HUMS development programs currently active with the UK MOD and the US Navy. Neither of these programs has been completed and the final outcome cannot be quantified to date. One fact that can be agreed is that the development has been much more difficult than expected and that the cost of development has been huge.

This situation has spawned a whole raft of smaller investigations, developments and offerings pertaining to meet the requirement

of HUMS. From this have grown the many new descriptions, such as partial HUMS or modular HUMS leading to a confusing scenario for the potential user.

After analysing data obtained from the review of user requirements it became clear that large savings could be made by supplying relatively few modules. Also clear as that some modules were common to all fleet requirements and these were to form the core of the development strategy.

- ◆ Rotor Track and Balance
- ◆ Vibration Analysis (Engines, Transmissions and Airframes)
- ◆ Engine exceedence (Temperatures, Pressures, Speed and Torque)
- ◆ Accurate Usage Monitoring
- ◆ Trending of Data
- ◆ FDR/CVR option

This provided the focus of our HUMS interest, a defined set of modules that would

provide many of the key elements to the user. The next problem was to construct a development strategy from information obtained during the evaluation.

With Helitune having over 20 years experience in vibration analysis and RTB it was an obvious conclusion for these elements to form the core of the system. With the RT2000 having been recently designed to meet both carryon and on board operation we had the ideal vehicle for these first elements. On board blade tracking was a problem concerning most of the HUMS suppliers and an area where Helitune had excelled in the past. The decision was taken to proceed with the development of a board tracker based around laser technology. This device would give constant and repeatable results working in all weather conditions without the need for blade targets.

This then gives us the ability to offer the RTB vibration module for a HUMS that on many aircraft would give up to 40% of the total savings at on 10/15% of cost for full HUMS.

To further the offering we then looked to add a stand alone Engine Exceedence and cycle counting. This unit would also be able to recognise regimes and consequently able to advise vibration/RTB module when to collect data. The engine exceedence module would be able to provide reports on exceedence relating to temperature, pressure, torque and power. Cycle counting and accurate usage time would also be available giving a good description of engine health.

Tools such as HUMSSAVE developed by Graham Forsyth DSTO can be used to evaluate the modules required.

Standard areas of interest such as RTB, Engine Exceedence Monitoring etc can potentially be supplied by different vendors as long as the system communications have been well defined. The definition of communications can be decided at a local

level or more globally using standards such as those defined by RITA in the USA.

This method however does put control back in the hands of the operator or user when deciding the HUMS that best suits their method of operation.

HUMS manufacturers would be focused on the customer needs of technical capability, cost and support and risk being replaced if found to be deficient in any of these requirements. It would be much easier for the user or operator to replace an RTB module or an engine monitor and so everyone involved would be focused on the task in hand.

Full HUMS options however modular in construction do not offer this flexibility as they have much greater integration with the aircraft being monitored.

With a distributed modular system upgrades can more easily be incorporated in as technology moves forward. This can be achieved in a controlled manner on a per module basis with the open architecture allowing for a plug and play option.

This incremental approach allows progress at a controlled pace without the large risk factor of fitting new HUMS.

With distributed modules the system can also be tailored to aircraft types within the fleet. This is extremely good news for the mixed fleet operators where the cost of fitting full HUMS to the smaller aircraft is not acceptable. In certain cases the value of the HUMS would be close to the value of the aircraft. The modular approach allows the operator to fit a complete range of modules to the most expensive aircraft such as CH47 with the possibility of fitting say an RTB or Engine module to the smaller aircraft such as squirrel, gazelle or Bell 205. The dilemma that the user faces is what is going to give them the best value for money and how can they calculate this in terms of cost benefit. This question also was at the forefront of Helitune

when it was decided how to move forward into the market.

The answer lay with many, long and open discussions with our users and the emergence of the cost benefit analysis tool developed by Graham Forsyth at DSTO (Melbourne). These two factors enabled Helitune to evaluate what was required in order to provide a value for money system that would bring quantifiable benefits with minimum risk.

To embark on this development the first task was to highlight the areas of importance for the end user and target areas of weakness in the current systems.

The first acceptance was undoubtedly the most important "there is no universal definition of HUMS, each requirement is unique to that operator".

To design a system that would answer this statement looked impossibility but in fact played a key role in providing a solution. Distributed modular design was the only logical method to provide pick and mix technology.

All collected data can be downloaded to the Ground station where it can be manipulated and trended for individual aircraft or fleet reports.

Vibration monitoring of engines, gearboxes and shafts can be handled by the RT2000. The internal design features enable this system to be re-configured to meet a wide range of vibration monitoring tasks. The RT2000 can provide analysis up to 30kHz and can be reconfigured to work with a range of sensors depending upon target application. Its unique FFT display allows the customer to set its own window for evaluation with ranges being set to best evaluate the area under investigation. Window's can be set from say 2-3Khz or 24-25kHz with a 6400 line FFT applied giving extremely good resolution.

With the fitting of independent modules for vibration and exceedence we can now accomplish 60% of the total HUMS at only 20% the cost of full HUMS. The units can operate completely independent or combined depending upon requirement only joining for data collection or Ground station analysis.

The final element of the modular HUMS will be the FDR/CVR, which can also be fitted as independent module. This element is now seen by many organisations as key to future evaluation and programs.

COST OF HUMS

This probably the most important issue to be addressed by all parties in considering HUMS.

Most operators have a mixed fleet of aircraft performing a range of tasks. This in itself can provide a problem as the aircraft and the task they perform will change the monitoring requirement of the HUMS.

Much effort has gone into the calculation of cost benefit analysis where operators can evaluate the savings of installing HUMS modules against aircraft type and usage. The results show that no aircraft or operational requirement is the same in terms of HUMS capability or requirement.

What is required is a pick and mix approach with the user able to select from a number of well defined stand alone modules working together as a complete system joined at the ground station to give complete trending analysis.

This in essence is what a distributed modular HUMS approach gives to the end user a series of well defined options that can provide 75% of the capability of full HUMS at 20% the cost.

The systems allow different in complexity and cost will be based around common modules and therefore provide consistent

and compatible data that can be used trended and matched by an integrated ground station.

The distributed modular system will allow HUMS technology to be implemented in a quick and controlled manner. Cost can be easily assessed on a case by case basis with chosen modules giving best value for money solutions. The technology is here today the risk is reduced and payback can begin in the near term. The ability to mix and match modules from different vendors will keep costs and support in the hands of the users.

The open architecture approach will allow new suppliers to enter the market and hence offer a wide choice of technology. Areas of expertise will be able to be exploited by the suppliers who can concentrate

development programs with a degree of certainty. Risk sharing between the HUMS supplier and end user will be encouraged to develop the generic modules.

The on aircraft modules will have minimum communications just enough to allow for synchronisation of collected data and regime recognition. This will allow the trend analysis and usage information to be utilised to maximum effect.

The introduction of the distributed modular concept would bring many advantages that can be easily quantified and advance the HUMS introduction in a way that benefits both HUMS manufacturer and user.

Simulation Of Vibration Signals From A Rolling Element Bearing Defect

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ABSTRACT

This paper describes the capability of transient analysis software to simulate rolling element bearing defects in a simple rigid rotor, flexible housing configuration. Numerical examples using a deep groove ball bearing are used to illustrate via rotor displacement and pedestal acceleration amplitude spectra and wave forms the effect of an inner or an outer race defect under gravity and/or unbalance loading. It is shown that inner and outer race defects affect the vibration behaviour of the bearing differently, depending on the loading and running conditions, and on defect size and location.

INTRODUCTION

Rolling element bearings are widely used in rotating machinery systems where high reliability and low power consumption are primary concerns. Modelling of such bearings taking into account the Hertzian force deformation relationship and possible existence of the radial clearance introduces nonlinearities into the dynamics of the system so that even when the conditions of the bearings are ideal, ie. there are no imperfections, transient analysis is needed to simulate the system responses (Tiwari et al, 1998; Feng and Hahn, 2000). Contact surface imperfections such as defects on the raceways and/or rolling elements also affect the responses and forces transmitted through bearings, and further complicate analysis of the system responses. There are diagnostic techniques for analyzing the bearing conditions from experimentally measured signals (Randall, 1987). However, depending on the forces present in the system such as gear forces and unbalance forces, and operating conditions such as running speed and clearances, the same surface defects may provide completely different system response

signals. Of benefit would be software which can simulate correctly the response signals emanating from rotating machinery containing gears, bearings etc. which could have a variety of defects, enabling subsequent signal processing to be applied to delineate the actual defects. This investigation describes the enhancement of existing in-house transient analysis software to model a rolling element bearing defect in a simple rigid rotor, flexible housing configuration; and the capability of this software in simulating the subsequent vibration responses. Though attention is here restricted to deep groove ball bearings with a single defect in either the inner or outer race, further enhancement of the model to cater for multiple defects and/or defects on the rolling element(s) in general roller bearing systems is not expected to prove unduly difficult.

NOMENCLATURE

- A defined in Eq. 3
- C radial clearance between rolling elements and raceway
- C_b damping coefficient of bearings
- C_d depth of defect
- C_p damping coefficient of pedestal
- C damping matrix of system

- D_b ball diameter
 D_p pitch diameter
 $\underline{F}$ vector of excitation and/or nonlinear forces
 F_y, F_z force components transmitted to both the inner and outer races in the y and z directions respectively
 K_b load-deflection factor
 K_p stiffness coefficient of pedestal
 $\mathbf{K}$ stiffness matrix of system
 M_p mass of pedestal
 M_r mass of rotor
 $\mathbf{M}$ mass matrix of system
 N_b number of balls
 t time
 U unbalance
 $\underline{X}$ vector of displacements
 y, z relative displacements of the rotor journal to bearing housing in horizontal and vertical directions respectively
 β_i 0 or 1 as defined in Eq. 5
 γ_i 0 or 1 as defined in Eq. 4
 $\Delta\theta_d$ angular extent of defect
 θ_d starting location of defect
 θ_{do} initial starting location of defect
 θ_i angular location of the i'th ball at any instant of time
 θ_o initial location of the first ball
 ω rotor speed
 ω_{bi} ball passing frequency in terms of inner race, $= N_b(\omega - \omega_c)$
 ω_{bo} ball passing frequency in terms of outer race, $= N_b\omega_c$
 ω_c cage speed
 ω_p pedestal natural frequency, $= (K_p/M_p)^{1/2}$

THE MODEL

The general equations of motion for a rotor bearing system involving nonlinear bearing forces are given as

$$\mathbf{M}\ddot{\underline{X}} + \mathbf{C}\dot{\underline{X}} + \mathbf{K}\underline{X} = \underline{F}(\underline{X}, \dot{\underline{X}}, t) \quad (1)$$

The following assumptions are made regarding the formulation of the force expression for the rolling element bearings:

1. Hertzian contact theory (Harris, 1966) is applicable;

2. Rolling element inertia can be ignored;
3. There is no slip in the bearing, even when contact is lost;
4. There are no contact surface imperfections unless otherwise specified, and only a defect on the inner or the outer race is considered;
5. Linear damping is applicable.

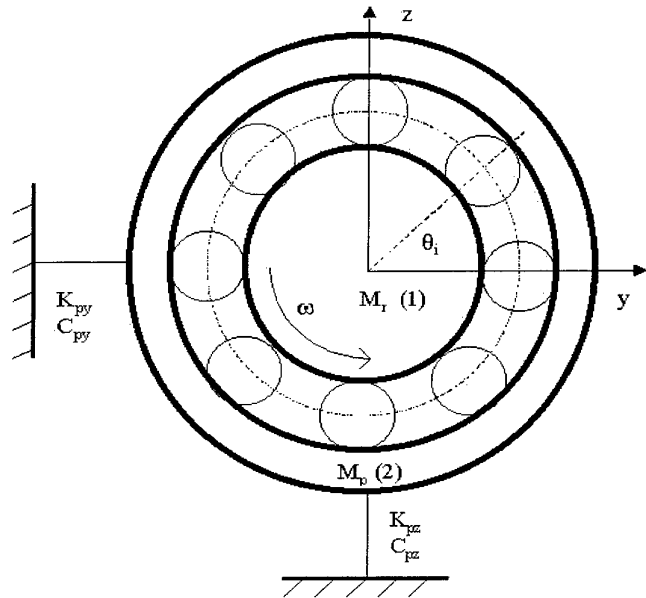


Figure 1: Rotor-rolling element bearing-pedestal schematic

Based on these assumptions and referring to Figure 1, the force components for deep groove ball bearings are given as:

$$\begin{Bmatrix} F_y \\ F_z \end{Bmatrix} = K_b \sum_{i=1}^{N_b} \gamma_i A^{1.5} \begin{Bmatrix} \cos \theta_i \\ \sin \theta_i \end{Bmatrix} \quad (2)$$

where

$$A = (y \cos \theta_i + z \sin \theta_i - C - \beta_i C_d) \quad (3)$$

$$\gamma_i = \begin{cases} 1 & \text{if } A > 0 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

$$\beta_i = \begin{cases} 1 & \text{if } \theta_d < \theta_i < \theta_d + \Delta\theta_d \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

$$\theta_i = \frac{2\pi}{N_b}(i-1) + \omega_c t + \theta_o \quad (6)$$

and

$$\omega_c = \left(1 - \frac{D_b}{D_p}\right) \frac{\omega}{2} \quad (7)$$

The outer race defect is fixed in location between θ_d to $\theta_d + \Delta\theta_d$, and normally occurs in the unidirectional loading zone; while the inner race defect rotates at the same speed as the rotor ($\theta_i = \theta_{do} + \omega t$) and normally occurs in the unbalance loading zone.

THE ROTOR BEARING SYSTEM

A simple fictitious rotor bearing system is chosen for the numerical simulation. A rigid rotor is supported by a single ball bearing which in turn is mounted on a flexible pedestal. The system contains two lumped masses, viz. lumped mass 1 (the rotor mass M_r) and lumped mass 2 (the pedestal mass M_p) as depicted in Figure 1. Each mass is assumed to have two translational degrees of freedom, denoted as y_1 , z_1 , y_2 and z_2 respectively, resulting in a total of four degrees of freedom.

Tables 1-3 summarize the rotor, bearing and pedestal parameters used in this study.

Table 1: Rotor parameters

$M_r = 3 \text{ kg}$ (Weight = 29.43 N)
$\omega = 1000 \text{ rpm}$
$U = 3 \times 10^{-4} \text{ kg.m}$

Table 2: Ball bearing parameters

$D_p = 52 \text{ mm}$	ω_c/ω	=
$D_b = 11.9062 \text{ mm}$	0.38552	
$K_b = 13.34 \times 10^9 \text{ N/m}^{1.5}$	ω_{bo}/ω	=
$N_b = 11$	4.2407	
$C = 0$	ω_{bi}/ω	=
$C_b = 2940 \text{ Ns/m}$	6.7593	

Table 3: Pedestal parameters

$M_p = 10 \text{ kg}$	$\omega_p = 40706 \text{ rpm}$
$K_p = 200 \text{ MN/m}$	
$C_p = 1000 \text{ Ns/m}$	

PROCEDURE AND RESULTS

In-house transient analysis software was modified to include the above force expressions and applied to the solution of the system equations of motion (Eq. 1). The software utilizes fixed step 4th order Runge-Kutta integration to determine the accelerations, velocities and displacements of all degrees of freedom of the system at any instant of time. A time step of 4096 points per cycle was chosen for all the results presented here. The number of points per cycle was occasionally doubled to check the adequacy of the step size and confirm some of the crucial results.

The output of the final 32 complete cycles of the data at 256 points per cycle was used to generate the frequency spectra, resulting in 4096 lines of components in which the 33rd is the synchronous. Half of the frequency components are displayed, covering a frequency range up to 1067Hz.

Though there are many parameters which may affect results, this paper is limited to displaying the capability of the software rather than carrying out parametric studies or detailed signal analyses. As a result, only limited results from selected cases are presented here.

For the idealized bearing (no defect) running at the above conditions, Figure 2 shows the amplitude spectra of the rotor absolute displacements (y_1 , z_1) and pedestal accelerations (A_{y2} , A_{z2}), and the wave forms of the relative displacements between the rotor and the pedestal (with the DC component in the vertical direction removed) and the pedestal accelerations for two rotor cycles. The corresponding spectra and wave forms for an inner race defect and outer race

defect are shown in Figures 3 and 4 respectively. From the wave form signals it can be seen that the inner race defect excites once per revolution but the outer race defect excites at the ball passing frequency ω_{bo} . These frequencies and their harmonics can also be seen in the displacement spectra. Note that because the system is gravity load dominant ($M_r g \approx 10Y\omega^2$), the outer race defect can only be detected if it is located in the loading zone near the bottom.

The above cases simulated a typical loading situation where there existed both unidirectional and rotational loads, the latter being one tenth of the magnitude of the former. However, it is possible to encounter loading situations where one or other of the load types is completely dominant. Thus, for the case of gravity load only, Figures 5 – 7 show the corresponding results for no defect, inner race defect, and outer race defect respectively. Without unbalance excitation, the signals are dominated by the ball passing frequency ω_{bo} and its harmonics as seen in Figure 5. The once per revolution excitation of the inner race defect is reflected clearly in the spectra.

On the other hand, one may encounter unbalance loads only as when the bearing is supporting a vertical rotor. Figures 8 – 10 show the corresponding results for no defect, inner race defect, and outer race defect respectively. The signals indicate the synchronous, and the ball passing frequency ω_{bi} as well as its harmonics modulated by the synchronous. For this case, the outer race defect has most effect on the responses. The inner race defect is detected only if it is located in the dynamic loading zone of the unbalance force.

Other parameters also affect the vibration responses. Figure 11 shows the spectra and wave forms for a bearing clearance of $C = 0.01\text{mm}$, all other parameters remaining the same as those for Figure 10 (ie. outer race

defect and unbalance load only). It can be seen that the results are noticeably different.

Figure 12 shows the spectra and wave forms corresponding to the case similar to that for Figure 3 (ie. inner race defect, unbalance and gravity loads) except for defect size and direction. Instead of a 0.1mm deep dent covering 10 degrees of circumferential extent, the defect is now an extrusion of $1\mu\text{m}$ height covering only 2 degrees on the inner race. The effect of this different type of defect is seen to be quite significant.

CONCLUSIONS

The in-house developed transient analysis software has been extended to simulate the effects of rolling element bearing race defects. Simple numerical examples using a deep groove ball bearing show that the program is capable of predicting the effects of such defects. It is shown that inner or outer race defects affect the vibration behaviour of the bearing differently, depending on the loading and running conditions, and on the defect size and location.

ACKNOWLEDGMENT

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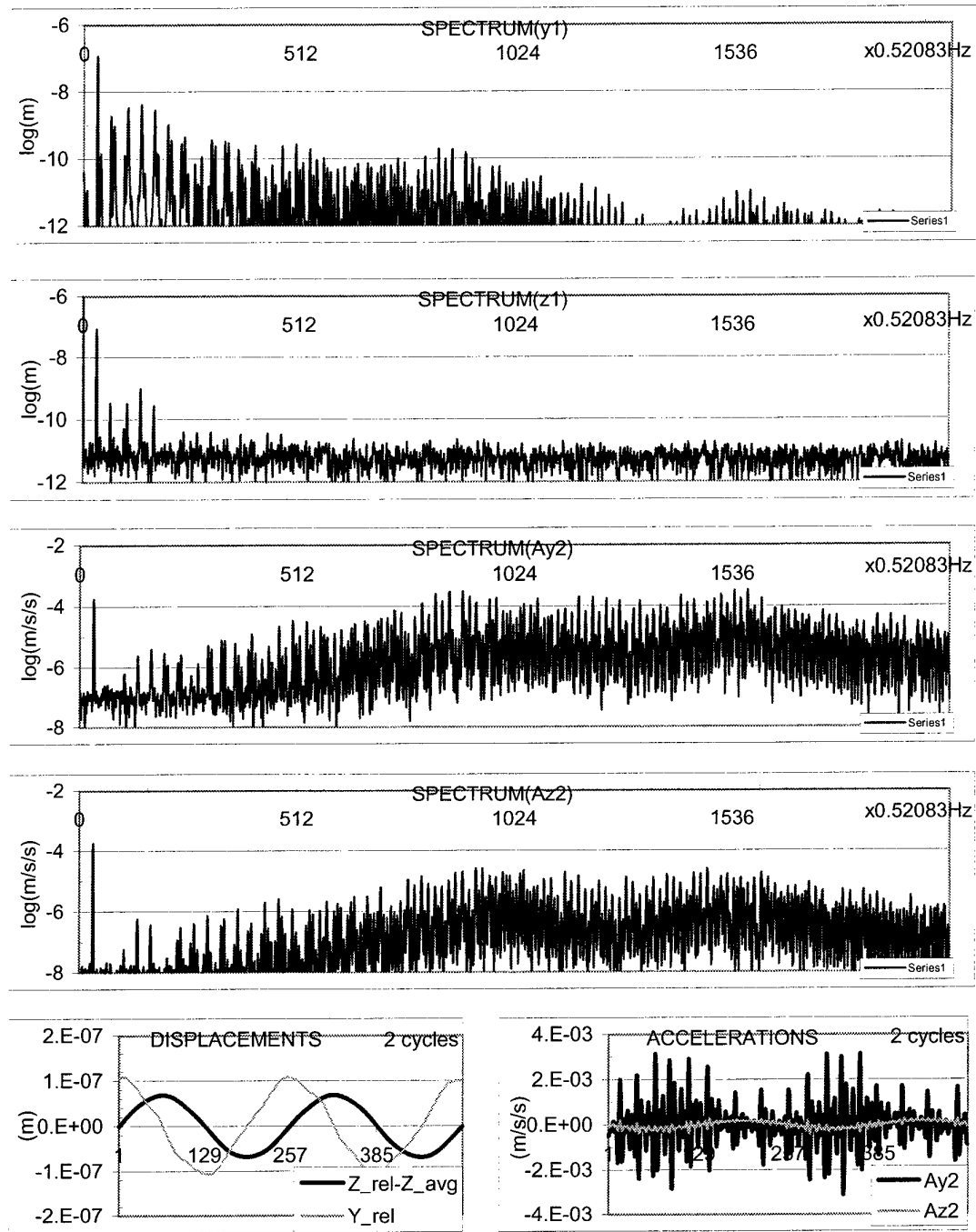


Figure 2: Spectra and wave forms (no defect, unbalance and gravity load)

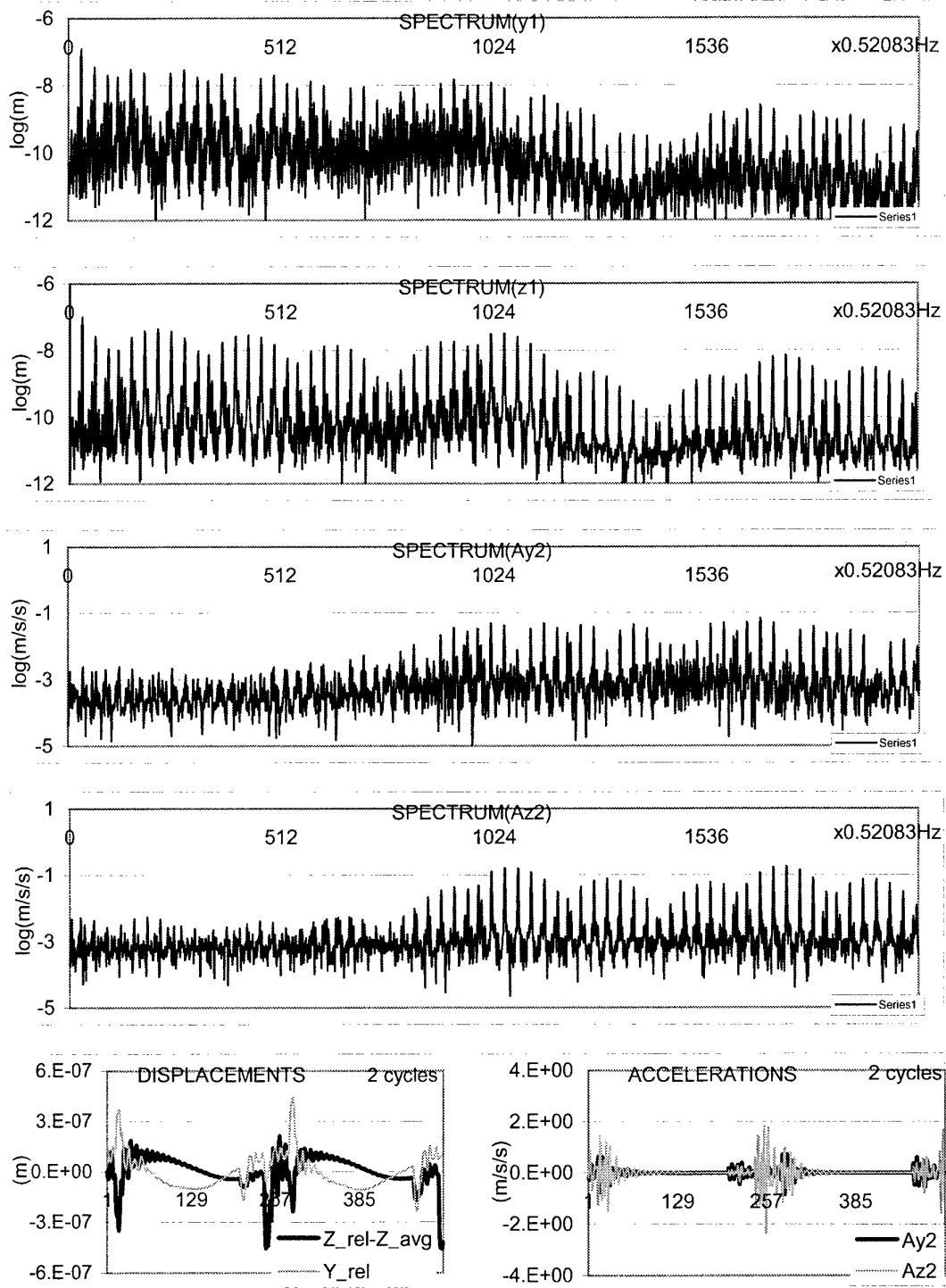


Figure 3: Spectra and wave forms (inner race defect($\theta_{do} = -90$ deg., $\Delta\theta_d = 10$ deg.), unbalance and gravity load)

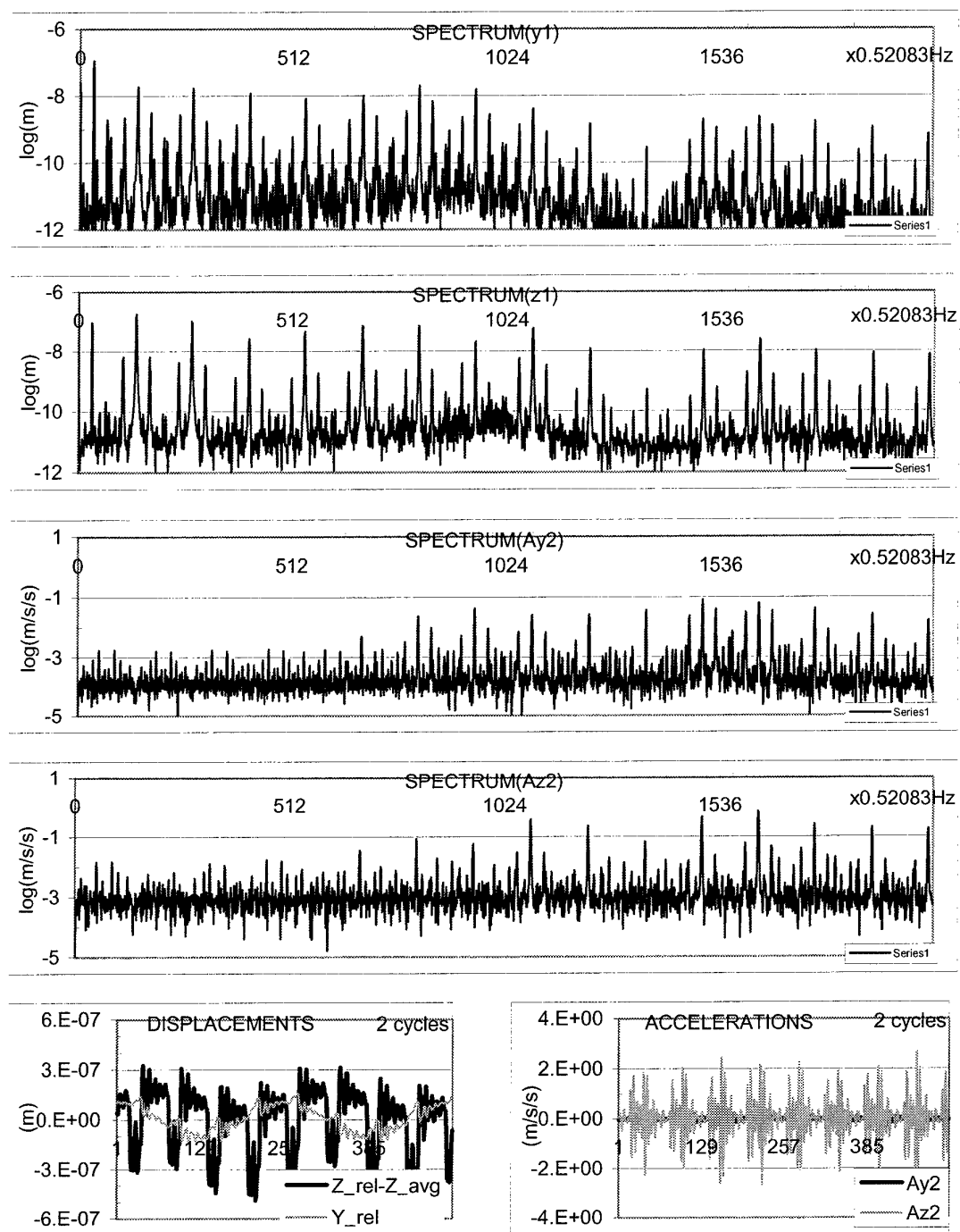


Figure 4: Spectra and wave forms (outer race defect($\theta_d = -90^\circ$, $\Delta\theta_d = 10^\circ$), unbalance and gravity load)

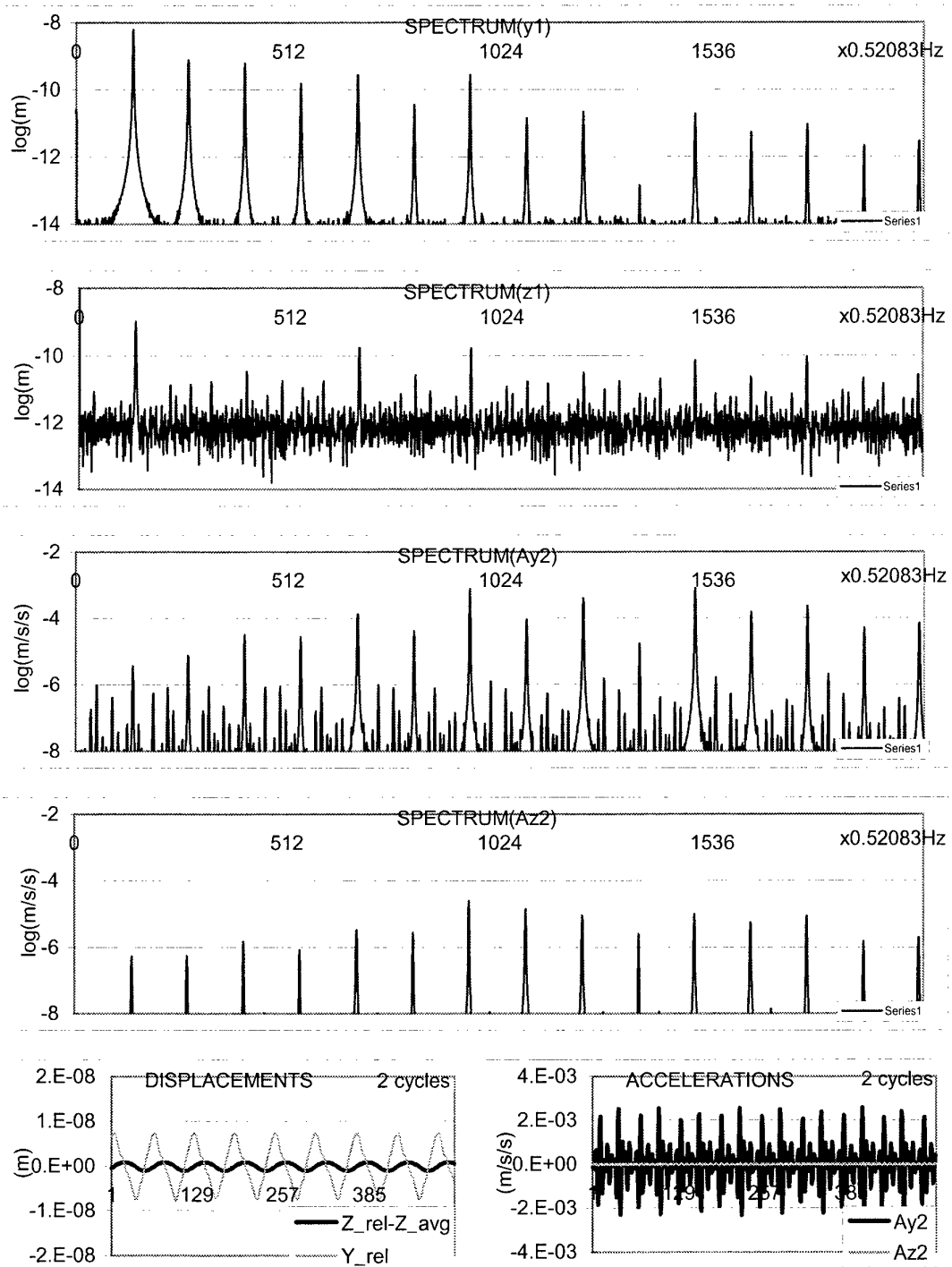


Figure 5: Spectra and wave forms (no defect, gravity load only)

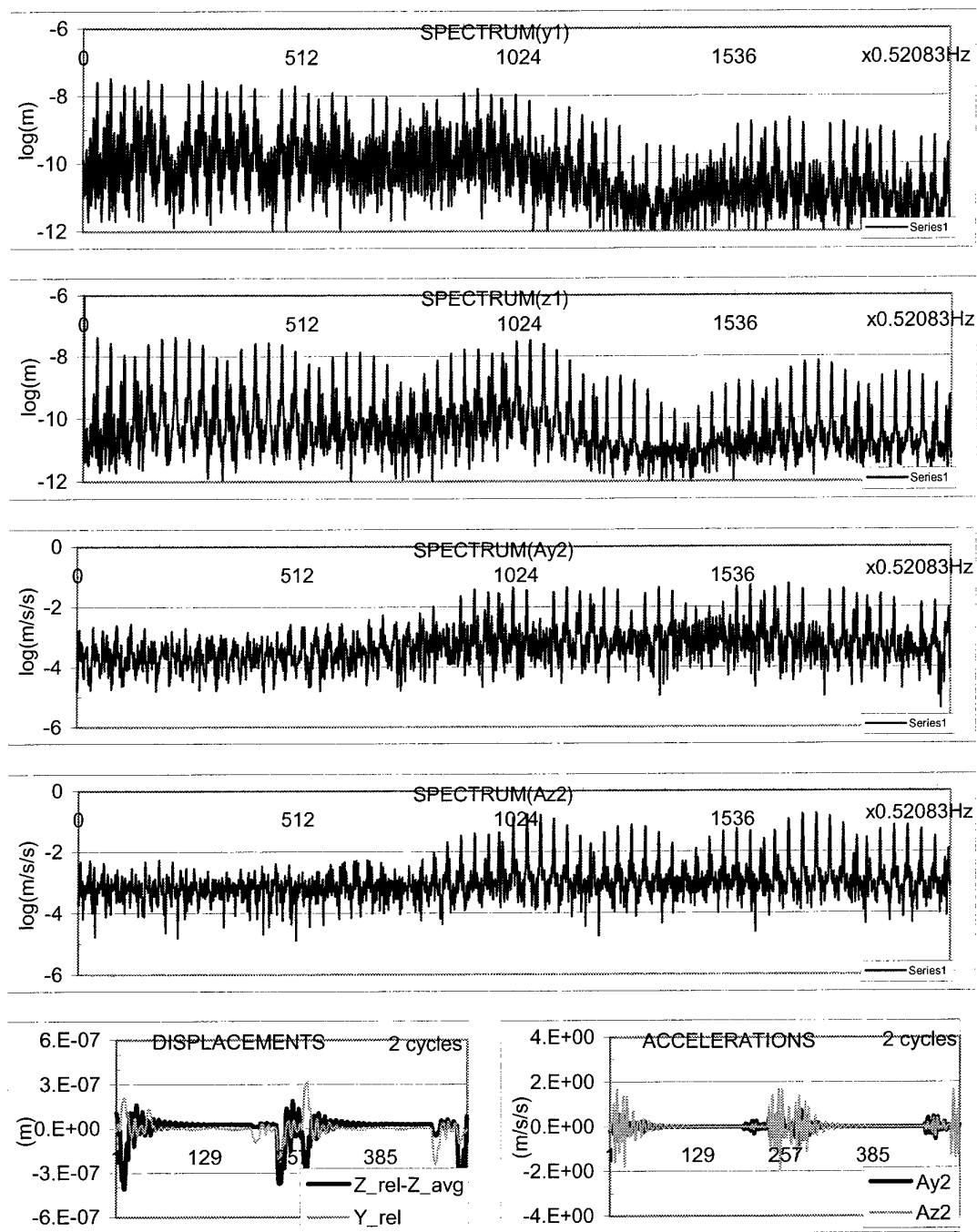


Figure 6: Spectra and wave forms (inner race defect($\theta_{do} = -90 \text{ deg.}$, $\Delta\theta_d = 10 \text{ deg.}$), gravity load only)

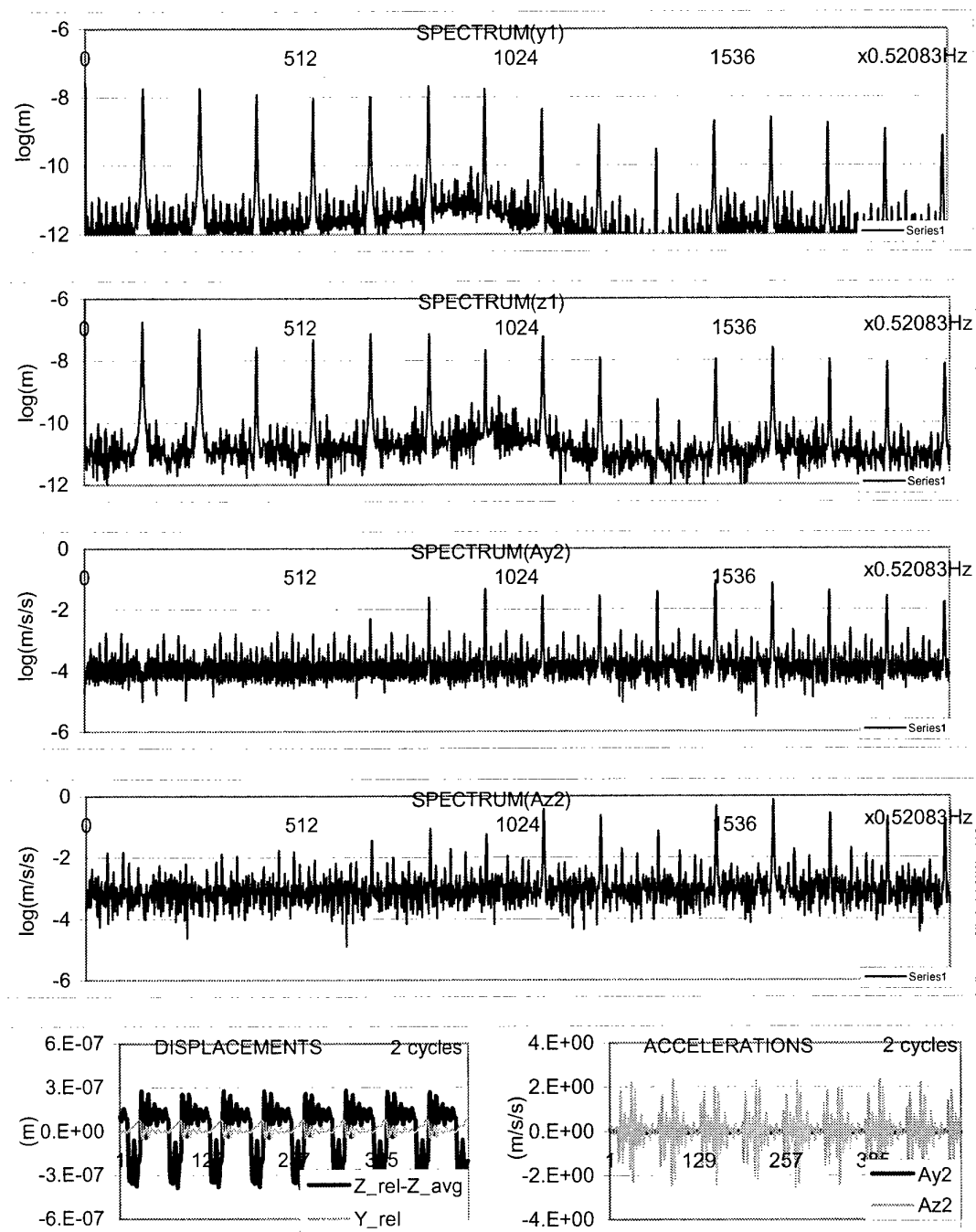


Figure 7: Spectra and wave forms (outer race defect($\theta_d = -90$ deg., $\Delta\theta_d = 10$ deg.), gravity load only)

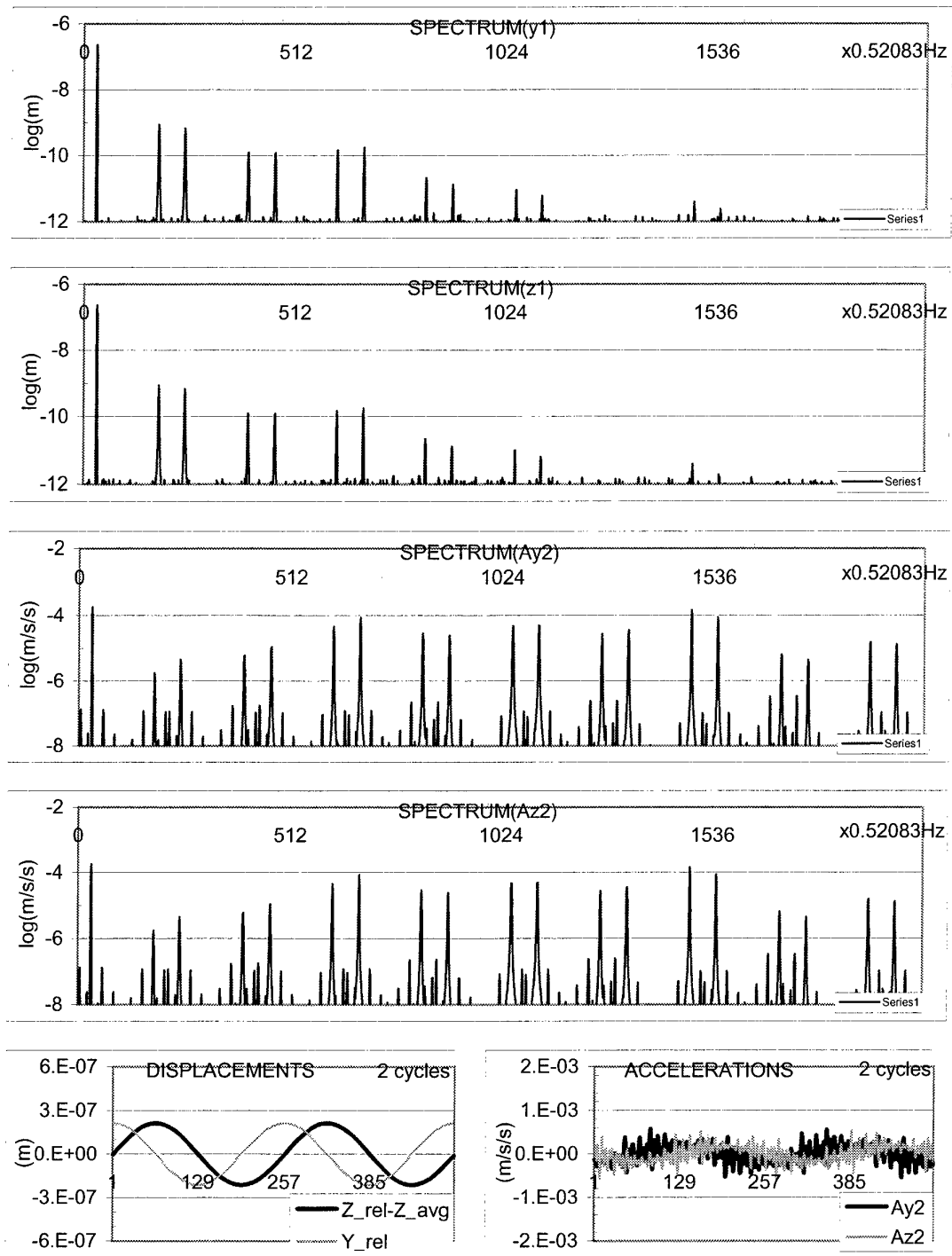


Figure 8: Spectra and wave forms (no defect, unbalance load only)

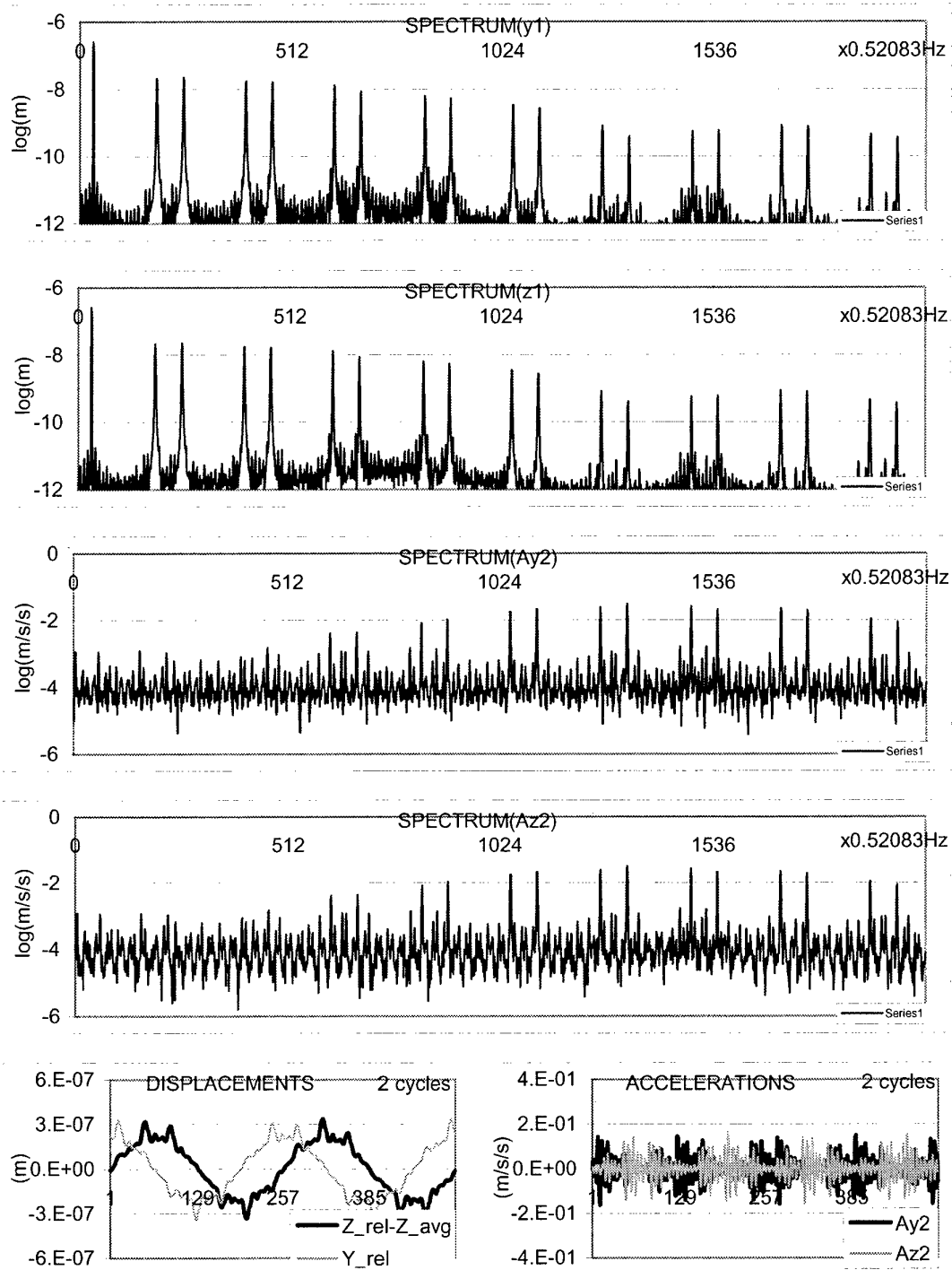


Figure 9: Spectra and wave forms (inner race defect($\theta_{do} = -90$ deg., $\Delta\theta_d = 10$ deg.), unbalance load only)

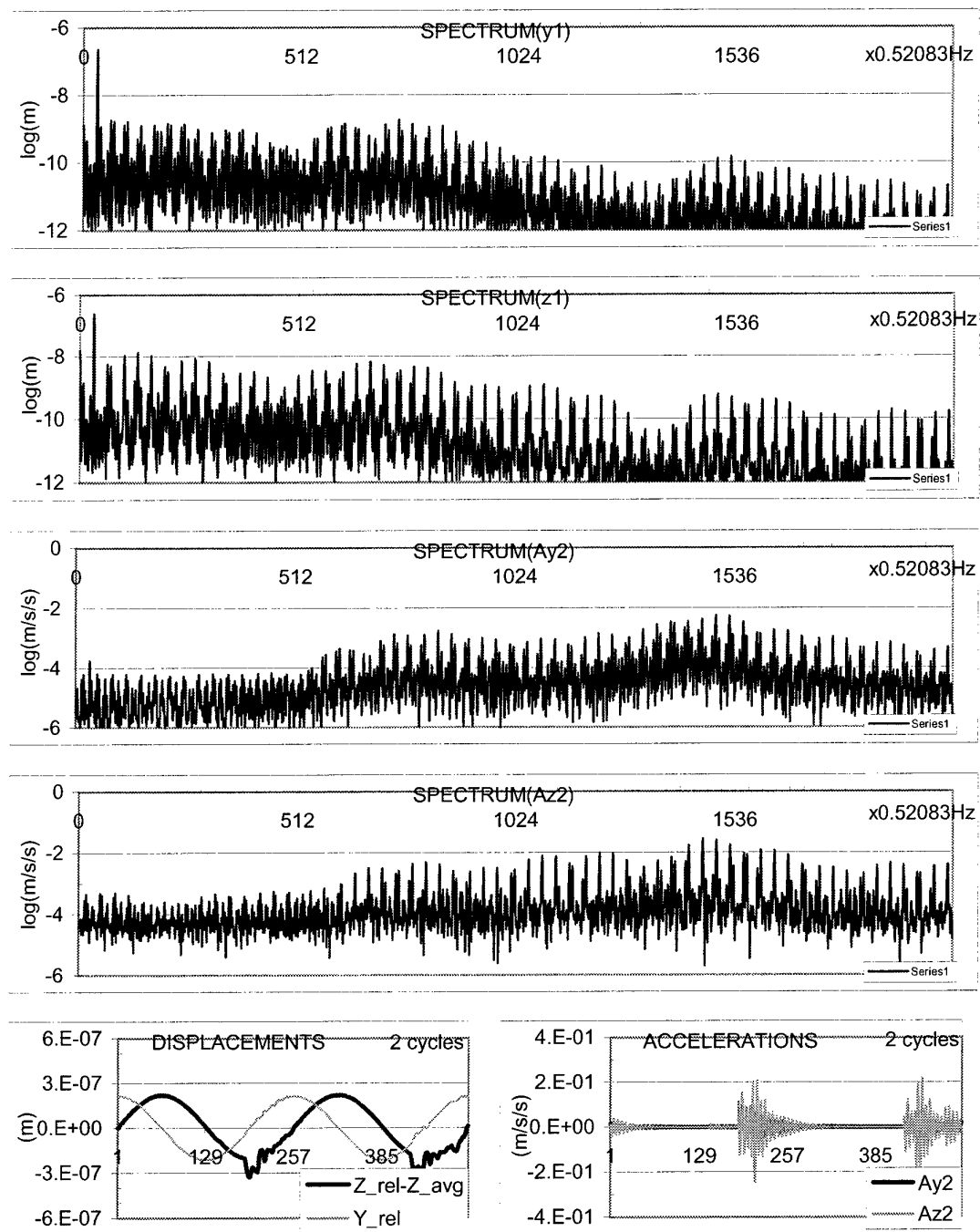


Figure 10: Spectra and wave forms (outer race defect($\theta_d = -90 \text{ deg.}$, $\Delta\theta_d = 10 \text{ deg.}$), unbalance load only)

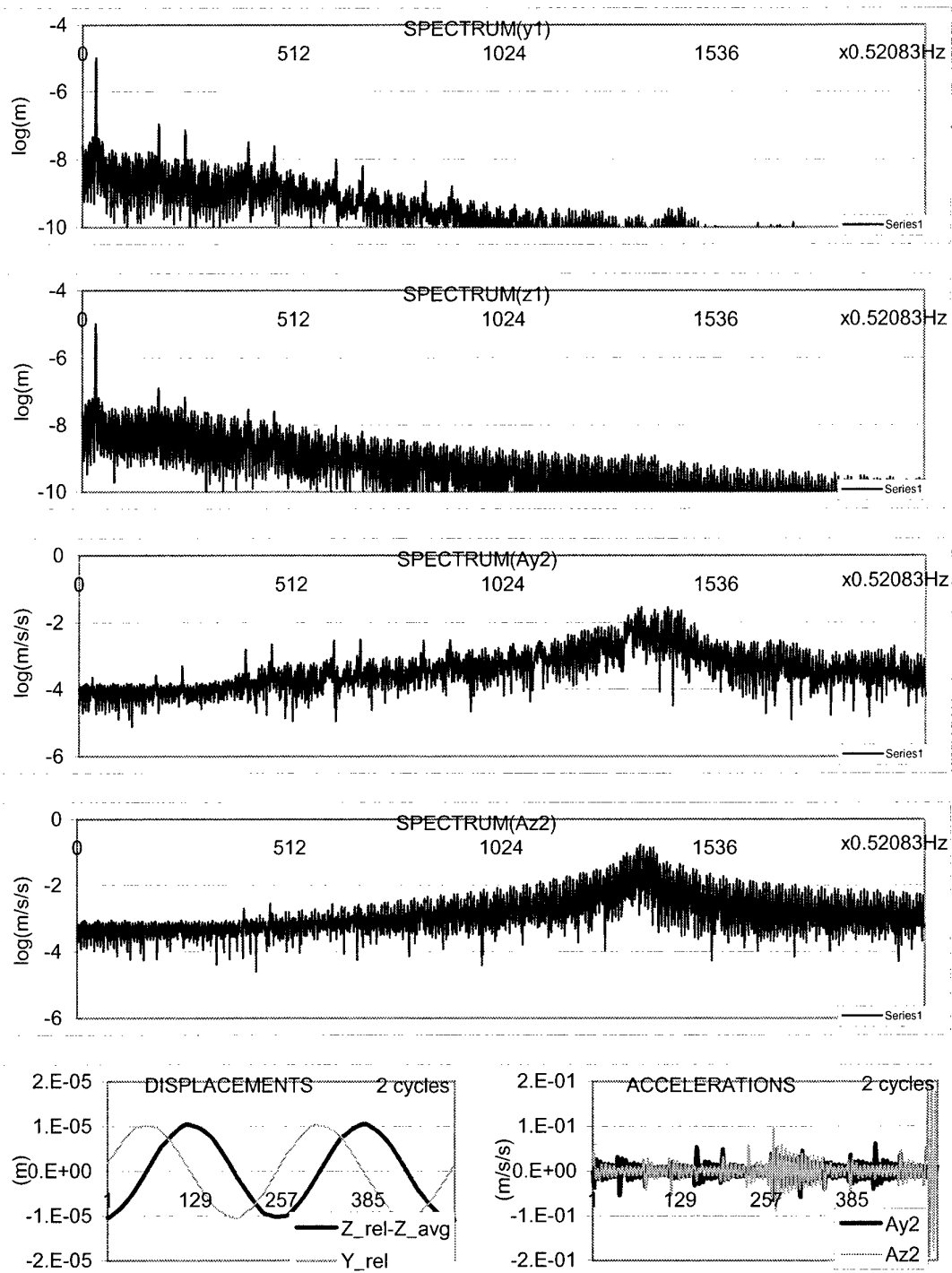


Figure 11: Spectra and wave forms (outer race defect($\theta_d = -90$ deg., $\Delta\theta_d = 10$ deg.), unbalance load only, $C \equiv 10^{-5} m$)

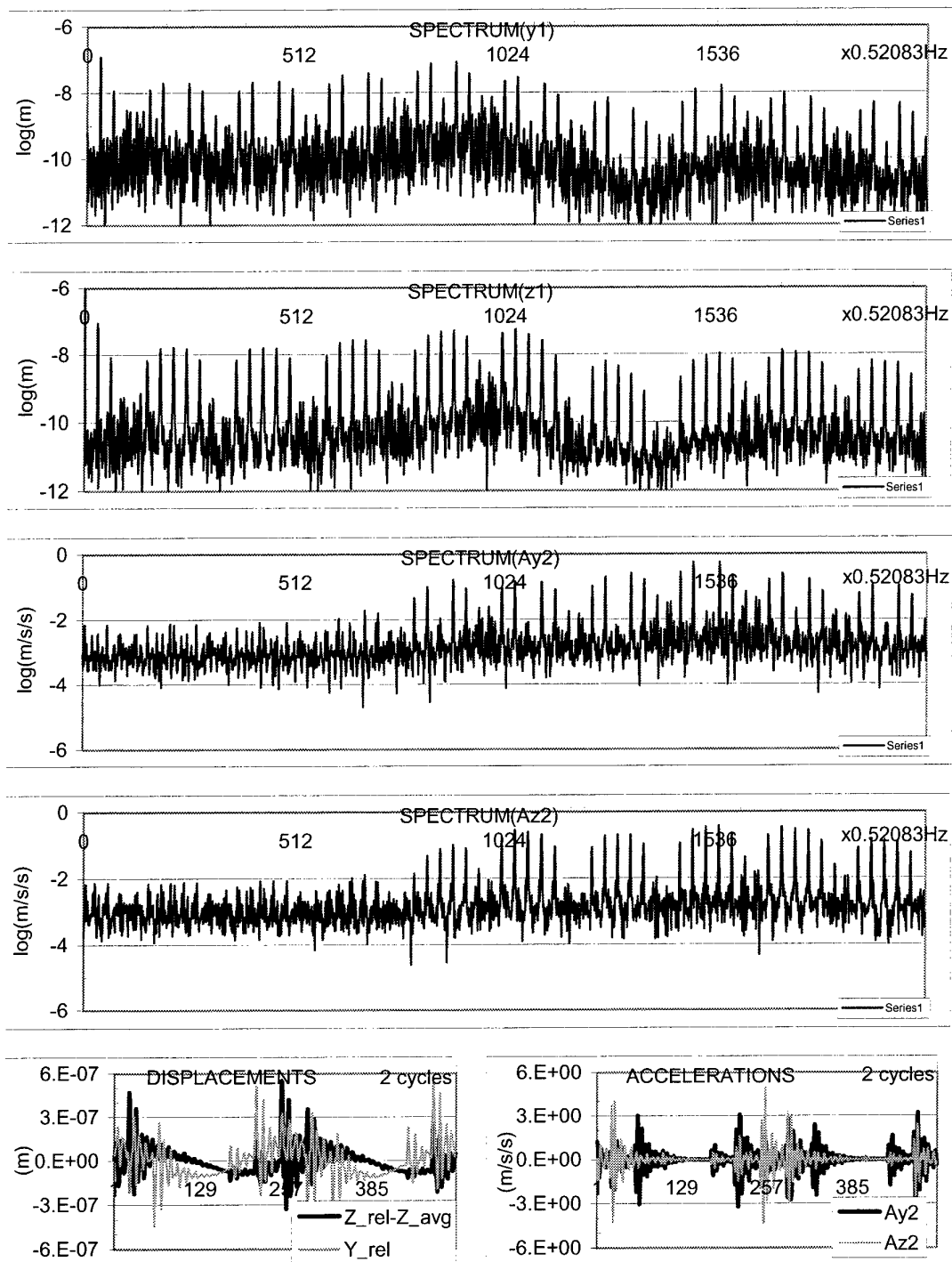


Figure 12: Spectra and wave forms (inner race defect($\theta_{d0} = -90 \text{ deg.}$, $\Delta\theta_d = 2 \text{ deg.}$, $C_d = -10^{-6} \text{ m}$), unbalance and gravity load)

Specifications for an Unified Strain and Flight Parameter Based Aircraft Fatigue Usage Monitoring System

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ABSTRACT

In the current environment of decreasing budgets, the need for an accurate and reliable fatigue usage monitoring system is of increasing importance to ensure the safe and economical utilisation of fixed winged aircraft, which are expected to last longer than ever. Strain based in-flight data recorders are perceived to provide an increase in accuracy over the conventional fatigue g meter, and have thus been implemented by many military fleet operators worldwide. Although this may be the case, these new generation recorders and the systems required for fatigue damage interpretation are complex, and many problems can arise with their use.

Military airworthiness regulations mandate the use of fleet fatigue monitoring systems, however these regulations are open to interpretation and thus the implementation of monitoring systems is variable. The open literature contains many examples of the implementation of monitoring hardware, yet there is a dearth of details regarding the philosophy chosen for their utilisation.

This paper proposes requirements, for implementation of a reliable fatigue monitoring system in modern agile military aircraft. These requirements aim to reduce undue conservatism in the estimation of fatigue accumulation by ensuring that the system is scientifically robust and as accurate as possible. It is hoped that these requirements will form the basis of a future specification for individual aircraft monitoring systems.

1. Introduction

As has been the convention for some time, military aircraft will continue to be procured with incorporated in-service (or as otherwise known as "fatigue") usage monitoring systems. These form one part of the Service Life Monitoring Program (SLMP) for the aircraft fleet. In fact the requirement for usage monitoring is mandated by several design regulations (eg.):

Def Stan 00-970 [1], "...each aeroplane should be fitted with a compact, robust and reliable recording instrument which monitors the usage of the major structural components. This may record

an indirect parameter such as normal acceleration, or a direct parameter such as strain for each component to be monitored. Each parameter should be chosen so that the most damaging loading actions on the component can be determined".

USAF Military Standard [2], ".... An airborne data acquisition system is required that collects and stores flight data which can be used to determine maintenance and inspection intervals The data acquisition system shall be capable of recording operational usage data and shall be compatible with the airframe and all air vehicle systems when installed and used. The system shall interface with the air vehicle systems and record the required data within required accuracies".

These standards specify the requirement and objective of implementing Individual Aircraft Tracking (IAT) and/or Operational Loads Monitoring (OLM) programs. OLM programs aim at direct measurements of parameters necessary to define actual loads experienced by the airframe. OLM systems have traditionally been more comprehensive than those used for IAT, as the results of OLM programs are used to define IAT programs.

Although the standards specify the need for a data recording system, albeit with differing emphasis (see above), they allow much scope for variation in the implementation of the systems and interpretation of the data. The same scope exists in the Royal Australian Air Force (RAAF) requirement [3] which is based on Def Stan 00-970.

A review of open English literature, detailed in [4], has found many examples of the implementation of usage monitoring hardware. However there is an obvious lack of reporting on the details of the philosophy intended for selection of the hardware requirements and the utilisation of the collected data. It is therefore not surprising that numerous and varying philosophies are used to varying degrees of success by various operators to monitor accumulation of fatigue damage for individual aircraft types. In summary, there is no recognised standard for the implementation of SLMP.

In light of the above contentions, this paper presents a set of generic requirements for achieving a reliable monitoring system for primary load carrying (safety of flight) structural members of agile aircraft. This paper builds on the unified monitoring philosophy previously proposed by Molent [5, 6, 7] which will be briefly summarised, and stems from a review of the RAAF's F/A-18 SLMP [8, 9]. The defined requirements were derived to meet the objectives of the proposed philosophy.

It is hoped that these requirements will eventually form part of a guidance / specification document for SLMP implementation. This will assist the fleet manager/program office in avoiding some of the potential problems associated with some SLMPs and thus aid in achieving the full potential that in-service usage monitoring can offer.

This paper will concentrate on the requirements for highly agile aircraft. Other aircraft types may not warrant the same level of consideration as will be outlined, however each should be considered based on the uniqueness and complexity of the missions performed. However the principles described should be applicable regardless of the aircraft type.

2. In Service Monitoring Objectives

The minimum objectives of a SLMP are considered to be to:

1. enable the safe fatigue life or inspection intervals to be determined for individual aircraft by:
 - a) tracking individual aircraft damage accumulation against design loads, or *more importantly against fatigue substantiation tests*⁶;
 - b) accumulating fleet and Squadron usage statistics, in terms of mission type severity, Point In The Sky (PITS - velocity, normal acceleration and altitude) utilisation, stores and their utilisation. Classifying different operational roles

⁶ From a safety perspective, aircraft should not be operated beyond the life demonstrated through testing (eg. potential onset of wide spread fatigue damage, next critical location unknown etc)

- provides the opportunity to reduce fatigue accumulation through mission management;
- 2. accumulate operational statistics to assist in the design or acquisition of new assets;
- 3. determine whether design limits were exceeded;
- 4. determine when maintenance action is required for individual aircraft (see [10] for example; and
- 5. provide feedback to the operators on aircraft fatigue accumulation on a timely basis.

If these objectives are met the role of a SLMP should be to provide the fleet manager with the information necessary to estimate the life-of-type, minimise the impact of usage variations on the operational readiness of the fleet, maintain flight safety and estimate through life cycle costs. Its implementation should enable the estimation of fatigue accumulation to be made on a scientifically robust basis and to be as *accurate as possible* (within economical restraints) thus reducing undue conservatism.

The SLMP should also be capable of accommodating evolving improvements as they are developed or become available.

3. Challenges for Agile Aircraft SLMP

Modern highly agile aircraft, like fighters, present particular challenges for fatigue usage monitoring. These include accounting for:

- ◆ Highly optimised structure with potentially large numbers of critical locations;
- ◆ Non-linear variations of loading with PITS due to adaptive control systems and high lift devices;

- ◆ Rapid control movement and thus rapid load fluctuations;
- ◆ Multiple mission types utilising various PITS and aircraft stores configuration;
- ◆ Significant variations within specific mission profiles [7];
- ◆ Significant asymmetric aerodynamic loading [11];
- ◆ Significant aerodynamic buffeting due to high angle of attack performance; and
- ◆ Aircraft "growth" and updates.

Considering the first point for illustration, the large loading variations experienced by modern fighters, coupled with the non-linear relationships between loading (N_z) and Wing Root Bending Moment (WRBM) or component stress at varying PITS⁷, leads to the conclusion that simple approaches to fatigue life monitoring are inappropriate. Therefore simple (constant) relationships between flight parameters and local stress (and thus simple monitoring systems) cannot accurately account for all loading actions experienced by the aircraft.

This precludes reliance on N_z counters, assumptions of constant operational PITS and thus uniform mission damage, and the use of constant linear transfer functions between loading and component stress.

For aircraft with significant fuselage lift contributions, the maximum WRBM (which generally drives the fatigue damage at the inner wing and centre fuselage) may not correspond to the maximum N_z [8]. It was shown for the F/A-18 that the two maxima could lag by as much as 2 seconds.

As an example of the affect of the above, a comparison of (WRBM induced) strain and N_z fatigue damage, using the same damage model, was conducted for a sample of F/A-18

⁷ As an example, the WRBM to wing attachment bulkhead strain response is non-linear and varies significantly with PITS for the F/A-18 [8].

spectra [8]. The transfer function relating N_z to the critical location was chosen to represent average PITS. This investigation revealed that the damage calculated from N_z data was approximately between 1.2 and 1.4 times that of the strain-based damage. Although this does not imply which data set produces the most accurate estimate of fatigue damage, it does indicate the level of difference achieved in analysing the two data sets. Systems in modern high performance aircraft that rely solely on N_z may experience a similar discrepancy.

These challenges also influence the decision between OLM and IAT. Generally, the SLMP philosophy should be applicable to a sample of fleet aircraft ("OLM") or to each aircraft in the fleet ("IAT"), dependant upon

fleet size, aircraft role variations and operator requirements. Economics may dictate that OLM be implemented, however it is considered that highly agile aircraft will have considerable usage variations within nominally similar missions thus favouring IAT.

4. General Fatigue Usage Monitoring Tools

Current universal fatigue usage monitoring tools are summarised in Table 1, along with their perceived advantages and disadvantages.

Table 1: Fatigue Monitoring Tools

Tools	Advantages	Disadvantages
1. Flight Hours	- No equipment needed - Simple/Cheap	Assumes each aircraft flies identical spectrum
2. Landing/Flight Cycle Counts	- No equipment needed - Simple/Cheap	- As above - Only applicable to landing and pressurised structure
3. Counting Accelerometers (N_z Based)	- Simple/Cheap - Robust (Note: normally augmented by pilot recorded flight time, mission type, stores and weight - assumed to apply for entire flight)	- Only components affected by N_z can be monitored N_z normally recorded at a fixed nominal CG location - Difficult to validate N_z data - Asymmetric loads not considered - Fixed N_z "trigger" levels - Time history lost - Weight and PITS must be assumed (conservative) - Transfer function between N_z and stress at critical location required
4. Range Pair Antennas (Strain Based)	- Relatively cheap - Directly monitors principal component - Some data processing conducted on-board	- Time history lost - PITS must be assumed - Difficult to validate data - Difficult to account for missing data - Reliability of sensors - Sensor calibration difficult due to data format

Tools	Advantages	Disadvantages
5. Multi-Channel Recorders (Parametric Systems)	• Can monitor flight parameters as well as strain • Time history retained • Can be used for other investigations (incidents, over-stressing)	<u>General:</u> • Expensive and normally production interfaced with flight computer • Software and post-processing intensive • Data validation needed <u>With Strain Gauges:</u> • Difficult to determine sensor locations • Sensors require calibration • Requires high reliability of sensors, amplifiers etc <u>Parameters Only:</u> • Large loads development program required • Abrupt manoeuvres, gust and buffet loads not accounted for
6. Optical Fibre Strain Monitoring, eg. [13]	• Insensitive to electro-magnetic interference • Replaces strain gauges - improved reliability • High strain resolution	• Needs development

For the reasons outlined in Section 3, flight hour, flight cycle and Nz counting are inappropriate for monitoring advanced agile military aircraft and will not be considered further in this paper.

Strain based in-flight data systems have been perceived to provide an increase in accuracy over the conventional systems, and have thus been implemented worldwide by many military fleet operators, for high performance aircraft.

This increased accuracy is principally achieved because judicious placement of the strain gauges can account for both aircraft weight and stores effects, and the variation of principal loads, such as WRBM, at various PITS constituting the flight envelope.

Strain range pair data counters have the advantage of a limited capability of on-board data processing, thus lessening the amount of data storage and processing required once the data is extracted from the aircraft. These systems were introduced in times when data storage limitations and data processing time were significant considerations. However, modern computers have alleviated these

considerations to a large extent. As noted in Table 1 difficulties arise with validating data in a tabular range pair format, in the absence of associated flight parameters [14], and the problem of determining strain gauge calibration factors⁸ [15] from data in range pair format are considered to outweigh the potential advantages of these counters.

Flight parameters alone can be used to estimate the dominant load affecting each critical component, and coupled with the use of transfer functions, can be related to stresses at critical locations. Although reasonable levels of accuracy can be achieved compared to strain based systems (as shown in [8, 17]), "parameter-only" based approaches (using standard flight parameters) cannot account for abrupt manoeuvres⁹ and gust loads nor directly measure buffet loading which, for

⁸ Gauges at nominally identical locations but on different aircraft will produce different responses for the same loading. Thus gauge response needs to be calibrated to a common reference. See [8,16].

⁹ Flight trials used in the load development process are normally conducted by an experienced test pilot whose flying techniques is normally less abrupt than less experienced squadron pilots.

certain components, may contribute significant fatigue damage.

Peak and valley load monitoring is favoured over continuous monitoring, providing the data is time tagged, as the damage contributing load levels are captured and can be stored in an efficient manner.

For the above reasons strain peak and valley based systems are the preferred option in the proposed philosophy [5]. However it will be shown that parametric based techniques have a significant role to play in a strain based system and these can provide an alternative monitoring capability (see Section 6.1). The resulting systems required for accurate fatigue damage interpretation are complex, and many problems can arise with their use. A major issue to consider is that of monitoring philosophy.

5. Load or "Hot Spot" Strain Monitoring Philosophy

Fundamental to the success of any SLMP is the identification of all critical structural locations to be monitored in conjunction with an airworthiness management plan. These locations can be chosen for several reasons ranging from flight criticality¹⁰ through to maintenance considerations.

Before deciding on the locations of strain gauges, the philosophy to be used to meaningfully relate the strain recordings to fatigue accumulation at critical locations must be established.

There are two generic philosophies, namely "loads" or "hot-spot" monitoring of critical locations. With loads monitoring, strain gauges are placed to monitor the primary

loading action affecting a structural component. With hot-spot monitoring the strain (and thus stress) at preselected critical locations is directly monitored.

However as stated in [5], several problems can arise from adopting the latter philosophy, namely:

- the sensor may not be dominated by the principal damage inducing load. A particular problem here is that it may be difficult to calibrate the sensor response;
- the hot spot may have a high stress gradient. Due to the short fixed active length of a strain gauge and positioning errors, there is no guarantee that the maximum strain is actually monitored or replicated on all aircraft;
- if a new hot spot arises, and the existing gauges do not respond predominantly to the load affecting this new location, then there will be no data available for assessment. Even if the option of placing an additional gauge exists, the problem of "filling-in" for past damage remains; and
- the hot spot may not be readily accessible and thus the sensors are not readily replaceable.

There are also perceived disadvantages with the loads monitoring philosophy including:

- Structural configurations differences are directly monitored with a hot-spot gauge, but must be considered separately (possibly by separate transfer functions) when load monitoring;
- A transfer function is required between primary load and critical location; and

¹⁰ Critical or primary structure: failure of which may directly result in the structural collapse, loss of control or motive power, unintentional operation or inability to operate essential services, or cause injury to any occupant [3].

- Load path variations are difficult to differentiate from normal strain gauge variations¹¹.

However it is considered that these are significantly outweighed by the hot-spot monitoring disadvantages. Therefore the unified approach proposed in [5] and summarised in this paper favours the use of the strain based load monitoring philosophy as the major SLMP component, complemented by parametric flight data measurements to aid in data verification. To enable monitoring of the principal load inducing the fatigue damage at the critical locations, the location of the gauges must be carefully chosen. In particular, care must be taken to ensure that the location of the sensor:

1. is dominated by the principal load (eg WRBM) and insensitive to other loading actions;
2. can be calibrated to the principal damage inducing load;
3. is in an area of low stress gradient;
4. can be directly related¹² to the stress at critical structural locations;
5. is replicated on the fatigue test article (see Section 2 - 1a) so that direct comparisons can be made [1]; and
6. not be prone to gauge "drift" (varying response to a nominal load over time¹³) or on a load path of a highly redundant structure which can be subjected to load redistribution [5, 11].

Although there are also logistical problems that arise from the use of strain gauges [5, 6, 8, 9], the main reasons they are considered necessary are that they:

- Can account for complex, non-linear and time dependant loading actions, typical of fighter aircraft;
- Are sensitive to abrupt manoeuvres and gust loads, and are able to directly measure buffet loading which for certain components may contribute significant fatigue damage; and
- Provide a direct relationship between individual aircraft and the test article, given those gauges are placed at nominally identical locations. This provides a direct measure of damage, rather than an indirect measure via load parameters which have an inherent error associated with the loads model development.

The following sections provide brief details of an optimised strain based system and indicate areas where parametric data are required.

6. Components of the SLMP

The number of strain gauges necessary to monitor all significant principal loads and the flight parameters to be recorded dictate the requirements for the Data Recording System (DRS) with the capability to record the recommended flight parameters and strains at the required rates. The gauge selection is determined by the particular aircraft configuration and is not discussed here. The list of flight parameters is summarised in Section 6.1. Once installed for a given aircraft type, there is still much processing to be conducted before the in-flight data can be used to assess the fatigue usage of an aircraft. After data retrieval a fatigue tracking system requires the following capabilities:

¹¹ Load path variations will not be identified by a parameter only based SLMP.

¹² Preferably by a linear relationship for both positive and negative loads.

¹³ F/A-18 WR lugs is an example of this, see [8].

1. *Pre-Processing of Collected Data:*

Generally, a code is required to format aircraft unique data so that it can be processed. The DRS should contain records which identifies the aircraft (tail number), date, mission type or Type Of Flight (TOF), stores, fuel weight, pilot identification, active sensors, missing sensor initialisation and data hours (generally from landing and take off codes) for each flight.

- Extract strain and flight parameter data;

2. *Data Checking Module* which should provide, as a minimum, the following functions:

Using the extracted data it should:

- Determine inoperative sensors (by comparing recorded against parametric based strain) and create a sensor log;
- Validate data and replace bad data by using flight parameters relationships;
- Compensate for missing data ("fill-in") by using flight parameters relationships or TOF damage; and
- Ensure aircraft and mission descriptors are correct.

3. *Data Conditioning Module*, which should:

- Calculate CG and weight of aircraft accounting for stores configuration, fuel consumption and other consumables (eg. ammunition) usage; and
- Normalise aircraft weight (to test article basic configuration); and then
- Perform strain sensor calibration by comparing response at specific PITS with a reference set of strain data;

4. *Sequence Counting Module:*

The module may be required to build a Rain Flow Counted¹⁴ (RFC) strain spectrum on a flight by flight basis. This provides damage on a mission and TOF basis and allows the squadron manager to assess the damage accumulated in each flight.

5. *Fatigue Damage Module*, which;

Calculates damage and fatigue indices for each flight for each critical location considered, based on crack initiation or growth algorithms calibrated against the appropriate fatigue durability test.

6. *Post-Processor Module*, which:

Should also update the cumulative "all time" damage database for each aircraft, and check if the accumulated damage equals target values, and warn if the damage rate exceeds a predefined design rate.

Updates a database file which contains fatigue indices and usage statistics for each aircraft processed through the SLMP, and the documentation file of the current software run. Produces a summary report, which includes all detected data anomalies, fatigue indices and usage statistics.

7. *Reporting to Fleet:*

The results must be interpreted and provided to the operator in a timely fashion. This is essential for pro-active fleet fatigue management.

- Tabulate PITS exceedance data and as means of qualitatively reviewing the trends and validity of the usage.

Each of these steps are necessary in a SLMP. It should be stressed that as the through life cost of maintaining the above mentioned

¹⁴ Also known as range-pair or hysteresis loop counting.

ground based system often far exceeds the cost of the on-board DRS [18], appropriate consideration must be given to these steps before the particular hardware and integrated processing system is chosen. Some of the more important issues identified above are discussed in detail in [5, 6, 8].

6.1 Required Flight Parameters

Flight parameters have an important role in the SLMP. They are required to calibrate, validate and fill-in for missing strain data. Further they can provide an independent check of the damage calculated via the strain gauges, as recommended in [6].

To achieve the former three requirements, sufficient synchronously monitored parameters are required to estimate the recorded strains to a desired level of accuracy. For example, it has been shown [17] that for empennage sensors the following parameters are significant:

- angle of attack;
- stabilator deflection;
- rudder deflection;
- trailing edge flap deflection;
- yaw rate;
- pitch rate; and
- aileron deflection.

6.1.1 Flight Test Data

As strain to flight parameter relationships are required in this proposal, these can only be developed if a substantial amount of flight test data at sufficiently high frequency is available, covering the full operational PITS and configuration variations of the aircraft. Flight trial data should include the necessary synchronous flight parameters, strains and primary loads as recorded by in-flight load bridges. Further ground calibration of the test sensors to known loads is required.

6.2 Fatigue Indices

An important product of any SLMP should be a number that indicates the fatigue accumulation status (amount of fatigue life consumed) or inspection threshold for the airframe. This number is normally referred to as the Fatigue Life Expended Index (FLEI).

The implemented SLMP should compare the usage of an individual aircraft to that of a representative fatigue test article. As an aircraft is designed and certified to a safe life or damage tolerant philosophy, when the damage accumulated on a particular aircraft matches that calculated to have been imparted to the test article at the completion of testing, with appropriate scatter factors applied, the aircraft is said to have consumed its safe life or reached an inspection threshold. The duration of all fatigue tests incorporate an appropriate scatter factor on design life which depends on the design specifications:

The test substantiated fatigue life is referred to as the Fatigue Index (FI). At full test life the total damage = FI = 1.0.

$$FI = \sum \left\{ \frac{\text{damage accrued on fatigue}}{\text{test article at demonstrated life}} \right\} = 1.0$$

Therefore a FLEI is defined as:

$$FLEI = \sum \left\{ \frac{\text{calculated damage accrued}}{\text{on aircraft at current life}} \right\} \times SF$$

(flight hours)

where:

- | | |
|----------|--|
| SF | scatter factor applied by the fleet manager |
| Σ | cumulative sum (using same damage algorithm) |

When the FLEI = FI the demonstrated life has been expended and action must be taken.

The FLEI rate should also be calculated to allow the fleet manager to extrapolate to anticipate maintenance action or to take steps (modify operational usage, rotate aircraft etc.) to ensure planned withdrawal date for the asset.

The model used to estimate fatigue damage accumulation should be calibrated against the appropriate fatigue test. It should be demonstrated that the model can accurately predict the initiation of detectable cracks or their growth rates. Further, it is essential to demonstrate (generally through coupon testing) that the model can scale accurately between spectra of varying severity (to cover the usage spread throughout the fleet).

7. The Fatigue Damage Estimation Data Flow

The following is a brief outline of the proposed procedure for utilising recorded strain to monitor a critical location, based on developments to the F/A-18 monitoring philosophy [5], using WRBM induced strain as an example. Here a gauge has been placed close to the Wing Root (WR) structure and has been demonstrated to respond predominantly to WRBM. The same methodology should be applicable to locations affected by other principal loads (eg. horizontal tail bending moment).

- The DRS records WR strain when a peak or valley is identified by the flight computer plus synchronously, all required flight parameters.
- Strain and flight parameter data on the DRS are down loaded periodically from the aircraft.

- The strain data from each strain sensor are initialised at the beginning of each flight by first removing any strain offset.
- Because the response sensitivity of strain sensors vary between aircraft, the strain data is then calibrated so that the same wing load reference condition (PITS) on each aircraft produces the same strain sensor value. This takes account of sensor differences and any drift in gauge response that may have occurred with time. The reference PITS should be carefully chosen to correspond to the PITS at which the majority of fleet flying occurs.
- The strain data is then checked by comparing the measured strains with strain predicted from the flight parameters. Any data deemed to exceed set error limits, or any missing data, are replaced using data "fill-in" techniques.
- The strain data are then normalised¹⁵ with respect to the relevant fatigue test measured response by dividing (or normalising) by the reference strain value which is obtained from applying the reference loading condition to the appropriate fatigue test structure being used as the data reference. This is analogous to producing a transfer function relating WR strain to WRBM at the reference PITS.
- The resulting normalised non-dimensional sequence is then sorted into a sequential peak valley form, before it is RFC (to form cycles of maximum peaks and valleys for fatigue analysis).
- The normalised RFC data are then multiplied by a reference stress, which converts the data into a stress for the critical location at which fatigue damage is

¹⁵ Suggested process. Other methods of determining principal load may be equally applicable.

to be calculated. This reference stress value has been chosen using the fatigue life prediction model (safe life or crack growth), such that at the chosen reference stress level, the damage model will predict the substantiated life for the fatigue test spectrum.

- The data are finally processed through the damage model, to calculate the damage that has accumulated over the data processing period for each aircraft. The result is a FLEI that relates the amount of damage accumulated on each aircraft to the damage accumulated during testing on the full-scale fatigue test article. A safety factor is applied to the result such that when the FLEI has reached 1.0, the aircraft has reached its safe life limit (FI) or inspection threshold.

As previously mentioned, it is prudent to have an alternative SLMP operating in conjunction with the primary SLMP. The FLEI produced by the secondary SLMP should be as independent to that of the primary as possible, so that potential anomalies arising in the primary SLMP can be readily identified. Although the secondary

system is considered necessary, it should impose a minimal additional cost penalty.

8. Proposed Requirements for an Individual Aircraft Tracking System

Drawing from the discussion in Sections 4 and 6, this section presents criteria or requirements for a reliable SLMP. These were developed in consultation with the RAAF Hornet Life Assessment Working Group (HLAWG), see [19], thus representing the views from aircraft fleet managers, structural integrity practitioners, researchers, computer systems operators and aircraft data processors. The criteria presented in Table 2 are a sample of some of the main requirements. A full list is available in Reference [20]. It is the interest of all fleet managers to have comprehensive guidance for the development of a reliable, cost-effective and accurate SLMP.

Table 2: Criteria for Individual Aircraft Tracking System

		Requirement
Philosophy	1.	Individual aircraft must be tracked against fatigue substantiation test results
	2.	SLMP damage calculation should be strain based
	3.	Individual aircraft tracking is required
Loads Monitoring		The following loads are required:
	4.	Wing Root Bending Moment
	5.	Wing Root Torque
	6.	Vertical Tail Bending Moment
	7.	Vertical Tail Torque
	8.	Horizontal Tail Bending Moment
	9.	Horizontal Tail Torque
	10.	Canard Root Bending Moment (if applicable)
	11.	Canard Root Torque (if applicable)
	12.	Fuselage Bending Moment
	13.	Speed Brake Bending
	14.	Engine Loads
	15.	Buffet
Strain Gauge Requirements		It must be shown that the gauge response:
	16.	Is dominated by principal load and insensitive to other loading actions.
	17.	Is in an area of low stress gradient.
	18.	Is protected from the environmental wear and corrosion.
	19.	Is replicated on a fatigue test so that direct comparisons can be made.
	20.	Can be directly related to stress at critical locations.
	21.	Can be calibrated to the damage inducing load.
	22.	Is not prone to gauge drift.
Health Monitoring Requirements		Must record:
	23.	Hard Landings
	24.	Overweight Landings
	25.	Limit load exceedances
	26.	Maximum roll rate exceedances
	27.	Maximum yaw rate exceedances
	28.	Maximum pitch rate exceedances
DRS		Must:
	29.	Record raw data
	30.	Record data synchronously, that is when a particular strain reaches a maximum/minimum, all other strains and flight parameters will be recorded.
	31.	Time stamp all records from the same clock, preferably in absolute time
	32.	Record continually on a separate register strain and flight parameter information at 5 Hz.

		Requirement
		Must:
Data Verification Module	33.	Validate flight parameters and strain data.
	34.	Initialise strain data taking into account different wing stores configurations at take off and during flight.
	35.	Compensate for missing data using flight parameter relationships or Type of flight damage table
Data Conditioning Module	36.	Calculate weight and centre of gravity of aircraft accounting for stores configurations, fuel consumption and other consumables.
	37.	Perform sensor calibration by comparing response at specific Point in the Sky (PITS - velocity, acceleration and altitude) with a reference set of strain data. The mission computer can be programmed to fly the aircraft at specific PITS to ensure appropriate data has been captured.
	38.	Create Peak-Valley strain files.
Damage Module		Must:
	39.	Calculate damage and fatigue indices for each critical location based on fatigue life criteria and/or growth algorithms calibrated against the appropriate fatigue durability test.
	40.	Calculate the fatigue life (or crack growth) accumulation rate (FLAR).
	41.	Be validated against good quality fatigue test results.
	42.	Calculate damage from the strain-based data.
	43.	Be capable of ranking the severity of various spectra.
	44.	Account for phenomena such as strain relaxation and crack growth retardation.
Post Processing Module	45.	Ensure that damage retardation effects in the model are conservative by nature.
		Must:
	46.	Update a cumulative "all time" database file for each aircraft that can be routinely interrogated such that any fatigue related information is readily available.
SLMP System Requirements	47.	Produce a summary report that included all detected data anomalies and usage statistics.
		The system must:
	48.	Be capable of tracking new or additional critical locations
	49.	Account for all Operational Flight Programs (OFP) and Stores Management Versions (SMS).
	50.	Have the capability to monitor individual aircraft structural components (Aircraft components may be interchangeable).
	51.	Be able to be easily modified to account for new features such as new material data, damage model upgrades etc.
	52.	Account for variation in weight over life of type.
	53.	Contain a simple, independent system to monitor damage calculation to ensure system integrity.
	54.	Have software that is computer platform independent allowing for ease of migration as new software versions become available.

9. Conclusions

This paper has defined preliminary individual aircraft Service Life Monitoring Program (SLMP) requirements for modern agile military aircraft. These are aimed at ensuring a scientifically based, economic and accurate fatigue damage monitoring for the aircraft fleet.

This paper has drawn from a previously published unified fatigue monitoring philosophy to develop requirements for its implementation into a SLMP. Further, these requirements have been rated in terms of desirability to represent the views from aircraft fleet managers, structural integrity practitioners, researchers, computer systems operators and aircraft data processors. With further developments it is hoped that these requirements will form the basis of a reference standard or specification to assist aircraft fleet managers develop a reliable SLMP.

In the current environment of decreasing budgets, the need for an accurate and reliable SLMP is of ever increasing importance to ensure the safe and economical utilisation of aircraft. The through life cost of the entire monitoring system far exceeds the initial cost of implementing the recording instruments, therefore due consideration to the monitoring philosophy to be adopted should be given early in the development or acquisition cycle. This should ensure that the cost of the fatigue monitoring system is optimised to deliver more accurate and cost-effective data for the safe and economical utilisation of the platform. The proposed philosophy and requirements are directed at this goal.

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USN Development Strategy, Fault Testing Results, and Future Plans for Diagnostics, Prognostics and Health Management of Helicopter Drive Train Systems ¹

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Abstract—A US Navy strategy was generated and is still evolving to develop and demonstrate diagnostics and prognostics for helicopter drivetrains. The SH-60 program was initiated as a proof-of-concept effort to develop, demonstrate, and integrate available and advanced mechanical diagnostic technologies for propulsion and power drive system monitoring. Included in these technologies were various rule based and model based analysis techniques which were applied to demonstrate and validate various levels of diagnostic and prognostic capabilities. Some of these will be discussed. Since spalling of the SB 2205 roller bearing integral inner race is the most common dynamic component cause for gearbox removal in the SH-60, it was tested as part of the original HIDS effort. Using this as a case example, diagnostic methods are used to identify the fault, and means of applying prognostics are discussed. Other more recent examples of "seeded faults" will also be discussed as case studies demonstrating various degrees of diagnostic and prognostic capabilities. These include the evaluation of an epicyclic planet gear separation algorithm developed by the Defence Science and Technology Organisation (DSTO), Australia. Multivariate analysis reasoners, and information fusion requirements and approaches will also be discussed. Most recently a strategy is evolving to more fully develop and demonstrate the predictive aspects of prognostics. Finally a full description, recent accomplishments, status and future plans for the NAWCAD Helicopter Transmission Test Facility (HTTF) will be presented.

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1. INTRODUCTION

The Helicopter Integrated Diagnostic System (HIDS) program developed and tested a prototype automated system to diagnose aircraft health and track life usage of parts [Ref. 1 – 4]. HIDS was conceived to fulfill the Navy requirement, as identified in a Mission Needs Statement from the Joint Atlantic and Pacific Fleet Commanders, for a reliable state-of-the-art diagnostic capability on-board rotary wing aircraft. Such a system is expected to enhance safety, increase aircraft availability, improve maintenance efficiency, and significantly reduce life cycle cost through its ability to accurately track parts life and predict impending failure of both structural and dynamic drive system components. Resulting system information can be used to direct on-condition maintenance actions, shorten troubleshooting time, and/or alert the pilot to conditions affecting flight safety.

A vendor selection competition was conducted and Technology Integration (later procured by BF Goodrich Aerospace) was selected to provide two systems for this non-production technology integration demonstration. The program approach was two fold, first to integrate available low risk monitoring technologies into a single comprehensive onboard system for flight evaluation and "showcase" demonstration at Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River, MD. Second, to use the unique drive train (SH-60 setup of T700 engines, main transmission, gearboxes, and shafting driven at full power) test cell facility at NAWCAD, Trenton, NJ to document and evaluate the systems capability to detect component faults through very intensive seeded fault testing. This seeded fault testing focused mostly on but was not limited to gearbox vibration diagnostics because gearbox vibration monitoring was the least understood and hardest to validate of the helicopter monitoring functions. The SH-60 HIDS provides engine monitoring (a new set of algorithms were procured from General Electric Aircraft Engines), vibration monitoring of all gearboxes, shafting and hanger bearings, oil monitoring, and in-flight rotor track and balance capability. The HIDS also has flight regime recognition algorithms so that, though not part of this program, it would be relatively easy to integrate airframe structural life monitoring capabilities. The

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test cell HIDS configuration also included advanced oil debris monitoring and engine electrostatic exhaust debris capabilities.

The diagnostic portion of HIDS targeted the detection and classification of mechanical component faults in the engine and drive train primarily because these systems are responsible for the majority of Navy helicopter Class A mishaps (loss of aircraft and/or personnel). The key capabilities of HIDS included:

- Condition monitoring of gears, bearings and shafts by vibration analysis
- Automation of existing shaft balancing procedures
- Automatic engine health checks (continually provides pilot with engine power available conditions)
- Parts life usage tracking
- Automated on-board Rotor Track and Balance
- User friendly ground station

Operational flight testing of HIDS began at Naval Air Station (NAS) Patuxent River in early 1995 on the SH-60 platform. For safety reasons, faulty parts are being tested and characterized with a second system at the NAWCAD HTTF. Together, the ground test facility and the SH-60 flight test aircraft provide a unique aircraft mechanical systems diagnostic laboratory to test current and emerging techniques and technologies, including several Small Business Innovative Research (SBIR) diagnostic technology efforts. The HIDS program served as the Navy's cornerstone effort to develop, evaluate, and demonstrate helicopter integrated diagnostic capabilities and provided high quality technical data and support to the H-53 Integrated Mechanical Diagnostic Health and Usage Monitoring System (IMD HUMS) and V-22 Vibration Structural Life and Engine Diagnostics (VSLED) programs.

2. DATA COLLECTION AND ANALYSIS

The data acquisition system developed by BF Goodrich records digitized vibration and tachometer data for up to 32 channels in parallel. Gear, shaft, bearing and data quality analyses are performed and displayed using the MATLAB computation and visualization environment. Each test cell run lasts roughly one hour with six acquisitions being taken at input torque ranging from 25 to 110 percent.

All vibration data was analyzed automatically using the BF Goodrich AutoHUMS and TrendHUMS diagnostic routines. AutoHUMS saves all of the diagnostic algorithm results into an indicator database that can be trended over time with TrendHUMS. The diagnostic system reports numerous health indicators from gear, shaft and bearing analyses. The bearing algorithms include indicators based on raw and enveloped vibration data. The system also performs a real time data quality check on all raw data.

3. SEEDED FAULTS AND DIAGNOSTICS – CASE EXAMPLES

Numerous seeded fault tests were conducted as part of the HIDS program, specifically targeted to address the major reliability and safety areas, and have been fully described [1]. Significant fault propagation tests were successfully conducted where a small EDM notch was used as a stress riser in the root of the tooth. Cracks were grown from the notch until root-bending fatigue occurred in the tooth. A complete data set, from crack initiation to failure, was acquired for these tests. The fault propagation tests are prominent because they provide an understanding of failure progression dynamics, and eliminate the discrete step characteristics of other seeded fault tests.

Planetary Gear Algorithm

An algorithm developed by the Aeronautical and Maritime Research Laboratory of the Defence Science and Technology Organisation (DSTO), Australia, for the improved detection of planet gear faults in epicyclic gearboxes was evaluated by NAWCAD using HIDS program data through the medium of The Technical Cooperation Program (TTCP).

The DSTO planet separation algorithm uses a unique windowing/synchronous-averaging technique to discriminate between the vibration signatures of individual planet gears [5-7]. Simply put, the technique measures the vibration at a fixed point on the ring gear, applies a window function to "separate" the signals from the planet gears as they pass the measuring point, and then synchronously averages the separated signals. The technique requires no additional instrumentation over that needed for regular synchronous averaging. The separation achieved with the algorithm is excellent and does not suffer from the windowing discontinuity problems present in other planetary separation algorithms. However, it has been found that the level of separation achievable is dependent on the level of planet-pass modulation evident at the accelerometer location, and that a stronger modulation results in a more effective separation.

The DSTO planet separation algorithm was evaluated using vibration data obtained from a seeded-fault test in an SH-60 main transmission in which $\frac{1}{2}$ of one tooth was removed from one of the five planet gears. This was a severe planet fault. Data were available from port and starboard ring gear accelerometers at three different torque conditions. Unfortunately, the vibration data were contaminated with a large noise signal from a generator electrical fault that overwhelmed the vibration signal (see Figure 1). This lessened the effectiveness of the algorithm. Regular and separated planet averages were computed from the data. As the fault was known to be impulsive, the averages were compared by applying the residual signal kurtosis analysis technique to both types of averages. This technique consisted of computing the kurtosis (normalized 4th statistical moment)

of the residual signal obtained after the mesh and other regular frequency components were removed from each average.

The results of the comparison are presented in Table I where the row denoted by "Comp. Planet" presents the composite planet results using regular synchronous averaging. Note that because there was no absolute planet index reference, the planets were numbered from that which produced the highest peak in the planet-pass modulation at the accelerometer position. This produced some discrepancy in the planet

numbering at the various torque settings because torque has a strong affect on vibration. However, it is easy to see that the DSTO planet-separation algorithm produced residual kurtosis figures at least twice as high as that of the regular synchronous averaging technique despite the low signal to noise problem. For comparison purposes, Figure 2 shows the regular and separated synchronous averages for the port accelerometer at 200 ft-lb where the separated average is for Planet 4. The fault impulse is clearly more evident in the separated average.

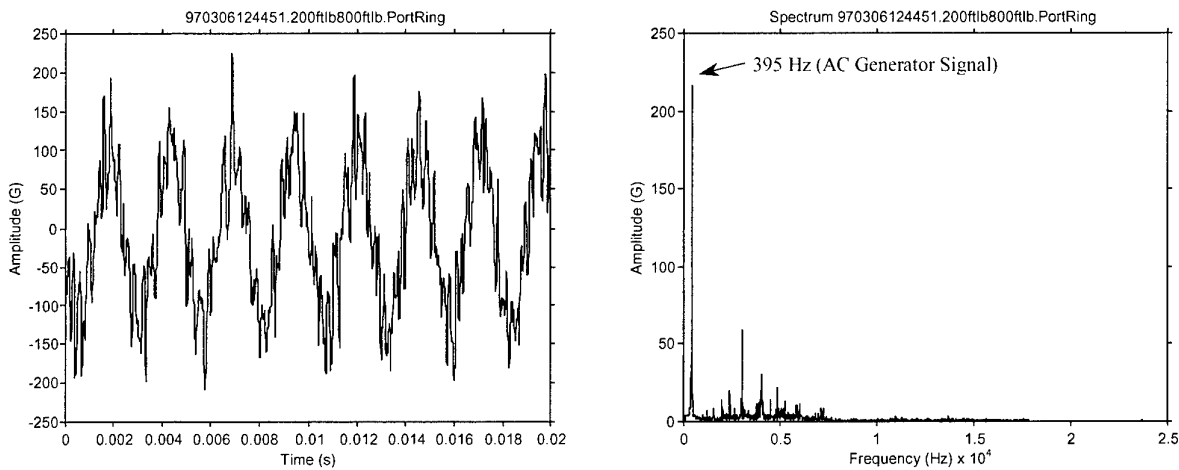


Figure 1 - Vibration signal showing noise contamination (395 Hz component).

Table I. Residual kurtosis values (mesh & additional frequencies removed).

Residual K	Port Ring Accelerometer			Starboard Ring Accelerometer		
	200 ftlb	300 ftlb	350 ftlb	200 ftlb	300 ftlb	350 ftlb
Comp. Planet	3.65	4.15	3.92	5.75	5.19	6.73
Planet 1	8.02	8.82	10.98	5.52	8.01	9.70
Planet 2	9.58	9.77	6.60	7.01	10.04	13.51
Planet 3	9.09	9.93	3.94	9.58	13.68	6.50
Planet 4	10.88	8.59	6.39	14.08	8.59	5.43
Planet 5	7.47	3.87	8.39	6.82	5.65	6.98

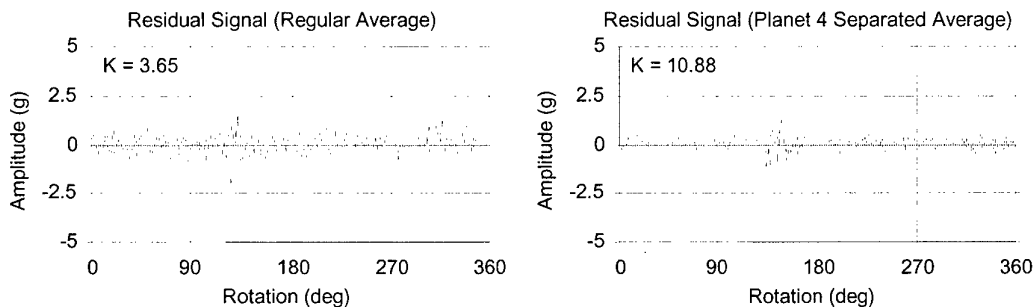


Figure 2 - Regular and separated planet averages (port accelerometer, 200 ft-lb).

Gear Mesh Anomaly

The HTTF officially commenced testing during the summer of 1999 after being transferred to Patuxent River from Trenton, NJ. The test article was a Coast Guard HH-60J main transmission input module emanating high vibrations at half of the gear mesh frequency. The Navy has encountered a few incidents of half-mesh input modules, where every other tooth of a semi-hunting mesh is highly loaded. Since both the pinion and gear have even numbers of teeth, wear occurs at a much faster rate. Moreover, aircraft with these half-mesh input modules have a history of rejecting engines because of power turbine shaft wear and resultant cockpit torque indication errors. The Coast Guard rejected one engine on the subject aircraft because of the torque indication problem. The cause of half-mesh anomaly is believed to be gear profile errors introduced in the machining process.

The objectives of the test were to exercise the input module in a highly controlled and instrumented environment to: a) develop a reliable method for the Coast Guard to identify half mesh modules using their field vibration equipment, b) determine if Navy tests could be conducted at lower torque than the current 75% requirement, making the test compatible with shipboard operations, c) test a novel fix, indexing the pinion by one tooth thereby changing mating teeth in mesh, and d) return the asset to service if within acceptable vibration limits.

All of the objectives of the test were successfully accomplished, with the exception that the material condition of the test article precluded a return to service. Prior to



Figure 3 - Input module with every other tooth wear pattern and spalled tooth.

initial test run, inspection of the mating gears via the input module inspection port revealed wear patterns and spalling, confirming high loading of every other tooth in the gear mesh (see Figure 3). The degree of spalling was unexpected, requiring the asset to be overhauled. However, the pinion was still indexed to determine whether vibrations at the half-mesh frequency could be brought to within acceptable limits. As exhibited in Figure 4, the vibration was reduced well below the Navy limit of 0.15 IPS, and would have allowed the asset to be returned to service. Reliable limits were

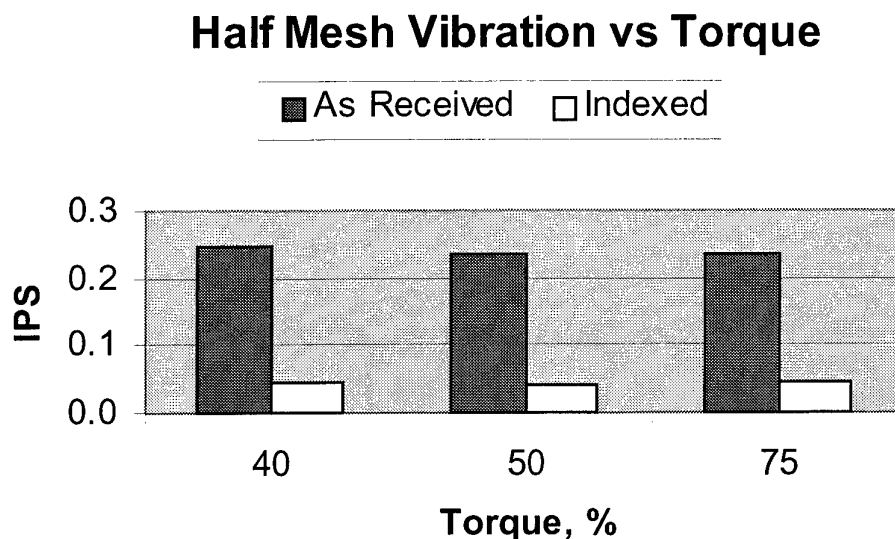


Figure 4 - Regular and separated planet averages (port accelerometer, 200 ft-lb).

developed for Coast Guard field vibration equipment by comparing measurements from several vibration monitoring systems. The chart also shows that a low 40% torque, such as required for single-engine flat-pitch operation, provides similar detection capability as for higher torques. With the real time monitoring capabilities of IMD HUMS about to enter the fleet, detection of aircraft system faults such as this half-mesh anomaly are automated and performed every flight, lowering operational costs and increasing safety.

4. DIAGNOSTICS VS. PROGNOSTICS

Diagnostics has traditionally been defined as the ability to detect and sometimes isolate a faulted component and/or failure condition. As a working definition for this paper: prognostics is the capability to provide early detection and isolation of the precursor and/or incipient fault condition to a component or sub-element failure condition; and to have the technology and means to manage and predict the progression of this fault condition to component failure. The detected, incipient fault condition is monitored, tracked, and safely managed from a small fault as it progresses to a larger fault, until it warrants some maintenance action and/or replacement. Through this early detection and monitoring management of incipient fault progression, the health of the component is known at any point in time and the future failure event can be safely predicted in time to prevent it.

Though it is often difficult to separate diagnostic and prognostic performance in a seeded fault program such as this, one of the by-products of this testing was the demonstration of the potential and performance of prognostics.

The prognostics problem can be thought of as being broken down into two related but distinct technical discipline areas: first, the sensors and technologies needed to find and "see" the early incipient fault prior to actual component failure, and second, the technologies and techniques needed to accurately predict useful remaining life at any current point in time.

The prediction of accurate useful life remaining is further broken down into major enabling areas. Statistical techniques can be used to establish the degree of confidence in any life remaining prediction. Related statistical techniques are also used for boundary life remaining predictions. Modeling techniques can be employed to develop a degree of understanding of individual component and/or sub-element failure progression characteristics. Validating these models would require the generation of enough examples of actual failure events to characterize specific fault to failure progression rates. Various components and different failure modes of the same component element may have very different fault to failure progression rates.

A significant degree of component failure prediction and prognostics was demonstrated during the seeded fault tests by applying many of the same algorithms and techniques used for vibration based mechanical diagnostics. Often the extrapolation of vibration frequency data, statistical parameters and/or trending of diagnostic indices is the technique used to enable failure prediction. It is of course key to have sensors, algorithms, and diagnostics indicators (or indices) that are sensitive and accurate enough to "see" the precursor or incipient "small" component fault. It is equally important to have a reliable experience database of similar types of "faults" so that the failure progression rate is well understood.

The experience database knowledge and the understanding of various types of failure progressions will both enable the intelligent setting of alarm thresholds for diagnostics and provide the initial basis for the prediction of useful life remaining predictions. It is envisioned that in most cases, the alarm thresholds for safety-of-flight (cockpit warning) will be significantly higher than for maintenance. Establishing these alarm thresholds is a very necessary step in implementing future failure event prediction and enabling prognostics. Without having the benefit of an extensive experience database of actual component failures with fault progression data and/or a comprehensive "seeded fault" trials as the SH-60 HIDS program, establishing these alarm thresholds approaches the realm of "magic".

There are other important elements needed in the "diagnostic tool kit" or "bag of tricks" before prognostics can be successfully implemented. One of these can be called "Model Based" diagnostics or prognostics. Another can be grouped as a series of approaches and techniques to handle data scatter and manage false alarms. Model based techniques require a detailed and accurate understanding of the underlying physics of the system to model how a specific component, system, or machine, operates in normal and degraded conditions. Using real or calculated parameters against this accurate model enables the determination of relative "health" of the component monitored at any point in time. Some of the approaches applied to deal with inherent data scatter and to manage false alarms include fuzzy logic and neural network techniques; data fusion; and multiple indications (driven by either sensor or algorithm indices) required prior to alarm. At times, and with varying degrees of application and success, all of these approaches and techniques were tried during this program. The recently introduced concept of applying a "Reasoner" to various levels of the diagnostic/prognostic decision process should also greatly improve accuracy.

5. PROGNOSTIC DATA DEVELOPMENT

Many factors are required to enable accurate prognosis of materiel condition. One factor that is of paramount

importance, and that was addressed under the HIDS program, is reliable, repeatable, high-quality failure progression data. Comprehensive seeded fault testing accomplished during the HIDS program generated some of this data, which provides insight into failure modes and the characteristics that accompany component failure, without jeopardizing safety. Common practice when fielding health-monitoring systems has been to collect failure data on an opportunistic basis from fielded systems. The drawbacks to this approach are obvious. Safety is only increased incrementally based on data from actual mishaps, and fault data takes many years to accumulate, and is of a limited scope due to limitations of on-board systems. Tests conducted in HTTF are conceived and conducted to short-circuit this cycle, thereby enabling increased safety with reduced false alarm calls earlier than would otherwise be achieved. The up-front investment to conduct testing will be saved many times over by increasing system effectiveness, thereby preventing mishaps.

6. A STRATEGY FOR PREDICTIVE PROGNOSTICS

Most recently a strategy is being evolved to more fully develop and demonstrate the predictive aspects of prognostics. This is a very difficult quest and currently this strategy is still being generated with many of the necessary steps only defined as potential (moving) targets. This strategy will become more definitive over the next year; but the present notional thinking and approach is presented below.

Predictive prognostics is an extremely difficult and challenging area for a number of reasons, including the following. There are usually many ways a specific component type can fail, and each failure mode may require an unique analysis. Failures are often very difficult to accurately model and models can ignore "real world" effects. There is a great lack of empirical data from actual controlled failure propagation tests on which to base prognostic calculations; and these tests are very difficult and expensive to perform. It is impossible to precisely determine the future loads that a damaged component will experience.

For the development of predictive prognostics to be an achievable and manageable proposition, it needs to be broken down into "bite-sized" portions. Since this endeavor will involve many technical disciplines and intensive testing, significant collaboration between various diverse organizations will have to be implemented wherever possible to improve outcomes and reduce costs. A basic strategy to develop predictive prognostics would include the following steps. Decide which drive-train elements (in a generic sense) are best suited to prognostics. Develop fault to failure progression characteristic and useful life remaining models for these targeted elements. Perform as many experimental seeded-fault tests as affordable to verify and validate these models. Modify the useful life remaining model predictions to account for the "real world" considerations.

Some initial thoughts for a predictive prognostics development and demonstration program based on the SH-60 and the HTTF might proceed as follows. First, attempt to identify those SH-60 drive-train components which might have understandable fault to failure progression characteristics. Though an analytical study, we could at the very least, identify and eliminate for consideration those components which have no chance of having understandable failure progression characteristics. Second, do seeded faults tests in the HTTF for those few SH-60 components that have been identified as having very high failure rates and also fall in the group of components that might have understandable fault to failure progression characteristics. Do enough seeded fault examples so that we have a defined database for understanding the fault to failure progression rates of these few components. Third, develop and/or procure component specific models on fault to failure progression characteristics that will be able to make useful life remaining predictions. These would likely be coupled with more highly evolved component failure progression models (maybe a combination of physical and statistically based) that were developed and validated using the component seeded fault database. This is the hard part and we will probably have to have several outside contractors and/or university supporting these modeling efforts. Also, I believe that basic material scientist will have to be involved. Fourth, implement this modeling software in the early SH-60 COSSI IMD fleet aircraft. Wait for fault and failure indications to occur during fleet operations. Fifth, if and when we get fault or failure event indications; pull the components and continue to run them in the HTTF to full failure and/ or do destructive tests to validate life remaining predictions.

The HTTF is a unique asset for doing some for this type of work. The SH-60 COSSI IMD program is the perfect aircraft platform to implement a fleet demonstration like this and would be an easy transition vehicle.

7. DIAGNOSTIC/PROGNOSTIC CASE EXAMPLE – MAIN BEVEL INPUT PINION INTEGRAL INNER RACE

The SH-60 main transmission module input pinion (P/N 70351-38104-102) is a complex part consisting of the female spline for the quill shaft, 21 tooth spiral bevel pinion and integral roller bearing inner raceway, Figure 5. Roller bearing SB 2205 reacts the radial load from the spiral bevel pinion and has 30 rolling elements with a roller diameter of 0.630 inches and a pitch diameter of 7.476 inches. This fault is particularly challenging since it is located deep inside the gearbox, suggesting it would be difficult to detect.

The starboard main sensor condition indicator toggles into alarm when the fault is implanted and reverts back to okay when the fault is removed. The port main sensor indicator is also sensitive to this fault because the sensor is located on the same structural housing member, and is rotated about 90 degrees around the housing from the starboard main sensor. The port indicator serves as confirmation of the starboard condition indicator.

Statistical parameters, such as enveloped kurtosis, were the main indicators used to evaluate bearing condition for this fault. One of the keys to obtaining meaningful results with this technique is to envelope an appropriate frequency range. The frequency range used in this analysis was determined analytically as well as experientially.

The statistical parameters used are sensor specific indicators as opposed to component specific. That is, they do not discriminate between bearings. One can however, determine the location of the fault to be on the starboard side as levels of the starboard main sensor are greater than that of the port main.

The purpose of bearing diagnostics as implemented in the HIDS program is to identify faults in the early stages of development. The fleet rejected bearing fault under test was in an advanced stage, with the spall covering approximately 1/3 the circumference of the part. Since most of the bearing health indicators are designed to detect localized faults, they did not respond to this distributed fault.

A useful approach implemented by the HIDS program is the simultaneous acquisition and analysis of a component signature by two different sensors. This is a data quality and analysis confidence measure aimed at improved diagnostics and reduced false alerts. Prior to the subject test, sensor starboard main was considered the primary sensor and starboard input the secondary. The starboard input sensor was not sensitive to this fault. Analysis to locate a sensitive secondary sensor identified the port main accelerometer as providing excellent results. While the port main and starboard input are a similar distance from the fault, the port main is on the same housing as the fault and has a better sensor orientation for this particular shaft. These efforts show the utility of redundant sensor analysis. It also exhibits the value of the parallel acquisition and storage of raw vibration data for all channels for re-processing purposes. One can then identify which accelerometer sensors and orientations are most appropriate for specific faults thereby optimizing a final, productionized version of the diagnostic system.

Prognostics could effectively be applied to the failure of this component. As the most common dynamic component cause for gearbox removal in the H-60 community, the failure mode is well recognized. The SB 2205 fault progresses in a repeatable manner from a small, localized spall into a larger one that will eventually encompass a good portion of the

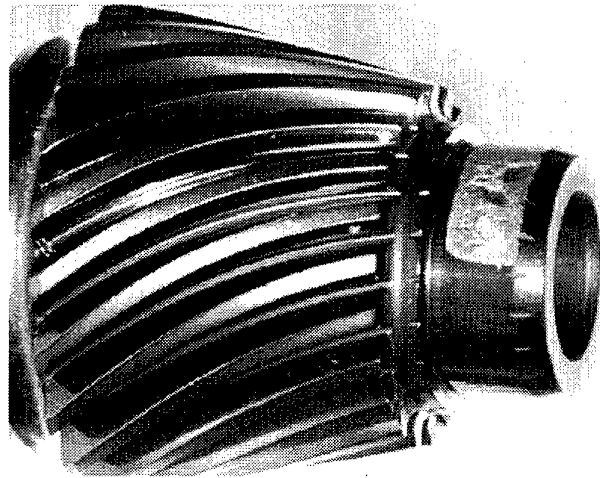


Figure 5 - Fleet Rejected Main Transmission Module Input Pinion with Spalled Integral Raceway of Bearing SB 2205.

inner race diameter. At this point, the chip detector will provide an indication of a failure somewhere in the gearbox with no indication of fault location or severity. On the other hand, the model based bearing indicators identify the presence of the fault early in this process. Specific indications from the inner race defect indicator will be observed. As the fault becomes progressively larger, the statistical indicators are among the dominant indicators that identify the degraded condition. By carefully tracking the progression of this fault via magnitude of response and migration across indicators, maintenance and mission planning can be conducted in an effective manner, and unscheduled downtime can be effectively reduced.

Prognostics can enable effective management of fleet assets based on the current tempo of operations. If the availability of a particular asset is not critical and a component with a well understood failure mode, such as SB 2205, is identified as degrading over time, maintenance can be scheduled in a timely manner so as to minimize secondary damage, thereby reducing repair complexity and cost. This particular component of the main transmission is readily accessible by pulling the input module. Given early detection capability, it is feasible to change the way maintenance is performed by repairing the gearbox on the aircraft, thereby precluding pulling and replacing the main rotor head and main transmission and performing the ensuing rotor track and balance evolutions. However, if aircraft availability is of paramount importance, the failure progression can be closely monitored to ensure aircraft safety while keeping a critical asset in service until such time as maintenance can be performed.

Further development and validation of advanced model-based analysis, data fusion, and other techniques is needed to reduce and/or eliminate false alarms and to completely implement a fully comprehensive prognostic capability.

8. HELICOPTER TRANSMISSION TEST FACILITY HTTF DESCRIPTION

The test cell uses aircraft engines to provide power to all of the aircraft drive systems except the rotors. Power is absorbed through both the main rotor mast and tail rotor shaft by water brake dynamometers. The main rotor shaft is loaded in bending, tension and torque to simulate flight conditions. There is a speed-increasing gearbox between the main rotor mast and the water brake, which increases the main rotor speed by a factor of 32. This gearbox allows water brakes to extract up to 8,000 shaft horsepower (SHP) and will soon be upgraded to handle up to 18,500 SHP. The complete aircraft lubrication system is used with the oil cooler, oil cooler blower and blower drive shaft part of the system assembly. The tail drive system is installed and power is extracted from the tail at operating speed. The tail water brake can extract up to 700 SHP. This capability provides for helicopter system level testing, uniquely enabling the detection and isolation of dynamic interface problems. Operational simulations include engine transients, topping, start up and cool down, clutch engagements, dual engine operation, over running clutch operation, one engine inoperative, rotor brake operation, and full accessories loading.

The tail drive system installation allows balance and alignment surveys on the blower, tail drive shafts and disconnect coupling. Aircraft viscous damper bearing assemblies support the installation. The length of the test cell limits the number of tail drive shafts, so two of the aircraft shafts are not installed. The test cell also supports the aircraft accessories. Generators and hydraulic pumps are mounted on the accessory gearboxes and loaded to simulate aircraft operation. This is a significant capability, especially when diagnostics using vibration acquisition is the test objective. Vibration signatures collected from the HTTF include frequency content from all dynamic components of the loaded power drive system. The complex signal is representative of the aircraft environment.

Since this cell has the ability to operate all the aircraft mechanical systems together, the diagnostic system can record all component "signatures" to a database. This database can then be interrogated to determine system health, and system performance rather than a diagnostic evaluation of a single component or fault. This is a significant improvement over single component regenerative rigs that tend to have two gearboxes that generate the same frequencies (and cross talk) bolted to a single stand and none of the adjacent mechanical systems.

9. HTTF ACCOMPLISHMENTS

HTTF has served as an indispensable fleet support asset, and has made significant contributions to a number of key US

Navy rotary wing platforms. These contributions are summarized below by platform.

H-60

- HIDS Extensive Seeded Fault Testing
- Qualified Improved Durability Gearbox
- Improved Durability Gearbox Sump cracking
- T-700 Flameout Testing
- T-700 Alternate Fuel Testing
- Second Source Qualification Testing
- ECP-319 High Speed Shaft
- Developed Detection Methods for Fleet Transmission Problems
- 700 Hour Simulated Mission Endurance Test
- USCG Half Mesh Detection Procedure

H-3

- Upgraded Main Transmission Qualification
- VH-3 Clutch Qualification
- Engine Flameout/Clutch Spitout Investigation
- Emergency Lube Flow Verification
- Disconnect Coupling Failure Test
- Torque Tube Gimbal Mount Modification
- Qualified Second Source Components
- Redesign of A-Frame Oil Cooler Support
- VH-3 Over-running Clutch Anomaly

H-1

- Bevel Gear Failure Investigation
- Upgraded Transmission Qualification
- 400 Hour Simulated Mission Endurance Test

10. HTTF STATUS

The HTTF, which was originally located at NAWCAD Trenton, NJ, last operated on July 31, 1997, and was shut down as a result of the Base Realignment and Closure (BRAC) action of 1993, which closed Trenton in 1998. The cell, which was configured to accommodate an H-60 aircraft drive system, was disassembled, and subsequently shipped along with other Trenton test cells and equipment, for incorporation into the Propulsion System Evaluation Facility (PSEF) at NAWCAD, Patuxent River, MD.

The Helicopter Transmission Test Facility has been reassembled to the Trenton H-60 configuration and officially commenced testing during the summer of 1999. Testing will continue, using seeded faults in an H-60 main, intermediate, and tail transmissions; as well as engine, shafting, hanger bearings, and accessories. This work will support the fleet wide introduction of the IMD HUMS into the H-60 and H-53 aircraft. Additional 'piggy-back' testing of various sensor technologies in support of the H-53, H-60, H-1, V-22, JSF, and other programs, as well as qualification testing for CIP and alternate source parts is also planned.

11. HTTF PLANNED TECHNOLOGY EVALUATIONS

Several new technologies have been procured to enhance our capabilities to evaluate diagnostic and prognostic algorithms and methodologies. Some of these technologies are being developed under Small Business Innovative Research (SBIR) programs to evaluate potentially beneficial and promising techniques. These new technologies will be used as advanced test cell instrumentation. They will also be evaluated on their own merit.

Oil System

Innovative Dynamics, Inc. is developing a real time oil debris monitoring system for use in the gearbox lubricating system flow path. The system is a combination of sensors allowing for the detection of multiple size particles, varying from 5 to 2000 μm in size. Algorithms used in the system discern air bubbles from wear particles and trend the amount of debris generation along with the particulate size. The concept has been proven in a water lab and computer oil-flow simulation model. IDI's oil debris monitoring system will be tested in the HTTF for further validation and verification before being flight-tested for incorporation in the SH-60R.

Vibration Sensing and Analysis

Hood Technology Inc. is currently working on a system to detect low cycle fatigue in gas turbine engines. The system uses multiple sensors to monitor rotor tip clearance as well as blade passage. A tachometer is used to monitor disk location and rotational velocity. Each blade is tracked to monitor for the onset of elastic and plastic deformation. Hub cracks are associated with a change of arrival time of the blades, while asymmetric lengthening of the blades is an indication of plastic deformation leading toward disk burst. The system is currently being tested in the US Navy Patuxent River spin pit facility and working toward military and commercial certification.

Stress Wave Analysis

SWANTECH, LLC has developed a technique that measures the energy content of friction and shock events to both identify and quantify damage in rotating machinery. A large benefit of stress wave analysis is its ability to detect low energy events, such as gear and bearing defects. This technology will be evaluated in the HTTF using the SH-60 drive system configuration with various seeded faults and will be evaluated against the corresponding vibration data and algorithms.

Neural Network and Data Fusion

Orincon classical and neural network diagnostic algorithms operating in the RIPPENÓ, (Real-time Interactive Programming and Processing Environment) software package will be evaluated in near-real-time mode using the SH-60 drive system configuration in the HTTF with various

seeded faults. The software package is a graphical based environment that allows you to quickly and easily create information processing systems which can be encoded into a variety of computer platforms. In addition, Orincon data fusion techniques will be demonstrated with the objective of maximizing fault detection ability while reducing incidence of false alarms.

Multivariate Analysis

Hotelling's T2 Multivariate Analysis is based upon the underlying correlation of the individual indicators used to build the composite T2 indicator. The greater the change in correlation in the presence of a fault, the more robust the component condition call. The effectiveness of the condition call is dramatically increased when used with statistical methods to select the indicators used. The indicator has been shown to change by orders of magnitude in the presence of a fault, over current multiple indicator hard-threshold based methods. Hotelling's T2 Analysis shows promise with a more robust classification of faults and a large reduction in false alarm calls. Future work in this area will be to explore alternative methods which better estimate in-control parameters, further decreasing false alarm rates while preserving the responsiveness of the T2 analysis to faults.

12. HTTF FUTURE EFFORTS

Currently the US Navy has a library of fault tests run in the HTTF. The library's database consists of artificially induced and naturally occurring faults. Continued seeded fault testing is planned to expand the library's database, as well as advance current diagnostic/prognostic techniques and evaluate new technologies. The database already contains some fault propagation data examples, from fault initiation to near failure conditions. Testing will be planned to expand the database of component fault progression examples. To evaluate the sensitivity of diagnostic and prognostics techniques to fault progression; components with varying degrees of degradation will be tested. Following a successful diagnosis of a most severe case, a fault propagation test is completed. These tests will also be used in an attempt to characterize failure progression rates.

The planetary drive system is the next major component group to be tested. The planned fault run is to insert a sun gear with 1/3 of a tooth removed (Figure 6). This testing will be completed in early February 2001. If testing of the faulted sun gear is successful, and the fault can be readily identified, a failure progression test using an EDM notch for crack initiation will follow.

In order to obtain naturally occurring faults the Navy is working closely with Storage, Analysis, Failure Evaluation and Reclamation (SAFR), an organization that tracks and collects faults found in fleet aircraft. The Navy has worked with SAFR to collect drivetrain components prone to

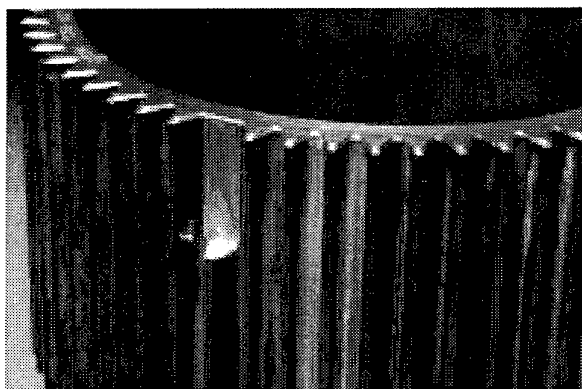


Figure 6 – Main Transmission Sun Gear with 1/3 Tooth Removed

operational or premature failure. In December 2000, SAFR was able to provide a main transmission ring gear and main bevel pinion gear, as well as a tail gearbox output gear to the HTTF. The Navy plans to test these components in varying stages of severity, from fault initiation to critical failure, in the HTTF in order to gain knowledge of the fault's signature so a fleet occurring catastrophic failure can be avoided.

13. CONCLUSIONS

Fault propagation tests provide an understanding of failure progression dynamics, and eliminate the discrete step characteristics of other seeded fault tests. Reliable, repeatable, high-quality failure progression data obtained from these tests is of paramount importance, enabling increased safety with reduced false alarm calls earlier than could otherwise be achieved.

Prognostics can enable effective management of fleet assets based on the current tempo of operations. If the availability of a particular asset is not critical and a component with a well understood failure mode is identified as degrading over time, maintenance can be scheduled in a timely manner so as to minimize secondary damage, thereby reducing repair complexity and cost. However, if aircraft availability is of paramount importance, the failure progression can be closely monitored to ensure aircraft safety while keeping a critical asset in service until such time as maintenance can be performed.

The HTTF has served as an indispensable fleet support asset, and has made significant contributions to a number of key US Navy rotary wing platforms.

Further development and validation of advanced model-based analysis, data fusion, and other techniques is needed to reduce and/or eliminate false alarms and to completely implement a fully comprehensive prognostic capability.

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VIBRATION AND USAGE MONITORING SYSTEM FOR THE KAMAN SH-2G(A) HELICOPTER

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ABSTRACT

The SH-2G(A) Super Seasprite helicopter has been developed for the Royal Australian Navy by Kaman Aerospace Corporation of Bloomfield, Connecticut, USA. When delivered in 2001, the SH-2G(A) Super Seasprite will be the most advanced intermediate naval helicopter available featuring a fully Integrated Tactical Avionics System (ITAS) including a glass cockpit, as well as a fully Integrated Weapons Systems (IWS) including Radar, FLIR, ESM, and air-to-surface missiles. The Royal Australian Navy will operate SH-2G(A) helicopters from ANZAC class frigates and from bases ashore along the Australian coast. The helicopter's primary missions of surface surveillance, anti-surface warfare and anti-submarine warfare requires not only modularity of installed systems, but reliability that can sustain the anticipated tempo of operations.

The level of integration introduced in the SH-2G(A) and the resident capability of the ITAS allows for the usage monitoring and recording of aircraft systems and components. A dedicated vibration monitoring system, for the powerplant, transmission, main and tail rotor systems and airframe is fitted in the aircraft, that can interface directly with the Chadwick-Helmuth 8500 system in service with the Royal Australian Navy. Additionally, the aircraft is equipped with a cockpit voice recorder and flight data recorder (CVR/FDR) to complete the suite of usage monitoring equipment. Downloading of the ITAS recorded data is accomplished via a Data Loader/Recorder, and playback and archiving of the information takes place at the Mission De-Brief Facility / Ground Station. Overall system design and capability will be presented and future development of the system discussed.

INTRODUCTION

The SH-2G(A) Integrated Weapons System (IWS) platform brings together the navigation, communication, sensors, and weapons suites in a glass cockpit environment, providing a true multi-mission "2-man-crew" capability. See Figure A.

The heart of the IWS is the Integrated Tactical Avionics System (ITAS) and its interface via the two dual-redundant MIL-STD-1553B data buses. The ITAS system can efficiently exchange data between the IWS subsystems and provide enhanced navigation, communication, tactical solutions, and self-protection features while executing



Figure A: SH-2G(A) Super Seasprite Glass Cockpit.

automatic flight profiles and monitoring all flight, power-train and other aircraft systems and parameters. Information is displayed in the cockpit on the four (4), centrally located color multi-function displays (CMFDs).

Of paramount importance has been the integration of Human Machine Interface (HMI) principles in the design of the system to allow the crew to efficiently control, manage and display the multitude of information available from the avionics and air vehicle systems. Control of the ITAS is through the two smart display units (SDUs), located in the cockpit lower center console, programmable "soft-keys" on each CMFD, one Multi-Slew Controller, and HOCAS (Hands On Collective And Stick) controls. The Multi-Slew Controller (MSC) is located in the lower center console, and is used to control the ITAS and the weapons sensors including manipulation of the tactical picture.

Significant growth capability to support additional modes and features is built-in through the use of an open architecture design and conservative design margins, both in hardware as well as software. The SH-2G(A) IWS includes the following six subsystems as shown in the block diagram, Figure B:

- Integrated Tactical Avionics System (ITAS)
- Communication Subsystem
- Navigation Subsystem
- Mission Sensors
- Armament Control
- Aircraft Subsystem

As part of the overall ITAS/IWS concept, means are implemented to monitor systems continuously and assure their performance throughout the anticipated missions. The SH-2G(A) ITAS provides usage monitoring and recording of many aircraft systems and components. A pre-flight Power-up Built-In-Test (PBIT) is performed upon aircraft start and records and displays status of aircraft systems. Operator initiated BIT is also available to monitor and record aircraft systems. Furthermore, continuous BIT In-flight Performance Management (IFPM) is run in background mode to support ITAS systems integrity whilst airborne.

Predefined data from the SH-2G(A) onboard systems are managed by the Mission Data Processors (MDP) and transferred to the Mission Data Loader/Recorder (MDL/R) for recording to removable data cards. Playback and analysis of the recorded information can take place at the Mission Debrief Facility (MDF), or ground play-back station.

In addition to the ITAS monitoring and recording capability, the SH-2G(A) helicopter is equipped with a Flight Data Recorder (FDR), a Cockpit Voice data Recorder (CVR), and a vibration monitoring system dedicated to the gearboxes, engines, main and tail rotor systems and airframe. This dedicated vibration monitoring system utilizes components directly compatible with the Chadwick-Helmuth CH-8500 system.

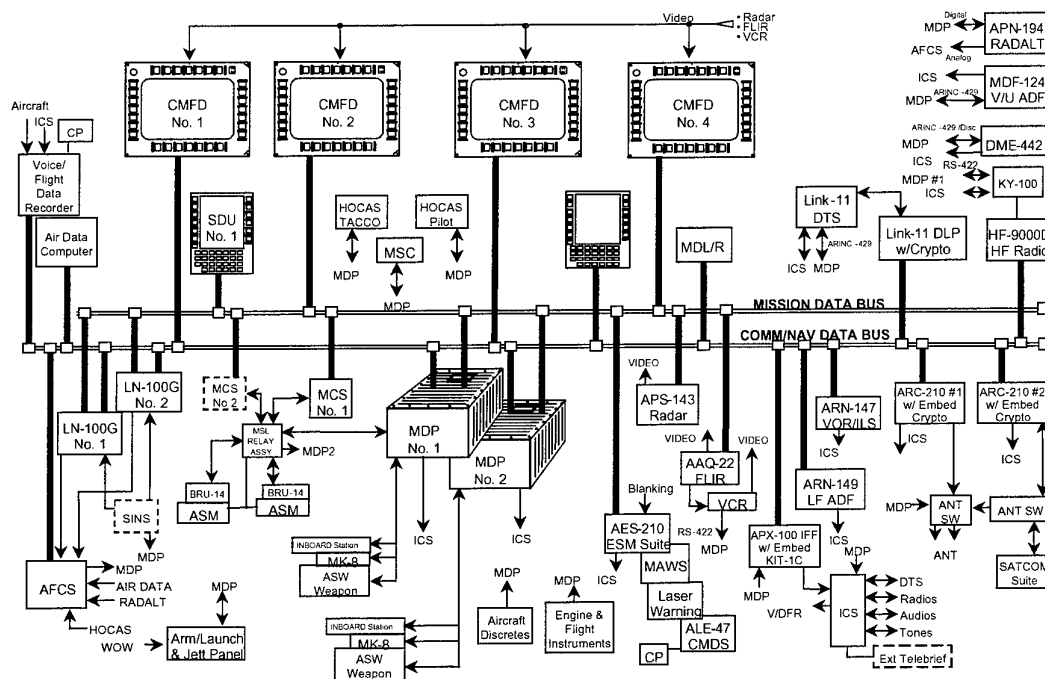


Figure B: SH-2G(A) IWS System Block Diagram.

ITAS MONITORING AND RECORDING SYSTEM

During all missions the SH-2G(A) ITAS system, in addition to providing crew warning and advisory information on the cockpit CMFDs, monitors and records the dataset shown in Table 1. Fifty-three record files are maintained by the ITAS Mission Data Processors and recorded by the MDL/R onto ruggedized Personal Computer Memory Card International Association (PCMCIA) cartridges via the MIL-STD-1553B Comm/Nav data bus (Reference Figure B). Upon mission completion, the PCMCIA cards are available to crew and/or maintainers for use at the MDF for processing.

Mission Data Loader/Recorder (MDL/R)

The tactical data recorder is called the ITAS Mission Data Loader Recorder (MDL/R). The MDL/R accepts two (2) ruggedized PCMCIA memory cards. Each data card stores 40 Mb of data storage.

The MDL/R unit is a compact and panel mounted device, into which the data cards are inserted. The unit is ruggedized for airborne applications and features a sealed card access door.

Mission Debrief Facility (MDF)

The MDF allows an operator to download MDL/R recorded data to graphically reconstruct mission events for post mission analysis. The MDF is portable, so mission debriefing and analysis can be undertaken either at remote sites or onboard ship. The MDF software runs on industry standard personal computers in a Windows NT® operating environment. MDF post-flight activities include monitoring aircraft system status and operator response, creating mission data files during a specified period of interest, and producing reports. The MDF

generates an event listing program (ELP) that provides the user the capability to produce a formatted textual representation of all datasets recorded during an SH-2G(A) mission. These are displayed in a standard scrollable, resizable window and the event listings data can be decluttered, searched, printed and saved. The ELP reports in either full event listing or summary event listing format.

Other post-flight MDF activities that enhance the health and usage monitoring of the aircraft and its systems include the capability to:

- examine graphically, the tactical scenario existing during a mission;
- create an output file containing ESM parameters;
- and produce Mission Script Files suitable as input to the Software Support Center (SSC) and Operational Flight Trainer (OFT) for training, and creating realistic test scenarios for functional testing at the SSC.

ENGINE AND DRIVE SYSTEM MONITORING AND RECORDING SYSTEM

The T700 engines are equipped with a history recorder that provides a cumulative record and display of engine running time, fatigue cycles and a time-temperature index.

Chip Detection

All SH-2G(A) gearboxes have chip detection with 'fuzz' burn-off capability. The T700-GE-401 engines are equipped with an integral Inlet Particle Separator (IPS) providing continuous protection against sand, dust, hail and ice. The T700 engines also provide magnetic chip detection. The cockpit CMFDs display chip detection on the Caution Warning Advisory page.

Table 1. SH-2G(A) ITAS Monitoring and Recording Dataset.

<i>Aircraft ID</i>	<i>U/VHF Radio Config</i>	<i>RADAR Config</i>
<i>Aircraft Data</i>	<i>HF Radio Config</i>	<i>RADAR Track Deleted</i>
<i>Nav Data</i>	<i>IFF Config</i>	<i>Link11 DTS Config</i>
<i>Fly-to-point Data</i>	<i>LN-100G Config</i>	<i>Link11 DLP Config</i>
<i>Baroalt Data</i>	<i>Engine Data</i>	<i>BIT Status</i>
<i>Ambient Conditions Data</i>	<i>Transmission & Hydraulic Data</i>	<i>Health Indicator Test</i>
<i>Store Station Load Data</i>	<i>Power Data</i>	<i>Warning, Caution, Advisory</i>
<i>Jettison Panel Signals</i>	<i>U/VHF ADF Data</i>	<i>Status Bar</i>
<i>Armament Panel Signals</i>	<i>VCR Config</i>	<i>Alert</i>
<i>MK-Inboard Stores Pylon Signals</i>	<i>VCR Event Mark</i>	<i>System Config</i>
<i>MK-8 Signals</i>	<i>FLIR Config</i>	<i>CMFD Display Settings</i>
<i>MK-46 Signals</i>	<i>FLIR Track</i>	<i>Software Version Number</i>
<i>BRU-14 Signals</i>	<i>FLIR Track Deleted</i>	<i>Date and Time</i>
<i>Missile Signals</i>	<i>ESM AES-210 Config</i>	<i>Mission Load File Header</i>
<i>Missile Control System Signals</i>	<i>ESM MAWS Config</i>	<i>System Event</i>
<i>Missile Control System Target Status</i>	<i>ESM TACDS Config</i>	<i>Recording Start</i>
<i>Missile Relay Assembly Signals</i>	<i>ESM Track</i>	<i>Recording Stop</i>
	<i>ESM Track Deleted</i>	

VIBRATION MONITORING SYSTEM

The SH-2G(A) vibration monitoring system measures vibration at each gearbox and engine, rotor blades and at specific airframe locations. A diagram of the SH-2G(A) vibration monitoring equipment installation is shown in Figure C.

The sensors, transducers and other components of the SH-2G(A) Vibration Monitoring System are compatible with the Chadwick-Helmuth CH-8500 portable diagnostics system in use by the Royal Australian Navy. Collected data are archived and may be analyzed on a ground-based PC with Chadwick-Helmuth VibraLog™ software. The VibraLog™ software can be used to analyze the collected vibration data for trend monitoring, troubleshooting and predictive maintenance.

Drive System and T700 Engines

The SH-2G(A) sensors measure drive system and engine vibration. There is one accelerometer installed on each of the nose gearboxes and the T700-GE-401 engines. Velocimeters are installed on each of the four other gearboxes. The accelerometers installed on the engines and nose gearboxes resist high temperature and are ruggedized for use in this type of environment. The vibration data, collected as acceleration (m/s^2) from these sensors is sent through charge converters to become velocity data (m/s) and finally sent to the CH-8500 analyzer. The data collected from the velocimeters installed on the other four gearboxes are sent directly to the CH-8500 analyzer.

N2 engine speed signal monitoring is via magnetic pickups, all with cables to a photocell interface box compatible with the CH-8500 analyzer.

Three locations have been carefully selected for monitoring airframe vibration. The forwardmost sensors are mounted approximately at STA 112 and the aftmost are mounted at approximately STA 421. Reference Figure C for locations. Structural and electrical provisions are made at these locations so that velocimeters may be installed during data collection flights. As with the rest of the signal distribution of the vibration monitoring system, the airframe signals are routed to the same single-point connector for interfacing with the CH-8500 system. This single-point connector is conveniently located in the cabin, facilitating the installation of the CH-8500 for data collection flights.

Rotor Blade Track

Unlike most of the rest of the industry, Kaman installs in its fleet of helicopters an Automatic Main Rotor Blade Track System (ABTS). This system contributes greatly to the low vibration characteristics of the Super Seasprite, and the very low fatigue levels encountered by the crew during extended missions. The system is simple and reliable, eliminating recurring maintenance. The ABTS is normally engaged in the automatic mode when in flight, requiring no input from the flight crew. The system also includes a manual mode via which the pilot may manually track the blades in flight.

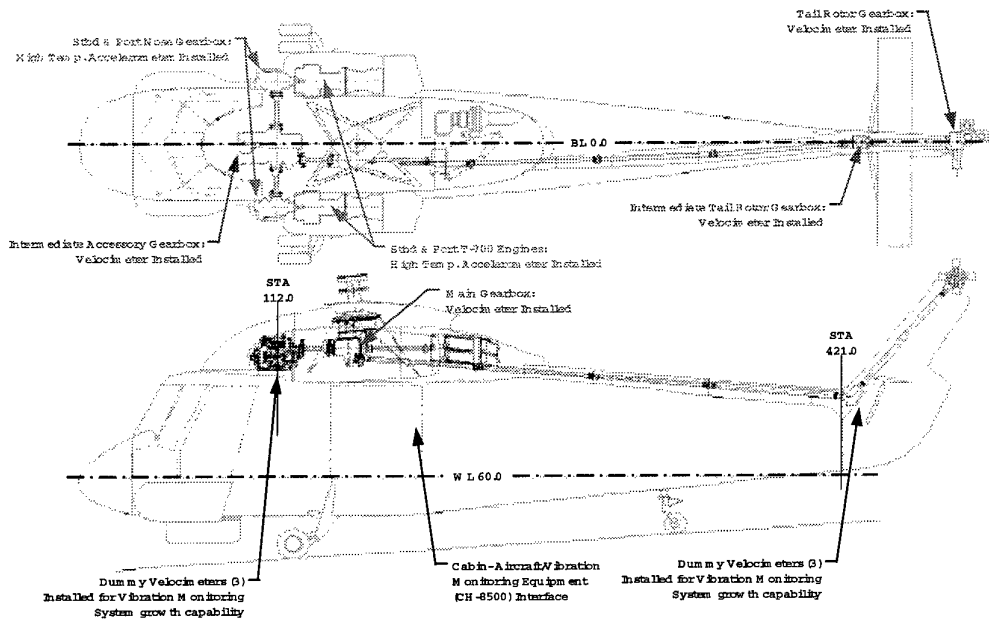


Figure C: SH-2G(A) Vibration Monitoring Equipment.

The ABTS identifies one blade as the master and the others are slaved to that in pairs. Because the blade pairs are tracked to individual references, two separate tracking planes may occur. This can be resolved by use of the B-D switch on the Blade Track Control Panel, installed in the cockpit, which adjusts the B and D blades simultaneously. When operating in the automatic mode, the system measures vertical vibration and resolves it into vectors correlated to a particular passing rotor blade. The ABTS then provides commands to the proper Blade Track Actuator, which initiates a corrective input to eliminate the out-of-track condition.

The speed of the main and tail rotor systems for vibration monitoring usage is sensed by magnetic pickups, all with cables to a photocell interface box compatible with the CH-8500 analyzer.

SH-2G(A) USAGE MONITORING SYSTEMS

Flight Data Recording

The EAS3000 system is installed in the SH-2G(A) helicopter. The EAS3000 is a combined flight data recorder (FDR), cockpit voice recorder (CVR) and emergency locator beacon (ELB) specifically designed to ensure the greatest possibility of recovery of FDR and CVR data. The EAS3000 beacon airfoil unit (BAU) is installed on the fuselage tailcone of the SH-2G(A) opposite the tail rotor. See Figure D.



Figure D: EAS3000 System & BAU installation on SH-2G(A).

A unique feature of the EAS3000 FDR & CVR is the crash-survivable memory is housed within a deployable, floatable, international orange BAU. See Figure E. In the event of an accident, the unit is automatically deployed, triggered by frangible and hydrostatic switches installed in the tail of the SH-2G(A). The BAU may also be manually deployed by activating the DEPLOY switch on the cockpit control panel.

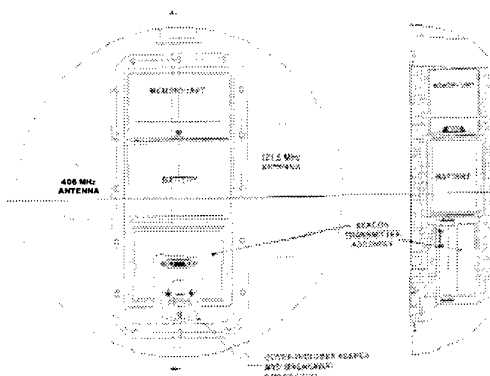


Figure E: EAS3000 BAU Diagram.

Monitoring of the crash switches and control of the BAU automatic deployment function is performed by the auxiliary battery pack (ABP) housed in the BAU. The ABP also contains a back-up NiCAD battery to ensure BAU release regardless of aircraft power availability.

FDR & CVR

The FDR holds at least eight (8) hours of SH-2G(A) flight data in the airfoil's memory module from the EAS3000 data interface unit (DIU), which interfaces directly to the SH-2G(A)'s MIL-STD-1553B COMM/NAV bus. The FDR records and stores the following parameters:

- Time*
- Aircraft Position*
- Aircraft Pressure Altitude*
- Aircraft Radar Altitude*
- Aircraft Heading*
- Aircraft Attitude (Pitch and Roll)*
- Aircraft yaw rate.*
- Outside Air temperature*
- Indicated airspeed.*
- Wind Speed and direction*
- Longitudinal accelerations*
- Normal Acceleration*
- Main rotor speed (Nr)*
- Flight critical control settings which include:*
 - lateral and longitudinal cyclic positions*
 - collective position*
 - tail rotor pedal*
 - rotor brake*
 - hydraulic selection*
 - landing gear position and*
 - Engine torque*
- Engine compressor speeds*
- Engine power turbine speeds and temperatures*

The FDR records and stores additional parameters:

Oil pressure and temperature for the following gearboxes:

Main

Right and Left Nose

Intermediate Accessory

Automatic Flight Control System mode and status

IWS equipment BITE results

All caution and warning signals

All voice data is input to the interface unit where it is compressed and sent to the BAU for storage. The CVR uses a continuous overwrite format to store the most recent two (2) hours of voice data. The CVR records pilot, TACCO, winch operator and cabin area microphone voice data on four separate channels.

ELB

The recovery of the EAS3000 FDR/CVR BAU is enhanced by incorporation of an ELB that automatically starts transmitting on international distress frequencies (121.5 & 406 MHz.) immediately following deployment. A data analysis and playback unit is part of the EAS3000 ground support equipment for flight data playback capability of the BAU, audio playback, and system maintenance.

CONCLUSION

The SH-2G(A) Super Seasprite helicopter of the Royal Australian Navy is fitted with an ITAS Monitoring and Recording System, Engine and Drive Monitoring System, Vibration Monitoring System and Usage Monitoring System that provide tremendous versatility and flexibility in an aircraft-wide usage/health monitoring capacity. All installations have been evolutionary requiring little in terms of investment. As the aircraft attains initial operational capability and matures in its role with the RAN, the availability of the data discussed in this paper may only contribute to the SH-2G(A)'s already high reliability, maintainability and availability to fulfill its mission objectives.

An Affordable *Modular* HUMS Certification Program in an EMS Helicopter

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Abstract

PURPOSE:

EMS missions are unpredictable, often dangerous, day and night missions, many times pushing the envelope of the aircraft - all in the good cause of savior of human life. The need is to provide our crews with the assurance that our helicopters have adequate safety margins to perform these missions, and that any problems associated with the aircraft are predicted and corrected before they become problems during a mission.

Additionally, EMS Direct Operating Costs (DOCs) are spiraling out of control; it is becoming more and more challenging to provide superior services while remaining competitive. The partial answer in EMS aviation operations is to tightly control maintenance operations by utilizing an automatic Maintenance Management System (MMS) to electronically record all the maintenance and financial records (Electronic Logbooks, etc).

METHODS:

Driven by—among other forces—CAA Regulatory Requirements, early Health & Usage Monitoring Systems (HUMS) were introduced into North Sea operations, by a number of manufacturers, for the Offshore Petroleum Industry. Although successful, this experience was only cost effective in the larger type helicopters such as Super Pumas and S-76Cs. The North Sea operations did not address the light and medium twin aircraft used in EMS operations. The requirement for HUMS grew in intensity as enhancement of safety, control and reduction of direct operating costs, and the need to meet new regulatory requirements were circulating within our industry. As a result, a New and Modular

HUMS, designated M-HUMS™, was developed specifically for the light and medium twin aircraft. M-HUMS™ is lower in cost, endorsed by the airframe and engine manufacturer, and enables each operator to select only the modules necessary to fit the mission.

RESULTS:

M-HUMS™ today is an “approved” system by the airframe and engine manufacturer, and is being “certified” by the CAA and DGAC. During development, the airframe manufacturer was involved from the beginning with the system supplier. This involvement required: Conducting an analysis on all of the System Requirement Specification (SRS) documents; Reviewing the technical specification, placement of sensors, and required thresholds; Providing relevant data to support all modules; Participating on site during operational validation; and Providing technical assistance in supporting the system integration.

The M-HUMS™ hardware consists of an Airborne Computer, Cockpit Display Unit with built-in PCMCIA Controller, an Engine Vibration Monitoring Unit, and an Air Data Computer. Cockpit Voice and Flight Data Recorder hardware is also available. The installation kit includes all required sensors and aircraft-specific mounting brackets. The full-up system provides five separate functional groups: Engine Usage compliant with JAR-OPS 3; Rotor Track & Balance (RT&B); Transmission Gearbox Health; Engine Vibration Monitoring (EVMU); and CVFDR/FDAU compliant with ED-55 and ED-56. The operator selects only the functions required for the mission.

As a result of the close collaboration between the supplier and the airframe

manufacturer, a prominent Scandinavian Insurance company funded a flight trial using a Norwegian EMS, Eurocopter type AS-365N Dauphin aircraft. All five modules were integrated into this aircraft after being inspected and approved by the Norwegian Authorities. After this system is operational for a period of six months, a decision will be made to install all five modules, or some number of modules of M-HUMS™, in this Operator's fleet of helicopters.

CONCLUSIONS

The benefits of M-HUMS™ are:

Anytime we are able to control and maintain vibration levels to a minimum, the helicopter will have a smoother ride, the life of the components—especially delicate electronics—is longer, and the engines become more durable. When using the Rotor Track & Balance (RT&B) module, as an example, the aircraft vibration levels are significantly reduced (40%) since the permanently mounted tracker is capable of monitoring the rotors at anytime (on command of the pilot). The pilot performs this action by depressing a button in the cockpit display panel activating the automatic/manual RT&B command. Most importantly, this eliminates the need to perform non-revenue flights, as in the case of RADS, for RT&B. This is a considerable cost savings to the Operator.

With the Engine Usage Module we are able to detect any exceedances (time and amplitude) that may have occurred during the last flight. The same engine parameters that are listed in the aircraft maintenance manual are monitored. Automatic Power Assurance Checks are also made. The M-HUMS™ Windows-based Ground Station maintains an electronic logbook resulting in more accurate control of the flying hours and engine cycles. The data improves the billing and invoicing procedures to the Operator's customers. The Ground Station can issue a report on the history of the aircraft and fleet if requested. This history will help increase the resale value of the aircraft.

Because the airframe and engine manufacturer validate the data coming from the M-HUMS™ Ground Station, the maintenance manuals and job cards are modified to accept M-HUMS™ as an approved Maintenance Tool, and may be used accordingly.

With this improved control over the maintenance operations and the monitoring of the individual aircraft, insurance companies have now become interested offering favorable premium discount rates to Operators and companies who are investing in this type of M-HUMS™ monitoring systems.

Smiths Industries
Generic Health and Usage Monitoring System
(GenHUMS):
A Modular Approach to Aircraft Data Management

Charles Trammel
Smiths Industries Aerospace

Abstract

Smiths Industries Aerospace (SI) offers a multi-aircraft capable Integrated Data Acquisition and Recorder System (IDARS) with built-in HUMS growth capability. A number of civil and military operators have selected the SI GenHUMS, including Bell Helicopter for the Bell-Agusta 609 civil tiltrotor and the UK Ministry of Defence (MoD) for the Chinook aircraft with additional options for Puma, Sea King and Lynx aircraft.

GenHUMS provides all conventional HUMS functionality, and incorporates key innovation in the areas of rotor track and balance, failure detection, flight regime recognition, alert generation, system configurability, and user interface. The architecture is unique in that all required airborne data acquisition and processing,

including crash survivable cockpit voice and flight data recording, are combined in a single line replaceable unit. This architecture significantly reduces space, weight and power requirements and results in the highest reliability, least risk, lowest life cycle cost, HUMS known today. Fixed and portable PC-based ground stations provide configurable, user friendly, data extraction and analysis capabilities.

GenHUMS incorporates broad flexibility in modular software and hardware design critical to efficient, low cost adaptation across different aircraft types. This paper describes the system capabilities and summarizes the GenHUMS open architecture design approach with specific examples from recent programs.

Smart Structures Technologies for Structural Health Monitoring

**S.C. Galea, N. Rajic, I. G. Powlesland, S. Moss, M. Konak,
S. Van der Velden, A. A. Baker**

DSTO, Australia.

I. McKenzie, Y.L. Koh and W.K. Chiu

DSTO - Centre of Expertise for Structural Mechanics, Mechanical Engineering Department,
Monash University, Clayton VIC 3168, Australia.

Abstract

Due to economic pressures, including the very high cost of replacement aircraft, the military in most countries (including the US) are forced to extend the life of their aircraft. Similar problems arise for some civil operators. It can be expected, therefore, that the problems of corrosion and fatigue cracking, associated with aging aircraft, will become increasingly severe in the future.

In the Australia a significant number of ADF aircraft are being operated well past their design life. For example the F-111C fleet will be in service till the year 2015 which is about 20 years more than the original design life of the aircraft. As fleets get older a greater share of the operator's resources need to be used on through-life-support of the airframe. One way of reducing costs and increasing aircraft availability is through the use of smart materials technology.

Smart materials are materials with the ability to respond to changes in the operating environment or to other stimuli in an intelligent way. This ability may be achieved from sensors and actuators embedded in or attached to the structure or, more simply, from an inherent response mechanism in the material. In the context of ageing airframes, smart materials/structures technology has excellent potential to provide improvements in through-life support, including health and

usage monitoring (HUMS), with the eventual aim of allowing condition based maintenance procedures to be adopted, rather than relying on current expensive time-based maintenance procedures.

This paper discusses the development and evaluation in DSTO of smart structure technologies to be applied to structural health monitoring of aircraft structures. Systems are being developed by DSTO with the specific aim of retro-fitting to existing airframe structures (e.g. smart repairs and reinforcements with the ability to self-monitor patch system integrity), need to be autonomous, distributed, robust and reliable. The paper describes some of the health monitoring techniques being developed and evaluated, including:

- (1) smart repairs and reinforcements (i.e. ability to self monitor patch system integrity),
- (2) use of piezotransducers for health monitoring,
- (3) optical fibre systems for loads and health monitoring and
- (4) MEMS-based devices.

The paper also discusses approaches taken in achieving system autonomy by the development of self-powering and wireless access techniques.

Implementing HUMS in the Military Operational Environment

M Augustin

Bell Helicopter Textron

A.Heather

Smith Industries Aerospace – DMS Europe

Abstract

Several Military programs including the U.K. MOD, U.S. Navy, U.S. Army, and Australian DSTO to name a few are now implementing or planning the implementation of Commercial Off-the-shelf HUMS originally developed in the Commercial Sector. Operational Requirements vary widely from those of the fleet of helicopters used in the offshore oil industry. Much has been learned in dealing with these issues in the fielding and implementation of HUMS in the Canadian Forces fleet of 100 CH146 Griffon Helicopters.

An engineering team has been working together with the Canadian Forces since early 1994 to develop, install and support the introduction to service of this fully functional HUMS system in the Canadian Forces Fleet.

The Canadian Forces are currently the largest military user of HUMS in the world and with a wide variety of operational roles assigned to the Griffon there have been many unique challenges associated with the commissioning of this system. The experience has

highlighted the differences between military and civil operational environments and has led to different approaches being taken to those developed previously with the predominantly offshore civilian HUMS operators that dominated the initial application of HUMS in the early 90's

This paper reviews the approach taken and experience gained over the last several years of operation.. Particular reference is made to the configuration of a HUMS to the military flight operational environment and the development of Helicopter Manufacturer backed HUMS threshold and alarm levels. Both factors being essential to ensure the early detection of mechanical anomalies within the helicopter while avoiding false alarms.

Other issues include maintaining Data Base Integrity across the fleet, Training, and the need for support across Canada and World-wide as the Griffons are deployed to field and remote areas.

Structural In-Service Monitoring of Advanced Combat Aircraft: Operational Benefits

Phillippe Perrin et al.

Dassault

Abstract

Innovative, original and accurate methods have been developed in Dassault Aviation in order to monitor the health and usage of advanced combat aircraft.

These methods were developed and validated in the 90's and have been applied to the dimensioning and the qualification of RAFALE.

The resulting Integrated Health and Usage Monitoring System performs fleet-wide monitoring of significant structural loading events and fatigue life consumption,

minimizing in-service structural maintenance actions.

The RAFALE advanced IHUMS is described. The description outlines the process from Finite Elements Modelization during the design phase down to the definition of simple but accurate In-Service Monitoring means and procedures.

The overall approach to IHUMS-based structural maintenance is addressed, yielding key outputs in terms of aircraft maintenance plan and means, end user autonomy and Life Cycle Cost reduction.

Advanced Knowledge Management for Helicopter HUMS.

Sunil Menon and Rida Hamza,
Honeywell Laboratories

Sam McRoberts
Chadwick-Helmuth Inc.

Abstract

Conventional helicopter HUMS systems rely on analysis algorithms to interpret the data collected from helicopter systems (engine, transmission etc.) and detect faults. Fault detection and diagnosis methods can be vastly improved by incorporating knowledge gained from other helicopter subsystems and earlier experiments.

In this work, we propose a fusion technique that transforms incomplete, or imprecise data provided by current sensors into more useful information by fusing it with stored data. The algorithm takes different inputs, from archived data, and combines them synergistically for the purpose of obtaining more comprehensive interpretation of current data. Data mining techniques are applied to

archived data to retrieve only relevant information to current system.

The choice of knowledge management architecture is a fundamental issue in developing a data fusion system and in deciding at what level to combine or fuse data in the processing flow of more than one data source. We devise an architecture that addresses this issue and we draw specific examples from fault detection and diagnosis of the helicopter transmission system. The advantage of this proposed architecture is that it permits us to apply earlier gained knowledge into some form of meaningful inference. Fault prognosis algorithms are also incorporated in this architecture and can be the basis for a more advanced helicopter fleet management system.

A Review of Permanently Installed Helicopter Gearbox Vibration Monitoring Systems in the Australian Defence Force.

Andrew Becker, David Blunt and David Forrester
Airframes & Engines Division, DSTO

Abstract

The prevention of catastrophic failure of helicopter gearboxes is the primary objective of gearbox vibration monitoring. In the past gearbox vibration monitoring involved the temporary installation of sensors and cabling followed by dedicated flights to record the data. This amounted to an added workload for squadron personnel simply to acquire the vibration data.

The Royal Australian Navy (RAN) recently commenced permanently installing (hard-wiring) the Sea King and Seahawk helicopters with vibration sensors and cabling to enable rotor track and balance, airframe vibration survey, engine vibration survey and gearbox

vibration analysis. The gearbox vibration analysis component of this system has been developed by the Defence Science and Technology Organisation (DSTO). The other vibration analysis is conducted using commercially available equipment

This paper discusses the DSTO developed gearbox vibration analysis element of the RAN hard-wired system. The system will be described in detail and the intended operating procedures outlined. The current status of the hard-wiring program in the RAN will be discussed together with proposed systems for other Australian Defence Force (ADF) helicopters.

The OTHER values of HUMS

Hanan Silverman

Presenter: **Marcia Shamo**
RSL Electronics, Israel.

Abstract

The benefits of Health and Usage Monitoring Systems (HUMS) have become well known to the maintenance and aircraft operations divisions of many fixed wing and rotary wing operators.

HUMS provides aircraft and engine maintenance staff with important data regarding the health and performance of the airframe and powerplant. In addition, RSL's Total HUMS (THUMS) offers the capability to analyze the data using state-of-the-art artificial intelligence tools and expert systems to provide prognostic and diagnostic information on the airframe's health, maintenance requirements, and continued airworthiness. This paper suggests that

THUMS may also serve as an important data source for flight operational safety programs such as Flight Operations Quality Assurance (FOQA), and other flight data analysis programs.

The paper first addresses the data and operational requirements of FOQA, and then briefly reviews the potential benefits that may be gained by an operator's adoption of such programs. The remainder of the paper examines the applicability of THUMS data for FOQA and similar programs, and discusses the way in which THUMS data may be best utilized to improve the operator's safety and operational efficiencies.

Certification of Engine Usage Monitoring Systems

SQNLDR Robert A Matchett

RAAF DMO (SCI4-DGTA)

Systems Certification and Integrity - Propulsion and Mechanical Systems

Outline:

- ADF is responsible for certification of state aircraft (including engine and systems)
 - ADF comparative std is DEF STAN 971,
 - Currently recognised stds include JSSG 2007, FAR 33, JAR-E
 - Focus of current stds is life substantiation
 - Limited coverage of the significance of tracking usage in-service
 - EUMS provides opportunity to increase safety, reduce LCC and increase operational availability
 - Certification of EUMS is critical to ensuring continued airworthiness of engines
 - ADF developing guidance for certification of Engine Usage Monitoring Systems (EUMS)
-

Diagnostic Sensor Fusion Test Program and Results

Paul L Howard,

Paul L Howard Enterprises and

John Reintjes

US Naval Research Laboratory

Abstract

The U.S. Navy, Office of Naval Research and Naval Research Laboratory have established a cooperative research program with Swansea University aimed at correlating vibration signatures, acoustic emission data and wear debris derived from wear tests.

The goal of the program is to improve the diagnostic accuracy of each technology by

combining information. Testing is in progress on four ball, pin on disk, gear test machine and bearing testers and data is now becoming available indicating the complementary nature of these technologies. This paper details the program plan and results to date.

Comprehensive HUMS (CHUMS)

Richard F Healing

Director, US Navy Office of Safety and Survivability

Abstract and Outline

I. Intro

Military aviation demands a high standard of excellence. Excellence = full mission performance, without injury or loss. Safety = no injury, no loss. Therefore, excellence is full mission performance, plus safety.

HUMS and FOQA have clearly saved immeasurable dollars and lives in the commercial world. Now is the time for the military to leverage the technologies which created the commercial success to implement a Comprehensive HUMS (CHUMS) and MFOQA system that will reduce mishaps, generate savings and improve operational readiness and quality of life.

II. Current Military Systems

1. Very few FDRs
2. Some analog systems
3. Many independent data sources
4. R&D/Procurement cycle unable to keep up with technology

III. Current Military Culture

1. Fear of "Big Brother"
2. Operational Security concerns
3. Traditional "autopsy" approach to data

IV. Current Military Trends

1. 16% Maint, 80% Human Factors in mishaps, 4% other
2. Increase in electrical-related incidents
3. Inexperience Maintainers and Flight Crews
4. Decreasing assets and resources for training
5. Aging fleet

V. Taking a systems approach

1. CHUMS

- A. Aging Systems require monitoring
- B. Increased reliance on electrical systems and controls create a critical link that must be monitored
- C. Benefits demonstrated in the commercial world can translate to the military
- D. Technology is available off the shelf

2. MFOQA

- A. Proactive
- B. Objective measurements, not reliant on aircrew memory
- C. Self-Correcting system
- E. Powerful debriefing tool
- F. Proven by Commercial Carriers

3. Written Reports

- A. Maintenance (SDRS, MEDA)
- B. Pilot reports (ASRS, ASAP)
- C. Operation Risk Management (ORM) as a complimentary system

VI. Success stories

1. HSL 41
2. CADS
3. HOMP, SESMA
4. FAA Demo Proj

VII. Conclusion

HUMS has demonstrated a significant benefit to commercial aviation by monitoring and reporting significant mechanical events. By exploiting new technology, a comprehensive HUMS system that monitors electrical health, integrated with measured and reported operational flight parameters, will give military aircraft improvements in operational readiness, maintenance efficiency, and safety.

Model-Based Decision Support Tools For T700 Engine Health Monitoring

Peter Frith and George Karvounis
Airframes & Engines Division, DSTO

Abstract

This paper describes the progress made by DSTO in developing a model-based approach to the diagnosis and prognosis of engine gas path health in Australian Defence Force (ADF) helicopters powered by General Electric T700 engines. In particular, two new model-based tools are presented: one for estimating power assurance and one for detecting abnormal engine operation.

These tools have been developed to take advantage of the engine parameters recorded by modern Health and Usage Monitoring System (HUMS). Such systems are under consideration for fitting to ADF helicopters as part of mid-life upgrade projects. The first tool, the T700 model-based power assurance estimator is proposed for use with the current Health Indicator Test (HIT) check

and it links the HIT check value to the power available for a given flight condition and scenario of component degradation. The second tool, a combined model-based detector and fuzzy-logic decision maker is proposed initially for use in a HUMS ground station to reduce the amount of data manually processed or interrogated.

The DSTO developed MATLAB-Simulink true twin T700 engine model with its demonstrated accurate tracking of transient flight data provides the means of detecting major shifts in in-flight engine condition over a given flight. A fuzzy logic formulation then provides the means to automate this detection process and provide an end of flight estimate for future prognostic trending.

Using Econometric Modelling to Determine and Demonstrate HUMS Affordability.

Graham F Forsyth

Scott A. Dutton

DSTO Aeronautical and Maritime Research Laboratory

Abstract and Paper Outline:

Between 1992 and 1996, staff from the Australian Defence Science and Technology Organisation (DSTO) provided technical support to an Australian Defence Working Party on helicopter health and usage monitoring. Although technical data on such systems was available, information on financial aspects proved harder to obtain and even harder to interpret when it was obtained.

As a result, one of the documents produced for the working party described a set of equations to model the financial impact, expressed in terms of discounted cash flows, of all the perceived costs and benefits of such systems. This model was then implemented in software as a program known as HUMSSAVE. The current version of HUMSSAVE (Version 3, release 2) runs on any windows platform.

Description of HUMSSAVE

HUMSSAVE implements the equations

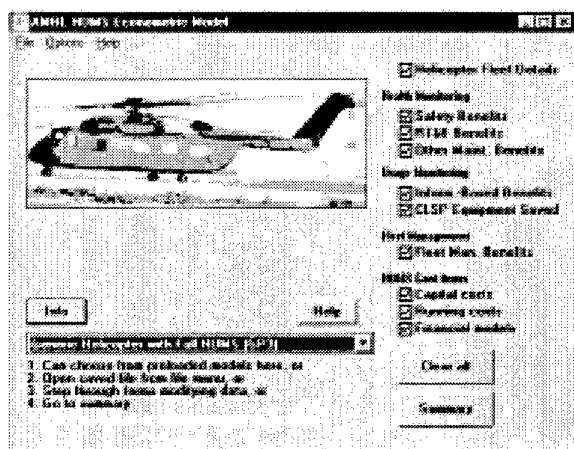
defined in the document "Australian Defence Organisation Working Party on Strategic Planning for Helicopter Accident Data Recording and HUMS Guidance Paper No. 3, HUMS Cost-Benefit Analysis Methodology, 15 May 1996" which is supplied with HUMSSAVE as a portable document format (pdf) file.

The main data entry screen is shown on the left. Data for the model may be contained in a pre-defined file or entered for each area of interest as indicated by the check-list on the right of the screen.

HUMSSAVE uses the normal Windows File menus allowing data to be saved and retrieved. Other menu set options and provide help to the user.

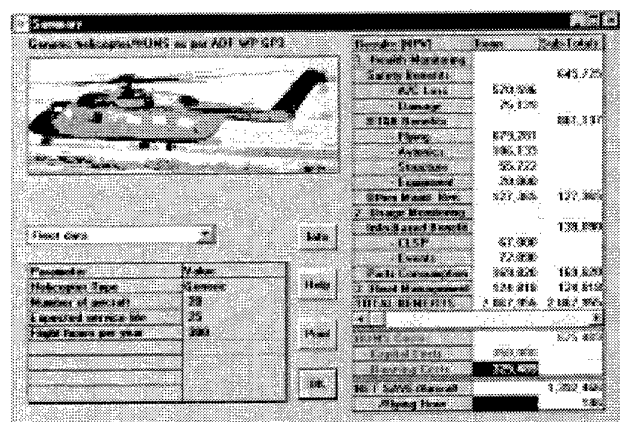
Normal data entry starts at the top of the check-list and proceeds until all the check-boxes are ticked but individual data changes can be made. A click on the Summary Button will then show a summary of the results. The main results of the HUMSSAVE program appear on the Summary form [right] and on the printed output generated by clicking the Print button on that form. Results are displayed in terms of each category and item as well as per aircraft and per flying hour.

Clicking any item on the results table displays the input table with the parameters and values which generated that result. Information on the equation and data format and help on using HUMSSAVE are directly available from the screen buttons marked INFO and HELP respectively.



Deficiencies in HUMSSAVE

Although HUMSSAVE can also be used to model cost benefit relationships for other helicopter monitoring systems and any other monitoring system which can be expressed using the same relationships (equations) or a sub-set of them, there is an in-built lack of flexibility with the formulas and variables hard coded into the program making it less valuable on other platforms or monitoring systems. As well, HUMSSAVE relies on the user to identify key numbers and monitor the source and accuracy of values entered. This means the HUMSSAVE results are often inaccurate without this fact being clearly displayed.



PCMS Analyser

PCMS Analyser is the second generation software package used to cost/benefit model condition monitoring systems on various platforms. The new software overcomes the lack of flexibility by being template driven. PCMS Analyser is effectively two programs, used by perhaps differing people. One program, defines or modifies templates, which specifies the generic format of a platform. The second program loads this template and allows the user to input the data to the software for the modelling of cost/benefits in "what if"

scenarios. The software is now not limited to one type of platform, but is dependant only on the provision of a describing template and input data.

The template specifies the categories, formula and variables which define the platform and its associated monitoring system. The template also indicates any help text that the model designer feels may be of assistance to the user who inputs the data. The production of templates is completely independent of the main analysis program, and may not even be necessary at all if the platform/ monitoring system combination is not dissimilar from the original HUMSSAVE model. Templates for some generic platforms/monitoring systems (based on the original HUMSSAVE format) will be included and these may be modified or used as required. The template file does not need to be distributed with the application once it has been imported into the analysis software, as it maintains its own file system.

Additional features of the new release will be the inclusion of a sensitivity analysis to determine the effect each variable has on the overall cost/benefit allowing the user to identify which variables need to be entered with a high degree of confidence, or areas where the greatest savings may be leveraged.

Conclusion.

Although programs such as HUMSSAVE demonstrate that the return from fitting health and usage monitoring on helicopters can be significant, the perceived initial cost is still a stumbling block.

New versions of the software and a survey of available cost information seek to replace the impression with a more scientific basis to choose the level of monitoring to implement on a helicopter fleet.

Vibration-Based Helicopter Gearbox Health Monitoring - An Overview of the Research Program in DSTO

A.K. Wong
DSTO Australia

Abstract

The Defence Science and Technology Organisation (DSTO) has a long and respected association with vibration-based condition monitoring technologies, and this paper presents an overview of the DSTO's program of work in this area. The paper briefly charts through over 2 decades of research and development, arriving at the current work program covering advanced algorithm development, experimental validation, field deployment, and commercialisation. The presentation concludes on glimpses of the future work that DSTO will embark on.

Project AIR87: Armed Reconnaissance Helicopter HUMS Requirements

CAPT M. Millar and MAJ P. Harris,
Project AIR87 Office

Outline.

Project AIR87 consider HUMS to be an integral and critical component to supporting the operational capability of the Armed Reconnaissance Helicopter. The presentation will cover the approach taken by the ARH Systems Project Office for the specification of the HUMS on the ARH.

Other Papers.

A number of accepted papers are not available as an abstract at the time of printing this document. These include the following papers:-

1. **"Engine Vibration Control for HUMS"**, Francois Cantegreil, SEMIA (which will be available as a PowerPoint presentation only).
2. **"The U.S. Navy/BFGoodrich Integrated Mechanical Diagnostics COSSI Program - an Update"**, Alan Duke, BFGoodrich Aerospace and LCDR Paul Thitchener, USN Multi-Mission Helicopters Program Office.
3. **"Potential HUMS Benefits from the S-70A-9 Black Hawk Flight Loads Survey"**, R Boykett, DSTO; C Crawford, GTRI, and Dr Tom Christian, USAF Special Forces (which will be available as a PowerPoint presentation only).

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19. ABSTRACT The concept of On-Condition Maintenance implies the need for Condition Monitoring to close the loop. Condition monitoring may be implemented at many levels requiring various degree of complication. As relatively fragile machines with catastrophic outcomes possible for many failure types, aircraft have always used some degree on monitoring. Recently, engines, mechanical sytems and airframes on both fixed-wing aircraft and helicopters are being fitted with permanent monitoring systems. These systems are also becoming more integrated to the extent that some are now called "Health and Usage Monitoring Systems" or HUMS. Following a successful conference in February 1999, DSTO have again sponsored an International Conference on Health and Usage Monitoring in conjunction with the Australian International Airshow in February, 2001.					