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

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Abstract

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

1. Introduction

DSTO has been active in the development and application of vibration-based health monitoring technology for over two decades. Early investigations included the use of spectral analysis for the condition assessment of gearboxes used in aircraft operated by the Royal Australian Air Force, covering both gears (McFadden, 1980a, McFadden and Edwards, 1981, McFadden, 1981) and bearings (Swansson and Favaloro, 1984, McFadden and Smith, 1984). In 1977, the Royal Australian Navy (RAN) had the foresight to establish a program of vibration analysis (VA) to assist with the health assessment of the main rotor gearboxes (MRGB) of its fleets of Sea King and Wessex helicopters, and DSTO was called upon to serve as technical adviser (McFadden 1980b). The system selected for this program was based on "off-the-shelf" equipment, and included a single accelerometer mounted on the MRGB, a battery-powered portable FM tape recorder, and a high resolution spectrum analyser. Vibration recordings of each gearbox were made at intervals of 25 to 50 flying hours, each consisted of five records of approx. 30 seconds duration, covering a range of torque settings. The spectral results were then examined by an experienced analyst and compared with the previous spectra for the same and other gearboxes. By 1979, this program was well established, and one of its first successes was in the detection of two damaged bearings in the MRGB of a Sea King shortly after overhaul. Whilst none of the other monitoring techniques used at the time could reveal any anomaly, McFadden (1980b) was able to deduce the type and locations of the fault, which were subsequently confirmed by physical examination of the gearbox during overhaul. Unfortunately, this early success was quickly overshadowed by a more serious fault that slipped through the net.

In December 1983, an RAN Wessex crashed into the Bass Strait due to a catastrophic fatigue failure of the input bevel pinion in the MRGB (WAK143) resulting in the loss of two lives. As this particular aircraft had been a candidate of the then existing VA program, it became clear that the analyses employed were simply not able to provide reliable early detection of such failures. Apparently, to find a meshing fault that occurs over a very short time interval in a complex system of gears like that of a helicopter MRGB, a more specialised form of analysis was required. McFadden (1985a) proposed an amendment to the program by incorporating the techniques developed earlier by Stewart (1977). Using the previously collected data for the Wessex MRGB WAK143, it was shown that by using synchronous signal averaging, narrow-band enveloping and statistical measures such as the kurtosis, the fatigue crack in question could have been detected more than 100 hours before the final failure.

2. Past Development

The tragic loss of the RAN Wessex highlighted the criticality of the power transmission system of a helicopter, and the importance of monitoring its health. The 1980's saw DSTO expending much more effort in this area. A gear-dynamics model was developed in 1984 based on the theoretical work of Rebbechi (1975). This model contributed much to the fundamental understanding of the vibrations produced by meshing gears, and provided an invaluable source of simulated gear vibration signals for algorithm development. McFadden initiated investigations into the role of structural resonance (1985b), vibration characteristics of epicyclic gears, the effects of transmission paths (McFadden and Smith, 1985, 1986), and the significance of amplitude and phase modulations (1986). This latter work was further refined by Forrester to produce the familiar "bullseye" plots that depict both the amplitude and phase modulations and proved to be extremely useful for fault diagnosis (see Blunt & Forrester, 1995). Figure 1 shows the bullseye plot for an undamaged Wessex input pinion, and that for the cracked Wessex WAK143 data collected 103 hours prior to final failure, clearly illustrating the change in both types of modulation resulting from the damage.

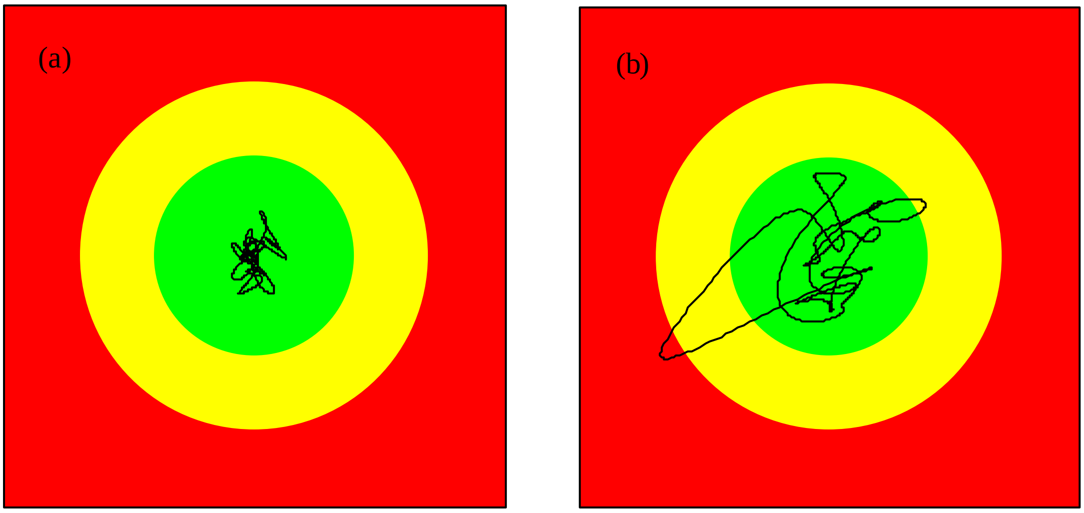


Figure 1. Bullseye plots illustrating the amplitude and phase modulations of Wessex input pinions. a) Undamaged and b) Wessex WAK143 at 103 hours prior to failure. The three coloured regions, green, yellow and red, represent the safe, caution and danger regions of operation, respectively.

Throughout most of the 1980's, the analyses of vibration data for gear diagnosis were invariably performed either in the time or frequency domain after suitable filtering of the synchronous signal average. However, this filtering process requires great expertise and experience as removing too many components could risk discarding vital information, whereas not removing enough could allow irrelevant signals to mask the fault. A significant advancement was made when Forrester (1989) introduced the use of time-frequency analysis for VA. Whilst the use of time-frequency functions such as the Wigner-Ville Distribution (WVD) had been known since the 1940's, and have been commonly used in the areas of signal processing and communications, it was the first time that such analyses were used for mechanical diagnostics. Forrester showed that the WVD of the signal average (with no further enhancement or filtering) was able to reveal the Wessex WAK143 fault (see Figure 2).

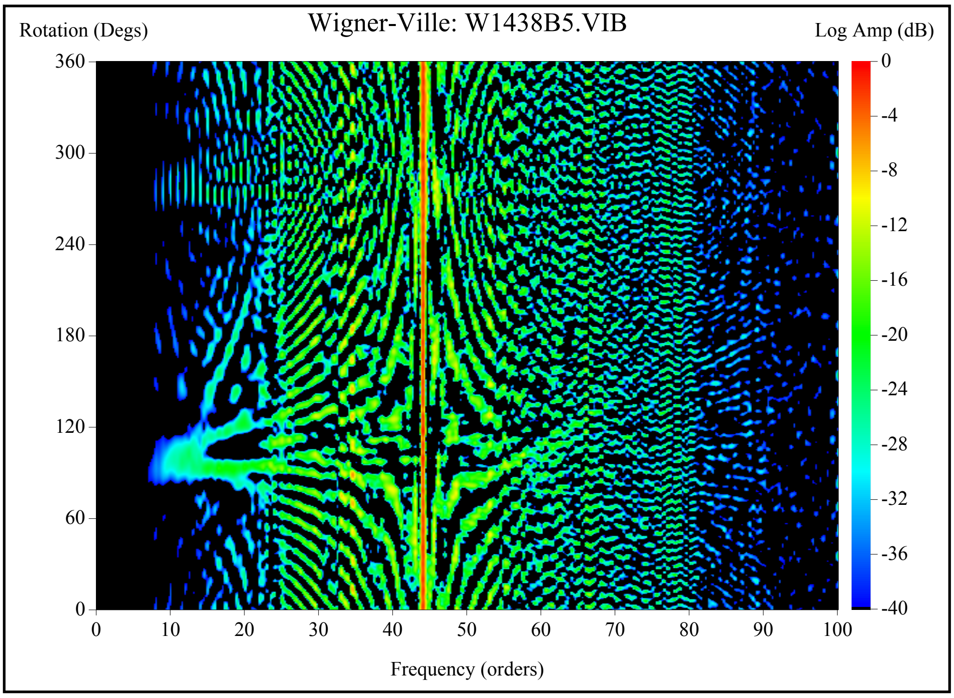


Figure 2. The Wigner-Ville Distribution of cracked Wessex input pinion at 42 hours prior to failure. The distinct disturbance of the signal about the 44 shaft-order near the 100° shaft-angle highlights the presence of the crack on the 22-tooth input pinion.

Since this pioneering work, the use of time-frequency analyses has been growing steadily amongst vibration analysts throughout the world, and has led to the investigation of many other time-frequency applications such as and wavelet transforms (eg., Staszewski and Tomlinson, 1994) and the number of variances of the WVD (eg., Williams and Zalubas, 2000) for VA. Forrester also later formulated a modified form of the spectrogram (herein referred to as the Forrester Distribution, FD) that retains all the advantages of the WVD but without the interfering cross-terms that sometimes make interpretation difficult. Figure 3 shows the FD for the same data set as that shown in the WVD of Figure 2. Besides the lack of interference terms, the FD has the added advantage of being a continuous function, thus allowing any region of interest to be studied at any desired level of detail. Forrester (1996) showed that an incipient fault could be detected at a very early stage by "zooming in" on the FD.

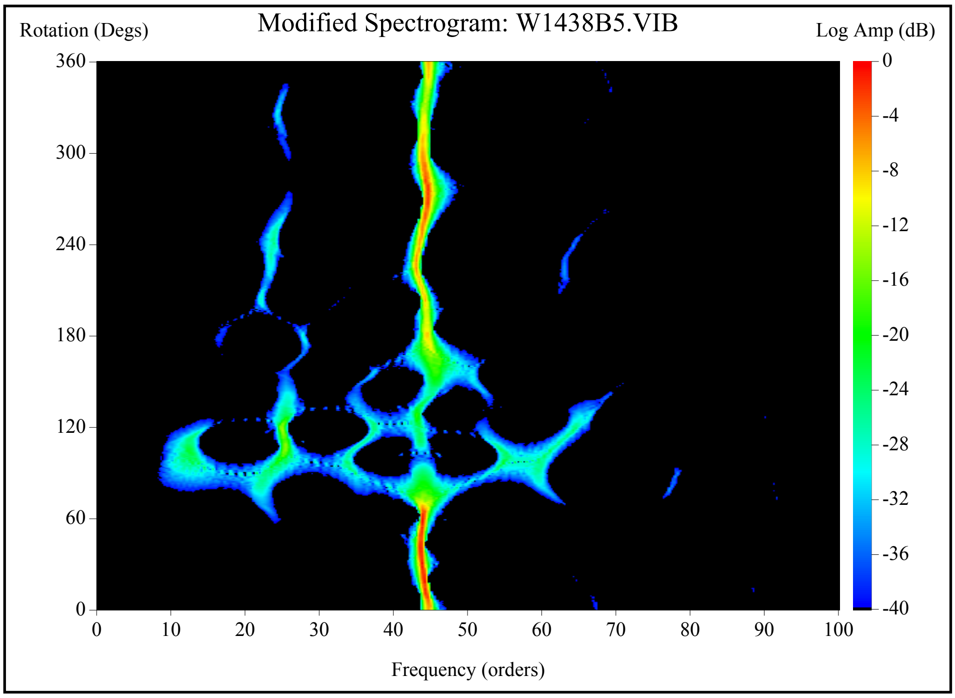
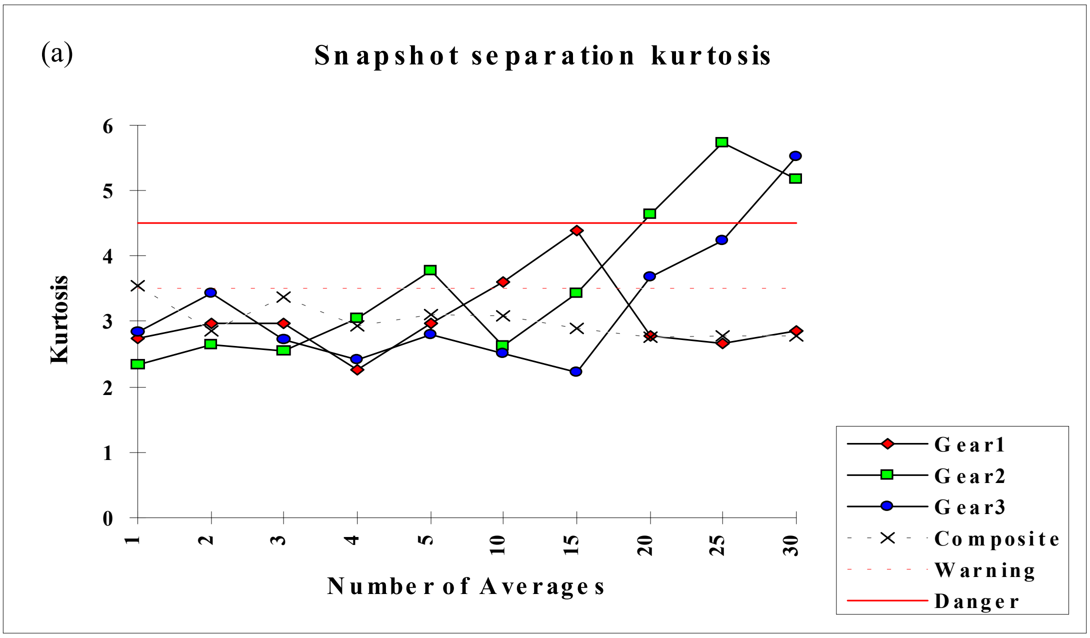


Figure 3. The Forrester Distribution of cracked Wessex input pinion at the same fault-state as that for Figure 2.

Another significant contribution that DSTO has been able to make is in the area of fault detection in the planetary gears of an epicyclic gear system. In such a system, the fact that there are multiple planets that are identical and whose axes move relative to a fixed measurement location poses a particularly difficult problem for the diagnostician. In an attempt to separate the vibration signals from the individual planet gears, McFadden and Howard (1990) first developed a "snap shot" method whereby small packets of data are captured as each planet passes the vibration sensor. As can be imagined, however, this process is necessarily inefficient as only a small fraction of all available data is utilised, and the time required to fully analyse a complex epicyclic helicopter gearbox would be unacceptable. Often, the assembly of discrete packages of data to form the final result also introduces discontinuities. Forrester solved both of these problems by applying an overlapping set of traversing windowing functions to the data. Being functions that are continuous and have certain conservative properties, it essentially means that no discontinuity is introduced and no data is wasted. In a test on an epicyclic gearbox consisting of three planets, Forrester (1995) showed that a tooth crack on one of the planet gears could be detected effectively and efficiently using this technique. Figure 4 presents a comparison of the signal separation effectiveness of the two methods for that test, where it may be seen that the Forrester Algorithm was able to correctly identify the faulty planet after only two averages whereas the snap-shot method largely failed. More recently, this technique was applied to the test data generated by the US Navy's Helicopter Integrated Diagnostic Systems (HIDS) program, and it was shown to be far superior compared to the standard method of analysis (Hardman *et al*, 2001). The epicyclic planet signal separation algorithm developed by DSTO is currently the subject of an Australian Patent and a US Provisional Patent (Forrester, 1994, 1998a).



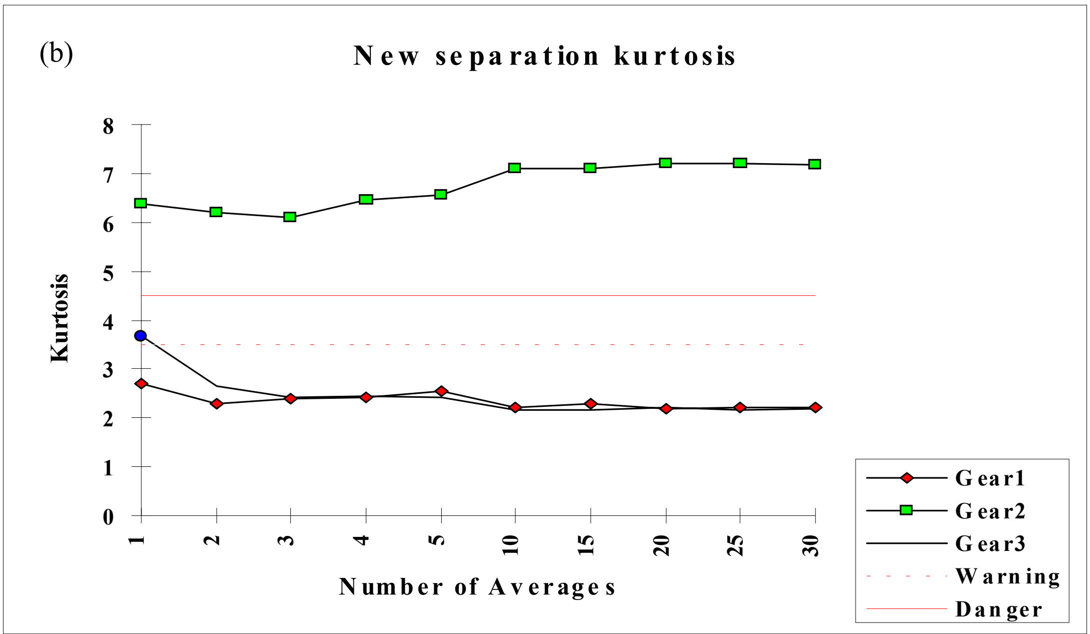


Figure 4. Separated kurtosis for a 3-planet epicyclic gearbox with a cracked tooth on Gear-2 using (a) the snap-shot technique, and (b) the Forrester Algorithm.

3. Current Activities

3.1 Advanced Algorithm Development

DSTO continues to operate at the leading edge of algorithm development, and contributes much to the general body of knowledge on gear fault detection and diagnosis. Forrester (1998b) further refined his epicyclic gear signal separation theory by deriving a generalised form of the windowing function that can be used effectively to decompose signals attributable to individual planet gears. As a result of this work, greater flexibility and room for optimisation can be made. Forrester (2001) also presented a rigorous analysis on the properties of digital synchronous signal averaging, thereby raising the fundamental understanding of this process, and provided a systematic means for selecting process parameters. In the same work, Forrester also investigated a number of digital re-sampling techniques commonly used by analysts, and showed that the use of the fifth-order spline interpolation to be the most efficient method.

The detection of gear faults under variable loads, or at least low loads, is also of interest in HUMS applications. For on-board systems, the ability to make use of data acquired at varying or low loads means that more of the data will be usable, and will lessen the chance of faults being left undetected. Rofe (1997) investigated several methods of linear modelling to tackle the variable-load problem, and showed (via the use of simulated data) that autoregressive moving average (ARMA) modelling techniques can account for the load variations. However, it was noted that in order for this method to work effectively, an extensive model needs to be created when the gearbox is known to be fault-free, and model parameters need to be determined over the range of operational loads. A less onerous approach is to tackle the steady, but low-load case, as this would also increase the amount of usable data. In addition, it is reasonable to assume that an algorithm that works well on low-load data will work even better at higher loads, thus making it more robust against false alarms. Wang (2000) showed that under a low-load situation, the use of wavelet analysis is more effective than a number of conventional methods of analysis.

One of the remaining challenges of vibration-based health monitoring is in making it more amenable to non-experts and for automation. Currently, there is still much art in processing, analysing and interpreting a vibration signal. Experienced VA experts are able to determine processing and analysis parameters (eg., frequency components/bands to discard) with almost mystical skills. However, to pass on this skill quickly to non-experts, or to encapsulate this knowledge into an automated system, is a major undertaking. The linear-modelling work of Wang and Wong (2000) showed that the use of autoregressive (AR) modelling could reduce the level of knowledge and skill required for making effective fault detection and diagnosis. Furthermore, it was shown that this technique significantly out-performed conventional techniques on a wide range of test data.

3.2 Experimental Work

Until recently, DSTO's test facility in this area consisted of a number of small test stands incorporating simple industrial type gearboxes. The commissioning of the Helicopter Transmission Test Facility (HTTF) last year has significantly boosted our experimental capabilities. The HTTF is a A$3.5M 520kW facility that permits the testing of the MRGB from either the Squirrel AS350B or the Bell 206 helicopters beyond full operational loads and with applied lift and thrust loads to simulate flight conditions. Figure 5 shows a view inside the test cell of the facility. Whilst our plan is to test the gearboxes with either naturally occurring or seeded faults, our present activities are on running the fault-free gearboxes to gain competence in operating the facility, and to gather data for our work on load-independent algorithms.

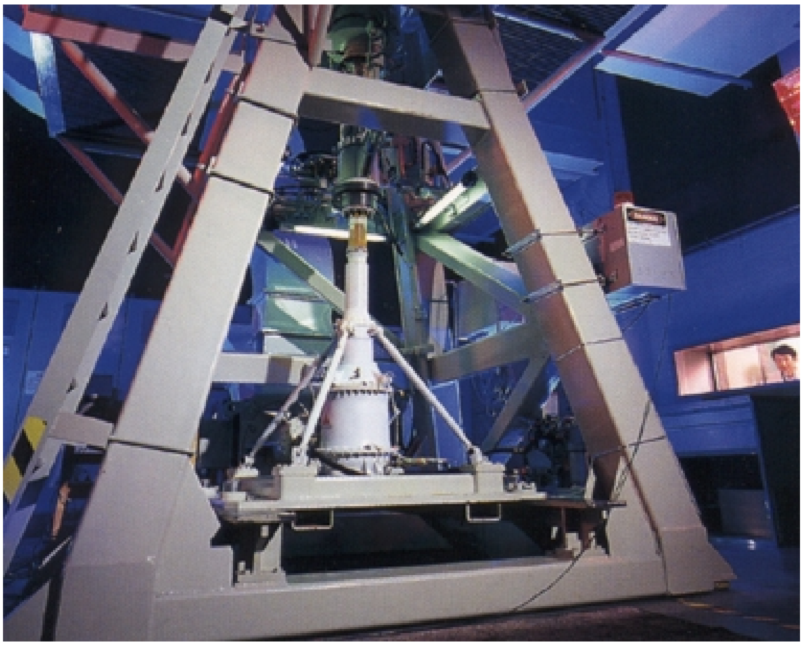


Figure 5. DSTO's Helicopter Transmission Test Facility fitted with the Squirrel AS350B main rotor gearbox.

3.3 Supporting the Australian Defence Forces (ADF)

DSTO is actively supporting a current major upgrade of the RAN VA monitoring program. To date, the RAN vibration-based health monitoring program has been based on tape-recorded data acquired via a small number of temporarily installed accelerometers. One major disadvantage with this approach has been the effort associated with the fitment of sensors, cables, and recording equipment to the aircraft each time that measurements are required. To make this monitoring program more effective and viable, the RAN has decided to adopt a 'hard-wired' system for its Sea King and Seahawk fleets. DSTO contributed significantly to the design and trialing of such a system. As part of a greater system that will enable rotor track and balance and other vibration surveys to be taken (eg., from the airframe and engines), the transmission VA system consists of a permanent installation of a network of up to five vibration sensors plus a photocell for providing a speed reference. The sensor-cables terminate at a cabin-mounted junction box, and data acquisition and analysis are carried out periodically using a piece of carry-on/carry-off equipment which is currently a ruggedised laptop computer incorporating the suite of DSTO-developed algorithms. A full description of system may be found in Blunt and Dutton (1996) (see also Becker *et al*, 2001).

Another ADF helicopter type that could easily benefit from a vibration-based health monitoring program is the CH-47D Chinook operated by the Australian Army. Because of the complexity of its power transmission system, and the prior history of gear fault related incidents, a good VA program could play an important role in the safe operation of this aircraft. Currently, the Australian Chinooks have a permanently-wired system that is intended to monitor the health of only a limited number of accessory components. However, DSTO has been tasked to investigate how this system could be used and/or augmented to monitor the power transmission system.

3.4 Centre of Expertise

In 1996, DSTO further increased its effort in vibration-based diagnostics by establishing a Centre-of-Expertise in VA (COE-VA) within an Australian university to undertake advanced research in the area. Through a competitive tendering process, the University of New South Wales was selected to foster the COE-VA under the leadership of Professor Bob Randall who is well known internationally in the VA circles. As DSTO has great strengths in gear fault diagnostics already, the initial emphasis for the COE-VA was to augment this with an equally advanced capability in bearing fault diagnostics. Under a formal agreement, DSTO is committed to the COE-VA with some level of continual funding (based on a four-year cycle) for conducting advanced research in areas that are of prime interest to DSTO. In return, DSTO gains access to the product of research and synergies that arise through a closer working relationship. This alliance not only ensures a more stable program and source of expertise within the University for DSTO to draw upon, but also provides a good degree of leverage for the work of both parties. Figure 6 shows a schematic of the DSTO/COE-VA relationship illustrating how leverage is gained through the injection of external resources, and synergies gained through exchanges between the gear and bearing research efforts.

Some notable outputs include the development of an adaptive noise cancellation algorithm for removing the dominating gear noise when analysing bearing faults (Ho and Randall, 1997, 1998), and the application of neural networks in fault detection and diagnostics (Gao and Randall, 1998). Due largely to the success of this program, this Centre has recently been renamed the Centre of Expertise on Helicopter Structures and Diagnostics, with the expanded scope of covering other areas of helicopter research such as structural dynamics and battle damage analysis.

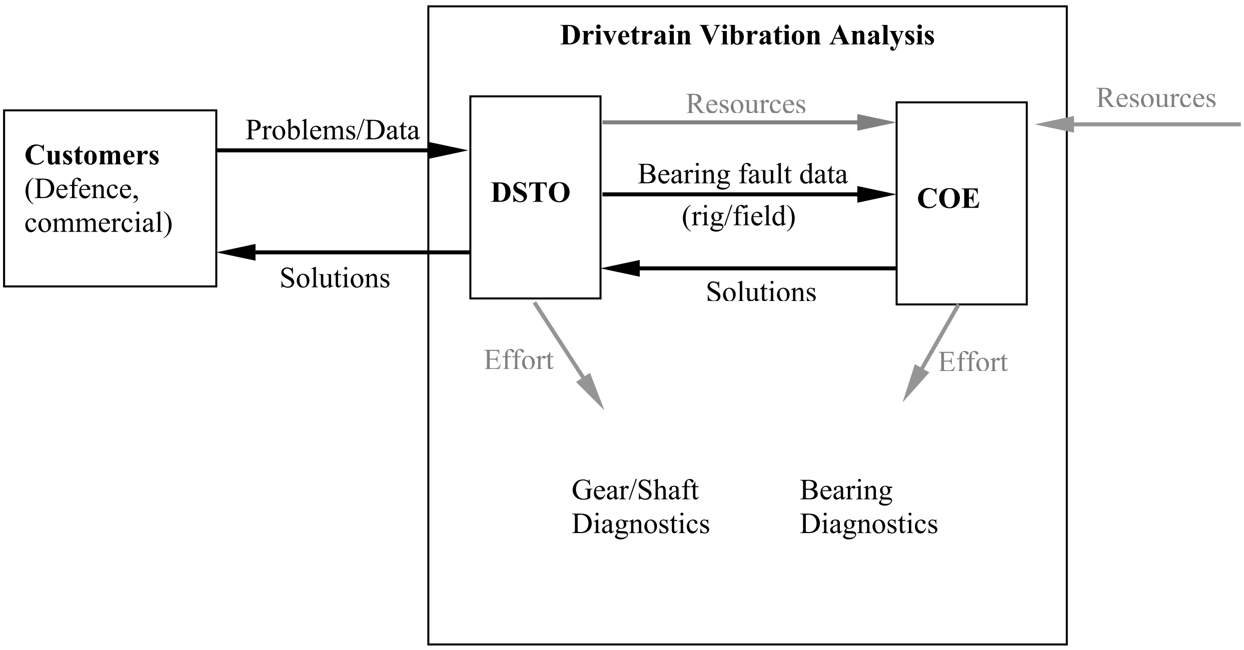


Figure 6. Schematic of the DSTO/COE-VA relationship.

3.5 Collaboration with the US Navy (USN)

DSTO has been collaborating with USN in the area of mechanical diagnostics for helicopters since the early '90s. One of the first programs was focussed on the SH-60 Sea Hawk, and involved the testing of transmissions with naturally occurring and seeded faults, the assessment of available diagnostic technologies, and the development of a vibration tape library. This collaboration included an extended attachment of a DSTO scientist to the US Naval Air Warfare Centre, Aircraft Division (NAWCAD) in Trenton to work on the USN's Helicopter Integrated Diagnostic System (HIDS) program. The outcome of this program provided much valuable data for algorithm validation and development, and for improving the specifications of production HUMS (see Frith, 1996). Since the relocation of NAWCAD's test rigs and personnel to Patuxent River, a follow-on to the HIDS program is currently in progress, and has a new emphasis on supporting the Integrated Mechanical Diagnostic Health and Usage Monitoring System (IMD HUMS) project. We have continued to maintain a close working relationship with the USN, and the recent attachment of another DSTO researcher to NAWCAD facilitated the exchange of much knowledge and experience between the two organisations (see Blunt, 2001).

3.6 Interaction with Industry

In the past, DSTO has worked with industries such as Sikorsky, and Technology Integration Incorporated (now part of BF Goodrich) in the investigation and evaluation of aspects of vibration-based health monitoring techniques. More recently, DSTO completed a collaborative program with Eurocopter France (ECF) in the analysis of a series of seeded fault tests on the Super Puma Mk II MRGB. The suite of DSTO algorithms was used to successfully analyse all 7 individual faults implanted by ECF. Negotiations are currently under way on a follow-on collaborative project to perform tests on seeded and/or naturally occurring faults in the Squirrel AS350B MRGB using the HTTF described in Section 3.2.

DSTO has been keen to see its technology not only enter the services of the ADF, but of a much wider field so as to maximise its impact, sustainability and supportability. To achieve this, DSTO needed an industrial partner who is competent in the VA area, and can develop the DSTO technology into a production system and provide subsequent customer support. In July 1999, a formal non-exclusive licensing agreement was entered into between DSTO and Chadwick-Helmuth Co. (CHC) for the rights to develop DSTO's helicopter gearbox health monitoring technology into a marketable product. Currently, a process of the technology transfer is being undertaken, and that CHC is well on its way in developing a prototype.

4. Future Directions

For the implementation of this technology to be more widespread, it needs to be even better and at a lower cost. Systems need to be effective, robust against false-alarms, easy to use and maintain, as well as being affordable. DSTO's future research effort will be devoted towards these goals. The development and testing of advanced algorithms that are more sensitive to faults and less on noise will form a significant part of our research activities. For this, we believe that we'll have to increasingly turn to model-based techniques such as linear-prediction and non-linear dynamics models.

On the cost-effectiveness question, it may be possible to tip the balance favourably if VA can be used as a maintenance tool. For this, however, we need to develop a good prognostic capability to allow the remaining life of components to be predicted accurately from measured data. The achievement of this can have a great impact on the way we view and practise condition-based maintenance. DSTO plans to pursue a program to develop a prognostic capability.

Another way of achieving cost-effectiveness is through the dramatic reduction of costs. The application of low-cost sensors and wireless technologies might deliver such savings. The use of acoustic signals to perform fault analysis maybe a fruitful area of research. Imagine the savings possible if a single microphone in the cockpit can replace the network of accelerometers wired throughout an aircraft, or better still, a single microphone on a base replacing all accelerometers of a fleet! For this reason, we plan to embark on a project to explore the potential of using acoustic signals for gear fault diagnostics in the coming years.

5. Conclusion

The health of the transmission system is critical to the safe operation of any helicopter, and a vibration-based health monitoring system is now generally recognised as the most effective way of detecting gear faults. DSTO has been an active player in this technology, and has contributed significantly to its advancement and maturity. This has been achieved through a solid program of fundamental research, experimental validation, field deployment, and interaction with academia and industry that spanned well over two decades. Despite this, room for improvement was identified in the areas of sensitivity, robustness and cost effectiveness, and some suggestions were made as to how these maybe approached.

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