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A comparative study of the effectiveness of vibration and acoustic emission in diagnosing a defective bearing in a planetry gearbox

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ABSTRACT

Whilst vibration analysis of planetary gearbox faults is relatively well established, the application of Acoustic Emission (AE) to this field is still in its infancy. For planetary-type gearboxes it is more challenging to diagnose bearing faults due to the dynamically changing transmission paths which contribute to masking the vibration signature of interest.

The present study is aimed to reduce the effect of background noise whilst extracting the fault feature from AE and vibration signatures. This has been achieved through developing of internal AE sensor for helicopter transmission system. In addition, series of signal processing procedure has been developed to improved detection of incipient damage. Three signal processing techniques including an adaptive filter, spectral kurtosis and envelope analysis, were applied to AE and vibration data acquired from a simplified planetary gearbox test rig with a seeded bearing defect. The results show that AE identified the defect earlier than vibration analysis irrespective of the tortuous transmission path.

1. Introduction

Planetary gearboxes are important components of rotating machines due to their high transmission ratio, higher torque to weight ratio and high efficiency [1]. As such this type of gearbox is widely used in many industries such as aerospace, wind turbines, mining and heavy trucks [2–6]. Different planetary gearbox configurations and designs allow for a range of gear ratios, torque transmission and shaft rotational characteristics. The planetary gearbox generally operates under severe conditions, thus the gearbox components are subject to different kinds of fault conditions such as gear pitting, and cracks [7–10]. Recent investigations on wind turbine applications of planetary gearboxes have shown that failures initiate at a number of specific bearing locations, which then progress into the gear teeth. In addition bearing debris and the resultant excess clearances cause gear surface wear and misalignment [10]. The accident to G-REDL [11], resulting in the loss of 16 lives, was caused by degradation of a planet gear bearing, resulting in the failure of the planet gear and, as a result, the loss of the aircraft.

Several authors have proposed numerous diagnostic approaches for planetary gearboxes, with vibration analysis the most commonly employed monitoring technology [1,7,9,12–14]. However, fault detection of bearings within the planetary gearbox is one of the most challenging diagnostic scenarios, as the resulting vibration signatures are influenced by the variable transmission paths from the bearing to the receiving externally mounted sensor. This leads to strong background noise which can mask the vibration signature of interest. This task is compounded by the fact that the gear mesh frequencies typically dominate the resultant vibration signal [7,13,15].

Early attempts utilised time domain averaging to separate the gear components from the measured vibration signal in order to reduce the signal-to-noise ratio (SNR). This involves combining a delayed version of the measured vibration signal with the original signal thereby reinforcing certain frequency components, whilst eliminating others. However, the signal to noise ratio (SNR) enhancement with this technique is not always sufficient to aid detection of bearing faults and hence this technique has not proved successful in identifying bearing defects within planetary gearboxes [7]. Time Synchronous Averaging (TSA) has also been applied to separate the bearing vibration components from the measured gearbox signature [13,16–19]. This minimizes the influence of speed variation by re-sampling the signal in the angular domain

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[13]. The process of re-sampling the signal requires a tachometer or phase marker and is not commonly applied for the sole purpose of separating the bearing vibration signature [18].

More recently, signal separation techniques have been applied in the diagnosis of bearing faults within gearboxes. The separation is based on decomposing the signal into deterministic and random components. The deterministic part represents the gear component and the random part represents the bearing component of the measured signal. The bearing contribution to the signal is expected to be random due to slip effects [8,18,20,21]. A number of methods for signal separation are available, each having relative advantages and disadvantages [18,22–24]. Techniques such as Linear Prediction (LP) have been employed for separation, allowing the separation of the deterministic (or predictable) part of a signal from the random background noise using the information provided by past observations [25,26]. The results of such techniques depend on the number of past observations considered. Smaller values of past observation produce a poor prediction, giving a result of negligible improvement in the signal-to-noise ratio, while very high values compromise computation time, over-constrain the prediction and tend to reduce even the main components of the signal (both deterministic and non-deterministic parts) [27,28]. Interestingly LP is applied only to stationary vibration signatures.

To overcome the problem of separation of non-stationary vibrations, adaptive filters were proposed. This concept is based on the Wold Theorem, in which the signal can be decomposed into deterministic and non-deterministic parts. It has been applied to signal processing in telecommunication [28] and ECG signal processing [29]. The separation is based on the fact that the deterministic part has a longer correlation than the random part and therefore the autocorrelation is used to distinguish the deterministic part from the random part. However, a reference signal is required to perform the separation. The application of this theory in condition monitoring was established by Chaturved and Thomas [30] where the Adaptive Noise Cancellation (ANC) algorithm was applied to separate bearing vibrations corrupted by engine noise, with the bearing vibration signature used as a reference signal for the separation process. However, for practical diagnostics, the reference signal is not always readily available. As an alternative, a delayed version of the signal has been proposed as a reference signal and this method is known as self-adaptive noise cancellation (SANC) [21] which is based on delaying the signal until the noise correlation is diminished and only the deterministic part is correlated [20].

Many recursive algorithms have been developed specifically for adaptive filters [31,32]. Each algorithm offers its own features and therefore the algorithm to be employed should be selected carefully depending on the signal under consideration. Selection of the appropriate algorithm is determined by many factors, including: convergence, type of signal (stationary or non-stationary) and accuracy [33].

The Spectral Kurtosis technique has been introduced recently for bearing signal separation [34,35]. The basic principle of this method is to determine the Kurtosis at different frequency bands in order to identify the energy distribution of the signal and determine where the high impact energy (transient events) are located in the frequency domain. Obviously the results obtained strongly depend on the width of the frequency bands Δf [36]. As noted earlier, in real applications background noise often masks the signal of interest and as a result the traditionally obtained Kurtosis value, in the time domain, is unable to capture the 'peakiness' of the fault signal, usually giving low Kurtosis values. Therefore, in applications with strong background noise, the Kurtosis as a global indicator is not useful, although it gives better results when it is applied locally in different frequency bands [35]. The Spectral Kurtosis (SK) was first introduced by Dwyer [37] as a statistical tool which can locate non-Gaussian components in the frequency domain of a signal. This method is able to indicate the presence of transients in the signal and show their locations in the frequency domain. It has been demonstrated to be effective even in the presence of strong additive noise [35].

In addition to the vibration analysis, the Acoustics Emission (AE) technology has emerged as a promising diagnostic approach. AE was originally developed for non-destructive testing of static structures, however, in recent times its application has been extended to health monitoring of rotating machines and bearings [34,38–40]. In machinery monitoring applications, AE are defined as transient elastic waves produced by the interface of two components or more in relative motion [41,42]. AE sources include impacting, cyclic fatigue, friction, turbulence, material loss, cavitation, leakage etc. It provides the benefit of early fault detection in comparison to vibration analysis and oil analysis due to the high sensitivity to friction offered by AE [43]. Nevertheless, successful applications of AE for health monitoring of a wide range of rotating machinery have been partly limited due to the difficulty in signal processing, interpreting and manipulating the acquired data [44–46]. In addition, AE signal processing is challenged by the attenuation of the signal and as such the AE sensor has to be close to its source. However, it is often only practical to place the AE sensor on the non-rotating member of the machine, such as the bearing housing or gearbox casing. Therefore, the AE signal originating from the defective component will suffer severe attenuation and reflections, before reaching the sensor. Challenges and opportunities of applying AE to machine monitoring have been discussed by Sikorska et al. and Mba et al. [41,47]. To date, most applications of machine health monitoring with AE have targeted single components such as a pair of meshing gears [48], a particular bearing or valve [49,50]. This targeted approach to application of AE has on the whole demonstrated success. However the ability to monitor components that are secondary to the main component of interest such as a bearing supporting a gear, as is the case with planetary gears in an epicyclical gear box, has not been well-explored. This is the first known publication to explore the ability to identify a fault condition where the AE signature of interest is severely masked by the presence of gear meshing AE noise.

Whilst vibration analysis of gearbox fault diagnosis is well established, the application of AE to this field is still in its early stages [43,51,52]. Moreover, there are limited publications on application of AE to bearing fault diagnosis within gearboxes [45]. The research programme described here aims to inform the next generation of HUMS systems by identifying and proving feasibility for new, and newly- applied, sensing technologies, with a specific focus on internal sensors. In addition, this paper discusses the analysis of the vibration and AE data collected using this technology from a lab scale and full scale helicopter test rig, and compares their effectiveness in diagnosing a bearing defect in the planetary gearbox. The data was collected for various bearing fault conditions and processed using an adaptive filter algorithm to separate the non-deterministic part of the signal and enhance the signal-to-noise ratio for both AE and vibration. The resultant signatures were then further processed using envelope analysis to extract the fault signature.

2. Gear and bearing diagnosis

The vibration signals associated with bearing defects have been extensively studied and robust detection algorithms are now available as off-the-shelf solutions. Conversely the dynamics associated with bearing diagnostics within gearboxes reduce the capability of traditional techniques. Therefore, it is important to understand the nature of the faulty bearing signal.