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Review of fault detection techniques for health monitoring of helicopter gearbox

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Abstract. In most cases the helicopter transmission system comprises of the main gearbox (MGB), auxiliary gearbox (AGB), intermediate gearbox (IGB) and tail rotor gearbox (TGB). A local gear fault will impose a force variation in the gearbox and changes the gear angular velocity resulting in frequency modulations, which in turn generates sidebands and changes the vibration signature. The change in vibration signature contains information about the health of the gearbox from which diagnosis can be made to prevent the catastrophic effect of propagated fault. The helicopter gearbox vibration mode differs from those of other systems due to the transmission noise, structural noise and aero acoustic noise which masks the sideband. Thus an attempt is made to review the condition indicators that have been applied for fault diagnosis on the helicopter gearbox. This review is intended to advance the knowledge and the performance of Health and Usage Monitoring System in the helicopter transmission system.

Keywords: Helicopter; transmission; gearbox; vibration; fault detection; condition indicators; health monitoring

1 Introduction

Onboard sensors for helicopter health and usage monitoring systems (HUMS) have been in use since eighties with increasing popularity for improved safety and condition based maintenance, and was certified in November 1991 for operation in the North Sea [Greaves,2014; Pipe, 2003]. Several HUMS technology have since emerged comprising of onboard system for data acquisition and storage and a ground based system for data analysis, fault detection with diagnostic and prognostic capabilities for effective maintenance management.

Vibration Health Monitoring (VHM) integrated into Health and Usage Monitoring System (HUMS) has been useful for identifying the presence of defective gear tooth within the helicopter gearbox before it become catastrophic. This practice aids

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condition based maintenance and improved safety of helicopter operations among other benefits [Draper, 2003; Milsom *et al*., 2003; Augustine, 2004; Qu *et al*., 2014].

The VHM-HUMS systems acquire composite vibration data through accelerometers strategically placed, tachometer signals and contextual parameters such as airspeed, temperature and torque [Alattas and Basaleem, 2007; Lebold *et al*., 2000; Samuel and Pines, 2003]. The system predicts gearbox health in terms of a single number, called a condition indicator (CI), representing the condition of the monitored gearbox. The CIs are then compared with pre-set threshold values, established based on historical data, to offer an indication of fault progression within the gearbox, thus providing a basis to assess the health of the gearbox for further diagnosis [Rzeszucinski *et al*., 2012; Keller and Grabill, 2003].

In this paper a review of various vibration techniques used in HUMS and HUMS technology for fault detection and diagnosis on helicopter transmission systems is presented and their potentials for fault detection and diagnostics capabilities is highlighted.

Nomenclature	
TSA	time synchronous averaging
x	vibration signal after TSA
$R_{1,-1}(x)$	amplitude of the first order left hand side sideband
$R_{1,+1}(x)$	amplitude of the first order right hand side sideband
RMS	root mean square
NA4	ratio of the kurtosis of the data record divided by the square of the average variance
$NA4^*$	normalized kurtosis of the data record divided by the squared variance of signals
E	enveloped of the band-passed signal
$\bar{E}$	mean value of the envelop signal
N	total number of data points in time record
M	current time record number in the run ensemble
D	difference signal
$\bar{d}$	mean value of difference signal
i	data point number in time record

M6	sixth statistical moment
$\tilde{M}$	variance of the residual signal
r	residual signal
$\bar{r}$	mean value of residual signal
j	time record number in run ensemble
S	raw time series signal
$\bar{S}$	mean value of the raw time series signal
$(S-\bar{S})^2$	variance of the data set
$S_{0\text{-}pk}$	peak level of the raw time series signal
FM4	the ratio of the fourth statistical moment to the square of the variance of the difference signal
M6	the sixth statistical moment
NB4	the ratio of the fourth statistical moment of the envelope signal to the averaged variance of the envelope signal, raised to the second power

2 Time domain analysis (TDA)

Simple signal metrics applied to the measured time domain signal can give some information regarding potential defects. However, they are insensitive tools for defect detection and cannot be used to diagnose defects [Wandel, 2006] but can be useful as pre-processing techniques for metrics in other domains [Keller and Grabill, 2003]. The time domain techniques can be categorize into statistical parameters, time synchronous averaging based method and filter based methods.

2.1 Statistical Parameters

1. Root mean square (RMS)

The RMS represents the energy of the signal representing a sequence of n discrete values and indicates the amount of energy in the non-meshing components. It is useful in tracking the overall noise level to detect a major out-of-balance, but it will not provide any information on which component is failing and may not show appreciable changes in the early stages of damage [Figo et al., 2010; Wiig, 2006].

It is mathematically expressed as:

$$\text{RMS} = \sqrt{\frac{1}{n}\{\sum_{i=1}^{N}[S_i]^2\}} \tag{1}$$

2. Crest factor

The crest factor (CF) is described as a simple measure of detecting changes in the signal pattern due to impulsive vibration sources. Peaks in the time series signal will result in an increase in the crest factor value. However, the crest factor feature is not considered a very sensitive technique [Decker and Lewcki, 2003].

$$\text{CF} = \frac{S_{0-pk}}{\text{RMS}} \tag{2}$$

3. Kurtosis

The Kurtosis (K) is the fourth statistical moment of an array of values and an indicator of the existence of major peaks in a set of data. However, the pitfall with the normalized kurtosis parameter is its drastic decrease in peak sensitivity as the number N of peaks of similar magnitudes increase beyond two. It is derived by normalizing the square of the variance of the signal [Alattas and Basaleem, 2007].

$$\text{KURTOSIS} = \frac{N\sum_{i=1}^{N}(S-\bar{S})^4}{\left[\sum_{i=1}^{N}(S-\bar{S})^2\right]^2} \tag{3}$$

2.2 *Time synchronous averaging (TSA) based methods*

In this group we have the time synchronous averaged (TSA) signal, residual signal (RES), and difference signal (DIFS)

1. Time synchronous average signal

This method employed the repetitive signals after TSA to indicate faults which need to be diagnosed. A discontinuous time synchronous averaging (DTSA) method has been proposed [Huff *et al*., 2003] to minimize torque and related non-stationary effects on the frequency content of transmission vibration signals using flight vibration data.

2. Residual signal

The RES which is developed to detect the onset of damage and monitor the fault development as it propagates and progresses, comprises of the NA4 and NA4*. The NA4 is the ratio of the kurtosis of the data record divided by the square of the average variance, while the NA4* is evaluated by normalizing the kurtosis for a data record by the squared variance of signals from a healthy gearbox [Hongyu *et al*., 2003]. They are mathematically expressed as:

$$\mathrm{NA4} = \frac{N\sum(r_i - \bar{r})^4}{\frac{1}{M}\sum_j\left[\sum_i(r_{ij} - \bar{r}_j)^2\right]^2} \tag{4}$$

$$\mathrm{NA4}^* = \frac{\frac{1}{N}\sum_{i=1}^{N}(r_i - \bar{r})^4}{(\hat{M}_2)^2} \tag{5}$$

3. The difference signal

The difference signal estimates the difference signal by removing the regular meshing components from the time synchronous averaged signal comprises of FM4, M6A, and M8A [Rzeszucinski *et al*., 2012; Decker and Lewcki, 2003]. The FM4 is evaluated by dividing the fourth statistical moment about the mean by the square of the variance of the difference which magnifies any abnormalities present in the difference signal, while the M6 metric is a continuation of the kurtosis and the sixth statistical moment normalized by raising the power of the variance to the third power. They are mathematically expressed as:

$$\mathrm{FM4} = \frac{N\sum_{i=1}^{N}(d_i - \bar{d})^4}{\left[\sum_{i=1}^{N}(d_i - \bar{d})^2\right]^2} \tag{6}$$

$$\mathrm{M6} = \frac{N^2\sum_{i=1}^{N}(d - \bar{d})^6}{\left[\sum_{i=1}^{N}(d - \bar{d})^2\right]^3} \tag{7}$$

$$\mathrm{M8A} = \frac{N^3\sum_{i=1}^{N}(d - \bar{d})^8}{\left[\sum_{i=1}^{N}(d - \bar{d})^2\right]^4} \tag{8}$$

Other TDA are the FM4* and M6* developed to overcome the limitations of FM4 and M6.

2.3 Filter based methods

Filter based methods include demodulation, Prony model, band-pass method and adaptive noise cancelling (ANC) used for removing noise and isolating signals [Hongyu *et al*., 2003].

The NB4 metric, a band-passed method is described as the time-averaged kurtosis of the envelope of the signal band-passed filtered about the mesh frequency [Lebold *et al*., 2000], obtained by dividing the fourth statistical moment of the envelope signal by the current run time averaged variance of the envelope signal, raised to the second power. NB4* was developed to overcome the limitation of the NB4.

$$\mathrm{NB4} = \frac{N\sum_{i=1}^{N}(E_i - \bar{E})^4}{\left\{\frac{1}{m}\sum_{j=1}^{m}\left[\sum_{i=1}^{N}(E_{ij} - \bar{E}_j)^2\right]\right\}^2} \tag{9}$$

Sideband level factor (SLF) is another TDA technique and described as the sum of the first order sideband levels about the primary gear meshing frequency normalized by the RMS of the synchronous time averaged signal [Nacib *et al.*, 2013]. It is mathematically expressed as:

$$\mathrm{SLF} = \frac{\mathrm{FOSL}}{\mathrm{RMS}} = \frac{R_{L-1}(x) + R_{L+1}(x)}{\mathrm{RMS}(x)}. \tag{10}$$

The energy ratio (ER) is also a TDA technique which compares the residual energy and the meshing energy by dividing the RMS of the difference signal with the RMS of the regular components of the signal [Wiig, 2006]. It is expressed as:

$$\mathrm{ER} = \frac{\mathrm{RMS}_d}{\mathrm{RMS}_r} \tag{11}$$

The root mean square, crest factor, energy operator, energy ratio, kurtosis, M6, FM4, NA4, NA4*,NB4, NB4*, M6*, FM4*, FM0, N6A, N8A, M6A and M8A to the vibration data of OH-58 helicopter main transmission [Decker and Lewicki, 2003; Lewicki *et al.*, 2011; Mosher *et al.*, 2003]. Modified FM0, Sideband level factor, energy ratio, sideband index, kurtosis, FM4 for monitoring planetary gears fault have been developed to detect planetary carrier fault of UH-60A helicopter [Keller and Grabill, 2003].

3 Frequency domain analysis (FDA)

The FDA techniques reveals the repetitive nature of a signal to indicate faults in a time-signal of a specific window using the discrete Fourier transform [Hongyu *et al.*, 2003], by making comparison of a measured spectrum to a reference spectrum of a healthy component to expose faults at different frequencies in the spectrum. These techniques are based on the assumptions of stationary vibration signals, however, for a complicated gearbox, the frequency spectrum is complex and is characterized by non-stationary transient components [Wandel, 2006], thus rendering ineffective this approach, coupled with the small energy of the signal and high level of noise [Klepka, 2011].

3.1 Fast fourier transform (FFT)

The FFT represent the average signal, dominant frequency components and other important characteristics of a time-based signal in the frequency domain. Though it is useful in identifying harmonic signals, however due to its constant time and frequency resolution, it is weak in analyzing transient signal components [Lokesha *et al.*, 2011].

3.2 Cyclostationarity

Cyclostationarity uses spectral correlation function to investigate the correlation degree between different frequency components of the spectrum and establish their relationship with each other [Li *et al*., 1996] for the early diagnosis of faults in gear systems

3.3 The power cepstrum

The power cestrum is useful for detection of sideband periodicities in a complicated vibration frequency spectrum which can be related to a defect. However, it is difficult to predict absolute sideband levels from the cepstrum [Wandel, 2006].

The cepstrum analysis and the spectrum analysis have been applied to helicopter gearbox diagnosis [Nacib *et al*., 2013]. The spectra analysis, the power spectrum analysis and amplitude demodulation was applied to the swash plate bearing of a CH-47D helicopter [Keller and Grabill, 2003]. The averaged harmonic ratio, non-regular meshing ratio was applied to epicyclic gearbox of a UH-60A Blackhawk Helicopter [Wu and Vachtsevanos, 2003]. Though the techniques indicate the progression of crack growth in a planetary gear plate it is however, based on linear correlation

4 Joint-time frequency domain analysis (JTFDA)

The time domain and frequency domain techniques are based on the assumptions of stationary vibration signals [Klepka, 2011], however, localized gear defects introduces non-stationary transient signal components in the meshing vibration that may excite structural resonances of the gearbox. A time-frequency distribution captures the time-varying frequency content so that changes in the amplitude of the signal could be analyzed in three dimensions of time, frequency and amplitude [Wang and Wong, 2000; Christian et al., 2007], and capable of tracking the development of the faults, which generate weak vibration power [Lakis, 2007], but requires complex computational analysis.

Examples in this domain are:

4.1 Short time fourier transform (STFT)

The STFT based techniques breaks down non-stationary signal into small windows, which is assumed stationary. However, this method suffered from resolution trade-off between time and frequency [Wandell, 2006].

4.2 The wigner ville distribution (WVD)

The WVD a bilinear function which is independent of the window function for excellent resolution in the time and frequency domains for a non-stationary signal. WVD has been employed on helicopter spiral bevel in a test rig at NASA Lewis Research Centre [Choy *et al*., 1996]. However, WVD is not always non-negative and prone to interference which makes it confusing and difficult to interpret.

4.3 The wavelet transform

The wavelet transform based techniques employs a family of window functions of variable lengths to study how the frequency content changes with time for localizing faults in vibration signals with non-stationary, transient characteristics [Farokhzad et al., 2013]. Short time Fourier transform (STFT), the wigner-ville distribution with the Choi-Williams kernel, the continuous wavelet transform (CWT) and the discrete wavelet transform (DWT) was applied to helicopter spiral bevel gear and pinion pair in a test rig [Mosher *et al*., 2003].

5 Other diagnostic techniques

Other diagnostics approach employed on the helicopter transmission not listed in the categories above are constrained adaptive lifting, probability density function, finite element formulation, principal component analysis and planet separation method. The constrained adaptive lifting (CAL) was applied to vibration data of a planetary gear [Samuel and Pines, 2003], though it shows potential for transmission diagnostics but it is limited to laboratory work. Likewise, the Amplitude probability Density Function (APDF) applied to a spiral bevel gear of helicopter drive train [Rzeszucinski *et al*., 2012], however fault detection is delayed and fault indication is very small and may not be useful for field applications. A finite element formulation was applied to the spiral-bevel gear and the planetary gear of a helicopter transmission [Stringer *et al*., 2009]. Though the technique demonstrates the potential of physics-based mathematical models, the model itself requires further development and testing. Planet separation method and planet carrier method was applied to epicyclic gear train of a helicopter [Blunt and Keller, 2006] which prove to be reliable under test-cell conditions but less effective under low torque on-aircraft conditions. Likewise, Principal Components Analysis (PCA) was applied to helicopter flight data [Turner and Huff, 2001], which demonstrate the potential to monitor changes in the vibration, but suffers from assumption of linearity of combination of the three axes of measurements and insufficient testing. Amplitude and phase modulations techniques has been applied to helicopter transmissions in a test rig [Krishnappa, 1997], though the techniques are effective for early gear fault detection, however limited data is used and required prior knowledge of the baseline condition of the gear. Harmonic index and intra-revolution energy variance was also tested on vibration data of planetary gears [Wu *et al*., 2005], with potentials to identify faults, however no experiments was carried out and further investigation is required.

Unsupervised pattern recognition has also been employed to detect abnormality in the vibration features. Single category based classifier was applied to a helicopter gearbox [Jammu *et al*., 1996] to detect abnormality scaling of the vibration features. The United Kingdom Civil Aviation Authority (CAA) in conjunction with Eurocopter and General Electric (GE) has also employed the advanced anomaly detection, an unsupervised learning approach based on data mining to define models of normal behaviour and abnormal behaviour.

The Integrated Mechanical Diagnostics Health and Usage Management Systems (IMDHUMS), the Generic Health and Usage Management Systems (GenHUMS) and Vibration Management Enhancement Program (VMEP) are commercial HUMS technologies which have demonstrated potentials for fault diagnosis and condition based monitoring. The Federal Aviation Administrator (FAA) and CAA have developed techniques to process vibration data and determine condition and health indicators used in commercial HUMS [Dempsey *et al.,* 2007]. Vibration Management Enhancement Program (VMEP) a data collection and processing test-bed for the continuing collection and analysis of large amounts of data in support of vibration monitoring, automated diagnostic and prognostic system development have also been developed by the US Army and Air force. The VMEP system has been employed on UH-60A Main Transmission Planetary Carrier to acquire and analyze on-aircraft data and test cell data [Keller and Grabill, 2003; Blunt and Keller, 2006; Grabill *et al.,* 2003]. IMDHUMS perform data acquisition, analysis, display and storage with maintenance management functions to mechanical diagnostics and operational usage [Hess *et al*., 2003]. The technology has being fielded on a number of helicopters with significant detection [Wright, 2005].

Multivariate statistical approach applied to Helicopter Integrated Diagnostic System (HIDS) developed by Naval Air Warfare Center in a seeded fault tests, produced clear fault detection with a reduced number of false alarms [Mimnagh, 2000]. A joint research of FAA and Army Aviation Engineering Directorate on Army helicopter fleet Health and Usage Monitoring Systems (HUMS) for Condition Based Maintenance (CBM) focuses on data analysis and development of component health and usage indicators for estimation of remaining useful life of dynamic and structural parts [Zion *et al*., 2016].

6 Conclusion

Vibration Health Monitoring (VHM) integrated into Health and Usage Monitoring System (HUMS) has contributed immensely to the reliability condition based maintenance of the helicopter transmission systems. Some of the conventional condition indicators generally used on the helicopter transmission system were discussed. Other diagnostics and prognostics methods and systems that have been developed were also discussed. It is important to document these techniques in order to advance the knowledge and the performance of Health and Usage Monitoring System in the helicopter transmission system.

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