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GEAR FAULT DETECTION PARAMETERS DEVELOPMENT BASED ON MODULATION TECHNIQUES

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ABSTRACT

The amplitude and phase modulation analysis techniques can be used to detect faults in rotating machinery components, which include bearings and gears. This paper discusses the development of several parameters based on amplitude and phase modulations and their applications to detect faults in helicopter transmissions. The parameters based on amplitude modulations, absolute measure of the percentage modulation of the amplitude envelope, negative peak count to measure the number of times the envelop modulated and kurtosis of the envelop. The phase modulation parameters include, percentage modulation of phase, kurtosis wrapped and unwrapped phase and kurtosis of the first derivative of phase modulations. The vibration data collected from the endurance test runs of OH-58A helicopter transmissions were used to develop and validate the effectiveness of these modulation parameters in detecting both incipient and advanced faults.

INTRODUCTION

Vibration analysis is a powerful technique for the early detection of faults in gear boxes and transmissions. A nominal gear produces almost sinusoidal signals in the time domain with the prominent peaks at the tooth meshing frequency and its lower order harmonics in the frequency domain. Fault diagnostics is based on the principle that the vibration signature of a component is modified by the changes in the condition of the component. A fault in any rotating machinery is likely to introduce amplitude and phase modulations. In a simple pair of gears it is relatively easy to identify sidebands around tooth meshing frequencies. In complex gear systems comprising large numbers of gear sets (e.g, helicopter transmission systems) it is more difficult to identify a specific gear because of the large number of meshing frequencies and sidbands present.

The vibrations produced by gears can be characterized by normal gear meshing vibrations, plus additional sidebands around the mesh frequency harmonics. Defects can be identified by amplitude and phase modulation techniques. Amplitude and phase modulation techniques were originally proposed by McFadden and Smith [1] and McFadden [2,3] and further developed by Nicks and Krishnappa [4]. This paper reviews the development of the parameters based on amplitude and phase modulations to identify gear damage in complex transmissions and their applications to helicopter transmissions.

ANALYTICAL METHOD

The basic principle of amplitude and phase modulation analysis is presented here to familiarize the reader.

Under ideal conditions, the time-domain average of the vibration of a pair of gears should consist only of the fundamental and harmonics of the tooth mesh frequency. This is shown in the following equation:

$$x(t) = \sum_{m=0}^{M} X_m \cos(2\pi mTft + \theta_m) \tag{1}$$

where f is the rotational frequency of the gear, T is the number of teeth on the gear, m is the mesh frequency harmonic (0,1,2,3....), and X_m is the vibration amplitude at the corresponding mesh frequency harmonic.

A discrete gear fault (such as a spall or fatigue crack) modifies this equation by introducing periodic amplitude or phase modulations into the vibration signal. The amplitude and phase-modulated vibration signal, $y(t)$, can be written as:

$$y(t) = \sum_{m=0}^{M} X_m (1 + a_m(t)) \cos(2\pi mTft + \theta_m + b_m(t)) \tag{2}$$

where $a_m(t)$ is the amplitude modulation function and $b_m(t)$ is the phase modulation function at time t for each mesh harmonic. Amplitude and phase modulations produce sidebands about the mesh harmonics in the frequency domain [3]. In practice, numerous additional factors contribute to the content of the measured vibration signal. While the use of time-domain averaging eliminates non-synchronous vibration components from the measured signal, other parameters, such as transmission path effects, cannot be simply removed and may contribute to the masking of faults.

The vibration function $y_m(t)$ for any mesh frequency harmonic m can be approximated by bandpass filtering the time-domain averaged vibration signal. It is not possible to isolate this function completely, as there is a possibility of interference between higher-order sidebands of adjacent mesh harmonics. The filter bandwidth used in these studies was equal to the fundamental mesh frequency of each gear under study and centered on a mesh harmonic. Bandpass filtering of the time-domain-averaged signatures was accomplished by performing a forward FFT and zeroing the frequency coefficients outside of the passband, then performing an inverse FFT.

Although the measured function $y_m(t)$ is real-valued, it can be considered a projection of the complex-valued analytical function $z_m(t)$. The function $z_m(t)$ can be represented by:

$$z_m(t) = y_m(t) + jH(y_m(t)) \quad (3)$$

where H is the Hilbert transform function. The amplitude and phase components of the analytical signal can be seen more clearly if equation (3) is expressed in terms of the amplitude envelope function, $A_m(t)$, and the instantaneous phase function, $\phi_m(t)$:

$$z_m(t) = A_m(t) \cdot e^{j\phi_m(t)} \quad (4)$$

The complex analytical signal (4) is derived by performing a forward Fourier transform on the real-valued time series $y_m(t)$ to produce $Y_m(f)$. The function $Y_m(f)$ is then filtered to obtain $Z_m(f)$ by multiplying the frequency coefficients by:

2	for $f > 0$,
1	for $f = 0$, and
0	for $f < 0$.

The inverse Fourier transform of $Z_m(f)$ produces the complex analytical time aeries $z_m(t)$. The amplitude envelope function, $A_m(t)$, and the instantaneous phase function, $\phi_m(t)$, are calculated from:

$$A_m(t) = |z_m(t)|, \quad (5)$$

$$\phi_m(t) = \arg(z_m(t)) \quad (6)$$

To extract the phase modulation function, the complex function $z_m(t)$ is multiplied by a unit length vector rotating at minus the mesh harmonic frequency m. This removes the frequency component of the harmonic itself. The resulting function represents the relative changes in the phase component produced by the sidebands of the meshing tone. The instantaneous phase modulation function, $\delta_m(t)$, is defined by:

$$\delta_m(t) = \arg(z_m(t) \cdot e^{-j\theta}) \quad (7)$$

where $\theta = 2\pi mTft + \theta_m$.

ANALYSIS PARAMETERS

Initial Amplitude and Phase Analysis

McFadden and Smith [1] extracted the amplitude modulation component of a narrowband vibration signal and used kurtosis analysis to identify the presence of discrete defects.

McFadden [2,3] employed graphical analysis methods and kurtosis analysis of the phase modulation component of the vibration signal to identify tooth cracks.

Kurtosis analysis of the amplitude and phase data, as discussed in (1) and (2), was not as effective as initially expected (4). Poor fault detection rates were obtained using the amplitude modulation data. The phase modulation data produced moderately better fault detection rates, although not in a consistent manner. Problems with kurtosis of the phase data were aggravated by the arctan function used to derive the demodulated phase signal. The arctan function is constrained within bounds of $\pm 180^0$ ($\pm\pi$). When the phase trace crosses the $+180^0$ or -180^0 boundary, a 360^0 phase shift occurs. This phase shift is generally indicative of a fault, although the phase signal can transit the arctan bounds when the baseline modulation is relatively high.

Amplitude Modulation Diagnostic Parameter Development

Poor results with kurtosis analysis led to an examination of the basic features of the amplitude modulation data. Amplitude envelopes typically exhibited moderate degrees of modulation in the baseline data, rising significantly when any faults were present. The severity of the modulations could be quite extensive in cases. Two main features were noted during review: any fault condition raised the modulation level significantly, and the number of times the envelope modulated, or fell near zero, appeared to vary with the severity of the damage. Amplitude modulation traces of undamaged and damaged gears are shown in Figure 1.

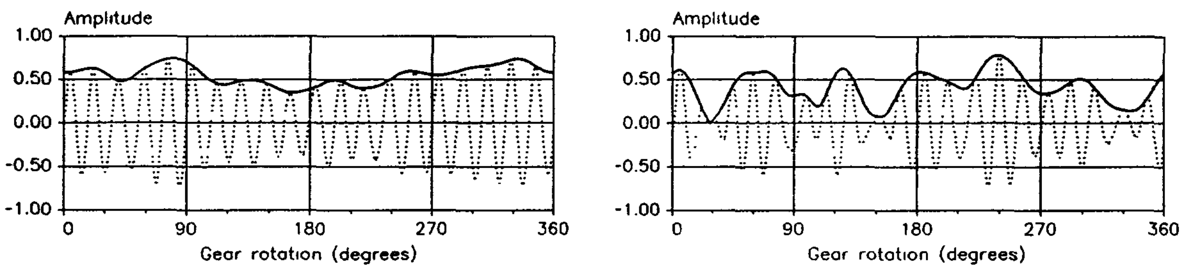

Figure 1 Amplitude modulation traces of undamaged and damaged gears

The first of these factors was incorporated into the AM (amplitude modulation) parameter – an absolute measure of the percentage modulation of the amplitude envelope. An inverse, or negative, peak count algorithm was used to determine the number of times the envelope modulated. This algorithm counted the number of times the envelope fell below a minimum threshold. An adaptive threshold was used to allow the sensitivity of the counting algorithm to adjust to the degree of modulation in the envelope. This eliminated the need for an operator to manually set a threshold limit. This parameter was designated MI (modulation index).

Phase Modulation Diagnostic Parameter Development

As with amplitude modulation, the major problems encountered with phase kurtosis analysis were saturation of the phase traces with numerous short-term signal shifts and large excursion non-impulsive shifts. Neither of these conditions are conducive to the use of kurtosis as a diagnostic indicator. The three main causes of phase shifts were found to be:

(a) Phase modulations in the vibration signal.

(b) Amplitude modulations in the vibration signal. The phase can shift by any multiple of 900 any time that the amplitude envelope falls near zero – these events appear to be the main source of fault-related instantaneous phase shifts.

(c) Toggling of the phase signal at the $\pm 180^0$ arctan limits, introducing non fault-related impulsive shifts into phase signature. Under normal operating conditions this condition would tend to raise kurtosis values and incorrectly indicate a fault. The phase signature can also become saturated with these impulsive shifts when faults are present, lowering the resultant kurtosis value and masking the defect.

A phase unwrapping algorithm was implemented to eliminate the toggling of the phase trace at the $\pm 180^0$ limits. The absolute percent modulation of both the wrapped and unwrapped phase signals was then calculated. The modulation level of the unwrapped trace cannot exceed 100%, while the modulation level of the unwrapped signature can. The unwrapped modulation value was designated PM (phase modulation). The kurtosis of both the wrapped and unwrapped functions was also calculated. One of the two kurtosis results was then discarded and the retained value designated PK (phase kurtosis). The selection of which value to retain was made according to the criteria discussed in Reference 4. Wrapped and unwrapped phase modulation traces of a damaged gear are shown in Figure 2.

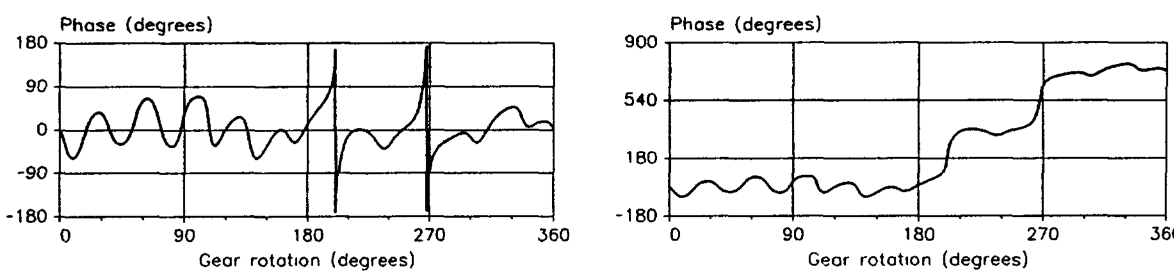

Figure 2 Wrapped and unwrapped phase modulation traces of a damaged gear

Data Analysis Considerations

Very few monitoring techniques can be effectively used for single-shot machinery assessment. The most effective results can be produced by acquiring a set of baseline measurements and establishing acceptable threshold limits from these. Thresholds are usually established using a combination of statistical limits and absolute variations, depending on the nature of the analytical parameter. Statistical thresholds are commonly established at some number of standard deviations from the mean of a (presumed) normally distributed population. In the case of absolute thresholds, two limits were calculated from the mean and the standard deviation of a set of selected data for a component in good running condition. These threshold levels were labeled Caution and Alarm and were calculated from:

$$Caution = \bar{x} + 4\sigma, \tag{8}$$

$$Alarm = \bar{x} + 8\sigma \tag{9}$$

The above limits set the upper bounds for each parameter. Lower-bound limits are also applicable for some analysis parameters such as RMS. The overall dispersion of the analysis parameters for each build was evaluated using the coefficient of variation (V):

$$V = \frac{\sigma}{x} \times 100 \tag{10}$$

It was found that V remained roughly constant for different builds of the transmission.

The modulation parameters AM and PM are non-negative and one-sided, with an optimum value of zero. There is no upper limit constraint on AM and PM. Attention must be paid to both the absolute mean level, x, and the stability, V, of these parameters. Evidence to date indicates that baseline AM values should normally fall into the 20% to 50% range; reliable PM baselines can be expected to fall below 25%. The modulation parameter MI values change in discrete steps and can appear unstable (high V) when there is any variation in the baseline. This is a case where an absolute-level threshold based on the characteristics of the parameter is more suitable.

Kurtosis-based parameters (AK,PK, and PKd) can be statistically trended, but the nature of the calculation must be considered with respect to absolute numerical results. The kurtosis is susceptible to the underlying distribution of the function and to any small variations in it. Kurtosis values between 1.5 and 2.0 are representative of linear and sinusoidal functions; a value of 3.0 is produced by a random distribution. Baseline values greater than 3.5 to 4.0 should be viewed with some caution, as this indicates some impulsiveness is present. The characteristics of the amplitude and phase modulation functions are such that baseline AK, PK, and PKd values should tend to fall into the 1.5 to 2.5 ranges (non-impulsive and non-random). Any variations will raise these values sharply, beginning with PKd – the most sensitive to small changes in the modulation.

RESULTS AND DISCUSSIONS

Initial development of the analysis parameters was done using seeded-fault trial data obtained from a gear test rig at Pratt and Whitney Canada. Baseline data verification and characterization were performed on data obtained from the reduction gearbox of an Allison T56-A14 turboprop. A more complete evaluation was done using data from the main gearbox of an OH-58A helicopter. A variety of naturally occurring faults was present in the OH-58A data. The aero-engine gearboxes contained fixed-axis, single-mesh gears and epicyclical gear systems.

Analysis Band Selection

A primary factor in the effective application of the modulation techniques was the selection of an appropriate analysis passband. The best results, for the gear systems that were examined, were obtained using a filter bandwidth equal to the mesh frequency of the gear under analysis. The passbands were centered on individual mesh harmonics.

With the single-mesh gears, the most reliable results were obtained from the band 1 data. Adequate results were obtained with the band 2 data in some cases. This data generally had higher baseline modulation levels, because of the reduced amplitude of the mesh harmonic relative to the background noise within the passband (reduced signal-to-noise ratio). Higher background noise levels make the modulation parameters less sensitive to small faults. The higher-order passbands produced poor results.

All of the gears in an epicyclical mesh with at least two other gears in the system. This appeared to have an effect on the analysis results. The band 2 data produced good results with the planet gears (two meshes). The sun gear in an epicyclical meshes with each planet in the system; band 3 worked well with the 3-planet systems and band 4 with the 4-planet systems. However, these analysis techniques cannot be applied to fixed annulus gears. The modulation parameters are designed to detect modulation and equate it to damage. The vibration signature of an annulus gear normally modulates significantly.

Modulation Based Parameters

The modulation parameters (AM, MI, and PM) have a theoretical minimum value of zero in a no-fault environment, increasing only when a disturbance is present. A baseline analysis is quite important, as a fault condition and a poor quality signal are often indistinguishable. A poor baseline will still permit detection of well-developed faults, but there is little advantage in using modulation techniques for this class of work. Figures 3 to 5 show AM, MI, and PM for gears at various fault conditions. The caution and alarm levels are shown are 4σ and 8σ.

The AM and PM parameters are quite similar in concept and execution. With the gear faults that have been studied to date, PM has been the more effective of the two in detecting small defects at an earlier point in time. It was also found to be quite effective in establishing the overall quality or suitability of a baseline signature. The AM parameter tended to respond slower and peak sooner than PM during the progression of any specific fault. The MI parameter was able to detect the extent to which damage was distributed around a gear. Gears that were scored or had similar distributed damage generally produced higher MI values than those with faults on only one or two teeth.

Kurtosis Based Parameters

The kurtosis calculation has the unfortunate characteristic of being self-limited – this reduces the scope of many kurtosis-based applications. The key to developing a kurtosis-based analysis parameter lies in preprocessing the signal in a manner that 'suits' the character of the algorithm itself. As with the modulation-based parameters, a reliable baseline is a necessity when using kurtosis analysis. The AK parameter was the least effective of the kurtosis-based analysis parameters presented in this paper. As it was unable to detect any defects until they were well developed. AK must be classified as a relatively weak fault indicator for gears. Better results were obtained using the PK parameter. The phase unwrapping and kurtosis selection process eliminated the uncertainty experienced when this analysis technique was first used. Both the false alarm rate and the number of missed faults were significantly reduced. The PKd parameter was the most effective of the three – it appeared to be quite sensitive to the small changes in the condition of a gear that occur early in the development of a fault. PKd limits for various gear damages are shown in Figure 6. Some care must be taken when using PKd because of the general limitations of kurtosis analysis and the sensitivity of this parameter.

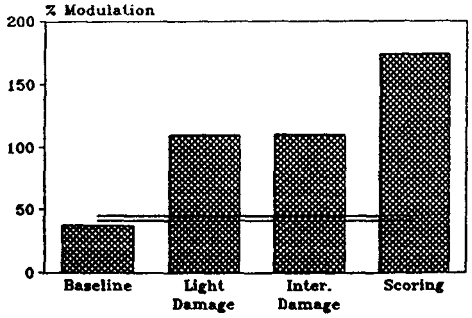

Figure 3. Amplitude Modulation, band 1.

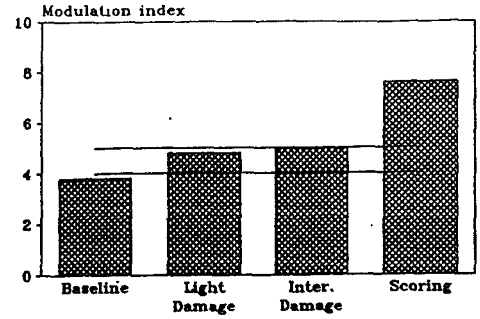

Figure 4. Modulation Index, band 3.

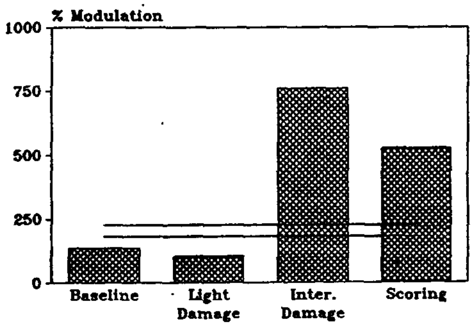

Figure 5. Phase Modulation, band 3.

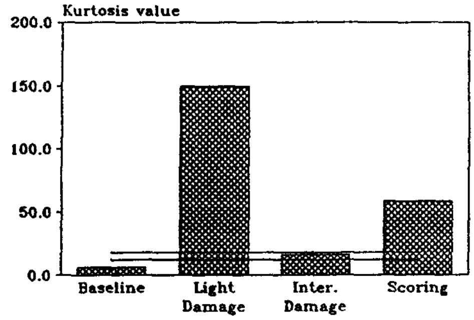

Figure 6. Phase Kurtosis derivative, band 2.

CONCLUTIONS

The amplitude and phase modulation analysis methods that have been developed and presented in this report have demonstrated themselves to be effective tools for fault diagnosis. Within the classification of gear faults, the phase parameters were the most effective. PM appears to have the broadest applications base and can be used to establish overall baseline quality. Amplitude and phase analysis techniques are to be very effective for early gear fault detection when the baseline condition of the gear has been well defined. These techniques can also be applied when the baseline state is unknown, although sensitivity to faults would be reduced in cases where the baseline was unstable. Further evaluation of these analysis techniques on other gear systems is essential because of the limited data available to date. The sensitivity of some of the analysis parameters would indicate their potential usefulness in acceptance testing and quality assurance (QA) of gearboxes.

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