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Misalignment diagnosis of a planetary gearbox based on vibration analysis

MISALIGNMENT DIAGNOSIS OF A PLANETARY GEARBOX BASED ON VIBRATION ANALYSIS

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As a critical power transmission system, planetary gearbox is widely used in many industrial important machines such as wind turbines, aircraft turbine engines, helicopters. Early fault detection and diagnosis of the gearbox will help to prevent unexpected breakdowns of this important equipment. Misalignment is one of the major operating problems in the planetary gearbox which may be caused by inadequate system integration, variable operating conditions and differences of elastic deformations in the system. In this paper, the effect of varying degrees of installation misalignment of planetary gearbox are investigated based on vibration measurements using spectrum analysis and modulation signal bispectrum (MSB) analysis. It has shown that the misalignment can be diagnosed in the low frequency range in which the adverse effect due to co-occurrence of amplitude modulation and frequency modulation (AM-FM) effect is low compared with the components around meshing frequencies. Moreover, MSB produces a more accurate and reliable diagnosis in that it gives correct indication of the fault severity and location for all operating conditions. In contrast, spectrum can produce correct results for some of the operating conditions.
Keywords: Planetary gearbox, Condition Monitoring, Misalignment, Modulation signal bispectrum.

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1. Introduction

The epicycle gearboxes or planetary gearboxes are widely used as important power transmission systems in critical machines such as wind turbine and helicopters. Because of multiple load paths of planetary gearing, the horsepower transmitted is divided between several planet meshes. Moreover, planetary stages can also be linked together efficiently to achieve high reduction ratios in a minimum space. Because of planetary gearbox compactness, their systems offer significant envelope and weight savings. They have reduced noise, vibration, and improved efficiency due to smaller, stiffer components. Since the output shaft axes and input shaft axes are concentric, they are effective in transmitting torque. Therefore, there are trends toward increased utilization of planetary gearboxes for industrial applications[1].

Because of the criticalness of planetary gearbox associated applications, condition monitoring of planetary gearbox has received significant attention by many researchers. As shown in the general review paper by Leia et al[2], considerable works have been carried out on the investigation of vibration characteristics for monitoring various faults including gear pitting, crack and wear. In addition, many different signal processing methods in the time domain, frequency domain, time-frequency domain and advanced intelligent methods have been applied to analyse the complicated vibration signal for defining accurate and reliable diagnostic features.

However, it has noticed that little research has been done in developing methods for monitoring misalignment which is deemed as the second most commonly observed disturbance source in rotor systems[3].Moreover, many signal processing methods applied are with insufficient consideration in characterising the modulation characteristics although the modulation effects in planetary gearbox is acceptable as one of the most important sources of vibration due to defects in gears[4-8]Especially, both AM and FM are taken into account in developing vibration signal models in reference[7] but the effect on spectrum structure has not been examined in analysing the measured signals for fault diagnosis.

To fill these gaps, this paper investigates the effect of varying degrees misalignment on vibration spectra of a planetary gearbox system to develop more reliable methods for diagnosing the faults. In addition to popular spectrum analysis methods in characterising the vibration signals, a modulation signal bispectrum (MSB), which is particularly effective in capturing the weak modulations in motor current signals for fault diagnosis [9], is also used to understand the AM-FM effects and to enhance feature components for the detection and diagnosis of the misalignment at different speeds and loads.

2. Planetary Gearbox Vibrations and MSB Analysis

2.1 Characteristic Frequencies for Diagnosis

A planetary gearbox, as illustrated in the Figure 1, generally consists of three planet gears, one sun gear, ring gear and a carrier. The carrier is floating and affixed to the output shaft by means of splines which allow it to move axially as required. According to this configuration, vibration characteristic frequencies for the case of error-free gears with the elastic deformation on tooth profile due to operating conditions:

The carrier:

$$f_{rc} = \frac{f_{rs}}{i} = \frac{z_s}{z_r+z_s} f_{rs} \tag{1}$$

The planet gear:

$$f_{rp} = \frac{(z_p-z_r)z_s}{(z_r+z_s)z_p} f_{rs} \tag{2}$$

And the meshing frequency

$$f_m = (f_{rs} - f_{rc})z_s = \frac{z_r z_s}{z_r+z_s} f_{rs} \tag{3}$$

where f_{rs} is the sun gear speed; the transmission ratio is $i = 1 + \frac{Z_r}{Z_s}$; z_r z_p and z_s denote the number of teeth for the ring, planet and sun gear respectively, and N is the number of planet gears.
In addition, considering that there is K number of planetary gears and the motion of planetary gears, there will be more characteristic frequencies compared with a fixed shaft gearbox [7].which includes:
faults on the sun gear

$$f_{sf} = \frac{f_m}{z_s} = K(f_{rs-}f_{rc}) \tag{4}$$

faults on the planet gear

$$f_{pf} = 2\frac{f_m}{z_p} = 2(f_{rc} + f_{rc}) \tag{5}$$

and faults on the ring gear

$$f_{rf} = \frac{f_m}{z_r} = K f_{rc} \tag{6}$$

In general fault detection and diagnosis can be carried out by examining the change of these characteristic frequencies in the frequency domain. However, it is often very difficult to identify and quantify these components because of the effects of interferences between high order of harmonics, and the attenuation and distortion of different wave transfer paths. More often, these components are also identified around the high frequency range typically around the meshing frequency at which the characteristic components are modulated to and acceleration measurement systems are more sensitive to.

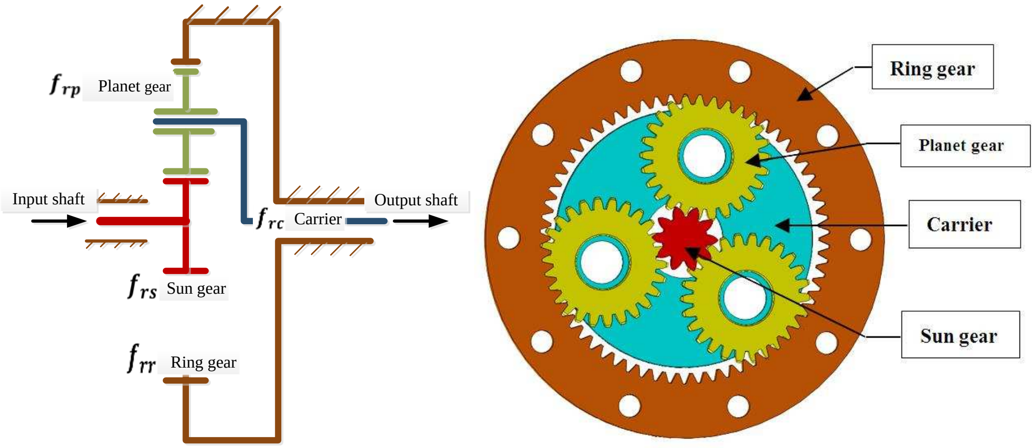


Figure 1. Schematic of a planetary gearbox with the standstill ring gear

2.2 Vibration Characteristics at Meshing Frequency

When inevitable manufacture errors and possible defects are taken into account, the vibration responses will be a complicated modulation process. As shown in references[7-10], vibration sources induced by faults at a meshing location can be modelled as a combined process of AM and FM, with the gear pair meshing frequency or its multiples as the signal carrier frequency, and the characteristic frequency of the damaged gear or its multiples as the modulating frequency. In general, the signal can be expressed at meshing frequency f_m by

$$X(t) = \sum_{h=0}^{H} M_h \cos[2\pi h f_m t + b_h(t) + \theta_h] \quad (7)$$

where H is the highest order of AM-FM harmonics to be considered, and AM modulating components $a_h(t)$ for fault component f_f at are

$$a_h(t) = c\sum_{n=0}^{N} A_{hn} \cos(2\pi n f_f t + \alpha_{hn}) \quad (8)$$

The FM components $b_h(t)$ are

$$b_h(t) = \sum_{l=1}^{L} F_{hl} \sin(2\pi l f_f t + \varphi_{hl}) \quad (9)$$

Where C is a dimensionless constant depending on signal amplitude; θ_h, α_{hn} *and* φ_{hl} are the initial phases of the meshing components, AM components and FM components respectively, L, N are the highest order for AM and FM harmonics to be considered respectively. To connection between AM and FM, only the 1st harmonic is considered in Equation (7), (8) and (9), which gives

$$X(t) = [M_0 + M_1\cos(2\pi f_f t + \alpha)]\cos[2\pi f_m t + F\sin(2\pi f_f t + \varphi) + \theta] \quad (10)$$

By ignoring the high order components in approximating FM, $X(t)$ can be approximated as superimposing of three components

$$X(t) = X1 + X2 + X3 \quad (11)$$

where the meshing component:

$$X1 = \frac{1}{2} M_0 \cos(2\pi f_m t + \theta) \quad (12)$$

sidebands due to AM

$$X2 = \frac{1}{4} M_1\{\cos[2\pi(f_m + f_f)t + \theta + \alpha] + \cos[2\pi(f_m - f_f)t + \theta - \alpha]\} \quad (13)$$

and sidebands due to FM

$$X3 = \frac{1}{4} M_0 F\{-\cos[2\pi(f_m + f_f)t + \varphi + \theta] + \cos[2\pi(f_m - f_f)t - \varphi + \theta]\} \quad (14)$$

It shows that the amplitude of sidebands is the vector sum of AM and FM components. As the phases will always changes with operating conditions the sideband components will asymmetrically distributed around the meshing frequency, which can be one of important causes of sideband asymmetry in addition to sensor position effects shown in reference[10]. For example, the upper sideband may disappear completely when the phase is opposite whereas the lower sideband would be doubled. This shows that the sideband will be asymmetric and can be fluctuated largely with operating conditions and gear faults. In addition, these asymmetric effects will be distorted further by vibration transmission paths. Therefore appropriate signal analysis methods need to be used to reduce the effect for a reliable and accurate diagnostic feature.

2.3 Modulation Signal Bispectrum

According to the definition of MSB in the frequency domain, the meshing frequency f_m and sideband f_r in a vibration signal can be correlated[9]as

$$B_{MS}(f_r, f_m) = E[X(f_r + f_s)X(f_r - f_s)X^*(f_m)X^*(f_m)] \quad (15)$$

where $X^*(f)$ is the complex conjugate of the Fourier transform $X(f)$ of acoustic signal $x(t)$; and $E[\,]$ is the statistical expectation operator. And the power spectrum of $x(t)$ is

$$PS(f_m) = E[X(f_m)X^*(f_m)]$$

Equation(15) shows that through the operation of vector average in the frequency domain, MSB can extract the combination of components at the meshing frequency, the lower sideband and the higher sideband. In the meantime, other components including random noise and interfering components that are not meet the phase relationship will be suppressed significantly. In this way the modulation effects in acoustic signal can be represented more accurately and reliably.

To examine the modulating components along, rather than that of the combination with the meshing component, a MSB sideband estimator (MSB-SE) can be used according to (17)

$$B_{MS}^{SE}(f_r, f_m) = E[X(f_r + f_s)X(f_r - f_s)X^*(f_m)X^*(f_m)/|X(f_m)|^2] \quad (16)$$

Because of the magnitude in equation (17) is normalised the magnitude of the MSB-SE is only the products of the lower and upper sideband, which reflects more the modulating component from faults.In addition, MSB coherence (MSBC) defined in Equation (17) can be based on to estimate the influences of random components and hence confirms the reliability of MSB peak detected

$$b^2{}_{MS}(f_r, f_m) = \frac{|\ B_{MS}(f_r, f_m)|^2}{PS(f_m)E[|X(f_m + f_r)(f_m - f_r)|^2]} \quad (17)$$

MSB coherence has boundary [0 1]. 1 means that MSB magnitude from true modulation effects. On other hand a zero value means that the MSB magnitude is mainly from random noise influences. Thus middle values of MSBC will indicate the reliability of MSB peaks. In addition, for a given measurement environment, the noise is relative the same. The increase of MSBC can be an indicator of modulation degree and used for detecting the presence of modulations.

3. Test Facilities and Experimental Setups

3.1 Test Facility

The planetary gearbox test rig used in this study is shown in Figure 2. It consists of a three phase induction motor of 11kWat 1465rpm, is flanged in a cantilever type arrangement to a two stage helical gearbox, a planetary gearbox, two of flexible tyre coupling, a DC generator for applying load to the gearbox .The helical gearbox is used as a speed reducer with a transmission ratio of 3.6 whereas the planetary is as an increaser with transmission rations 7.2 so that the system can be load effectively by the DC motor. In addition, the system can be controlled through a variable speed controller for operating under different load and speed.

A shaft encoder mounted on the end of the induction motor shaft produces 100 pulses per revolution for measuring the motor speed and are based for identifying characteristic frequencies of gearbox vibration. The vibration is measured by an accelerometer on the housing of the planetary gearbox with the sensitivity of100 mv/g, and frequency response range is from 1HZ to 10 kHz. All these data are logged simultaneously by a multiple channel high speed data acquisition system operating at 100 kHz rate and 16bit resolution.

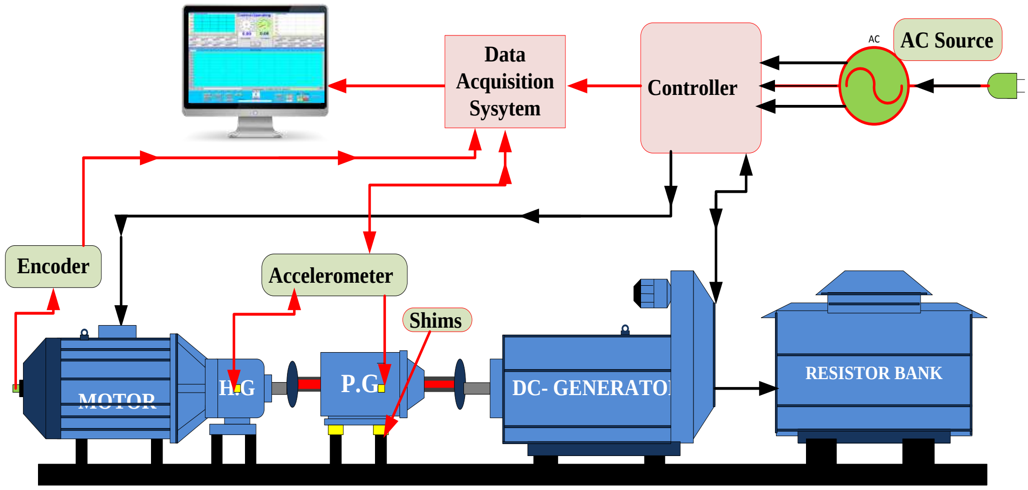


Figure 2. Schematic diagram of planetary gearbox test facility

3.2 Test Procedure

To examine the influence of the operating condition on fault diagnosis performance the test was carried out when the speed of the AC motor is at two speeds (30% and 40%). Because of the transmission ratios the planetary gearbox will operates at 60% and 80 of its full speed correspondingly. At each speed the system are load under five loads (0%, 25%, 50%, 75% and 90% of the full load). These operating conditions will allow an exploration of different influences on vibration contents for developing a reliable diagnosis method.

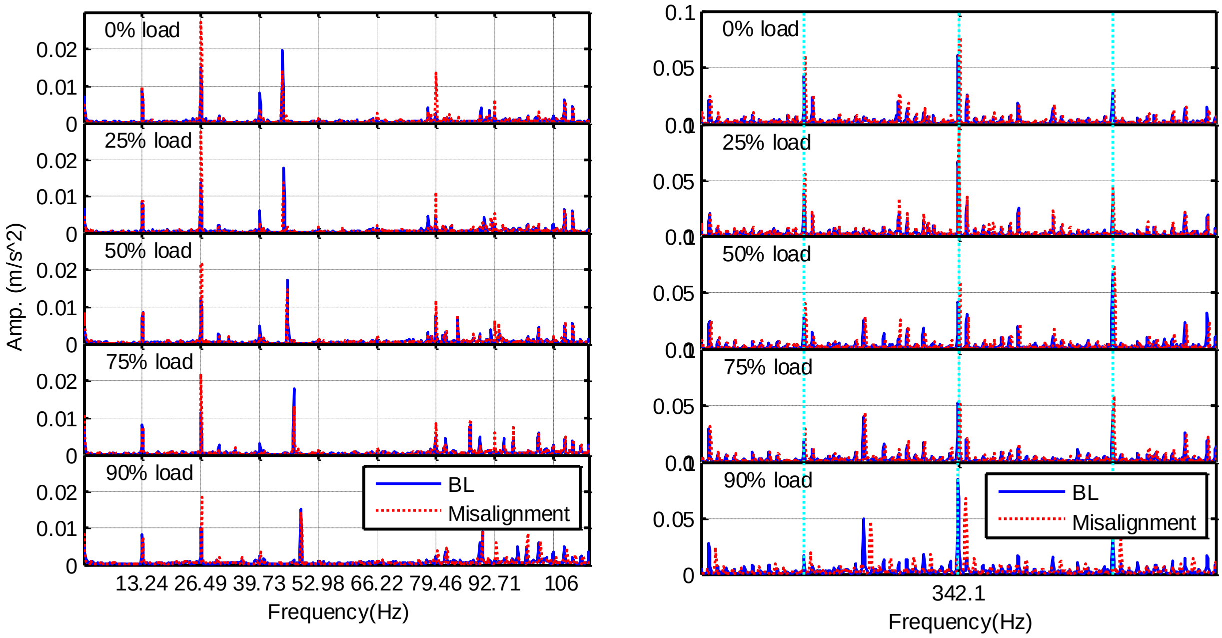
When all shafts in the system are aligned and checked using a dial-gauge method, a baseline test was conducted to collect data under the designed operating conditions. Then the parallel misalignment or vertical offset on the planetary gearbox was induced by adding shims underneath the installation legs. Three tests were carried sequentially when the shim thickness is at 0.4mm, 0.7mm and 1.0mm respectively, which allows three degrees of severity to be examined.

4. Results and Discussion

The vibration signals collected were processed with both MSB and power spectrum using fast Fourier transform with a Hanning data windows of 524288 points, which achieved a frequency resolution of 0.1362Hz, allowing the carrier frequency to be differentiate sufficiently. In addition, an average of 80 times is applied to obtain a more reliable spectrum by suppressing possible noise and interfering components in MSB analysis.

4.1 Spectrum of Vibration Signals

Fig. 3(a) and (b) show the spectra in the low frequency range and around the 3rd harmonics of the meshing frequency for different load at the lower speed. It can be seen that from Fig.3 (a) that the spectrum for the baseline is predominated by harmonics of f_{rs} and other components such as at f_{sf} and f_{rp}maybe visible under different load. Moreover, under the misaligned condition of 1.0mm, spectral amplitude increase clearly at $2Xf_{rs}$ and $6Xf_{rs}$ but not$4X$, which is not fully consistent with misalignment features that the amplitudes at even numbers should increase with the degrees of misalignment. In addition, the amplitude also show a slight decrease with load, showing that effect of the nonlinear stiffness of the flexible couplings that allow a smaller torsional oscillation at high static load. For the similar reason the amplitude at f_{rc} is very small because it undertakes a load 7.2 time of that at the sun gear shaft.

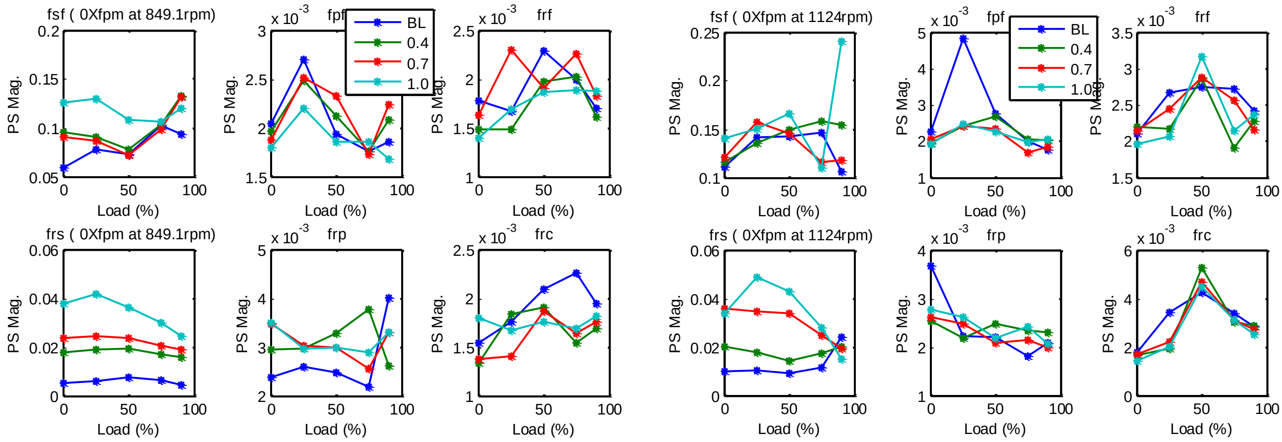


(a) Spectrum in the low frequency range (b) Spectrum around 3rd meshing frequency

Figure 3. Baseline and misalignment vibration spectra under different loads

In the meantime, the spectrum sections around $3Xf_m$ for the baseline case are generally higher than that of the low frequency range. Except for sidebands at ($3Xf_m \pm f_{rs}$), it is difficult to identify other sideband patterns, indicating the AM-FM effects. Moreover, the differences between the baseline and the misalignment is much smaller, compared that of the low frequency range. This shows that the misalignment may cause a small effect on gear meshing processes due to the damping of key ways. In other words, this type of misalignment should be detected in the low frequency range.

To accurately quantify and locate the misalignment, spectral amplitudes up to 10th order of harmonics at all characteristic frequencies overviewed in section 2 are extracted from corresponding spectrum in both the low frequency range and that of different meshing frequencies. However, the spectral amplitudes of sideband obtained around meshing frequencies show inconsistent changes with the fault severity and operating conditions. This may indicate the adverse effect of AM–FM which may cause the sideband oscillates with different conditions. On the other hand, as shown in Figure 4, the amplitude at f_{rs} from the low frequency range increases consistently with the degrees of misalignment, showing this spectral amplitude allows the misalignment to be diagnosed appropriately at the lower speed. However the amplitude could not make differences at the high load condition. This may be due to the influences of high background noise from the test system and the stronger vibration sources inside the gearbox.



(a)Spectra amplitudes of characteristic frequencies at lower speed

(b)Spectral amplitudes of characteristic frequencies at higher speed

Figure 4 Diagnosis of misalignment by spectral amplitudes for different load and speed

In addition, at the lower speed, amplitudes at f_{rf} and f_{rp} also show higher amplitudes under low loads, compared with that of baseline case. These changes may lead to incorrect diagnosis results that faults also occur or influences on the planetary gears.

4.2 MSB of Vibration Signals

To clarify possible misleading results from power spectrum, MSB analysis is applied to corresponding signals. Figure 5 presents a typical MSB results. It can be seen from the top row of Figure 5 that the increasing amplitude with the degree of misalignment is enlarged because MSB magnitude is able to exclude non-modulation components including the random noise. In the meantime, MSB coherence, shown in the bottom row, exhibit nearly unity amplitude which confirms the magnitude are due to the effects of modulation.

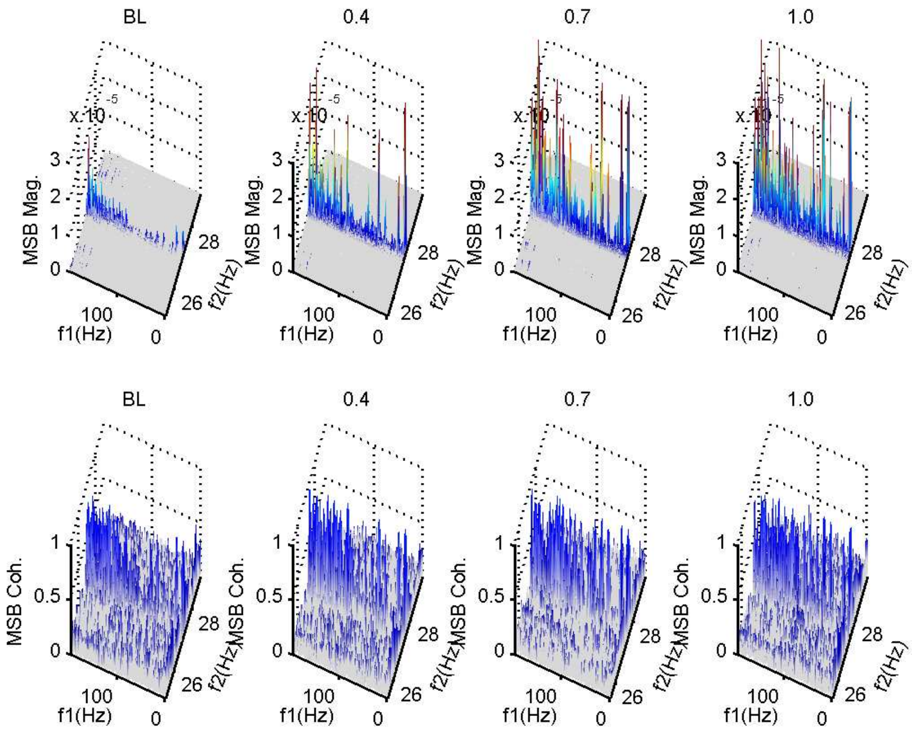
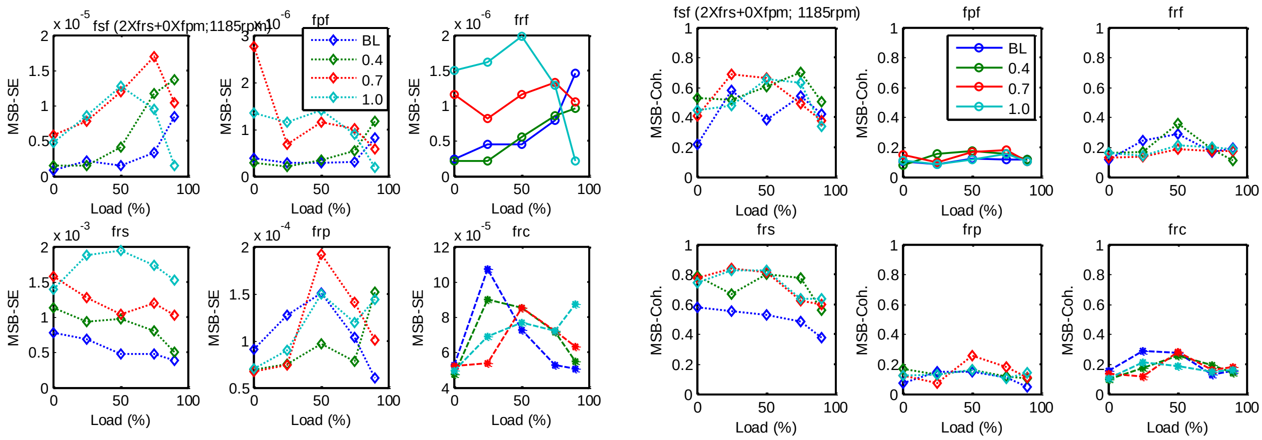


Figure 5 MSB results for different cases at lower speed and high loads

To make more accurate comparison MSB amplitudes at the characteristic frequency are extracted in a similar way to the power spectrum, as shown in Figure 6. To benchmark diagnosis performance MSB results are presented for the higher speed at which PS may provide incorrect and misleading results. It can be seen that different degrees of misalignment under high loads for f_{rs}can be differentiated properly because of the MSB capability of suppressing noise and interferences. Unfortunately MSB-SE magnitude along is also unable to make difference between the two higher degrees of misalignment at 0% load. This may be due to the highly unstable operation at low load conditions of the gearbox.

Moreover, MSB coherence provides complementary information on the diagnosis results. As shown in the figure the amplitude at f_{rs} has amplitude more than 0.6. Especially the amplitudes for misalignment cases are all higher than that of baseline. This shows that the level of modulation degree is high and increase with misalignment. In the meantime MSB coherence also show high amplitude at f_{rf}, This confirms that the increase in their magnitudes is mainly from modulation effects and hence the meshing process is abnormal, which is understandable as the misaligned shaft will influence the meshing quality inevitably. However, magnitude increases for characteristic components are associated with very low coherence amplitude. Therefore, these increases are still from the background noise rather than the effects from any faults.



(a) MSB diagnostic results for high speed operation

(b) MSB coherences for high speed operation

Figure 6 MSB diagnostic results at higher speed

5. Conclusion

Vibrations from planetary gearbox show complicated spectrum patterns due to the combined effect of co-occurrence of AF and FM processes and noises. Especially, the effect will lead to high fluctuation in spectral amplitudes, causing difficult to define a stable diagnostic feature. MSB analysis has high performance in selecting modulation components with sidebands which are less asymmetric, and in suppressing random noise. So it allows more stable diagnostic results to be obtained. Moreover, as complementary information MSB coherence ensures the quality of MSB magnitude and can be an effective detector of modulation. The misalignment can be diagnosed in the low frequency range in which spectral fluctuation due to AM-FM effect is relatively low. However, MSB produces a more accurate and reliable diagnosis in that it gives correct indication of the fault severity and location for all operating conditions. In contrast, spectrum can produce correct results for some of the operating conditions.

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