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An Investigation of the electrical response of a variable speed motor drive for mechanical fault diagnosis

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ABSTRACT

Motor current signal analysis has been an effective way for many years to monitor electrical machines. However, little research work has been reported in using this technique for monitoring variable speed drives and their downstream equipment. This paper investigates the dynamic responses of the electrical current signals measured from a variable speed drive for monitoring the faults from a downstream gearbox. An analytical study is firstly presented in the paper to show the characteristics of the current signals due to load variation, fault effects and signal phase variation. Experimental study is then conducted under different gear fault conditions to explore the changes of the signals. Both conventional spectrum analysis and an amplitude modulation (AM) bispectrum representation are used to highlight the changes for reliable fault detection. It has been found experimentally that mechanical faults lead to much higher increases in bispectral amplitudes compared to conventional spectra and hence that detection performance of the AM bispectrum is better when the drive operates non-slip compensation mode. For slip compensation, more accurate signal analysis techniques have to be developed to differentiate the small changes in the signals.

Keywords: Gearbox, Variable speed drive, Motor current signature analysis, Bispectrum analysis.

1. INTRODUCTION

The induction motor is the most generally known driving machine elements in a mechanical power system (Benbozide, 2000; Pole, 2009; Nagi, 2007). Gearboxes, pumps, fans, etc. are driven by such motors, With higher demands of variable operating speed for these driven machines, variable speed drives (VSDs) have been developed (Naji, 2007), but there is concern about untimely breakdown in these driven machine components and these early failures often

+have considerable economic losses, and possibly cause catastrophic consequences(Naji, 2007; Al-Arbi, 2009).

As yet, a limited amount of research in the gearbox condition monitoring field have been conducted using motor current signature analysis (Gu et al., 2011; Benbozide, 2000). very little research deals with fault diagnosis of such drives VSDs. Conventional techniques for monitoring vibration signals depend on the assumption that the gearbox health may be diagnosed by indicating alters in the measured current signal response (Naji, 2007; Benbozide, 2000). However, this assumption can be true for changing operation conditions such as speed. The slip compensation is an improvement technique of open loop concept, monitor motor current using drive output current transducer. When the induction motor is loaded, the output frequency is not change, the slip increases, the shaft RPM decrease and the current of the motor increases. The difference is that the slip function compensates for the dropping in rotor speed by increasing the applied voltage and frequency to the induction motor (Pole, 2009).

In this paper, current waveforms were collected for healthy and faulty gears under both non-slip compensation and slip compensation operation modes. These waveforms were analysed with spectrum and bispectrum techniques to examine the characteristics of current signals obtained from the two operation modes and hence to develop more accurate ways to detect gearbox faults in a motor drive system.

2 ELECTRICAL RESPONSE DUE TO FAULTS

2.1 Phase current response of healthy condition

When the rotor of a mechanical system is healthy i.e. no faults such as misalignment, the electromagnetic relationship of the driving motor can be examined in phase *A* only because the three phases of a power supply are symmetrical. neglecting the higher order harmonics and referring to supply voltage signal, the current signal in phase *A* for a health motor drive can be expressed (Obaid et al., 2003; Bellini, 2001) as

$$i_A = \sqrt{2} I \cos(2\pi f_s t - \alpha_I) \tag{1}$$

Correspondingly, the magnetic flux in the motor stator is

$$\phi_A = \sqrt{2}\phi \cos(2\pi f_s t - \alpha_\phi) \tag{2}$$

The electrical torque produced by the interaction between the current and flux can be expressed as

$$T = 3P\phi I \sin(\alpha_I - \alpha_\phi) \tag{3}$$

where I and ϕ denote the root mean squared (RMS) amplitudes of the supply current and linkage flux respectively, α_I and α_ϕ are the phases of the current and flux referring to supply voltage, f_s is the fundamental frequency of electrical supply and P is the number of pole pairs.

2.2 Phase current response of faulty condition

If there is a fault occurring in the rotor system (including the motor's rotor and the rotational components connected to the rotor mechanically), there will be an additional torque component oscillating around the electrical torque. Supposing that the additional torque ΔT is a sinusoidal wave with a frequency f_F, current amplitude I_F and phase α_F, the oscillatory torque can be obtained using Eqn. (3) as

$$\Delta T = 3P\phi I_F \sin[2\pi f_F t - (\alpha_I - \alpha_\phi) - \alpha_F] \tag{4}$$

Correspondingly, this oscillatory torque causes speed fluctuation. From the motor torque balance equation, the speed fluctuation due to this oscillatory torque can be derived as

$$\Delta\omega = \frac{P}{J}\int \Delta T dt = -\frac{3P^2\phi I_F}{2\pi f_F J}\cos[2\pi f_F t - (\alpha_I - \alpha_\phi) - \alpha_F] \tag{5}$$

and the angular oscillation is hence

$$\Delta\alpha_F = \int \Delta\omega dt = \frac{3P^2\phi I_F}{4\pi^2 f_F^2 J}\sin[2\pi f_F t - (\alpha_I - \alpha_\phi) - \alpha_F] \tag{6}$$

where J is the inertia of the rotor system. This angular variation produces phase modulation to the linkage flux and Eqn. (2) becomes

$$\phi^F{}_A = \sqrt{2}\phi \cos\{2\pi f_s t - \alpha_\phi - \Delta\phi \sin[2\pi f_F t - (\alpha_I - \alpha_\phi) - \alpha_F]\} \tag{7}$$

where $\Delta\phi = \frac{3P^2\phi I_F}{4\pi^2 f_F^2 J}$. This shows that the flux wave contains nonlinear effects because of the fault in the rotor system. This nonlinear interaction of linkage flux will produce a corresponding electromagnetic force (EMF) and hence induce a nonlinear current signal in the stator.

Considering $\Delta\alpha_F$ to be very small, results in $\cos(\Delta\alpha_F) \approx 1$ and $\sin(\Delta\alpha_F) \approx \Delta\alpha_F$, the linkage flux now can be simplified and examined in three components explicitly:

$$\begin{aligned}\phi^{F}{}_{A} &\approx \sqrt{2}\phi\cos(2\pi f_s t-\alpha_\phi)+\sqrt{2}\phi\Delta\alpha_F\sin(2\pi f_s t-\alpha_\phi)\\ &=\sqrt{2}\phi\cos(2\pi f_s t-\alpha_\phi)\\ &+\sqrt{2}\phi\Delta\phi\ \cos[2\pi(f_s-f_F)t-\alpha_I-\alpha_F]\\ &-\sqrt{2}\phi\Delta\phi\ \cos[2\pi(f_s+f_F)t-2\alpha_\phi+\alpha_I-\alpha_F]\end{aligned} \tag{8}$$

Eqn. (8) shows that the flux contains not only the fundamental part but also sidebands around the fundamental frequency. This simplified flux allows the current expression to be obtained based on the motor equivalent circuit:

$$\begin{aligned}i^{F}{}_{A} &=\sqrt{2}I\cos(2\pi f_s t-\alpha_I)\\ &+\sqrt{2}I_l\cos[2\pi(f_s-f_F)t-\alpha_I-\alpha_F-\varphi]\\ &-\sqrt{2}I_r\cos[2\pi(f_s+f_F)t-2\alpha_\phi+\alpha_I-\alpha_F-\varphi]\end{aligned} \tag{9}$$

where φ is the angular displacement of the motor equivalent circuit impedance at the supply frequency, I_l and I_r are the RMS values of the lower sideband component and the upper sideband component, respectively, which are the currents induced by the back-EMF voltages produced by the flux variations at frequencies of $f_s - f_F$ and $f_s + f_F$. This simplified expression of current signal is employed widely for motor fault condition monitoring. By checking the amplitude of the sidebands through spectrum analysis, various faults such as rotor bar breakage and eccentricity can be diagnosed with a high degree of accuracy.

However, conventional spectrum analysis uses amplitude information only and overlooks the phase effect which also contains fault information, as shown in Eqn. (9). The consequence of ignoring phase information may degrade diagnosis performance for the case of incipient faults when the sideband amplitude is very small and is masked by random noise. This is particularly true for diagnosing faults from the downstream mechanical system. Fortunately, bispectrum analysis allows the retention of both the amplitude and the phase information, and it also has good noise suppression and identification of nonlinear effects.

3. TEST FACILITES AND FAULT SIMULATION

3.1 Test facility

Figure1 shows construction of the test rig. It consists of a three phase induction motor, a two stage helical gearbox and a DC generator for applying load to the gearbox. Table 1 presents the details of the gearbox. For operating the rig under different speed and load, the rig is equipped with a control system a variable frequency AC drive for speed variation and a load variation capability. The AC drive can operate in either slip compensation or non-slip compensation mode, the former allowing more accurate speed control whereas the latter allows rotor slippage which is similar to a conventional induction motor.

Description	First Stage (Input Shaft)	Second Stage (Output Shaft)
Number of teeth	Z1/Z2=58/47	Z3/Z4=13/59
Shaft speed(Hz)	Fr1=24.42 Fr2=30.13	Fr3=6.64 (output)
Mesh frequency(Hz)	Fm12=1416.36	Fm23=391.76
Contact ratio	1.45	1.469
Overlap ratio	2.89	1.289

Table 1 Gearbox specification

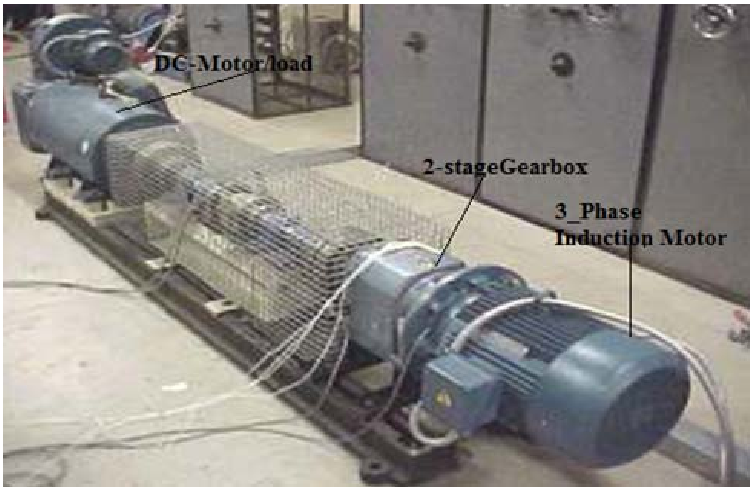

Figure 1 Test rig construction

3.2 Fault simulation

Two types of gearbox faults are examined in this research. One of them is tooth breakage i.e. one complete tooth of the input pinion was removed. This type of fault is very common in gear transmission andhas been studied extensively in condition monitoring. Because of the high overlap ratio the power transmission has little influence by such a tooth breakage. This faulty gear is labeled Gear #3 as it is one of 12 gear sets involved in condition monitoring experimentation.

The second fault is a shaft misalignment which is introduced by misaligning the coupling between the output shaft of gearbox and the driven shaft downstream with 0.46mm parallel misalignment.

Both types of fault induce an additional small load oscillation to the motor but at different frequencies. It was anticipated that such small changes can be extracted from current signals to identify and differentiate them accordingly.

3.3 Data acquisition

Electrical current signals are measured by a hall-effect sensor with a linear frequency response from 25Hz to 4kHz, which allows the content in a wide frequency range, especially around the supply fundamental (50Hz), to be measured accurately. To examine the influence of the operating condition on CM performance, electrical current signals were measured for the two modes of operations at different loads: 10%, 18%, 32%, 54%, and 76% of the full operating load. In addition, vibrations from gearbox casing was also measured to benchmark the performance of the current signal based fault monitoring.

All of the measurements were sampled simultaneously at a rate of 100kHz and with a data length of 16 seconds per channel. For performing a sufficient degree of average and obtaining reliable results each measurement was repeated three times.

4. RESULTS AND DISCUSSIONS

The test rig was operated under two control modes: with slip compensation and with non-slip compensation. The signals obtained under these modes were analysed by conventional spectrum and bispectrum methods.

4.1 Current spectrum under non-slip compensation mode

Figure 4.1 shows spectrum comparison between healthy and faulty conditions under different loads. It can be seen that there are three sideband components around the 50Hz, which correspond to the input shaft 24.42Hz, mids haft 30.1Hz and output shaft 6.6Hz. These spectral components link the load and speed fluctuations due to the imperfections of each shaft and shows that the phase current can reflect the mechanical changes as addressed in section 2.

As the load increases from 0-77.3%, amplitude differences start to develop between healthy condition and faulty condition. It is evident from the figures that there is gradual increase in the amplitude of the second rotational speed frequency. This increase in the amplitude frequency components could be due to the change of the periodicity of the vibration signal when the fault is present and/or could be a related to the change in the pinion gear characteristic since the gear fault was simulated on a similar pinion but not on the same pinion gear used for the healthy condition. Nevertheless, Figure 4 also exhibits an increase in the magnitude of the input shaft rotational speed frequency as the load increase from 9.09% to 18.2% which reveal the occurrence of the fault in the pinion gear.

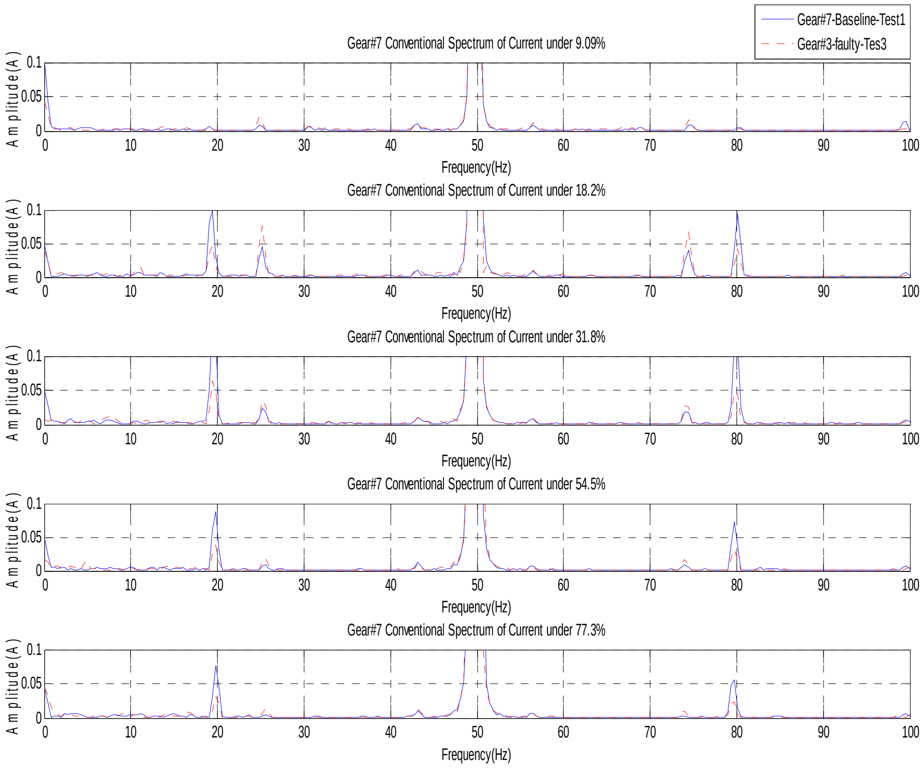

Figure 4 Motor current signals in non-slip compensation mode

4.2 Current spectrum in slip compensation mode

Figure 5 shows the spectra when the induction motor is operating in slip compensation mode but the gear conditions and operating loads are the same. The main frequency is located at 50Hz at 0% load but it shifts higher during the load increase in order to maintain motor speed In addition the figure illustrates that the rotational speed frequencies are not clear especially at low load even with existence of the fault, so the detection of fault in this operating mode is difficult.

Furthermore, more frequent components for the faulty gear show up at high load, but no more features can be extracted to diagnose the gear health. Even though unknown frequencies appear at high load and some change is seen in the amplitude of the first and second shaft rotational speed it is still difficult to diagnose gear health in this operating mode.

It can be concluded that it is not possible to detect the faulty gear via sideband analysis when the VSD is in slip compensation mode. Further examination of the spectrum shown that there are many low frequency components withhigher amplitudes for the faulty case, and it is thus may be to detect the faulty case using these spectrum features.

The spectrum of current can show features faulty gear but the features varies with load, which is different to when using conventional motor drive and also not convenient to implement in practice.

In addition, the fundamental frequency of power supply also increases significantly (from 50Hz to 51.5.2Hz) with load increase. This change in fundamental frequency may will change the electromagnetic characteristics of the motor under investigation and hence may alter the diagnostic feasibility. For this reason more advanced signal processing techniques have to be implemented in order to diagnose the gear health during this operating mode.

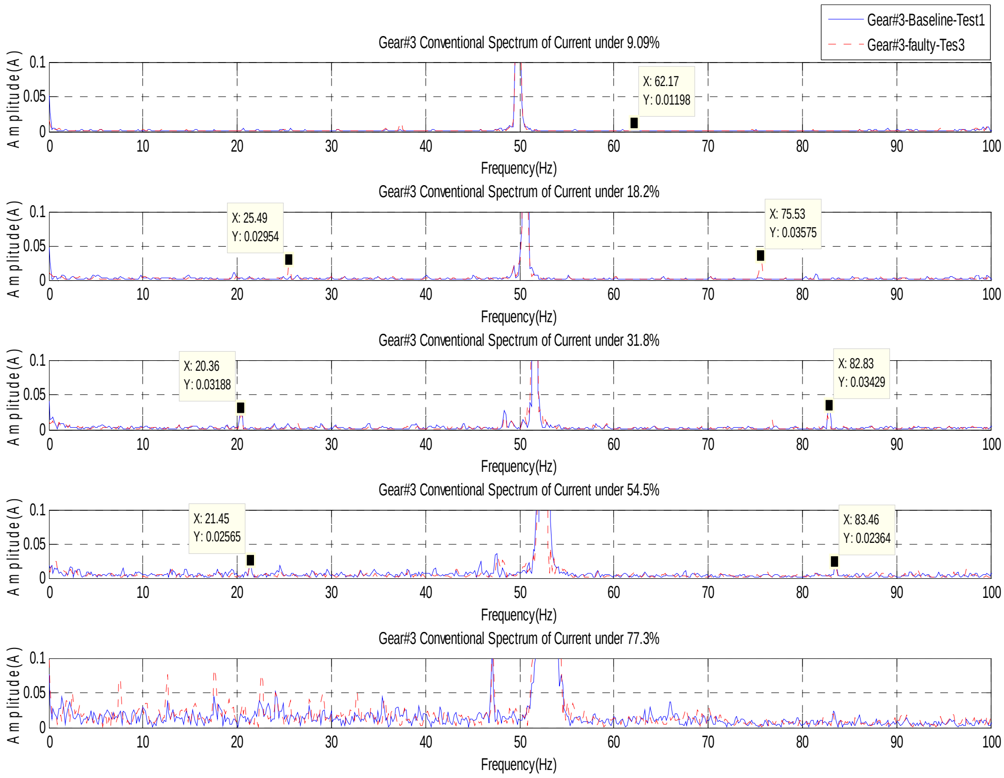

Figure 5 Motor current signals in slip compensation mode

5. BISPECRUM ANALYSIS

For more accurate diagnosis of the gear health status the, bispectrum technique was also applied to the current signals. The bispectrum, including its bicoherence is calculated using an amplitude modulation (AM) bispectrum algorithm (Gu et al., 2011). For noise reduction, it is averaged 30 times.

The AM bispectra are presented as a three-dimensional image with two of the coordinate axes for frequencies f1 and f2, and the third axis for amplitude. the conventional spectrum is also presented for comparison

The three-dimensional graph in Figure 6 shows the bispectrum and its corresponding bicoherence for healthy gear condition. The bispectrum shows a very clear presentation and only three components can be seen at bifrequencies (50, 24.4), (50, 30.1) and (50, 6.6), each of them linking respectively to input shaft, middle shaft and output shaft frequency whereas the bicoherence is nosy but with amplitude of 1 at the three components confirms that the signal-to-noise ratio is sufficiently high to ensure that the bispectral amplitudes are a result of nonlinear effects between the mains and the shaft frequencies. Many of the bicoherence amplitudes are much less than 1, indicating that there are zero or fewnonlinear effects in the corresponding frequencies.

From the spectrum shown by the graph of Figure 6, the sideband components relating to the input shaft and output shaft are very small. Especially because of high ground floor noise amplitudes it is difficult to identify these two small spectral components. On other hand, the unit amplitudes of the bicoherence can be relied on to identify these two small components in the bispectrum.

Figure 7 shows the bispectrum of faulty gearbox condition. Comparedwith that in Figure 6, it can be seen that it has a significant amplitude increase at bifrequency (50, 24.4), which gives a clear indication of the existence of a severe fault in the pinion gear on the input shaft.

Moreover, the amplitude at (50, 24.4) is about 5 times more than its baseline of Figure 6, which is much higher compared with conventional spectrum. The , bispectrum clearly gives better fault detection performance.

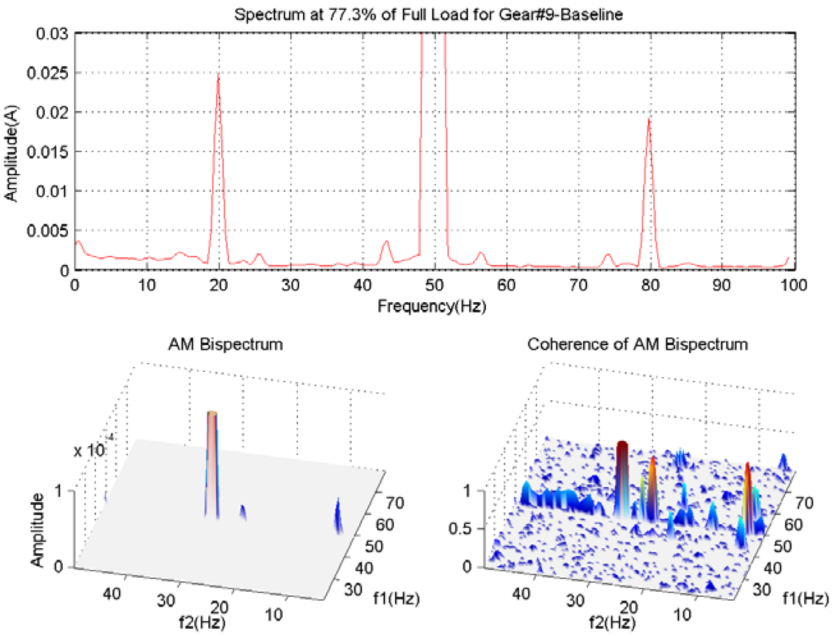

Figure 6 Spectrum and bispectrum at 77.3% of full load for healthy gear

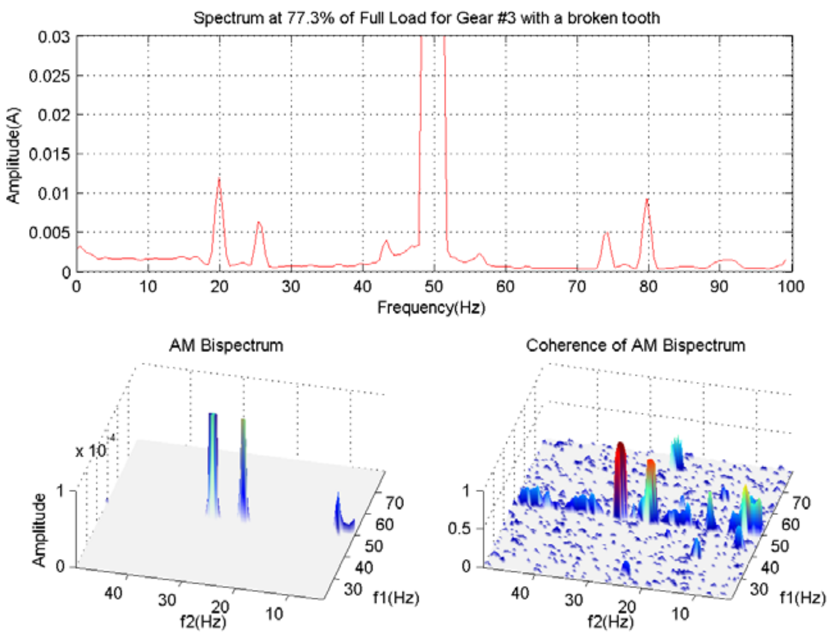

Figure 7 Spectrum and bispectrum at 77.3% of full load for gear with broken tooth

For the misalignment fault, both the conventional spectrum and the bispectrum show an increases in amplitudes relating to output shaft frequency, demonstrating that the fault can be identified by both methods.

However, as shown in Figure 8, the sideband amplitudes of the conventional spectrum increase by a factor of 2x at 50±6.4Hz, compared with that of the baseline shown in Figure 7., The bispectral amplitude at (50, 6.4)Hz is more than 4 times higher than that of Figure 7. This means that the bispectrum amplitude is more sensitive to small changes and has better performance in detecting incipient faults.

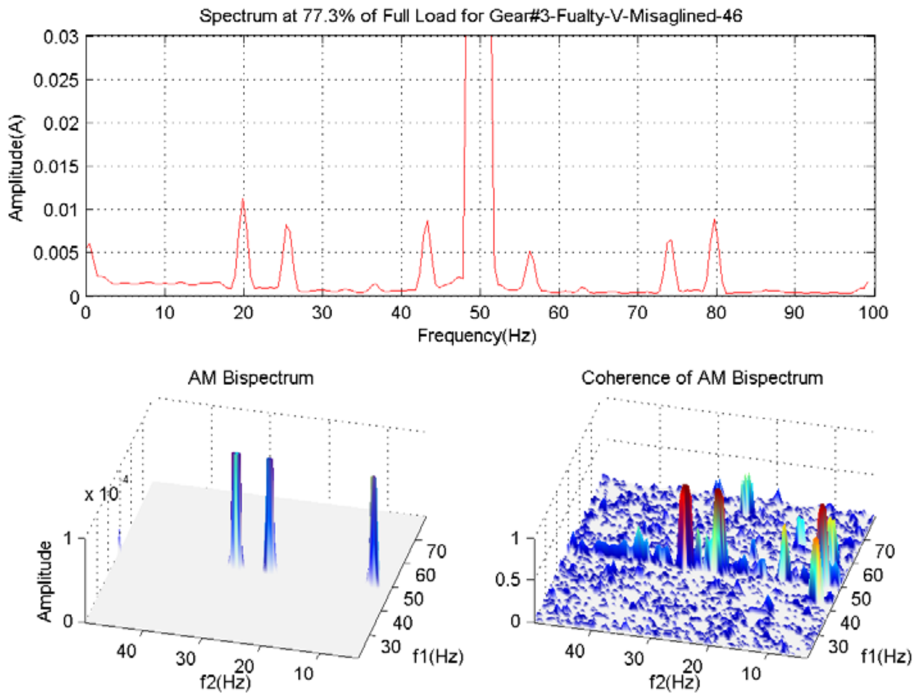

Figure 8 Spectrum and bispectrum at 77.3% of full load for gear with broken tooth and 0.46mm misalignment

6. CONCLUSION

The electrical dynamic response of a variable speed drive has been studied analytically to understand the characteristics of the electrical current signals due to load variation, fault effects and signal phase variation. It has been shown that load and speed oscillations arising from different types of mechanical faults will lead to a modulation in the supply components. However, because the extent of modulation is very small, the AM bispectrum analysis gives better detection performance because of its capabilities of noise reduction, nonlinear effect detection and phase information retention.

Experimental study has shown that both the conventional spectrum and AM bispectrum can be used to detect tooth breakage and shaft misalignment but bispectrum amplitudes are more sensitive to small changes and hence give better fault detection performance.

In addition, it has also been found that it is difficult to detect faults when the variable speed drive operating under slip-compensation mode, and this provides scope for future research and development work.

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