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Fault Diagnosis for Crankshaft Bearing in Diesel Engine Based on Bispectrum Analysis

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Aimed at the problem of the feature of nonstationary vibration signal can not be extracted easily; the bispectrum analysis technique was researched in this paper. Bispectral characteristic frequency faces were searched along the parallel to the diagonal line at certain step in the bispectral modulus field and the mean magnitude was calculated to get the feature parameters. The method was applied in fault feature extraction of crankshaft bearing in diesel engine successfully.

1. Introduction

Because of the combined shock raised by multi-mechanism motion, the vibration signal of diesel engine is nonlinear and nonstationary in strict meaning on the condition of diesel engine running steadily. Therefore, the vibration feature of diesel engine components cannot be reflected by time-domain waveform and spectrum analysis preferably. The main reason of abnormal sound or vibration being too acute is abnormal gap induced by wear (Xiao, 2006). The vibration signal of crankshaft bearing is influenced by impact caused by other components inescapably, and the amplitude is increasing along with the rotate speed being rising, which belongs to nonstationary signal. But the vibration signal of engine has periodicity, the natural frequency of each component is invariable, when the sampling frequency is high, the vibration signal of crankshaft bearing can be regard as a sort of cyclic stationary signal (Bai et al., 2005).
Bispectral is a high-order cyclic cumulant, which can separate stationary signal and cyclostationary signal availably, and can completely control any stationary or nonstationary colored gaussian noise. At the same time, bispectral can distinguish the time-varying phase information and characterize nonlinear signal, which has been applied in the area of mechanical fault diagnosis and vibration analysis (Zhang and Bao, 1998).
In this paper, bispectral technique was applied in analyzing the vibration signal of crankshaft bearing on the different conditions, and the bispectral feature frequency face was gained, which was regarded as feature parameters, the diagnosis effect is preferable.

2. Bispectrum Calculation

2.1 Define of Bispectrum

For cyclostationary process $x(t)$, order $X(w)=\sum_{t=0}^{T-1} x(t)e^{-jwt}$, which denotes the finite Fourier transform of $x(t)$, the bispectrum define of the process can be described as Eq.(1) (Liu, Zheng, Zhu and etal, 2000, Zheng, Chen and Li, 2002, Yang, Stronach, MacConnell and etal, 2002):

$$B_x(w_1,w_2)=E[X(w_1)X(w_2)X^*(w_1+w_2)] \tag{1}$$

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2.2 Calculation of Bispectrum

There are two methods to do bispectrum estimation, including nonparametric model and parametric model, and each model includes direct method and indirect method. In this paper, the direct method of nonparametric model estimation is adopted, whose computational cost is less than indirect method.

Hypothesize the length of observation sequence $\{x(t)\}(i=1,2,...,N)$ is N, and the sampling frequency of which is f_s. In the bispectrum-domain, the frequency sampling number of w_1 and w_2 is N_0, thus, the frequency sampling interval is $\Delta_0 = f_s / N_0$. The calculational step of this method is as follows:

1) The length of data is N, order the number of subsection as k, each subsection includes M observation samples, and permit each subsection data to superpose. Then, subtract the mean of each subsection data.

2) Do the DFT transform to the j th subsection data:

$$\hat{X}^j(\lambda) = \frac{1}{M}\sum_{i=1}^{M} x^j(i)\exp(-j\frac{2\pi}{M}i\lambda) \tag{2}$$

3) Based on the coefficients of DFT, calculate the bispectrum estimation of each subsection data:

$$\begin{aligned}\hat{B}_x^j(\lambda_1,\lambda_2) = \frac{1}{\Delta_0^2}\sum_{k_1=-L_1}^{L_1}\sum_{k_2=-L_1}^{L_1}&\hat{X}^j(\lambda_1+k_1)\hat{X}^j(\lambda_2+k_2)\\ &\hat{X}^j(\lambda_1+k_1+\lambda_2+k_2)\end{aligned} \tag{3}$$

4) Statistical average the bispectrum estimation results of each subsection data:

$$\hat{B}_x(w_1,w_2) = \frac{1}{k}\sum_{j=1}^{k}\hat{B}_x^j(w_1,w_2) \tag{4}$$

In the Eq.(4), $w_1 = \left(\frac{2\pi f_s}{N_0}\lambda_1\right)$, $w_2 = \left(\frac{2\pi f_s}{N_0}\lambda_2\right)$.

The value of bispectrum estimation is complex number, do the modular operations to the bispectrum-domain, and consider the symmetry of bispectrum, the 12 symmetrical intervals can be gained:

$$\begin{aligned}|B_x(w_1,w_2)| &= |B_x(w_2,w_1)| = |B_x(-w_2,-w_1)|\\ &= |B_x(-w_1,-w_2)| = |B_x(-w_1-w_2,w_2)|\\ &= |B_x(w_1,-w_1-w_2)| = |B_x(-w_1-w_2,w_1)|\\ &= |B_x(w_2,-w_1-w_2)| = |B_x(-w_2,w_1+w_2)|\\ &= |B_x(w_1+w_2,-w_2)| = |B_x(-w_1,w_1+w_2)|\\ &= |B_x(w_1+w_2,-w_1)|\end{aligned} \tag{5}$$

The position of each interval is shown in Fig. 1.

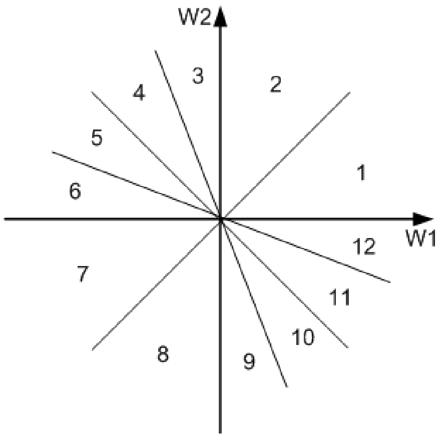


Figure 1: The symmetrical intervals in the field of bispectrum modulus

In Fig.1, the amplitude symmetry axis in interval 1, 2, 7 and 8 is $W_2 = W_1$; the amplitude symmetry axis in interval 3, 4, 9 and 10 is $W_1 = -W_2/2$; and the amplitude symmetry axis in interval 5, 6, 11 and 12 is $W_2 = -W_1/2$. Thus, we only have to analyze amplitude in some intervals.

3. Vibration Signal Acquisition of Crankshaft Bearing

The diagnosis object is the mechanical power train of a Cummins 6BT diesel engine installed in an automobile of Dongfeng EQ2102, the engine has a turbocharger and 6 cylinders inline, and the rated power is 85kw. In the experiments, three conditions were set as Table 1. The locations of the vibration sensors are shown as Fig. 2.

Table 1: Fault parameter setting

Condition	Design condition	Fit clearance of crankshaft bearing
Condition F_1	Normal condition	0.08mm
Condition F_2	Fit clearance is big	0.20mm
Condition F_3	Fit clearance is too big	0.40mm

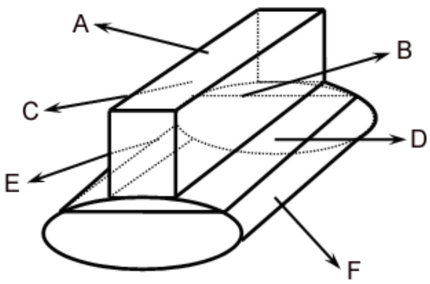


Figure 2: Locations of accelerative vibration sensors
A. Top of the third cylinder; B. Right upside of the third cylinder; C. Left upside of the third cylinder; D. Right connection parts between cylinder body and oil pan of the third cylinder; E. Left connection parts between cylinder body and oil pan of the third cylinder; F. Oil pan

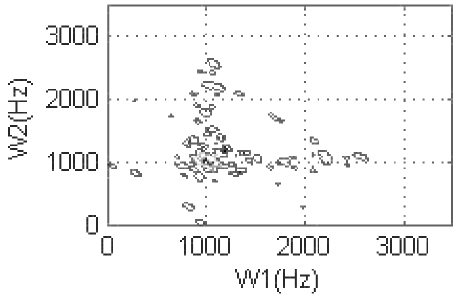
The preset value of the starting rotary speeds for the nonstationary data acquisition system is 800 r/min, 1300 r/min, 1800 r/min and 2100 r/min respectively while the engine is operating in acceleration process. The sample frequency is 25,600 Hz, the sample number are 16,384.

4. Bispectrum Analysis

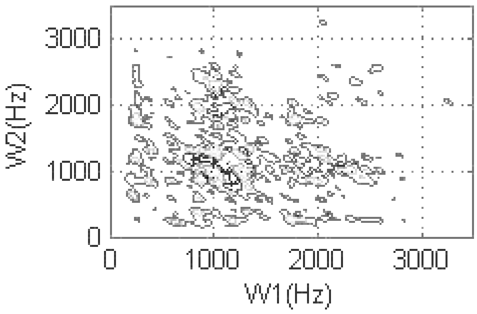
The length of data is N=16384, order each subsection observation samples M=1024, the superpose degree of each subsection data is 50%, and the number of subsection is K=2*N/M-1. When the rotary speed is 1800 r/min, calculate the bispectrum of vibration signal in Location E of the third cylinder on the three conditions. The amplitudes and contours are shown in Figure 3.

From Figure 3, we can see that the valid frequency focus within 3000 Hz, the contours on different conditions have large difference. Following the increasing of fit clearance, the peak value of feature frequency is more and more obvious. In order to seek the fault features, search and compare the amplitudes in interval 1. In this paper, the method for searching feature face is searching along the parallel beelines which parallel with diagonal.

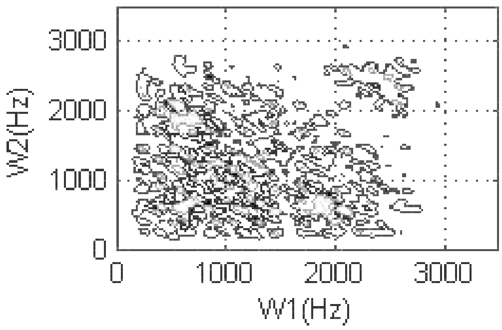
Search the feature face to the signal, and arrange descend the feature face according to the patency degree, which are shown in Figure 4.



(a)



(b)



(c)

Figure 3: The bispectrum modulu amplitudes and contours in Location D of the third cylinder on the three conditions. (a) Fit clearance is 0.08mm (b) Fit clearance is 0.20mm (c) Fit clearance is 0.40mm

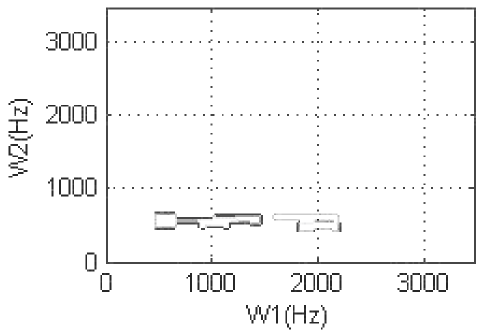


Figure 4: Bispectral feature face of crankshaft bearing vibration signal of the third cylinder on location E

Compare the bispectrum analysis result of vibration signal acquired in 4 kind of rotary speeds on 6 locations, select the 6 most obvious feature face each rotary speed, which are shown in Table 2.

Table 2: feature face of crankshaft bearing vibration

Rotary speed (r/min)	Location of sensor	*W11* (Hz)	*W21* (Hz)	*W12* (Hz)	*W22* (Hz)	Sum of amplitudes in feature face		
						0.08 (mm)	0.20 (mm)	0.40 (mm)
800	F	450	375	550	475	21.3	34.8	103.7
	E	425	425	675	675	12.2	23.0	91.3
	E	1900	475	2275	575	13.3	23.2	90.3
	E	1900	525	2125	625	10.2	17.3	81.6
	E	1850	625	2125	725	17.9	20.9	69.8
	D	2300	1075	2450	1175	34.5	56.7	67.2
1300	C	1800	1675	2425	1775	12.5	23.8	152.9
	C	1800	1725	2225	1825	8.6	19.8	135.7
	C	1850	1775	2325	1875	8.7	15.4	121.3
	C	1250	1250	1675	1675	31.8	41.3	95.1
	D	1025	475	1425	575	19.6	34.0	88.1
	C	1825	1575	2325	1675	8.1	13.9	73.9
1800	C	1575	1575	1800	1800	21.9	41.7	195.4
	E	1600	525	2175	625	35.6	50.2	193.0
	A	625	625	950	950	21.6	72.9	144.4
	E	575	475	1225	575	34.0	57.4	143.7
	D	1550	575	1875	675	38.4	50.5	142.8
	D	2175	2075	2375	2175	38.1	54.2	125.0
2100	D	1150	1150	1375	1375	121.2	232.6	397.9
	E	375	375	725	725	62.9	113.3	361.5
	E	1600	575	2300	675	43.1	74.1	312.9
	D	1875	1075	2475	1175	63.8	167.7	309.0
	D	350	350	675	675	37.1	100.1	308.0
	D	1600	375	2250	475	44.4	73.8	268.4

In Table 2, the feature faces in each rotary speed are arranged based on the obvious degree. W11 , W21 denote the left-below frequency of feature face, and W12 , W22 denote the right-above frequency of feature face.

As shown in Table 2, feature faces centralize on location C when the rotary speed is 1300 r/min, in other rotary speed, feature faces centralize on location D and E, which shows the signal acquired on location D and E holding higher reliability. The distribution of feature faces in 1800 r/min and 2100 r/min are same, and the feature faces on location D and E are same, which match up to the symmetry of location D and E on the diesel engine.

5. conclusions

1) The optimal diagnosis positions is the right and left connection parts between cylinder body and oil pan, the optimal diagnosis rotary speed is above 1800 r/min,

2) Bispectral feature face can describe preferably the feature of fault signal, and the primary feature faces exist on the diagonal;

3) The signal features of bispectrum analysis not only exist on the diagonal, but also exist on other area.

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