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UTILISATION OF AUDIO-ACOUSTIC SIGNALS FOR MONITORING ROLLING ELEMENT BEARING USING SPECTRUM AND CEPSTRUM ANALYSIS

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1. ABSTRACT

A change in audible acoustics signals is known to occur prior to failure in machine components. However, little literature is available on the use of such signals for defect-detection and diagnostics purposes. This paper reports on a study carried out on the application of sound intensity and sound pressure level for detection of defect and diagnosis in rolling element bearings. The limitations and advantages of using such signals are identified. A simultaneous study using vibration analysis is also carried out for comparison. The strength and limitations of the use of the Fourier transform method and the use of cepstrum analysis to study the data obtained are also presented in the investigation.

The results indicate that the presence of the bearing defect frequency can be seen clearly using the cepstrum analysis method. However, use of sound intensity signals can only reveal the defect frequency when the shaft speed is higher than 1000rpm.

2. INTRODUCTION

The application of vibration signals for machine condition monitoring has been established since late 1960's [1,2]. The number of research literature published on the usage of audio acoustic signal for defect detection in machine components is however very limited. A change in audible -acoustic (sound) signal has been known to occur prior to failure in a machine component. Thus, it is possible to use such a signal to detect the presence of defects and any malfunction characteristics in a machine component. This is most appropriate especially where the application of vibration method is not possible.

The most attractive features of using audible-acoustics signals are the non-contact and non-intrusive nature of the transducer. In many cases acoustics analysis is also relatively easier to do than vibration analysis. Moreover, it is much faster to make the readings using a sound pressure microphone when compared to an accelerometer.

The applications of sound pressure signals and sound intensity signal to detect defects in rolling element bearing have been studied by previous researches [3,4]. However, the analysis were limited to the use of the sound pressure spectrum and sound intensity spectrum to identify different types of defect in tolling element bearing. In addition, acoustics signals have also been used to study the condition of gear boxes and transmissions [5], and the study performance of diesel valves engine [6].

In this paper the advantages as well as the limitations of using sound pressure signals and sound intensity signals will be tested and clarified. The results from using vibration signals will also be presented for comparison purposes. In addition to using frequency spectrum, other signal analysis methods such as cepstrum analysis and side band analysis are also used. One main advantage of using sound intensity method is its vector characteristic. It is found that this can be utilised to improve the signal-to-noise ratio for the analysis.

3. SIGNAL ANALYSIS METHODS

The sources of vibration and noise in rolling element bearings are often caused by manufacturing inaccuracies and improper installation of maintenance. A major excitation of noise is a pulse type due to the small displacement of bearing parts caused by deviation from circularity. The external parameters that have direct effect on the emission of noise in bearings have been identified to be the speed, load and the lubrication condition of the bearing [7,8].

In this paper the signal obtained will be analysed using frequency-based analysis, such as spectrum analysis, cepstrum analysis and side band analysis.

2.1 Spectrum Analysis

The time history of acoustic and vibration signals can be transformed and manipulated in the frequency domain with the Fourier transform method. The fast Fourier transform (FFT) algorithm is currently the standard method used to perform spectral analysis for digital acoustic and vibration data. The Fourier transform of a time based signal can be represented as

$$x(\omega) = \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t} dt \qquad (1)$$

where x(t) is a continuous function in time domain and $x(\omega)$ is the Fourier transformed function. For a real discrete-time signal.

$$x(\omega) = \sum_{n=-\infty}^{\infty} x(n)\, e^{-j\omega n} \qquad (2)$$

The amplitude frequency and content of a time domain derived signal from equation (1) and (2) is called the signal spectrum.

2.2 Cepstrum Analysis

In general, the response signal measured is the result of the convolution of the input signal and the impulse response of the total system. Thus, the signal available from the measurement, is also obscured by the transmission medium through which it passes. Cepstrum analysis can be used to separate the excitation spectrum from the transfer-function component. This is presented in the following equation:

$$y(t) = \int_{\infty}^{t} h(t - \tau)x(\tau)d\tau \tag{3}$$

Therefore, the Fourier transform of the output signal $y(t)$ can be presented as

$$Y(\omega) = H(\omega)X(\omega) \tag{4}$$

From a property of logarithms, the logarithm of the spectrum is used to separate the two components.

$$\log Y(\omega) = \log H(\omega) + \log X(\omega) \tag{5}$$

The logged spectrum is transformed again to obtain

$$\Im[\log Y(\omega)] = \Im[\log H(\omega)] + \Im[\log X(\omega)] \tag{6}$$

Where $\Im$ is the Fourier transform of the frequency based functions. The above process is known as the cepstrum analysis and shows the signal in quefrency domain, measured in units of time [9]. An intensity result of cepstrum analysis is that it can be considered as a spectrum of a logarithmic amplitude spectrum. Therefore, it can be used for detection of any periodic component in a spectrum [10].

2.3 Side Band Analysis

The Fourier transform of a repetitive impulse function can be derived using the Poisson sum [10].

$$\sum_{n=-\infty}^{\infty}\delta\left(t-nT\right)=\frac{1}{T}\sum_{k=-\infty}^{\infty}e^{jk\omega_o t} \qquad (7)$$

where $\omega_o T = 2\pi$. The Fourier transform of equation (7) gives

$$\Im\left\{\sum_{n}\delta\left(t-nT\right)\right\}=\frac{1}{T}\sum_{k}\Im\left\{e^{jk\omega_o t}\right\}$$
$$=\frac{2\pi}{T}\sum_{k}\delta\left(\omega-k\omega_o\right) \qquad (8)$$

Equation (8) reveals that the frequency spectrum of a repetitive impulse function will also show a repetitive frequency component with the frequency-difference equal to the rate of repetitiveness of the impulse function. Thus, the presence of repetitive impulse in the time domain can be detected easily in the frequency domain using the side band analysis.

4.0 FORMULATION OF DEFECT FREQUENCIES

4.1 Bearing defect frequencies

The formulae to calculate the different types of bearing defect frequencies have been presented by several researches [11, 12, 13, 14]. Basically, the formula for calculating defect frequencies on the outer race, inner race, and rolling element can be summarised as follows:

$$f_{or}=\frac{nN}{120}\left(1-\frac{r}{R}\cos\beta\right) \qquad (9a)$$

$$f_{ir}=\frac{nN}{120}\left(1+\frac{r}{R}\cos\beta\right) \qquad (9b)$$

$$f_{re}=\frac{NR}{60r\cos\beta}\left[1-\left(\frac{r}{R}\cos\beta\right)^2\right] \qquad (9c)$$

where

N = shaft rotational speed (rev / min)

r = radius of roller

R = pitch circle radius for the roller

n = number of rolling element

β = contact angle

The type of bearing used for these sets of investigations is the cylindrical roller bearing NSK NF209K with the dimension of r = 32.5mm and n = 14.

4.2 Signals from other moving components on the rig test apparatus

A schematic diagram showing the general layout of the test rig is presented in Figure 1. The moving components are identified to be the motor, the drive-shaft and the toothed-belt connecting the motor and the drive-shaft. The mean diameter of the motor-sprocket is 290mm and it has 73 teeth on its circumference. On the other hand, the mean diameter of the shaft-sprocket is 70mm and it has 18 teeth on it. Pulse frequencies generated by the shaft-sprocket and the motor-sprocket due to the passage of the toothed-belt are

$$f_{pS} = \frac{n_{TS}N}{60} \qquad (10a)$$

$$f_{pM} = \frac{n_{TM}N_M}{60} = \frac{n_{TM}N}{60}\,\frac{D_S}{D_M} \qquad (10b)$$

where

n_{TM} = no. of teeth on the motor sprocket

n_{TS} = no. of teeth on the shaft sprocket

N_M = rotational speed of motor sprocket

D_M = mean diameter of motor sprocket

N = rotational speed of shaft

D_s = mean diameter of shaft sprocket

Equations (9) and (10) are used to calculate the bearing defect frequencies and also the frequencies obtained from moving components of the rig and the results are presented in Table 1.

The test-bearings are cleaned using 1.1.1 Trichloroethane and the lubrication for each experiment is maintained at 10ml using universal oil. The minimum load required in rolling element bearing is 2% of the dynamic load rating to ensure ideal behaviour of the roller [16]. Thus, during the study the radial load is maintained at 1.5KN. The overall features of the test-rig is shown in Figure 1.

5.0 ANALYSIS OF RESULTS

To identify defect signals from a simple inspection of frequency spectrum is often a very difficult task to do. This is in part due to the many variables that affect the spectrum analysis, such as the transfer function of the transporting medium, the resonance characteristics of the mechanical structure, and the effect of other sources. An example of such a signal is given in Figure 2 where the first diagram shows the frequency spectrum of sound intensity signal emitted by a small screw attached to the circumference of a rotating shaft. Every time the shaft rotates the screw will hit a mass spring system to produce a repetitive impulsive sound. When the shaft rotates at 430rpm (7.2Hz) the frequency spectrum does not show the fundamental frequency of the signal. However, the cepstrum diagram clearly indicates the presençe of a repetitive signal at the exact frequency expected. Figures 3, 4, 5, and 6 show similar results whereby cepstrum analysis offer better attempts at indicating the presence of defects in rolling element bearing compared to the spectrum analysis obtained using vibration and sound intensity signals. A summary of the results obtained are presented in Table 2 and 3.

The results obtained using sound pressure signals are found to be similar to the results obtained using sound intensity signals when operated under favourable laboratory conditions. However, sound intensity measurement can offer better results when there is a background noise present up to the level almost as high as the sound signal to be studied. This is illustrated in Figure 7. Thus, sound intensity signals can offer advantages in obtaining a better signal-to-noise ratio when used in the field where less favourable conditions exist.

One of the limitations of using sound intensity signals found is that it is unable to indicate the presence of defect signals at shaft-speeds lower than 1000 rpm. This is shown in Figure 8. However, the results from the use of vibration signals is also not very clear at 500rpm as shown in Figure 9. Further detailed study is being carried out to identify the parameters that affect the detection of defect signal for low shaft-speeds.

Side band analysis as described previously, can also be used to detect the repetitive defect signal from a frequency spectrum. This is shown in Figure 3 (e), 4 (e), and 5 (e).

In a parallel study, sound intensity signal has been found to fail to detect a missing roller in a bearing compared to vibration signal. This is clearly indicated in Figure 10.

6.0 CONCLUSION AND RECOMMENDATIONS

This paper represents some results of a study in the use of vibration, sound intensity and sound pressure signals to detect defect signals from a rolling element bearing. It shows that the sound intensity signal can be used to detect defect in the bearing when the shaft-speed is higher than 1000rpm. A detailed study to identify the parameters that limit the applicability of sound intensity signal for low speed shaft is currently in progress.

The results obtained in this study show that sound intensity can offer signals with better signal-to-noise ratio in the presence of high background noise when compared with the use of sound pressure signals.

However, it is also found that in one particular case a sound intensity signal not capable of indicating a missing roller when this is detected to the result obtained using vibration signals under the same conditions.

Cepstrum analysis has been successfully used to indicate the presence of defect frequencies which are very close to the theoretical values calculated from formulae established by other researchers. On the other hand, spectrum analysis sometimes failed to display the presence of the fundamental defect frequencies. The presence of a repetitive impact signal can often be identified from a frequency spectrum using side band analysis.

7.0 REFERENCES

1. Chapman, (1967), "Vibration Analysis Applied to Machinery Maintenance" Naval Engineers Journal, N.79, n.3, pp 431-437

2. Weichbrdt and K.A. Smith, (1970), "Signature Analysis Non Intrusive Techniques for Incipient Failure Identification. Application to Bearings and Gears", General Electric Co., Schenectady, N.Y., Report No. 70 C-364

3. N.Tandon & B.C. Nakra, (1990), "The Application of the sound intensity Technique to Defect Detection rolling - element bearings", Applied Acoustics, v.29, pp 207-217

4. Kim, (1984), "A Review of Rolling Element Bearing Health Monitoring (II) Preliminary Test Results on Current Technologies", Proc. of Machinery Vibration Monitoring, pp 127-137

5. Antosiewicz, 1992, "Predictive maintenance: Monitoring of Health of Gear Drives", Tappi Journal, August, pp 67-68

6. Sun, H. Wang and X.Xu, (1991), "Trouble Diagnosis of Diesel Valves By Sound Intensity and Vibration Signals", Modal Analysis, Modelling, Diagnostics and Control - Analytical and Experimental, ASME DE, v.38, pp 145-148

7. Igarashi, (1964), "Noise of Ball Bearing in Electric Motor", Bulletin of JSME, V.7, n.25, pp 200-208

8. Jayaram and F. Jarchow, (1978), "Experimental Studies on Ball Bearing Noise", Wear, v.46, pp 321-326

9. Haddad and T.W. Parsons, (1991), DIGITAL SIGNAL PROCESSING: Theory, Applications and Hardware, W.H. Freeman and Co., New York, pp 348-352 and pp 535-546

10. Brown and T.Jensen, "Machine-Condition Monitoring using Vibration Analysis for Bearing fault Detection", Bruel & Kjaer Application Notes, 11p.

11. Scheithe, (1992), "Better Bearing Vibration Analysis", Hydrocarbon Processing, July, pp 57-64

12. Braun, B. Dartner, (1979), "Analysis of Roller/Ball Bearing Vibrations", Journal of Mechanical Design, Transactions of the ASME v. 101, January, pp 118-125

13. Daadbin and J.C.H. Wong, (1991), Different Vibration Monitoring Techniques and Tehir Application to Rolling Element Bearings. Int. Journal of Mechanical Engineering Education, v.19, No.4, pp 295-304

14. Igarashi and S. Yabe, (1983), "Studies on the Vibration and Sound on Defective Rolling Bearings", Bulletin of JSME, v.26, pp 1791-1798

15. SKF General Catalogue, (1989), Printed by Carl Gerber GMBH, p 519.

Table 1. Calculated defect-frequencies from bearing and moving components of the test-rig

Shaft Speed	Outer race Defect Freq. (Hz)	Inner race Defect Freq. (Hz)	Rolling element Defect Freq. (Hz)	Pulse Freq. of Motor-sprocket (Hz)	Pulse Freq. of Shaft-Sprocket (Hz)
500	49.3	67.3	52.9	144.8	150
1000	98.7	134.6	105.8	289.7	300
3000	296.1	403.8	317.3	867.0	900
5000	493.6	673.0	528.9	1448.3	1500

Table 2. Summary of results obtained using cepstrum analysis of vibration signals.

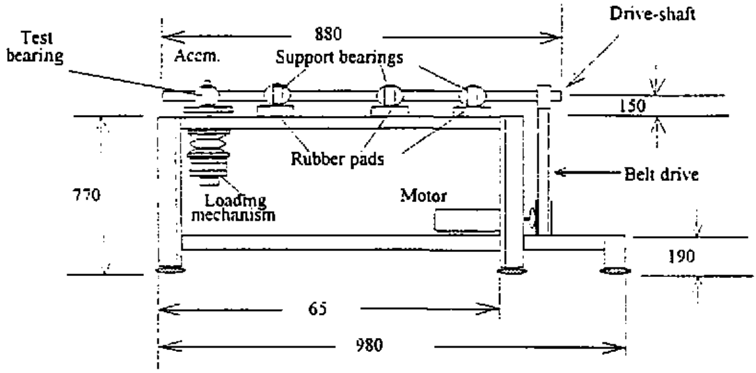
Speed of shaft (rpm)	Defect Type*	Quefrency (s)	Defect freq. (Hz) $\left(\frac{1}{\text{Quef.}}\right)$	Amplitude (dB) p-p
500	DLE	0.02125	47	0.05
500	DOL	0.02273	44	0.16
1000	DLE	0.00984	102	0.074
1000	DOL	0.010625	94	0.242
3000	DLE	0.003125	320	0.14
3000	DOL	0.003438	291	0.15
5000	DLE	0.00188	533	0.13
5000	DOL	0.00203	493	0.17

where *DOL = outer ring line defect
DLE = rolling element line defect

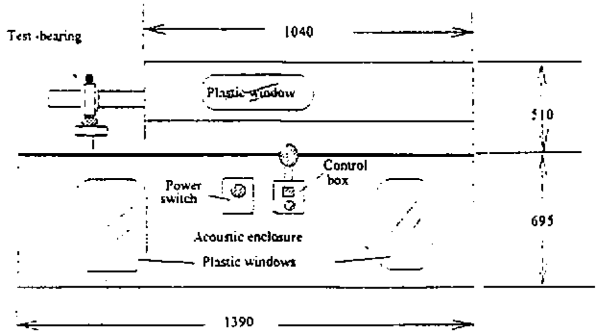
Table 3. Summary of results obtained using epstrum analysis of sound intensity signals

Speed of shaft (rpm)	Defect Type*	Quefrency (s)	Defect freq. (Hz) $\left(\frac{1}{\text{Quef.}}\right)$	Amplitude (dB) p-p
500	DLE	0.0228	44	0.075
500	DOL	0.0228	44	0.084
1000	DLE	0.01013	99	0.036
1000	DOL	0.01076	93	0.054
3000	DLE	0.00316	316	0.025
3000	DOL	0.00332	301	0.023
5000	DLE	0.00190	527	0.20
5000	DOL	0.00206	486	0.14

where *DOL = outer ring line defect
DLE = rolling element line defect

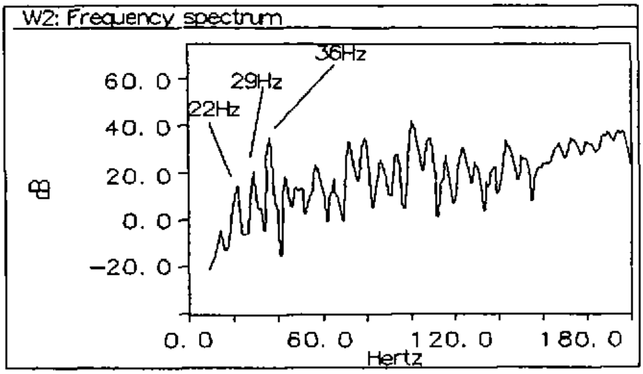


(a) Front view of the rig without acoustic enclosure.

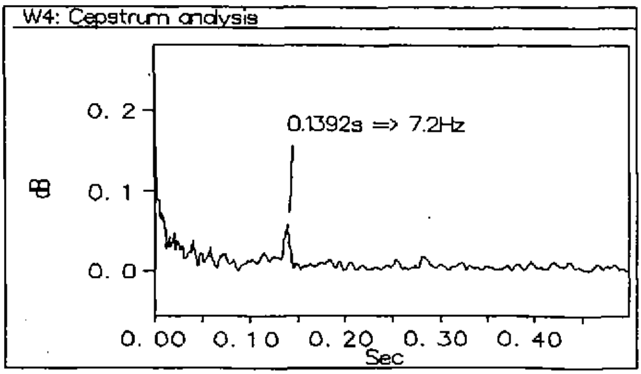


(b) Front view of the rig with acoustic enclosure.

Figure 1. Schematic diagram of the test rig. All dimensions are in mm.

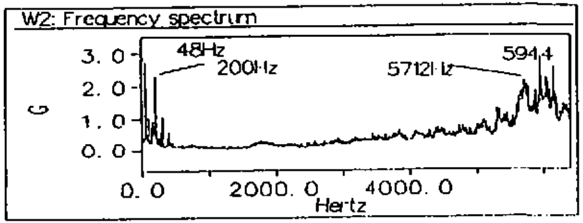


(a) Frequency spectrum of a sound intensity signal.

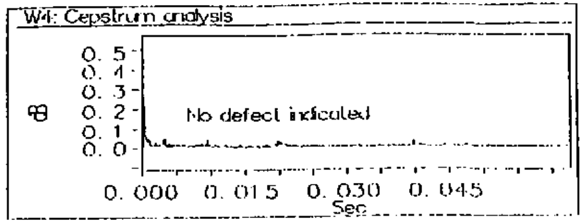


(b) Cepstrum analysis of the sound intensity signal.

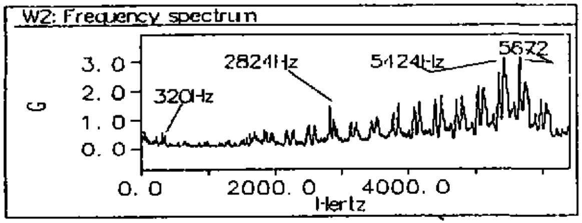
Figure 2. Comparison between spectrum and cepstrum analysis of a repetitive impulsive sound.



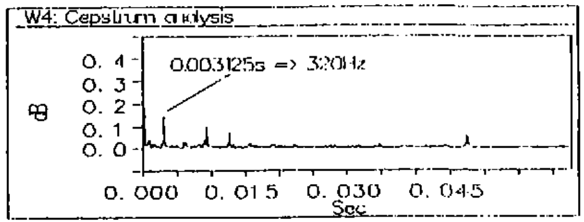
(a) Frequency spectrum with no defect in the bearing.



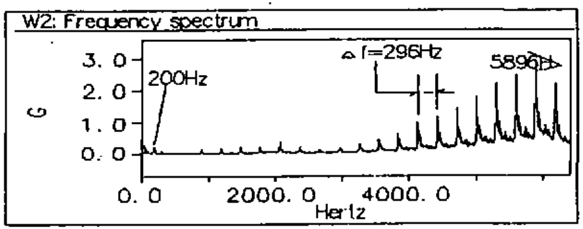
(b) Cepstrum analysis with no defect in the bearing.



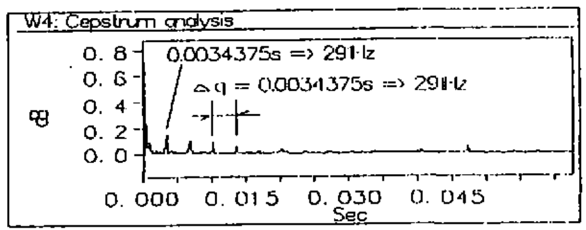
(c) Frequency spectrum with line defect on one of the roller.



(d) Cepstrum analysis with line defect on one of the roller.

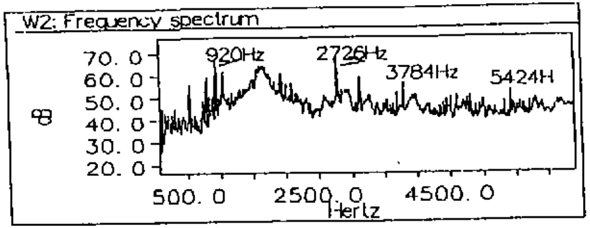


(e) Frequency spectrum with line defect on the outer ring.

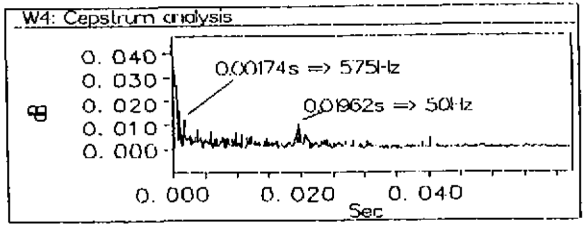


(f) Cepstrum analysis with line defect on the outer ring.

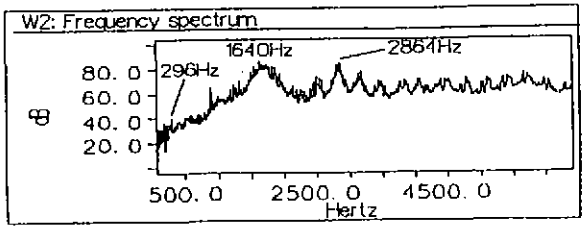
Figure 3. Comparison between spectrum and cepstrum analysis of vibration signal from a bearing running at 3000rpm.



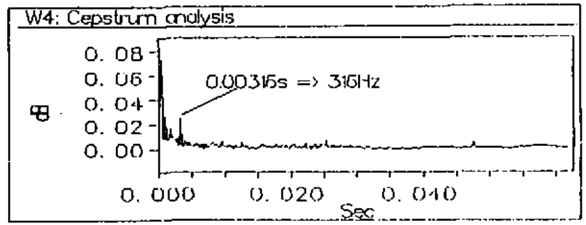
(a) Frequency spectrum with no defect in the bearing.



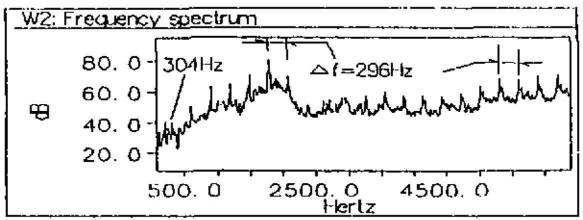
(b) Cepstrum analysis with no defect in the bearing.



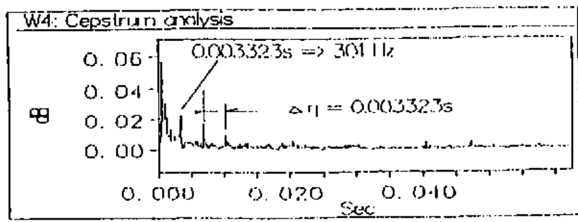
(c) Frequency spectrum with line defect on one of the roller.



(d) Cepstrum analysis with line defect on one of the roller.

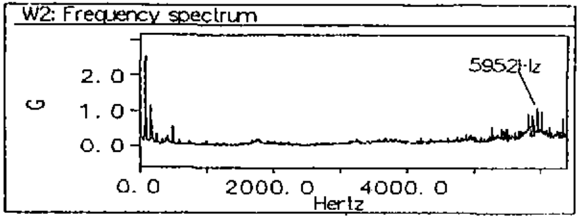


(e) Frequency spectrum with line defect on the outer ring.

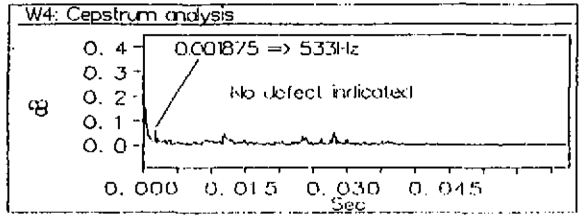


(f) Cepstrum analysis with line defect on the outer ring.

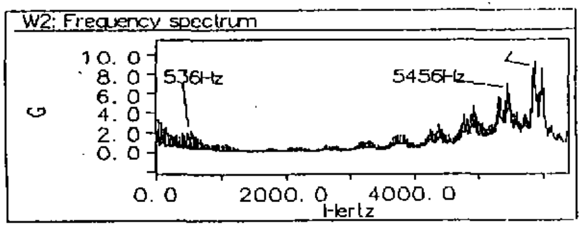
Figure 4. Comparison between spectrum and cepstrum analysis of sound intensity signal from a bearing running at 3000rpm.



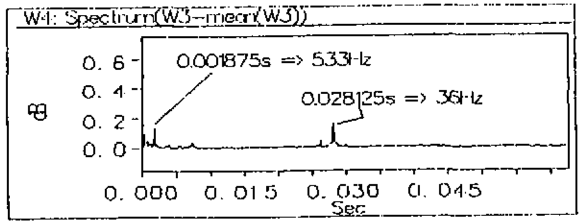
(a) Frequency spectrum with no defect in the bearing.



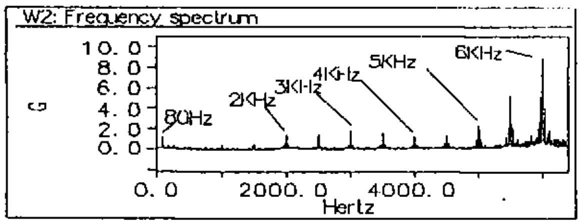
(b) Cepstrum analysis with no defect in the bearing.



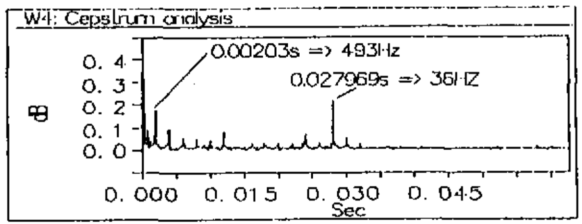
(c) Frequency spectrum with line defect on one of the roller.



(d) Cepstrum analysis with line defect on one of the roller.

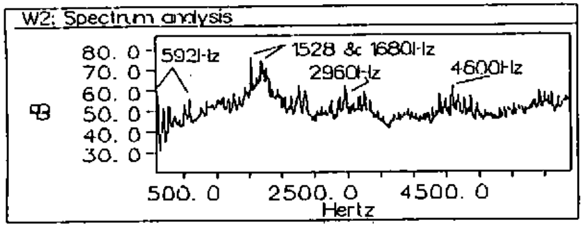


(e) Frequency spectrum with line defect on the outer ring.

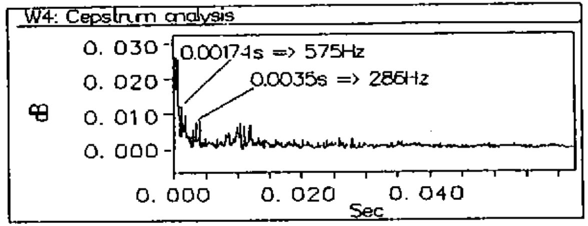


(f) Cepstrum analysis with line defect on the outer ring.

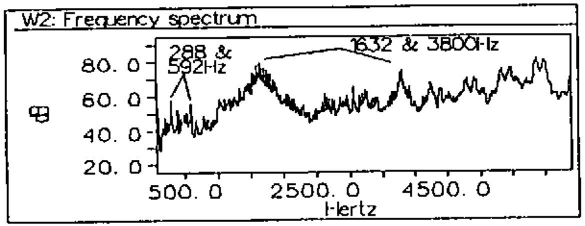
Figure 5. Comparison between spectrum and cepstrum analysis of vibration signal from a bearing running at 5000rpm.



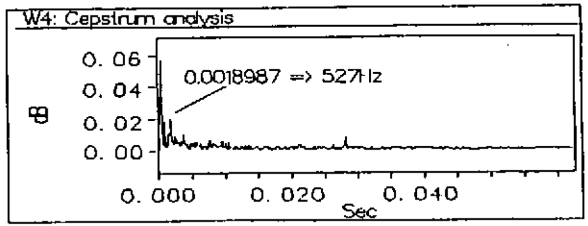
(a) Frequency spectrum with no defect in the bearing.



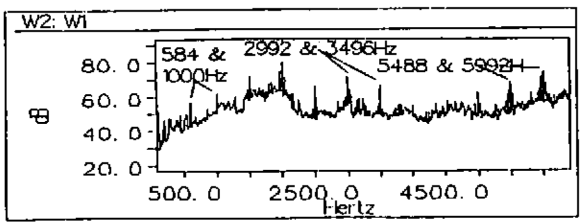
(b) Cepstrum analysis with no defect in the bearing.



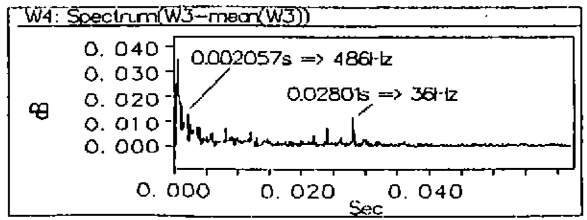
(c) Frequency spectrum with line defect on one of the roller.



(d) Cepstrum analysis with line defect on one of the roller.

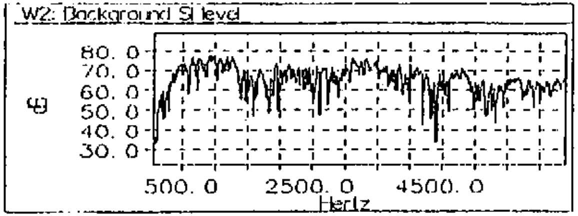


(e) Frequency spectrum with line defect on the outer ring.

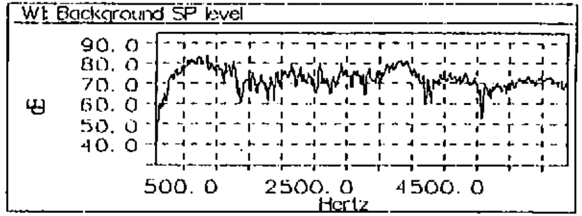


(f) Cepstrum analysis with line defect on the outer ring.

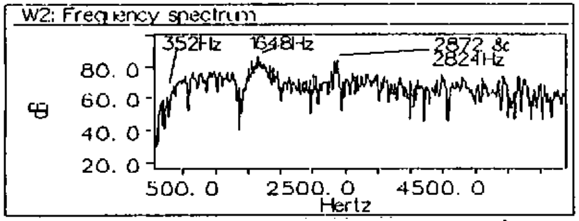
Figure 6. Comparison between spectrum and cepstrum analysis of sound intensity signal from a bearing running at 5000rpm.



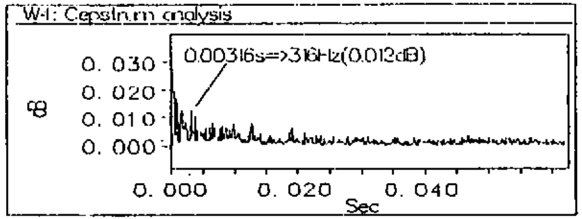
(a) Sound intensity reading
of the background noise.



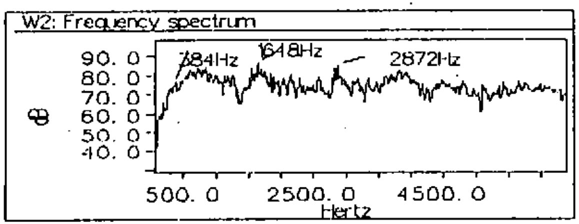
(b) Sound pressure reading
of the background noise.



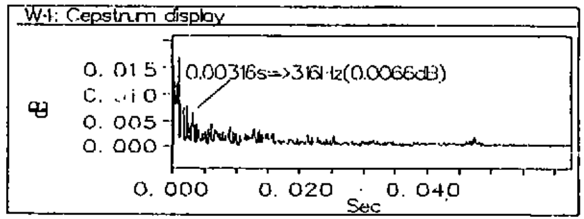
(c) Frequency spectrum of sound intensity
with line defect on one of the roller.



(d) Cepstrum analysis of sound intensity
with line defect on one of the roller.

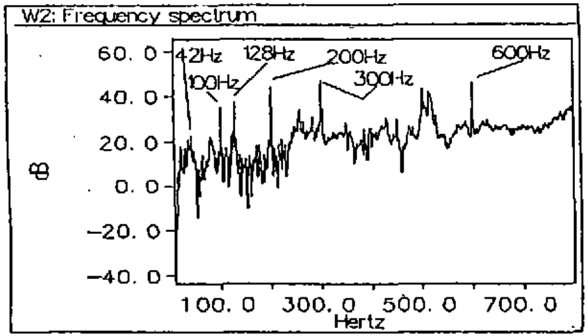


(e) Frequency spectrum of sound pressure
with line defect on one of the roller.

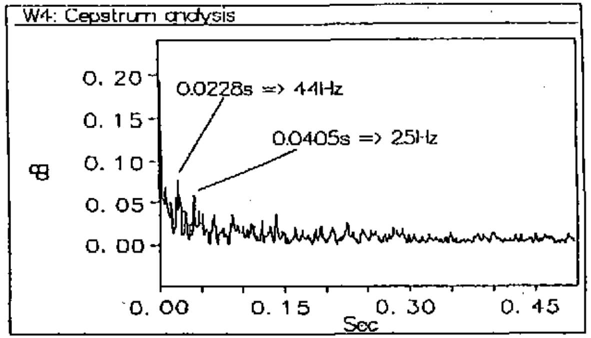


(f) Cepstrum analysis of sound pressure
with line defect on one of the roller.

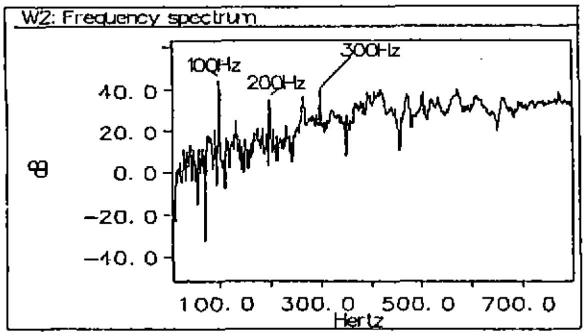
Figure 7. Comparison between using sound intensity and sound pressure signals with the inclusion of background noise from a bearing running at 3000rpm.



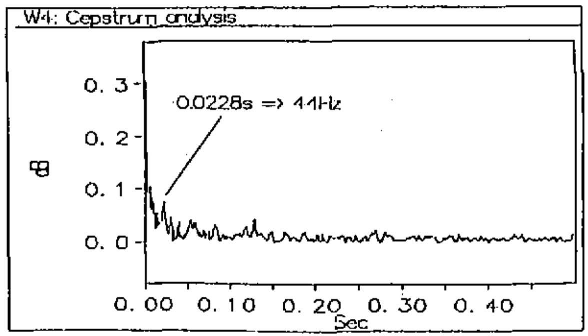
(a) Frequency spectrum of the signal with no defect in the bearing.



(b) Cepstrum analysis of the signal with no defect in the bearing.

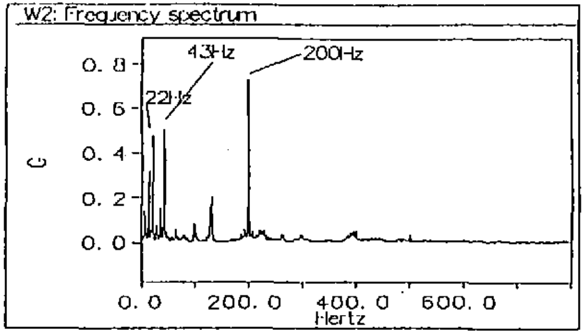


(c) Frequency spectrum of the signal with line defect on one of the roller.

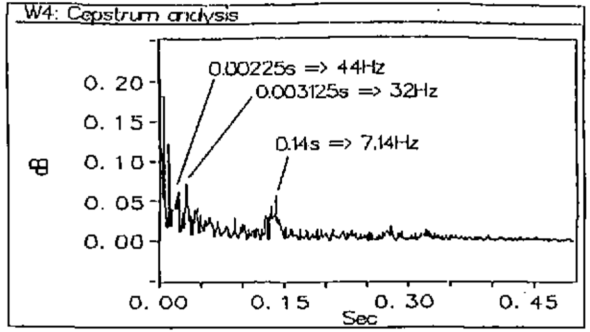


(d) Cepstrum analysis of the signal with line defect on one of the roller.

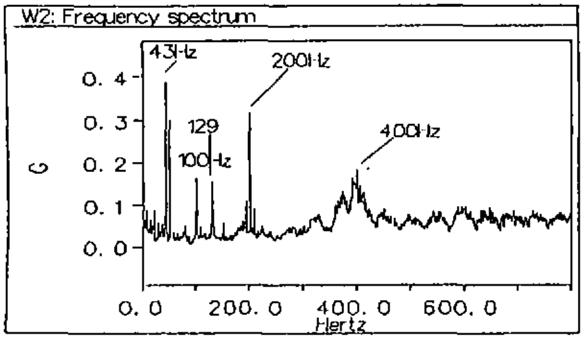
Figure 8. Analysis of sound intensity signal from a bearing running at 500rpm.



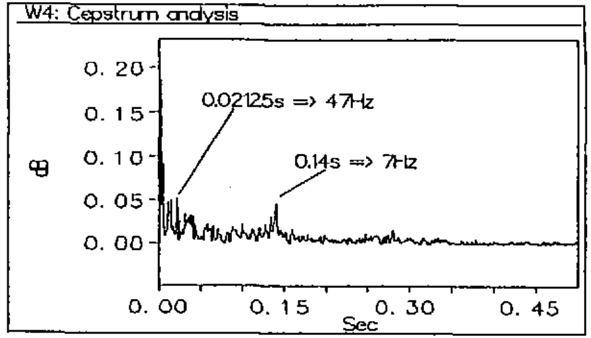
(a) Frequency spectrum of the signal with no defect in the bearing.



(b) Cepstrum analysis of the signal with no defect in the bearing.

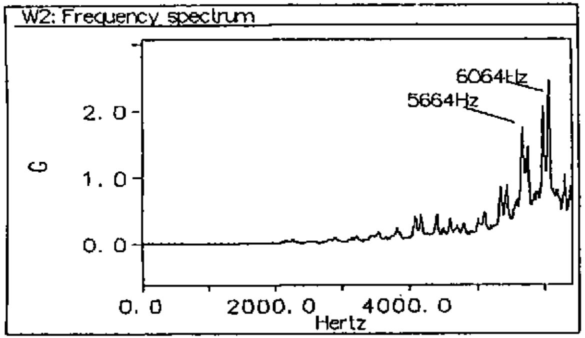


(c) Frequency spectrum of the signal with line defect on one of the roller.

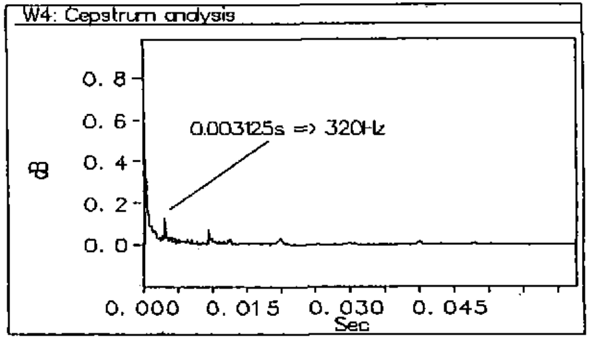


(d) Cepstrum analysis of the signal with line defect on one of the roller.

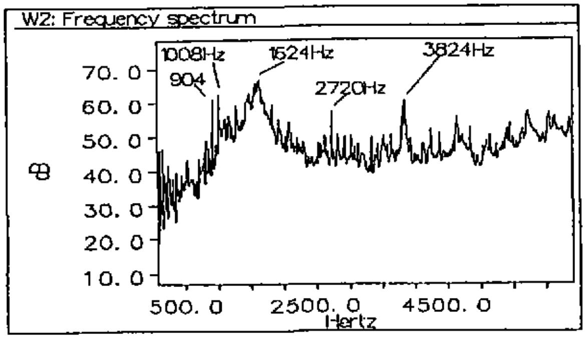
Figure 9. Analysis of vibration signal from a bearing running at 500rpm.



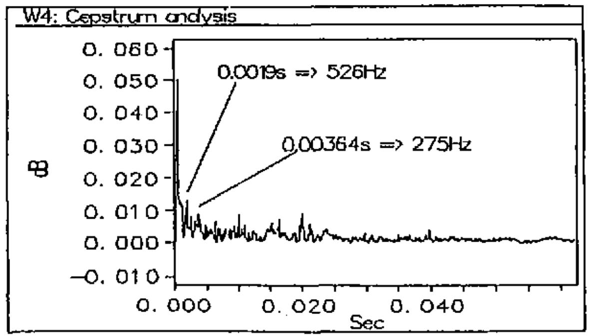
(a) Frequency spectrum of vibration signal.



(b) Cepstrum analysis of vibration signal.



(c) Frequency spectrum of sound intensity signal.



(d) Cepstrum analysis of Sound intensity signal.

Figure 10. Analysis of vibration and sound intensity signals to detect a missing roller in a bearing running at 3000rpm.