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Cepstrum Analysis — An Advanced Technique in Vibration Analysis of Defects in Rotating Machinery

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ABSTRACT

Conventional frequency analysis in machinery vibration is not adequate to find out accurately defects in gears, bearings, and blades where sidebands and harmonics are present. Also such an approach is dependent on the transmission path. On the other hand, cepstrum analysis accurately identifies harmonics and sideband families and is a better technique available for fault diagnosis in gears, bearings, and turbine blades of ships and submarines.

Cepstrum represents the global power content of a whole family of harmonics and sidebands when more than one family of sidebands are present at the same time. Also it is insensitive to the transmission path effects since source and transmission path effects are additive and can be separated in cepstrum.

The concept, underlying theory and the measurement and analysis involved for using the technique are briefly outlined. Two cases were taken to demonstrate advantage of cepstrum technique over the spectrum analysis. An LP compressor was chosen to study the transmission path effects and a marine gearbox having two sets of sideband families was studied to diagnose the problematic sideband and its severity.

1. INTRODUCTION

All rotating machinery generate vibration, the analysis of which renders valuable information about the condition of machines. The old and conventional method of vibratory assessment is not adequate to predict the defects well in advance, whereas with the advent of FFT analysis and desk top computers, vibration signal analysis has become an extremely handy, early warning technique[1] for predicting the onset of defects, giving adequate time to plan and undertake preventive measures.

Spectrum analysis[2] has some constraints in the vibration analysis which are overcome in a cepstrum analysis. 'Cepstrum' is the spectrum of a "spectrum on a logarithmic scale". Thus, it is a further analysis of the spectrum reducing each harmonic and sideband family in the spectrum to a single component and a few 'rahmonics' (it may be noted that CEPS is the inversion of SPEC in spectrum).

A conventional frequency analysis[3] of a spectrum will have transmission path effects affecting the true source signature and also cannot pinpoint the defects accurately where the problem is associated with more than one sideband and harmonic in case of gas turbines, steam turbines and gearboxes of on board ships and submarines. Transmission path effects are additive and can be separated in cepstrum and also it gives an accurate detection of periodic structure in a spectrum associated with many harmonics and sidebands as a single component for each family of sidebands without any difficulty in interpreting the sideband structure like in spectrum.

2. THEORY

Initially, 'cepstrum' was defined as the 'power spectrum of the logarithmic power spectrum'[4]. A

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number of other terms, commonly found in the cepstrum literature are derived in an analogous way, like cepstrum from spectrum, quefrency from frequency, rahmonics from harmonics. However, the distinguishing feature of the Cepstrum is not just that it is a spectrum of a spectrum, but rather it is a spectrum of a 'Spectrum on logarithmic amplitude axis'. By comparison, it can be stated that its auto correlation is the inverse Fourier transform of the power spectrum without logarithmic conversion[4].

There are two types of cepstra, viz. power cepstrum and complex cepstrum. The power cepstrum is defined as the 'inverse fourier transform of the logarithmic power spectrum . This differs primarily from the original definition, in which, the result of the second Fourier transformation is not modified by obtaining the amplitude squared at each 'quefrency'. Hence, it implies that the power cepstrum is reversible back to the logarithmic cepstrum. The 'complex cepstrum'[5] constitutes phase as well as logarithmic amplitude information at each frequency in the spectrum and hence it is reversible to a time signal.

Mathematically[6],

Power cepstrum, $C_p(T) = P \; \{log\, F_{xx}(f)\}$.

Complex cepstrum, $C_c(T) = P^1 \; \{log\, F_x(\mathrm{f})\}$

Auto correlation, $R_{xx}(T) = P^1 \; \{ \; F_{xx}(\mathrm{f}) \; \}$.

Where, $F_{xx}(f)$ is a power spectrum,

$F_x(f)$ is a frequency or amplitude of complex spectrum and P is an inverse Fourier transform.

Also, $F_{xx} \; (f) = A^2 \; (f)$

and $F_x = A \; (f) \; e^{i\omega t}$

$\log F_{xx}(f) = 2 \log A \; (f)$

Thus power cepstrum = complex cepstrum for spectra with zero phase.

Vibration signals generally represent a combination of source and transmission path effects. For example, internal forces in a machine which are the source of vibration act on a structure whose properties may be described by a frequency response function between the point of application and the point of measurement. The source and transmission path effects are involved in the time signals. These are multiplicative in the spectra and additive in the logarithmic spectra and the cepstra.

$x(t)$ $h(t)$ $y(t)$

$X(f)$ $H(f)$ $y(f)$

source transmission path combined signal

$|Y(f)|^2 = | \; X(f) \; |^2 \; . \; | \; H(f) \; |^2$

$\log Y = \log X + \log H$

$P^1 \; \{ \; \log Y \; \} = P^1 \; \{ \; \log X \; \} + P^1 \; \{ \; \log H \; \}$

Thus source and transmission path effects are additive in the cepstrum.

3. VIBRATION MEASUREMENT AND ANALYSIS

Vibration measurements were carried out on an LP Compressor at two different points on the same bearing (Fig. 1) to distinguish between Cepstrum and Spectrum with regard to transmission path effects. The location of measurement was the coupling bearing between the gearbox and the compressor. The RPM of the compressor was 13,000, with a step-up gearbox driven by an alternator of 1500 RPM.

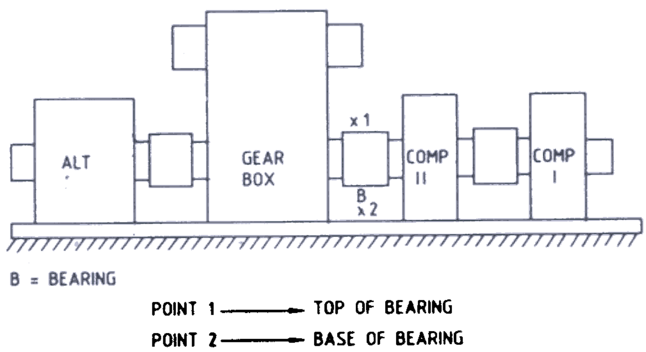


Figure 1 Measurement location of the LP compressor (point 1, top of bearing; point 2, base of bearing).

To study sideband activity, a marine gearbox, installed on the test bed after refit, driven by a gas turbine was considered. The machine consists of two-stage reduction gear system with input from power turbine of RPM 4500 and with an output to propeller shaft of RPM 456. The output shaft is connected to a dynamometer. The measurement location was chosen over the intermediate shaft bearing and is shown in Fig. 2.

In both the cases the direction and the parameter of measurement[7] were taken as radial and acceleration

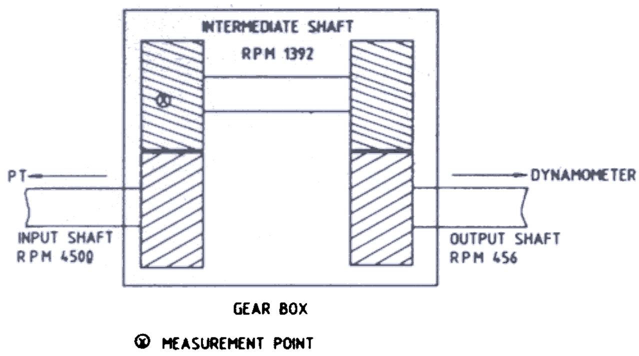


Figure 2. Measurement location of Gearbox (Measurement point).

respectively. The measurements were made in the frequency range of 0-10 kHz.

The following instrumentation was used to carry out the measurements.

a) Portable tape recorder

b) Accelerometer B&K Type 4366 with charge sensitivity 4.75 pC/ms^2, frequency range 1-10 kHz.

c) Charge amplifier B&K Type 2635 with sensitivity up to 10 V/pC.

Scanning of recorded data showed the absence of peaks at high frequencies and hence the analysis was restricted to 2 kHz in the case of the compressor and up to 5 kHz in the case of the gearbox. The following equipment was used for data analysis. (i) vibration analyser, (ii) IBM PCAT computer, and (iii) dot matrix printer

The Cepstrum display shows the power spectrum amplitude in dB on vertical axis with respect to the quefrency in milliseconds on the horizontal axis.

4. RESULTS AND DISCUSSIONS

Vibration levels are recorded at two points on the bearing of the LP compressor. The recorded data was analysed first using the 'spectrum mode' and then in 'cepstrum' to identify series of harmonics in the spectrum. It is observed that 75 Hz harmonics are present, which is the "1/3rd harmonic" of the compressor rotation, signifying the mechanical looseness of the system. The cursor was positioned at 75 Hz and the cepstrum analysis was carried out for the same points. The spectra in Figs. 3(a) & 4(a) taken at

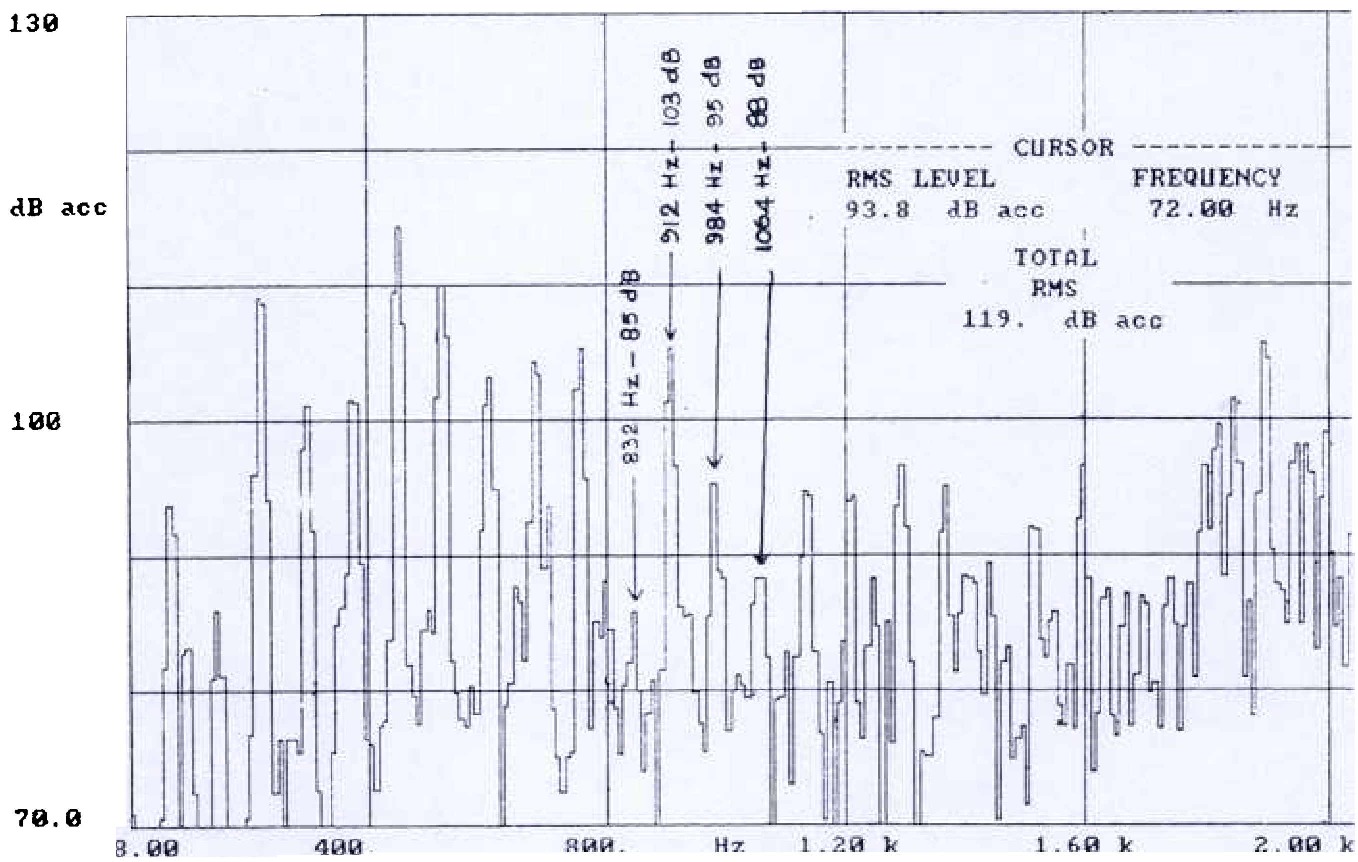


Figure 3(a). LP compressor : Point 1 : spectrum analysis.

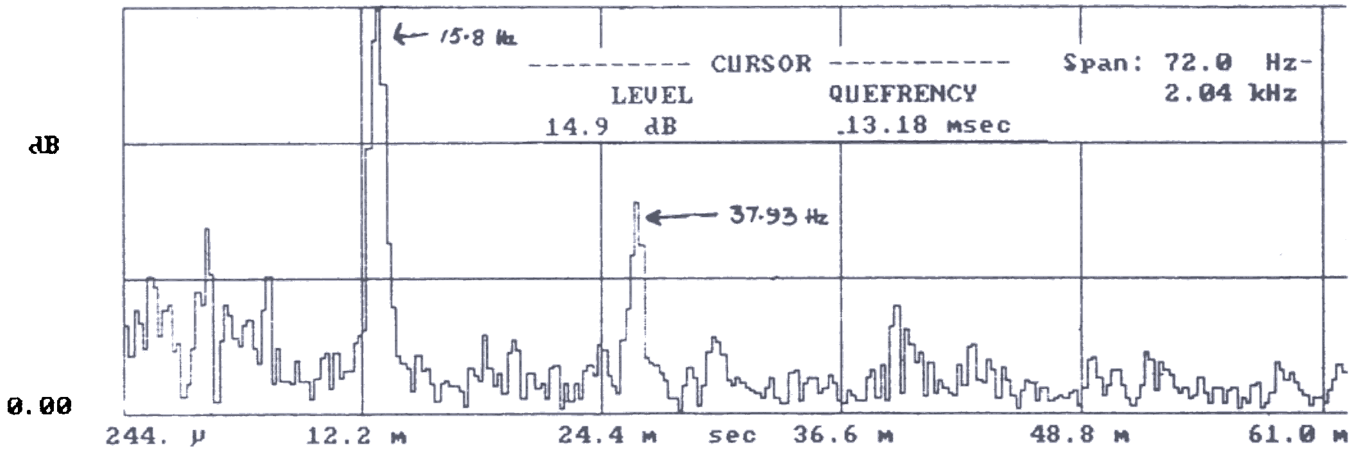


Figure 3(b). LP compressor : Point 1 : cepstrum analysis.

points 1 and 2 appear similar, but differ in details at most of the frequencies. A peak is present at 832 Hz at point 1 in the spectrum, which is not present at point 2. Similarly, the several peaks present at some, components in the spectrum at point 1 are not present in the spectrum at point 2. This signifies the impact of the transmission path differences between the two points even though the source of vibration is the same.

On the other hand, 75 Hz component is the only single significant peak at both the points in the cepstra which is from the source and shown in Figs. 3(b) & 4(b). This clearly shows the elimination of the transmission path effects. Hence, it can be inferred that 'cepstrum' separates the transmission path effects from those of the vibration source and gives 'true vibration picture' irrespective of structural differences of a

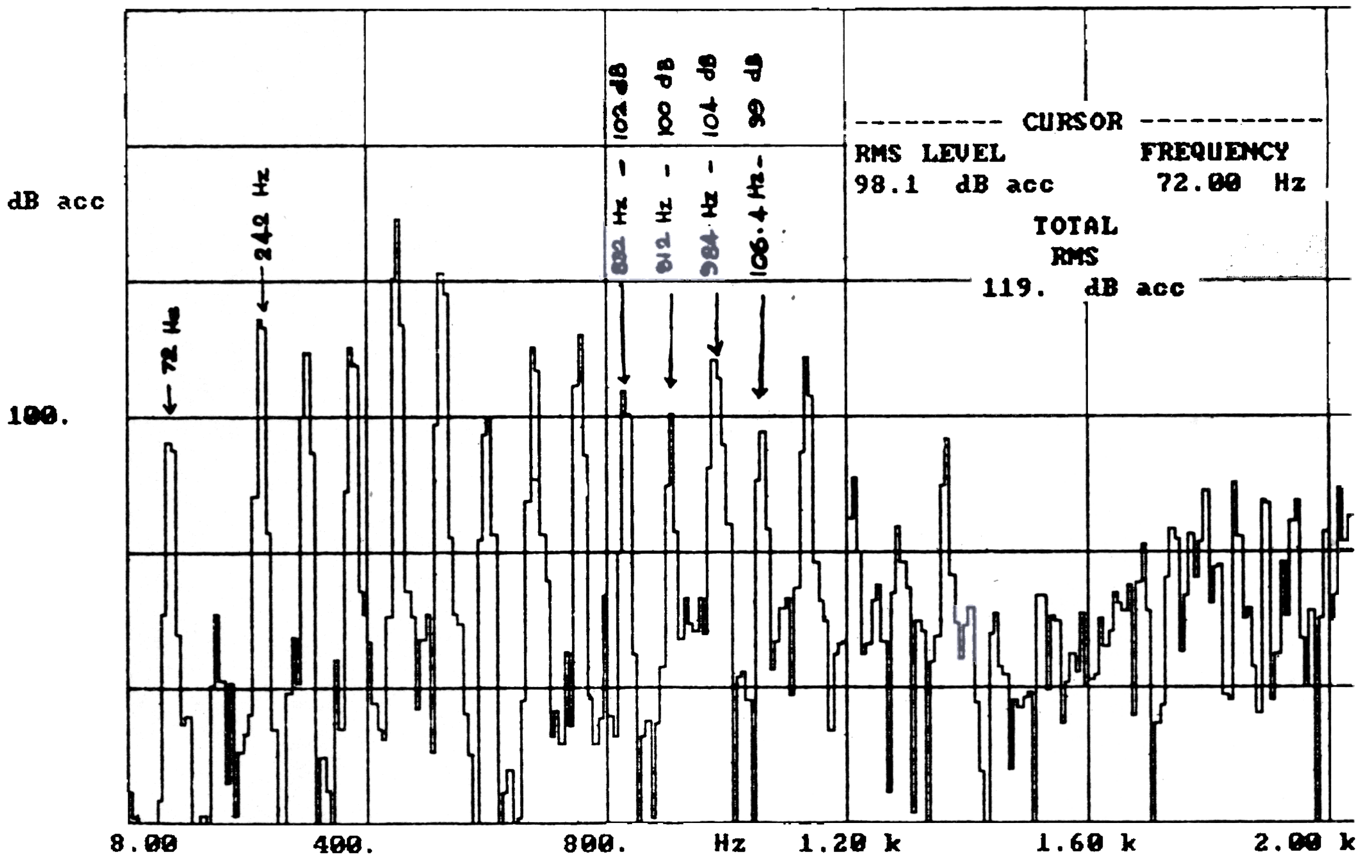


Figure 4(a). LP compressor : Point 2 : spectrum analysis.

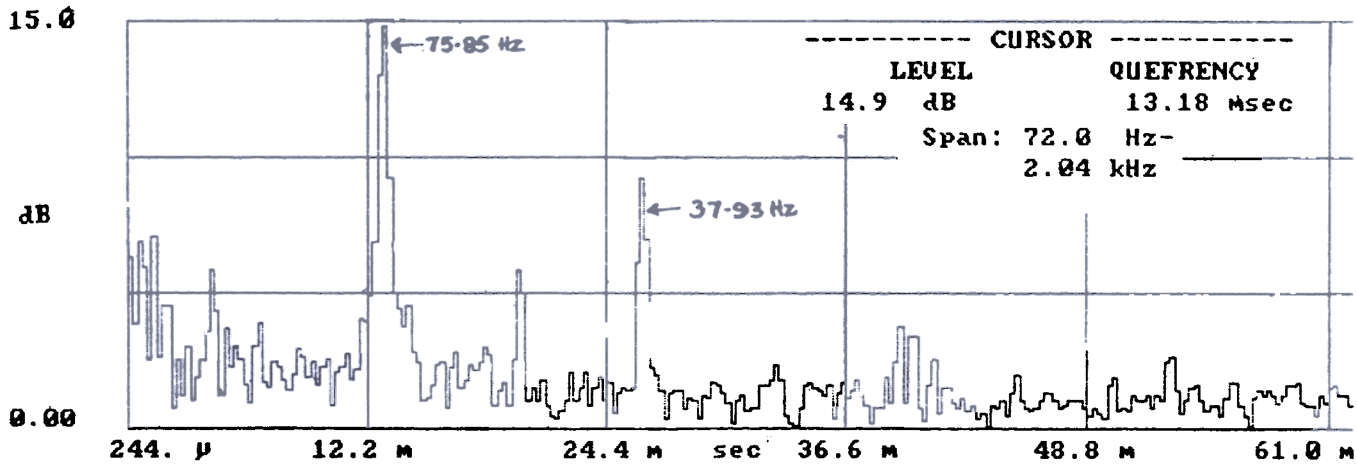


Figure 4(b). **LP compressor : Point 2 : cepstrum analysis.**

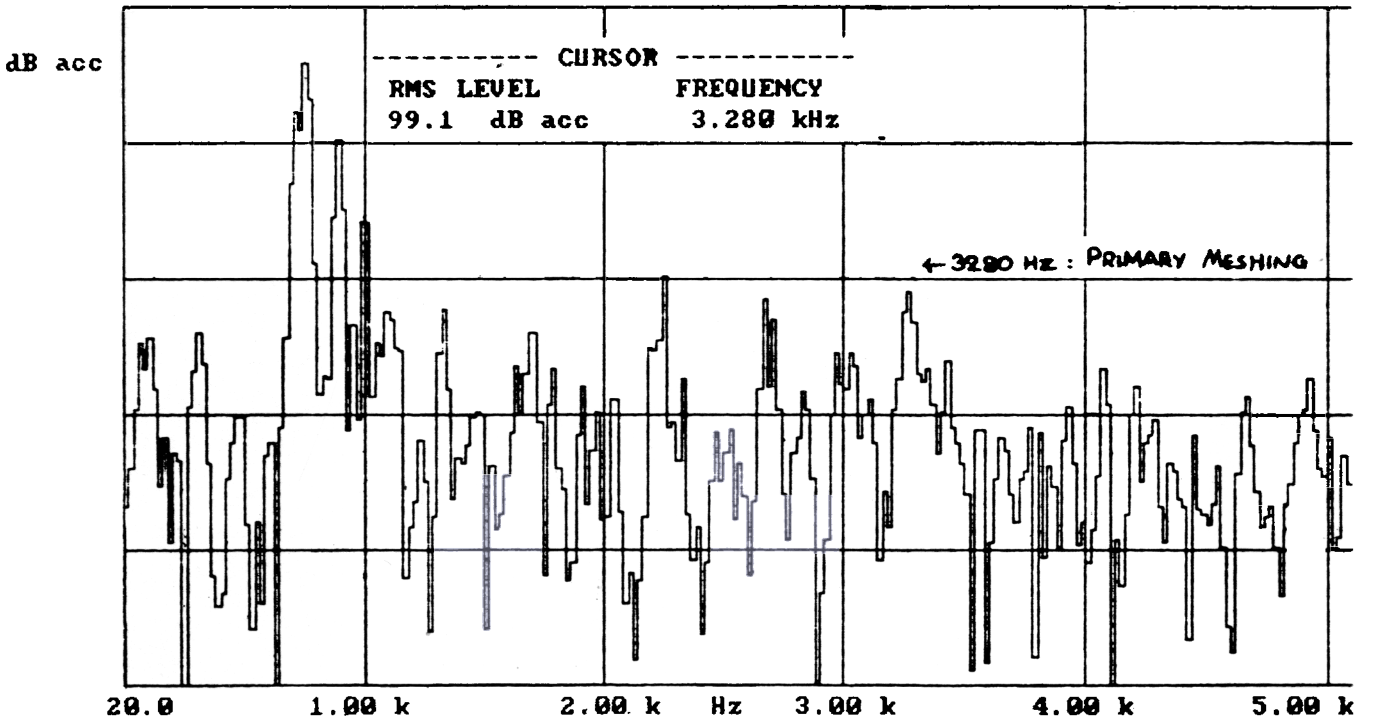
machine. To obtain a distinct peak in the cepstrum, a reasonable number of members of the corresponding harmonics or sideband family must be present, because, cepstrum represents global power content of a whole family of sidebands. These uniformly spaced components must be adequately resolved in the spectrum. For achieving this, it is often advantageous to perform a cepstrum analysis on a spectrum obtained by zoom FFT[8]. The power cepstrum provides the ability to detect a periodic signature in the spectrum at a single location with well defined peak since it is the square of all the significant amplitude periodic peaks put together on a logarithmic scale.

Figure 5 shows the spectrum, zoomed spectrum around the primary meshing (3280 Hz) and the corresponding cepstrum analysis respectively at point 1 on a marine gear box (GB) of two stage reduction. This GB was driven by a gas Turbine. The GB output was connected to a dynamometer through the shaft in the test bed. In the present case, there are no sufficient number of sidebands around primary meshing as seen from the zoomed spectra. Consequently, there are no well defined rahmonics present in the cepstrum. From this it can be inferred that there is no sufficient sideband activity around the primary meshing. Hence, there are no peaks representing the whole family of sidebands.

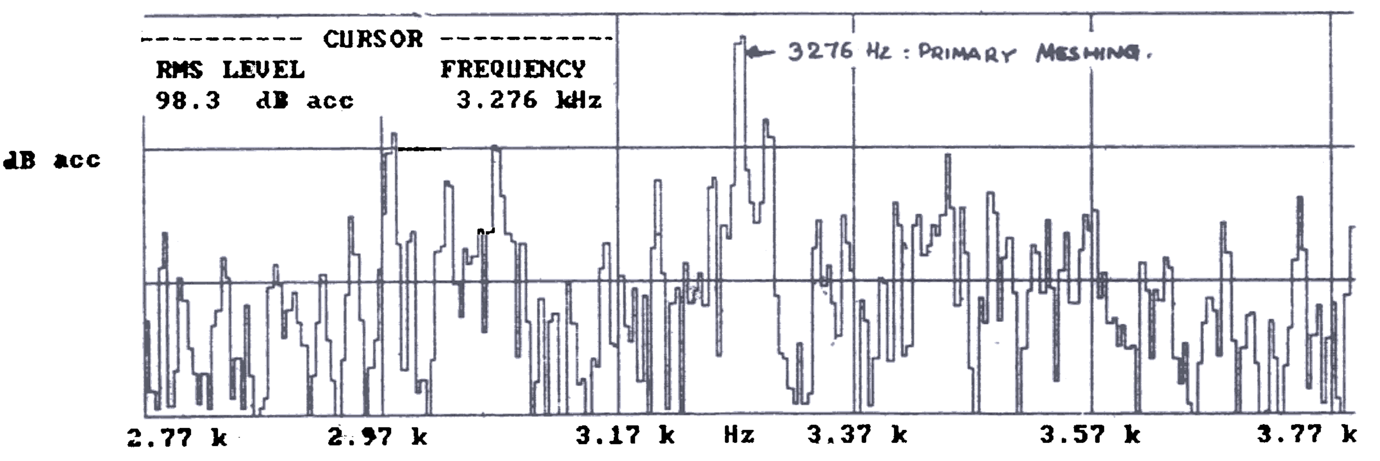
Figure 6 shows the spectrum, zoomed spectrum and the corresponding cepstrum analysis for the same gearbox at the same location. But, in this case, the zooming is performed at the secondary meshing (760 Hz). Two types of sidebands; one at the intermediate shaft frequency(23.2 Hz) and another at the output shaft frequency (7.58 Hz) are observed from the zoomed spectra which are not clear in the base band spectrum. But from the observations of zoom spectra also it is not possible to conclude which sideband is severe. The corresponding cepstrum shows only one quefrency component at the output shaft frequency i.e. at 7.58 Hz and its rahmonic. The level of the quefrency at intermediate shaft frequency is very low since there are only limited number of sidebands. Multiple sidebands are observed at the output shaft frequency, while the total power content of the whole family of sidebands in the spectrum, appearing at intervals of 7.58 Hz, exists as a single component in the cepstrum analysis. It means that cepstrum analysis accurately depicts the problematic sideband by showing a single prominent component. This is due to the output shaft gear modulation caused by the misalignment of the gear. Thus power cepstrum gives accurate measure of sideband spacing including separation of different families and at the same time it is insensitive to the transmission path effects.

5. CONCLUSION

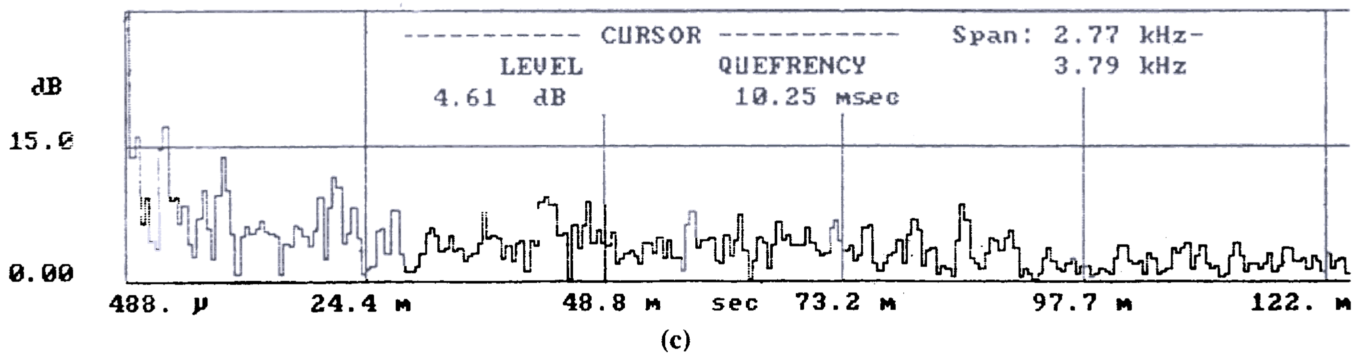
The study proves that the cepstrum analysis technique in the field of machinery fault diagnosis, using vibration signatures is superior and accurate compared to the frequency analysis technique, where sideband activity and harmonics are present. Also, the method is insensitive, to a high degree, to phase differences in the original signal, and to the influence from the transmission path effects. Spectrum analysis is prone to errors because of the surrounding noise contamination of the recorded signal and transmission path effects. The spectra taken at two points of a bearing are not



(a)



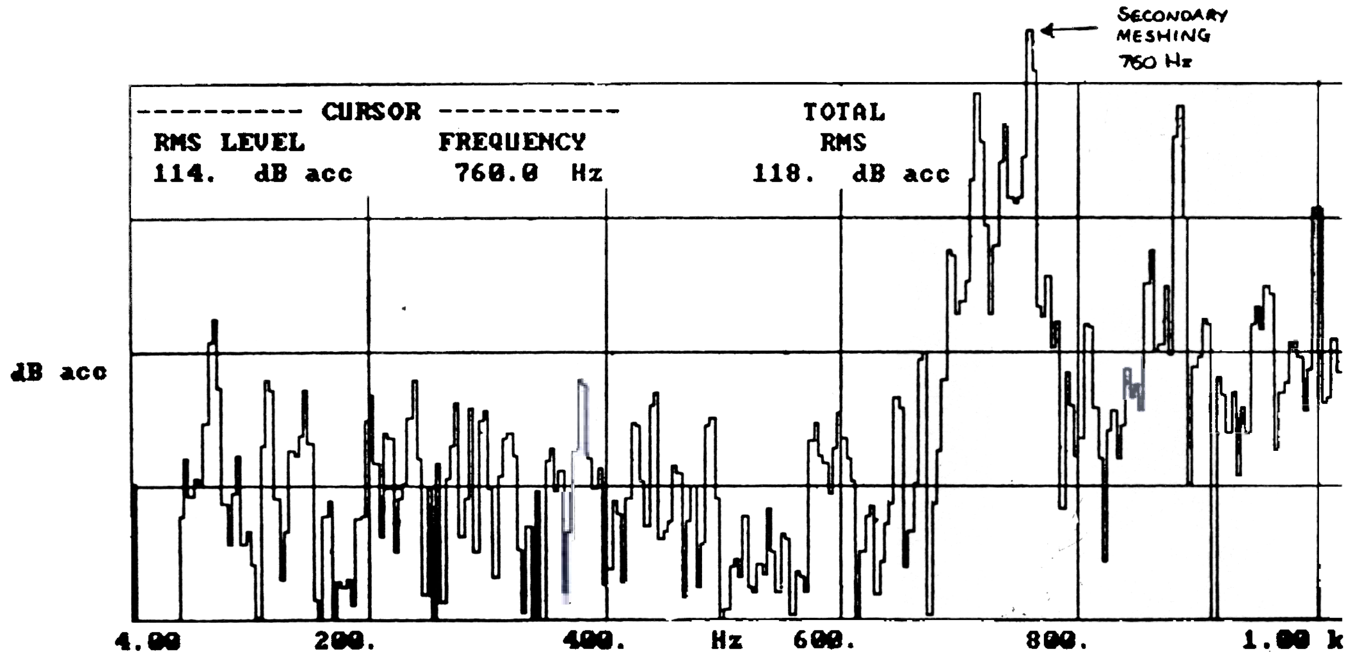
(b)



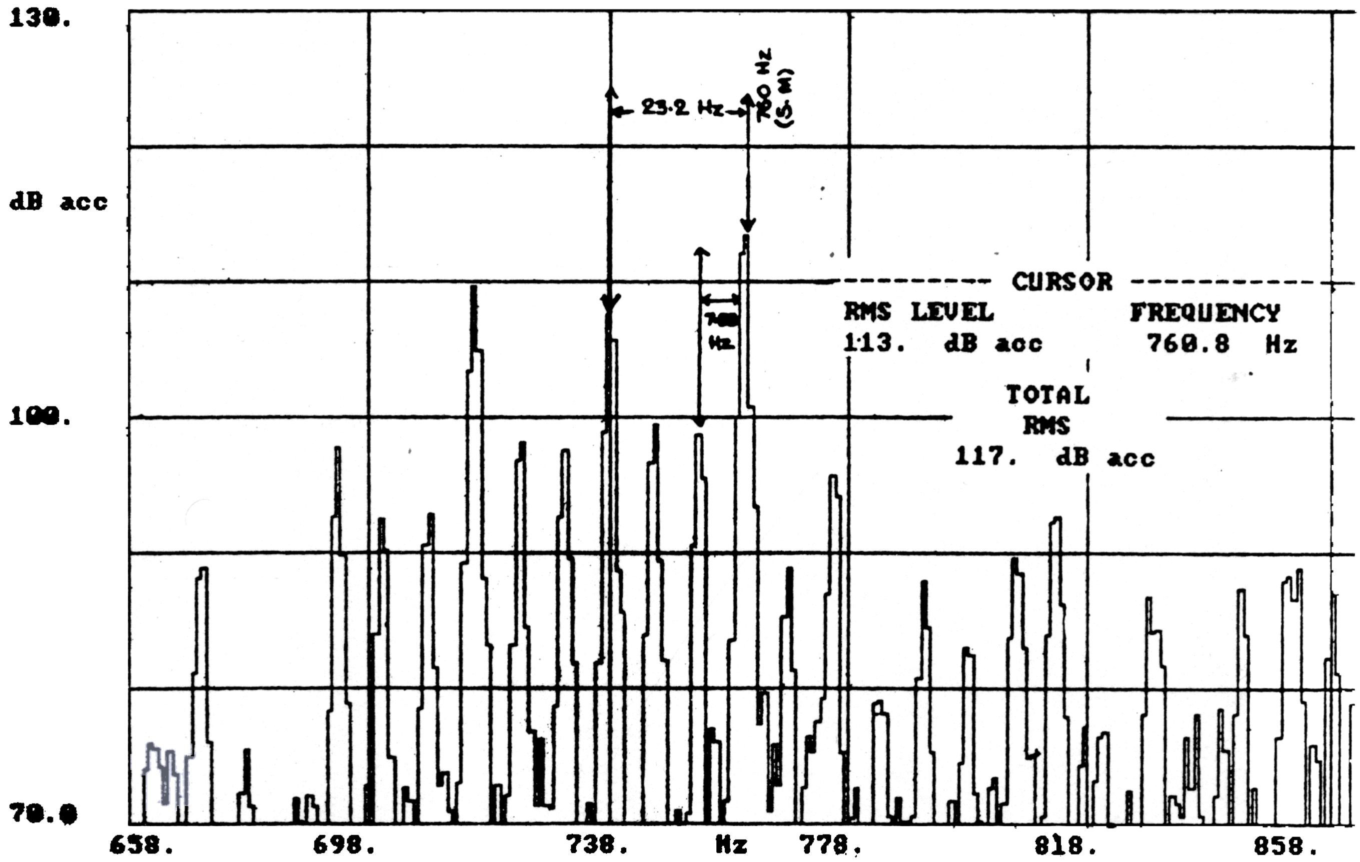
(c)

Figure 5. Analyses on the gear box performed at the primary meshing (3280 Hz): (a) spectrum analysis, (b) zoom spectrum analysis, and (c) cepstrum analysis.

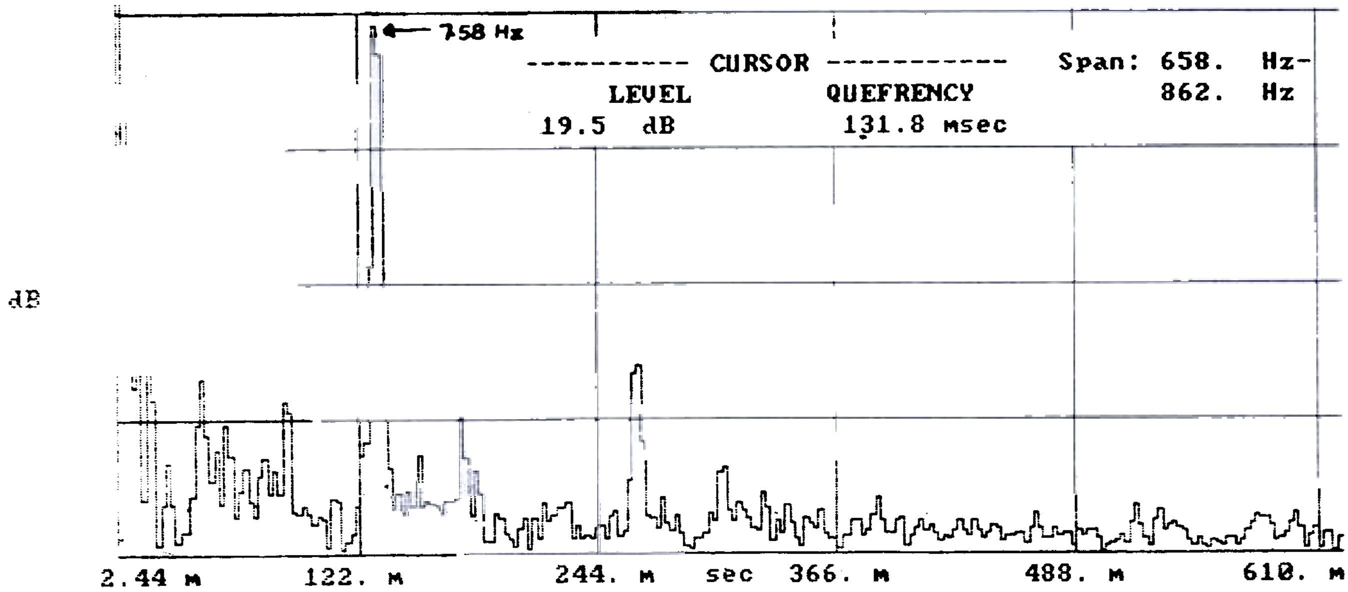
the same due to path difference, while the cepstra are alike. The results of the gearbox spectrum are confusing and it is difficult to identify the problem due to the presence of more than one type of sidebands. Whereas in the cepstrum the severity of sideband or defect is indicated as a single component only. Cepstrum analysis makes it possible to precisely determine the problematic periodic peak out of many periodic peaks and is thus a



6(a)



6(b)



6(c)

Figure 6. Analyses on the gear box performed at the secondary meshing (76 Hz): (a) spectrum analysis, (b) zoom spectrum analysis, and (c) cepstrum analysis.

reliable diagnostic tool for defect identification. Further, it is an invaluable technique for detection and monitoring the developments of faults in gears, rolling element bearings[9], turbine blades, etc. where a family of harmonics and sidebands exist.

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