Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 8, Issue, 06, pp.33313-33321, June, 2016

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

ISSN: 0975-833X

RESEARCH ARTICLE

CONDITION MONITORING OF GEAR BOXES IN REAL TIME

*Pramod Bhatia

Department of Mechanical Engineering, The NorthCap University, Gurgaon 122017, Haryana, India

ARTICLE INFO

Article History:
Received 07th March, 2016
Received in revised form
10th April, 2016
Accepted 21st May, 2016
Published online 30th June, 2016

Key words:

Modulation, Side-bands, Spectrum, Cepstrum, Quefrency.

ABSTRACT

Analysis of the vibration signals is one of the most powerful techniques available for determining the condition of operating machinery. Most serious faults will result in an increase of vibration level before actual breakdown, and thus allow shutdown before catastrophic failure. One such machinery is a gearbox, which finds its application in many areas. Spectrum analysis helps in converting the time-domain signal from the gearbox into the frequency-domain, thus enabling identification of the troubling frequency. But this tends to become difficult as the signal becomes complicated due to the multiple gear pairs in a gearbox. Therefore, in order to get a clearer picture of the condition of the gearbox, another mathematical tool called Cepstrum is needed which separates the side bands and makes the diagnosis easy. Here we present this tool, which was developed by us, and its results.

Citation: Pramod Bhatia. 2016. "Condition monitoring of gear boxes in real time", *International Journal of Current Research*, 8, (06), 33313-33321.

INTRODUCTION

A gearbox is one of the indispensable components in industry. It finds its application in almost all the machines, having strategic use (like turbines) to the ones being used for more ordinary purposes like lathes, automobiles, etc primarily because it is the only durable and convenient means of speed and directional change for motion in power industry. Being a critical part, its proper functioning has always been a matter of consideration. The most common method used for ensuring that is – Measurement of Vibration Signal. It forms an important element of the maintenance schedule of the machine and helps in the identification of any fault that may be present.
A gearbox has multiple shafts and gears. It has always been desirable that the vibration signal should give a clear picture of the present status of the shaft and the gears inside the gearbox for proper diagnosis. This may include exact determination of faulty shaft as well as the gear present in the gearbox. The main objective is to identify the problems present in the gearbox, so that a corrective measure may be taken before the problem assumes a bigger dimension. For this, the following, was needed, to be achieved:

- Presentation of the results of vibration analysis in a form easily understood by the maintenance personnel, which will help detection.
- Estimation of the fault present, to give a quantitative picture to the problem.
- This paper describes the development of a cepstrum software for the real-time condition monitoring of a gearbox. Cepstrum is a mathematical tool, which takes vibration signals from a gearbox and through some analysis and graphs is able to tell about the present working condition of the gearbox. This would enable the detection of any defective gear present in it.

Corresponding author: Pramod Bhatia,
Department of Mechanical Engineering, The NorthCap University, Gurgaon 122017, Haryana, India.

CEPSTRUM

In many acoustical and vibration measurements, it is much more convenient to work in the frequency domain rather than the time domain. Often, the time domain signal gives too much information in an unintelligible form. Conversion of the signal to frequency domain, however, can make the interpretation of data contained by it a much easier matter. This has led to the idea of frequency analysis, where the amplitude against time signal is converted to amplitude against frequency, see (Rao, 2001). Such an analysis of the vibratory signal in the frequency domain is called spectrum analysis. The vibratory signal of a machine running under steady conditions is in the time domain and is called its *signature*. This signature is generally periodic in nature since the disturbing forces may have different fundamental frequencies and their harmonics. A periodic motion can be broken down into several harmonic motions using Fourier analysis. A plot can be obtained in the frequency-amplitude plane. Such a transformation (time domain to frequency domain) is advantageous because of the following reasons:

- Changes in the minor spectral components which may be the first indication of incipient failure may not always affect the overall vibration level, but can be picked up by spectrum monitoring.
- A rise in overall level will indicate that something has changed but not give any information as to the source, whereas this will often be indicated by the frequency at which the change occurs.

This change from the time domain to frequency domain can be accomplished with the help of Fast Fourier Transform. But the situation may get complex when the signal is from a gearbox, which has a number of gear pairs. This may give rise to more than one family of side bands around each of the tooth meshing frequencies, see, Chang, Rao and Shiau (1996), making its visual recognition (on a spectrum plot) very difficult, if not impossible. This tells that for complete diagnosis, a tool other than spectrum is needed that would clearly distinguish the side bands making their recognition easy. This tool is called cepstrum. Cepstrum is defined as the inverse Fourier transform of the logarithmic power spectrum or amplitude spectrum. (Rao, 2001)

$C_{xx}(\tau) = F^{-1}(\log S_{xx}(\omega))$

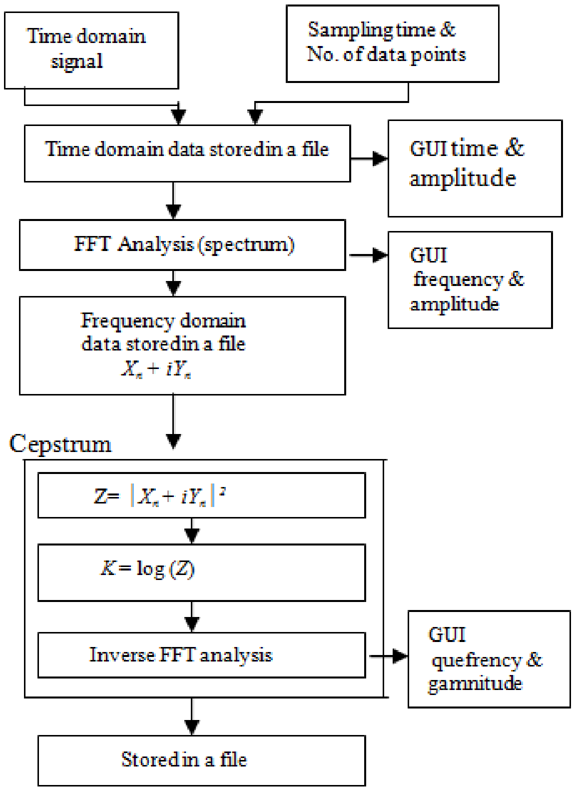
If $S_{xx}(\omega)$ is a typical component of the power spectrum of the time function $f_x(t)$, then the cepstrum is obtained by Inverse Fourier transformation of the sequence of $\log\{S_{xx}(\omega)\}$ values, and by extracting the amplitude squared values of the result.
Therefore, if seen fundamentally, then cepstrum is the spectrum of a spectrum. This is because a spectrum separates out the periodic components in the time domain signal whereas a cepstrum separates out the periodic side bands in the spectrum. However, to differentiate the *cepstrum* from the *spectrum,* following terms are used.

- Cepstrum for Spectrum
- Quefrency for Frequency
- Rahmonics for Harmonics
- Lifter for filter
- Gamnitude for magnitude
- Saphe for phase

Cepstrum plots the gamnitude at the ordinate axis and the quefrency at the abscissa axis. Since families of side bands are periodic in the spectrum with constant bandwidth, the cepstrum will evidently contain peaks corresponding to the dominant side band spacing. The reciprocal of the *quefrency* (dimensions of time) associated with such peaks would give the corresponding side band spacing and thus the modulating frequency whereas the gamnitude would tell the relative strength of the peaks. For example, if there are two families of side bands in a spectrum with frequency differences of δf_1 and δf_2 Hz, then these will be represented in cepstrum by two distinct peaks at quefrency equal to $1/\delta f_1$ and $1/\delta f_2$ sec. Thus, this frequency analysis results in a separation of these different periodicities into single lines, which also give information as to the relative importance of a certain side band spacing over the other side band spacings.

Program

Digital Signal processing (Gold and Rabinger, 1992) is used to develop a stand-alone computer program. The flowchart of the code written is given below:



Validation of the program code

A signal from a gearbox is simulated to validate the code, wherein some gears of the gearbox are assumed to be defective. An expected continuous time domain signal is generated with appropriate constants and coefficients, known from the theory, for the defective gearbox. Then, the vibration values are discretized and fed into the code through a file and the results are analyzed and crosschecked with the initially assumed defective gears. The details of the simulation are covered as follows.

The diagnosis of the problem in the gearbox and the identification of the defective gear using the spectrum and cepstrum analysis can be best understood by considering the example of a single speed reducer gearbox, see Fig. 1.

Gear meshing frequencies:

$f_{AB} = 30 \times 25 = 750$ Hz
$f_{CD} = 19 \times 16.66 = 316.54$ Hz

Gears A and C are assumed defective, thus modulated frequencies correspond to the rotational speeds of the input and the counter shafts. Both the carrier and modulated frequencies' terms are periodic in nature, thus, are expanded into harmonic components. Six harmonics of the modulated frequencies 25 and 16.6 Hz along with carrier frequencies (gear mesh) 750 and 316.5 Hz are accounted. Thus,

$$
\begin{aligned}
Y(t) =\ & (100 + 100\cos 105t + .. + 40\cos 735t)\cos 1989t \\
& + (50 + 50\cos 105t + .. + 20\cos 735t)\cos 3978t \\
& + (100 + 100\cos 157t + .. + 40\cos 1099t)\cos 4712t \\
& + (50 + 50\cos 157t + .. + 20\cos 1099t)\cos 9424t
\end{aligned}
$$

The spectrum and cepstrum plots of the signal are shown in the Figs. 2 and 3 respectively.

The spectrum in Fig. 2 contains the gear meshing frequencies f_{AB} and f_{CD} and their higher harmonics (in this case only one) i.e. peaks at 316.5 Hz, 633 Hz, 750 Hz and 1500 Hz. Due to the defective gears A & C, 16.6 Hz side bands should be present around 316.5 Hz & 633 Hz and 25 Hz side bands around 750 Hz & 1500 Hz. The cepstrum of the signal in Fig. 3 has two predominant peaks, one at the quefrency of 0.06 sec (1/16.6 Hz) and the other at 0.04 sec (1/25 Hz). Apart from this, the cepstrum also has peaks at sub-harmonics as well as higher harmonics of the fundamental quefrencies. Thus, the predominant peaks in cepstrum occur at 0.02 sec, 0.03 sec, 0.04 sec, 0.06 sec and at 0.12 sec, i.e. at 50 Hz, 33.3 Hz, 25 Hz, 16.6 Hz and 8.3 Hz respectively. Starting with the 0.02 sec peak, it could be inferred that the shaft rotating with the speed of 50 Hz has some problem, which may be present on the shaft itself or the gear mounted on it. Now, it is known from the input data of the gearbox that no shaft rotates with the speed of 50 Hz, but at half the value of 25 Hz. This rotational speed's peak also occurs in the cepstrum plot at the quefrency of 0.04 sec. This would imply that it is the 25 Hz shaft that has some problem and the peak at 0.02 sec is the sub-harmonic of the peak at 0.04 sec. Similar analysis holds for the peak at 0.06 sec whose sub-harmonic occurs at 0.03 sec, implying that the shaft rotating with the speed of 16.6 Hz carry some problem. Since, only one gear is mounted on the shaft rotating with 25 Hz, it is evident that either the shaft or the gear mounted on it is having a problem. If it would have been a problem in the shaft itself, then in the spectrum plot, peaks would have occurred at 25 Hz and its higher harmonics, which is not the case as is seen from the spectrum plot. Whereas, presence of peaks at 750 Hz & 1500 Hz together with the side bands in the spectrum plot, does indicate that the gear A has some defect.

For the shaft rotating with 16.6 Hz, absence of any peak at 16.6 Hz and its higher harmonics indicates that it is the gear, which has a defect. This shaft carries two gears B & C. In order to identify which gear is defective, the spectrum plot has to be analyzed. The presence of 16.6 Hz side bands around gear meshing frequency of 316.5 Hz and its higher harmonic of 633 Hz, indicates that gear C is defective and not the gear B. These results match with what was assumed in the beginning. Thus, this example tells how the defective gears can be identified from the many present in a gear train.

The third peak corresponding to 8.3 Hz occurs because in the cepstrum small peaks occur at the integral multiples of the fundamental quefencies which are at 0.06 sec (16.6 Hz) and 0.04 sec (25 Hz). These small peaks therefore occur at 0.12 sec, 0.18 sec, etc. due to the 0.06 sec peak and at 0.08 sec, 0.12 sec, etc. due to the 0.04 sec peak. As is evident, at 0.12 sec cumulative effect of the two small peaks result in a predominant peak which in itself does not signify anything.

Experimentation

An old four-speed gearbox with one reverse speed is chosen for experimentation. The details of the gearbox are given in Fig. 4. The block diagram of the experimental rig is shown in Fig. 5, see ref (4).

The gearbox and the motor were mounted on two different beds and the motor transmits power to the gearbox through a V-belt. Vibration signals from the gearbox were picked up by a B&K accelerometer and given to a charge amplifier. This in turn was connected to an oscilloscope where the input signal could be seen. The signal was then fed to an A/D card, where it was digitized with the help of a software and stored as a data file. This data file was given as input to the software. The number of samples taken were 32768 with a sampling rate of 2000 samples per second. The rotational speed of the input shaft was 748.8 rpm (12.48 Hz), measured with the help of a tachometer. Then, one of the tooth of the fourth gear on the input-output shaft was damaged a bit. This affected the first and the reverse gear engagements and therefore, the vibration signal from the gearbox for these two gear engagements was analyzed.

RESULTS AND DISCUSSION

The various gear meshing (carrier) and modulation frequencies for three different gear engagements, for the gearbox in Fig. 4, are shown below.

First Gear → O1 → C1 → C4 → O4 →

w_i = 12.48 Hz
w_c = 12.48 * 17/40 = 5.3 Hz
w_o = 5.3 * 14/42 = 1.76 Hz

Carrier Frequencies
f_1 = 12.48 * 17 = 212.16 Hz
f_2 = 1.76 * 42 = 74.17 Hz

Forth Gear → O1 → O4 →
└→ C1

w_i = 12.48 Hz
w_c = 12.48 * 17/40 = 5.3 Hz
w_o = 12.48 Hz
Carrier Frequencies
f_1 = 12.48 * 17 = 212.16 Hz

Reverse Gear → O1 → C1 → C2 → R1 ┐
← O4 ← R2 ← ┘

w_i = 12.48 Hz
w_c = 12.48 * 17/40 = 5.3 Hz
w_r = 5.3 * 23/26 = 4.69 Hz

w_o = 4.69 * 16/42 = 1.78 Hz

Carrier Frequencies
f_1 = 12.48 * 17 = 212.16 Hz
f_2 = 5.3 * 23 = 121.99 Hz
f_3 = 4.69 * 16 = 75.07 Hz

Test Results with no Gear Defect

Fourth Gear

In this gear arrangement, gear O1 is in mesh with the gear O2 on the same shaft and the gear C1 on the counter shaft. Gear O2 has internal gears and comes over the gear O1, thus rotating with the same angular speed of 12.48 Hz. Gear C1 rotates with an angular speed of 5.3 Hz with a gear meshing frequency of 212.16 Hz.

Assuming no defect in the gearbox, the spectrum should contain a peak at the gear meshing frequency and no side bands. Thus, the cepstrum also should not show any predominant peak. The spectrum and the cepstrum plots of the actual signal are shown in the Figs. 6 and 7 respectively. Considering the spectrum plot, it has peaks at 12.5 Hz (rotational speed of input shaft), 24.8 Hz, 37.3 Hz, 49.1 Hz, 62.2 Hz and 74.6 Hz showing that higher harmonics of 12.5 Hz are present. The cepstrum plot gives a predominant peak at 0.081 sec. The presence of higher harmonics indicate misalignment. This being a very old gearbox, a considerable misalign-ment was found upon examination. This interval of 12.5 Hz gets reflected in the cepstrum at the quefrency of 0.081 sec (1/12.34 Hz). The misalignment of the shaft is so severe that the gear meshing frequency gets totally overshadowed by the misalignment frequencies

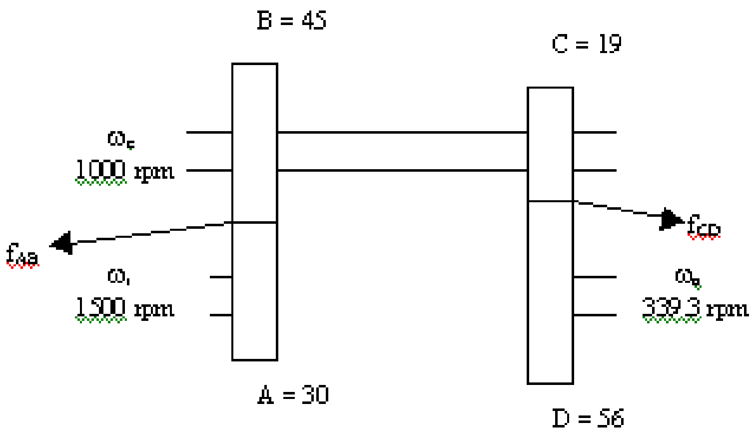


Fig. 1. Single Speed Gearbox

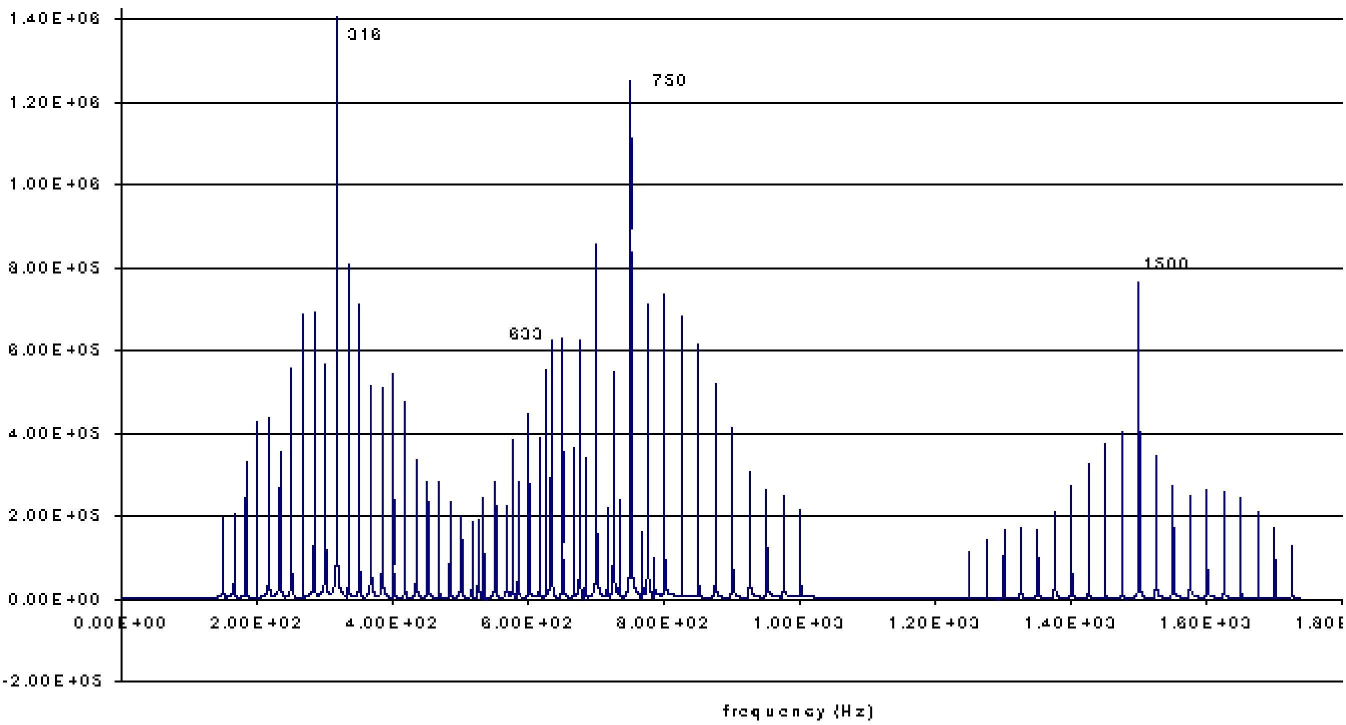


Fig. 2. Spectrum of the gearbox

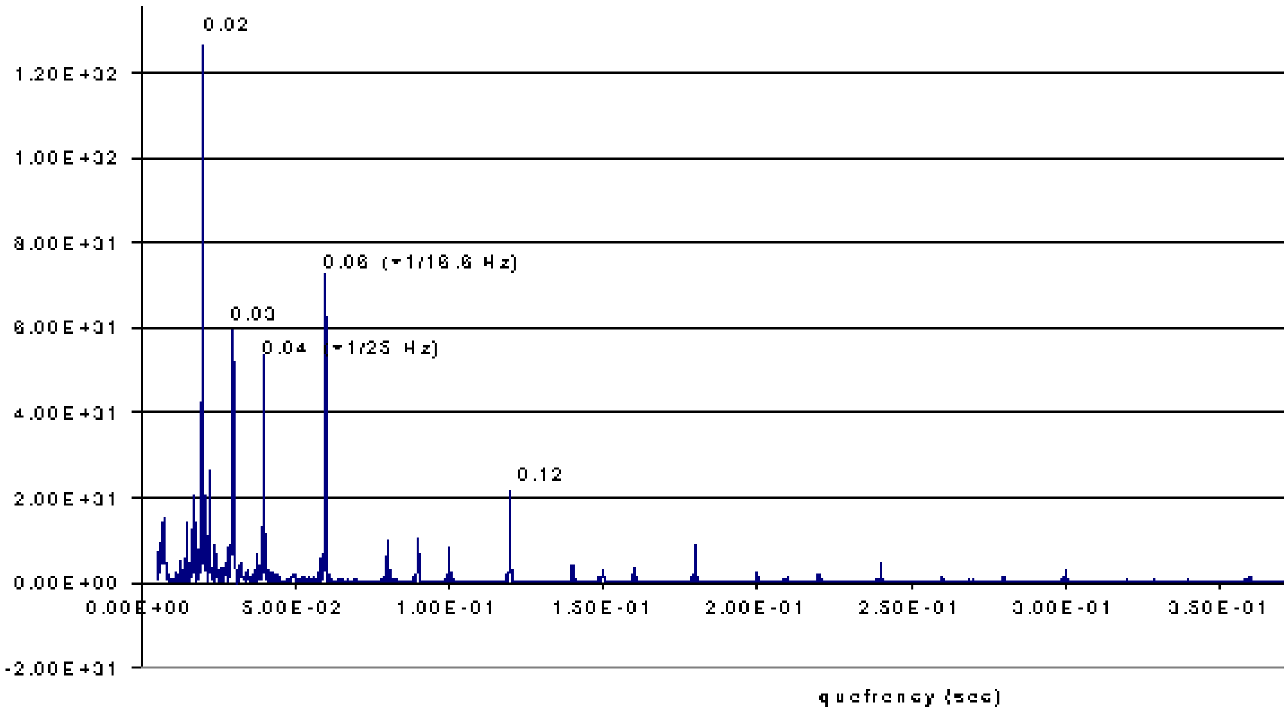


Fig. 3. Cepstrum of the gearbox

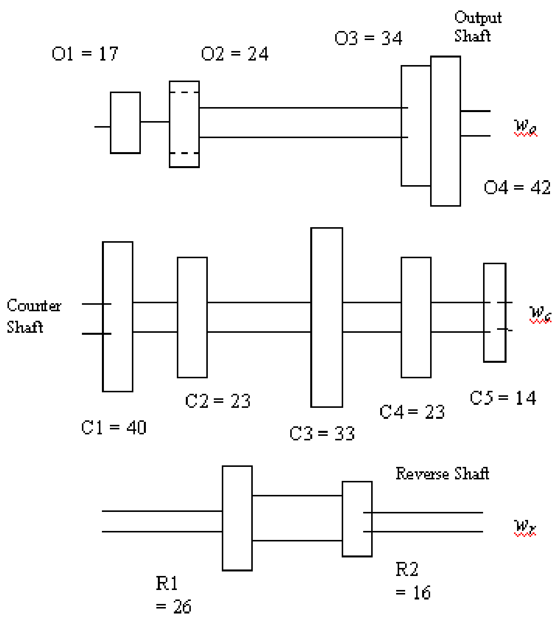


Fig. 4 Experimental Gearbox

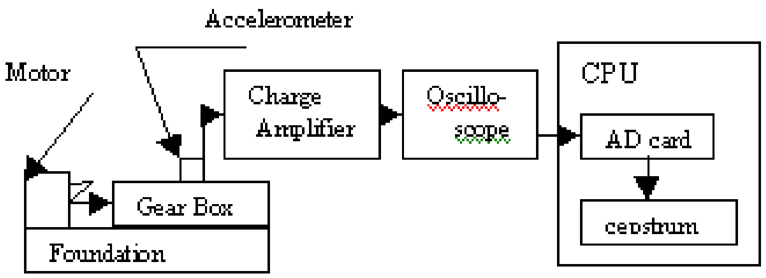


Fig. 5. Block Diagram of the Experiment

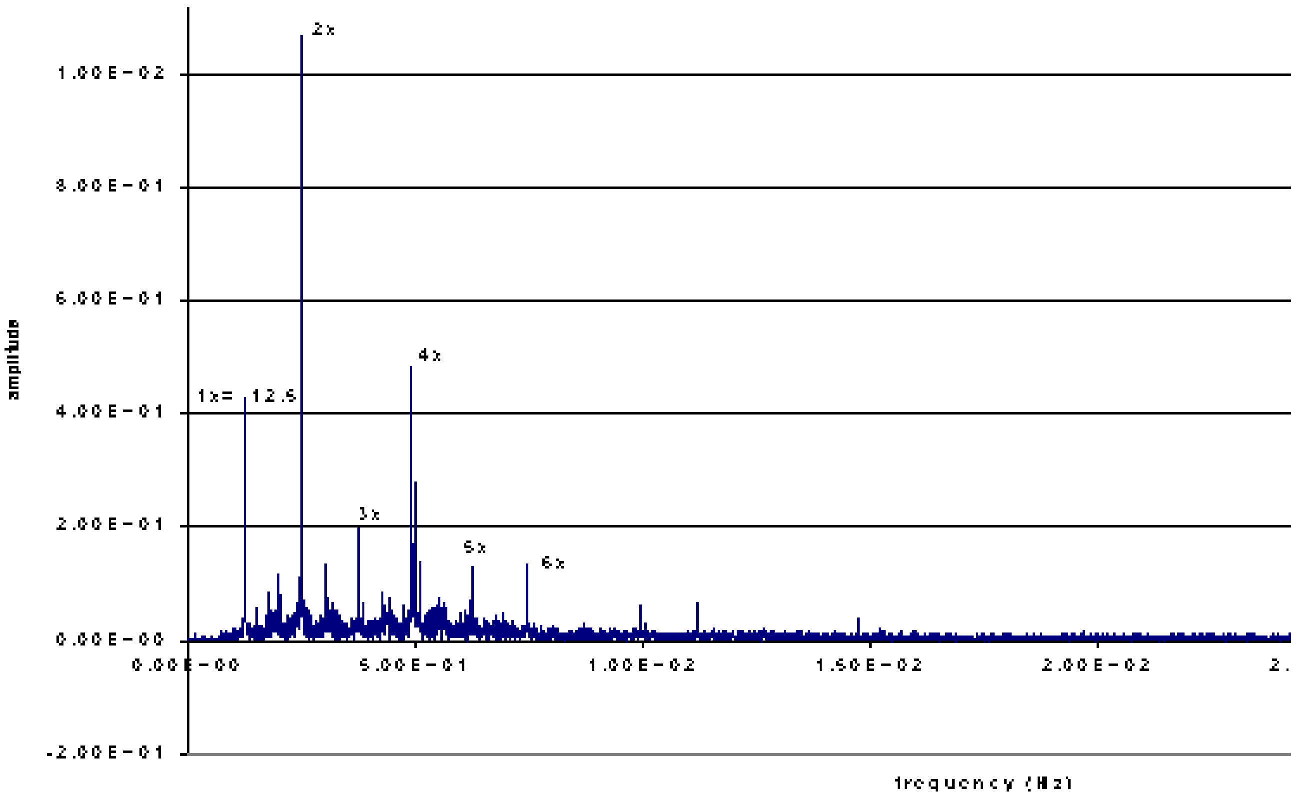


Fig. 6. Spectrum (4th Gear, without defect)

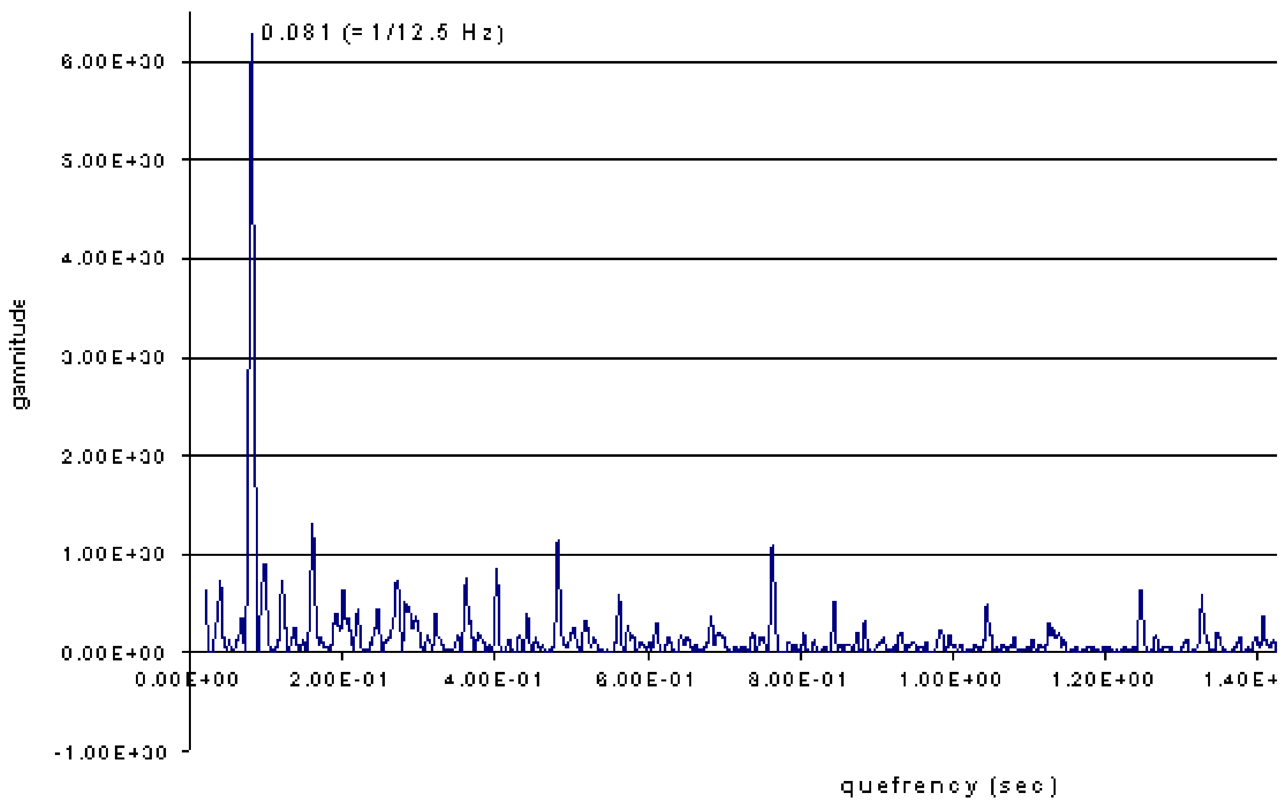


Fig. 7. Cepstrum (4th Gear, without defect)

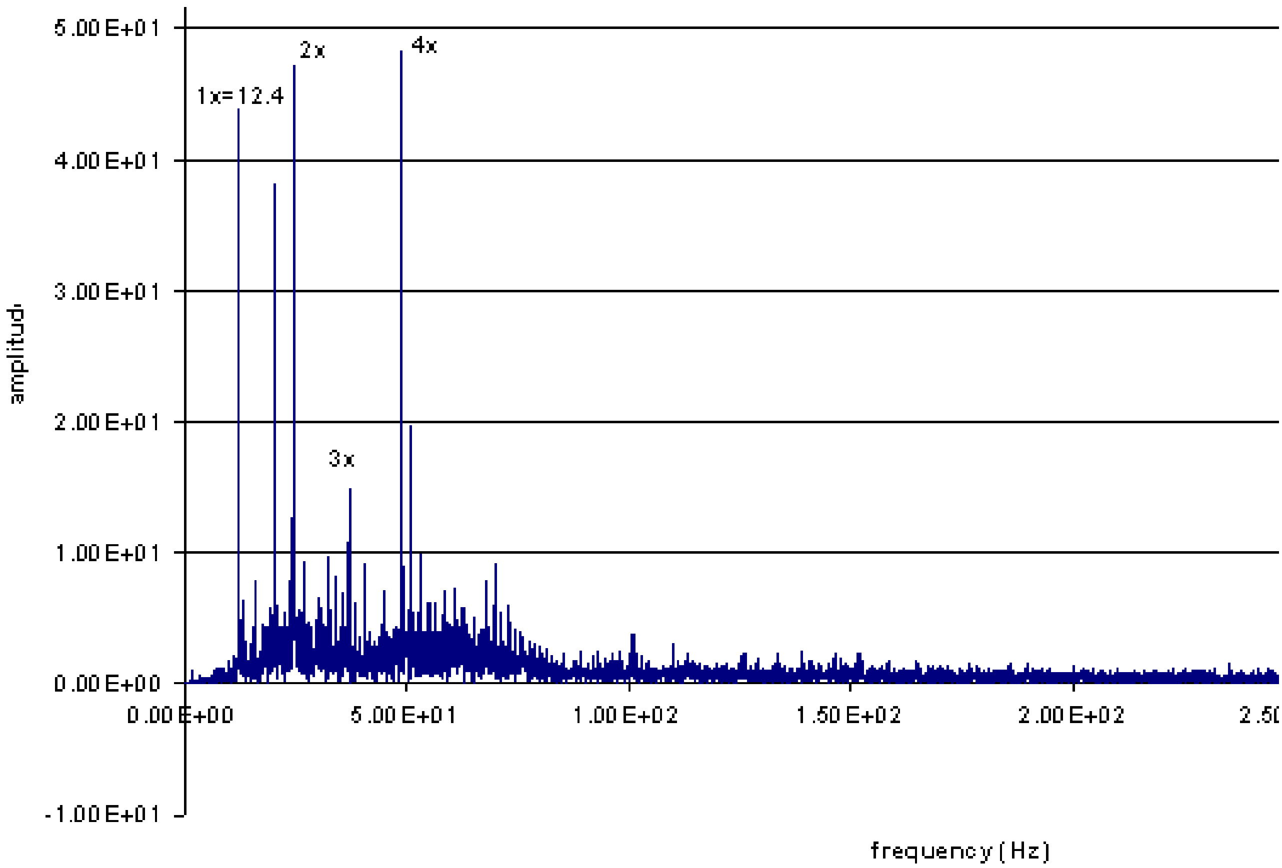


Fig. 8. Spectrum (Reverse Gear without defect)

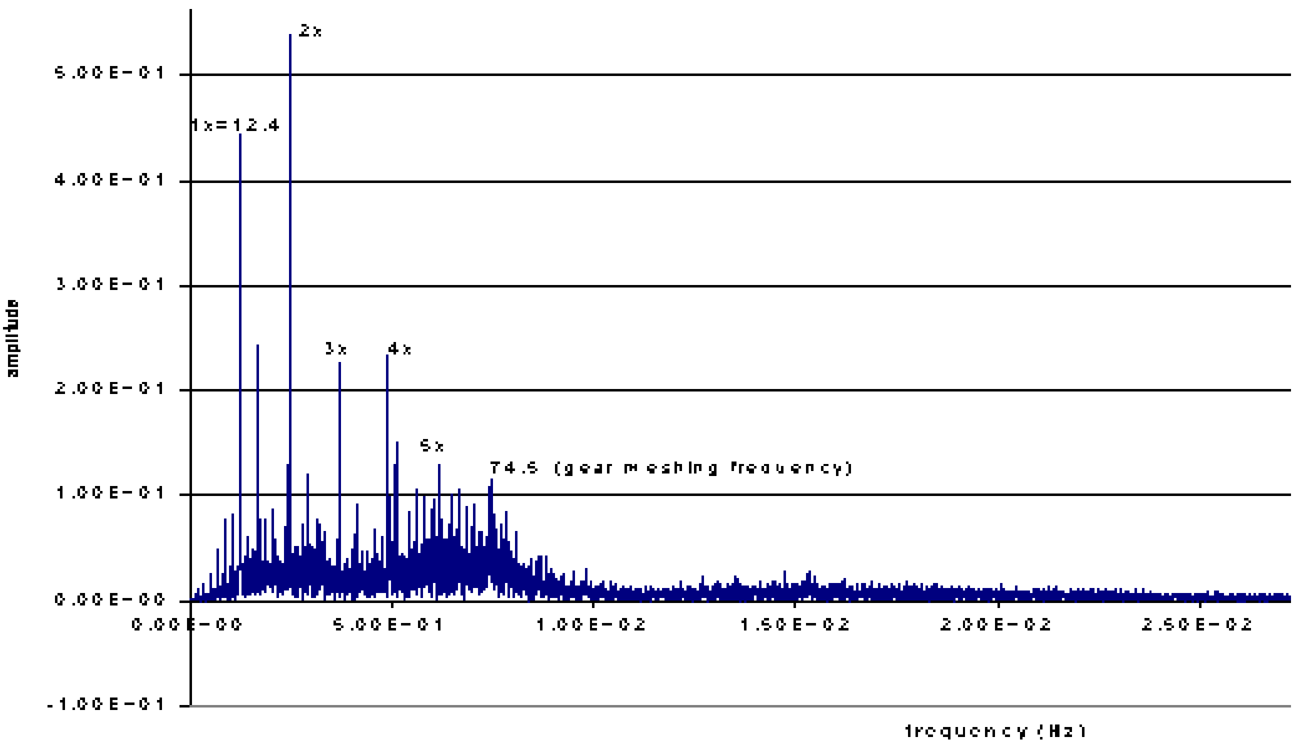


Fig. 9. Spectrum (I gear with defect)

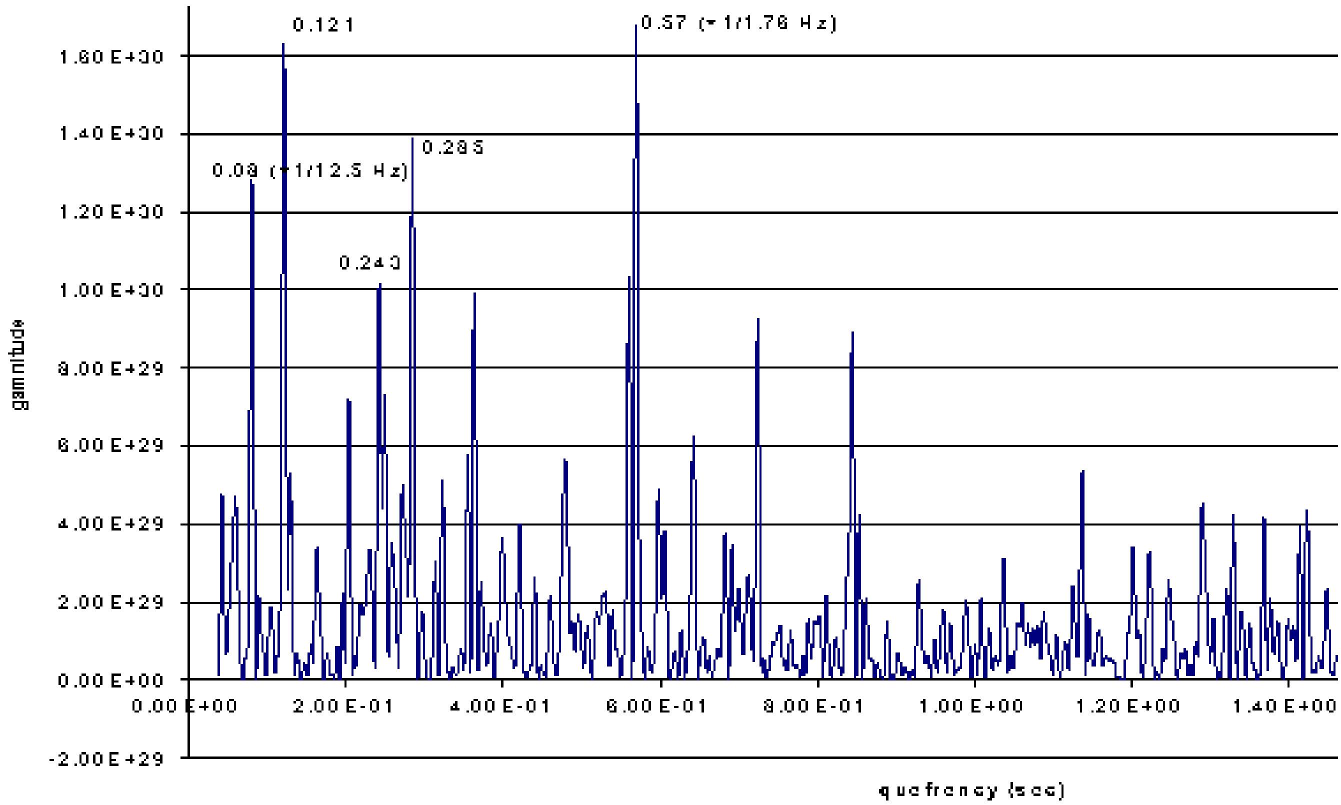


Fig. 10. Cepstrum (1st Gear with defect)

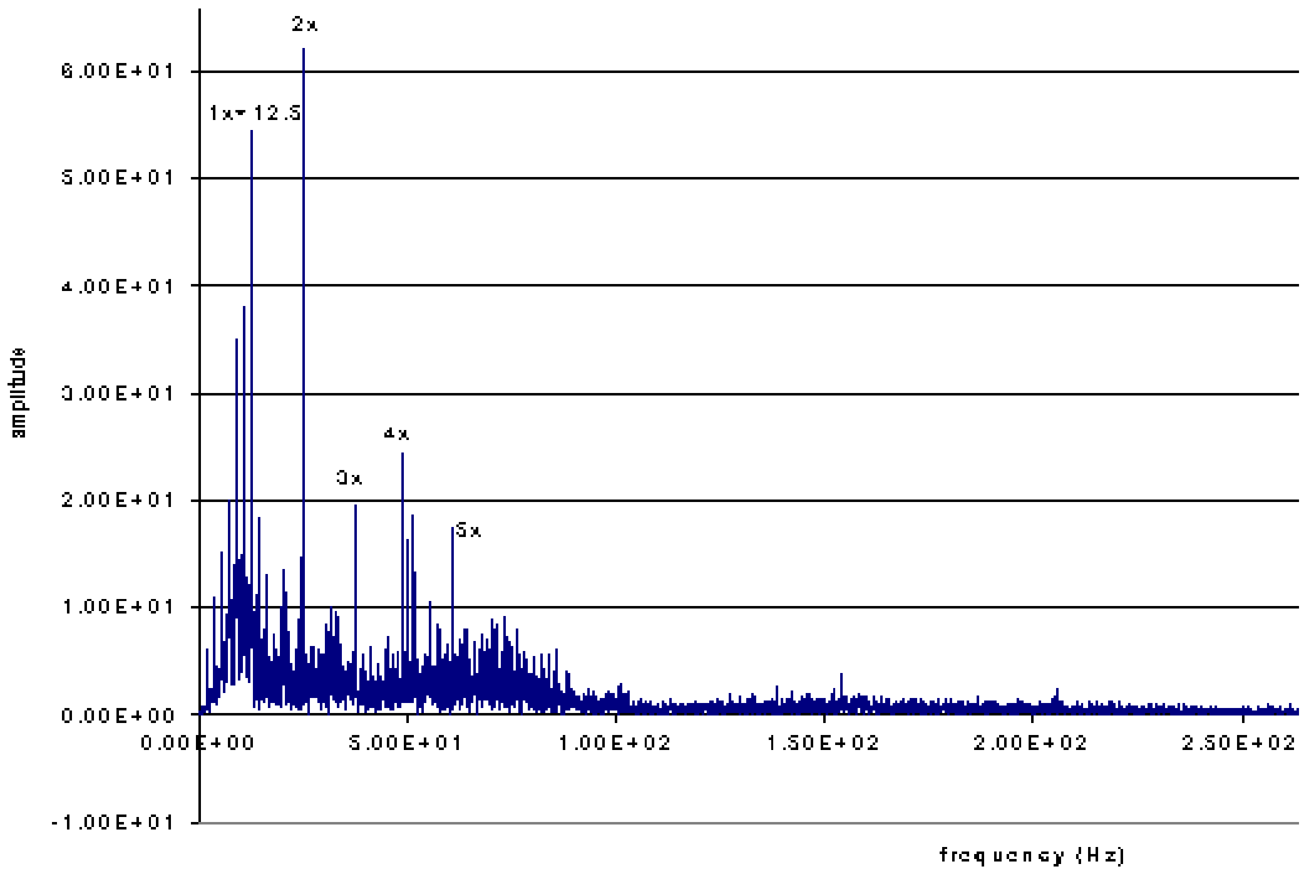


Fig. 11. Spectrum (Reverse Gear with defect)

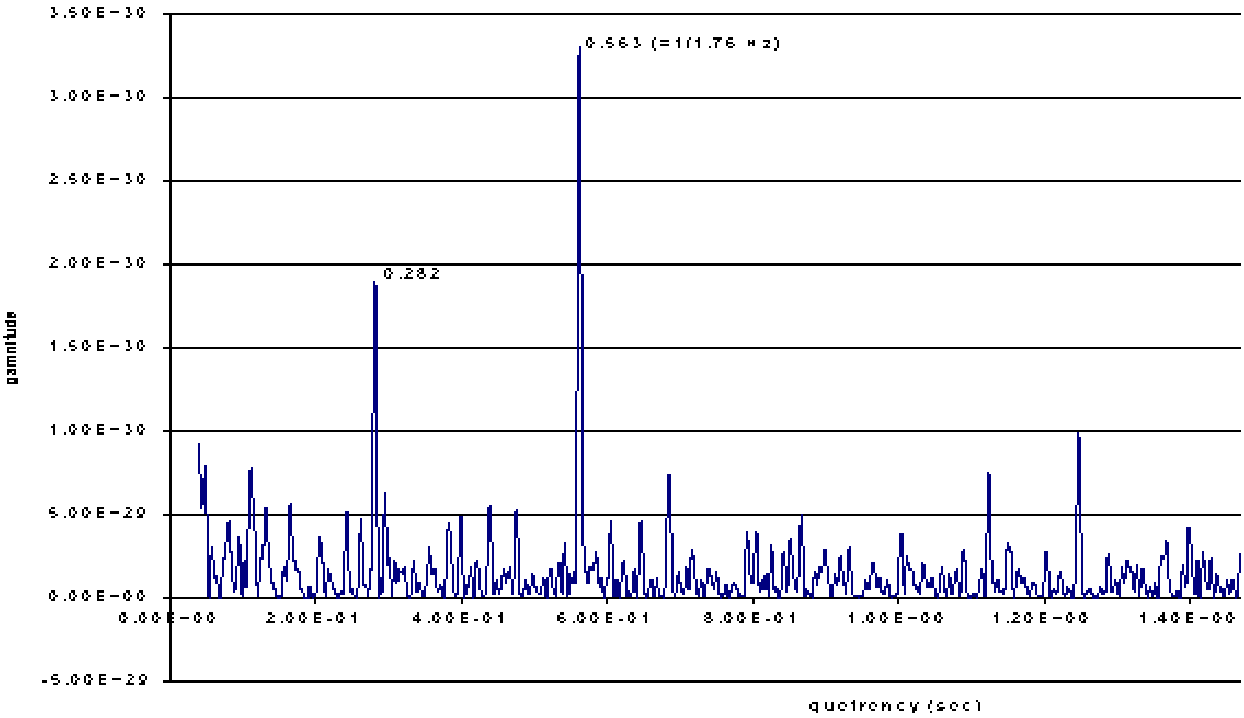


Fig. 12. Cepstrum (Reverse Gear with defect)

Reverse Gear

In this arrangement gear O1 is in mesh with the gear C1 on the counter shaft at a gear meshing frequency of 212.16 Hz. Gear C2 is in mesh with the gear R1 on the reverse shaft at 122 Hz and the gear R2 with the gear O4 on the output shaft at 75.1 Hz. Input shaft rotates with an angular speed of 12.48 Hz, counter shaft with 5.3 Hz, reverse shaft with 4.69 Hz and output shaft with 1.78 Hz approximately. The spectrum of the signal is shown in the Figs. 8. It has peaks at 12.4 Hz, 24.8 Hz, 37.1 Hz, and 48.9 Hz showing that higher harmonics of 12.5 Hz are present. The cepstrum plot remained same as Fig. 7. As seen in the fourth gear, the same misalignment causes the peaks to appear in the spectrum. It now becomes clear that the misaligned shaft is the input shaft and not the output shaft, as the spectrum does not contain any peak corresponding to the rotational speed of the output shaft.

Test Results with Gear Defect

First Gear

In this arrangement, gear O1 is in mesh with gear C1. Fig. 9 shows the spectrum obtained. The spectrum again has peaks at 12.4 Hz and its higher harmonics whereas the cepstrum shows peaks at 0.285 sec and 0.57 sec. Predominance of misalignment is again underscored by the presence of peaks at 12.4 Hz and its higher harmonics. Fig. 10 shows the cepstrum obtained in this case. Appearance of peaks at 0.285 sec and 0.57 sec in the cepstrum does tell that side bands of 1.76 Hz are present around the gear meshing frequency of 74.17 Hz.

Reverse Gear

The spectrum and cepstrum plots obtained are shown in Figs. 11 & 12, respectively. In this case also spectrum has a peak at 12.5 Hz and its higher harmonics, which justifies the predominance of misalignment. The cepstrum plot has peaks at 0.282 and 0.563 sec, showing that side bands of 1.78 Hz are present around the gear meshing frequency of 75.07 Hz.

Conclusion

A stand alone software for analyzing the time domain signal in frequency and quefrency domains is developed. The usefulness of the cepstrum analysis for gearbox in identifying gear defects is demonstrated through a simulation. An experiment is conducted on an old gearbox by inducing defect on one gear. The experimental results show a clear advantage of using cepstrum analysis in identifying this defect.

REFERENCES

Bruel and Kjaer Publishers, “The Application of Vibration Measurement and Analysis in Machine Maintenance”.

Chang, J.R, J.S. Rao and T.N. Shiau, 1996. “Dynamic Coupling in Simple Geared Rotor Bearing System”, IMechE, C500/127, pp. 599-608.

Gold, B. and L.R. Rabinger, 1992. “Theory and Application of Digital Signal Processing”, Prentice Hall India.

Rao, J.S. 2001. “Vibratory Condition Monitoring of Machines”, Narosa Publishing.

****