World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:8, No:9, 2014

Vehicle Gearbox Fault Diagnosis Based On Cepstrum Analysis

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***Abstract*—**Research on damage of gears and gear pairs using vibration signals remains very attractive, because vibration signals from a gear pair are complex in nature and not easy to interpret. Predicting gear pair defects by analyzing changes in vibration signal of gears pairs in operation is a very reliable method. Therefore, a suitable vibration signal processing technique is necessary to extract defect information generally obscured by the noise from dynamic factors of other gear pairs.This article presents the value of cepstrum analysis in vehicle gearbox fault diagnosis. Cepstrum represents the overall power content of a whole family of harmonics and sidebands when more than one family of sidebands is present at the same time. The concept for the measurement and analysis involved in using the technique are briefly outlined. Cepstrum analysis is used for detection of an artificial pitting defect in a vehicle gearbox loaded with different speeds and torques. The test stand is equipped with three dynamometers; the input dynamometer serves asthe internal combustion engine, the output dynamometers introduce the load on the flanges of the output joint shafts. The pitting defect is manufactured on the tooth side of a gear of the fifth speed on the secondary shaft. Also, a method for fault diagnosis of gear faults is presented based on order Cepstrum. The procedure is illustrated with the experimental vibration data of the vehicle gearbox. The results show the effectiveness of Cepstrum analysis in detection and diagnosis of the gear condition.

***Keywords*—**Cepstrumanalysis,fault diagnosis, gearbox.

I. Introduction

THEgearbox is an important part of any machinery as it provides speed reduction or overdrive depending on the gear arrangement. Gearboxes are used in various conditions, such as high speed and/or for high load. Any minor fault in a gear of such gearbox can lead to an unexpected failure of the machinery. An efficient condition monitoring scheme is capable of providing warning and predicting faults at early stages. This has the benefit of reducing consequential damage, increasing machine life, reducing spare parts inventories, and reducing breakdown maintenance. Gearboxes have a complex structure and a fault causes significant loss in terms of time and money. Early detection of a fault and its location can reduce these losses. For early detection of a fault, avibration signal from the machinery is analyzed. There are many methods for analyzing vibration signals [1]. Many of these methods are effective in simple machinery components, but for complex components, such as a vehicle gearbox,the effectiveness of these methods degrades. For such conditions Cepstrum analysis [2]-[4] provides more efficient results.

All rotating machinery generates vibration, the analysis of which renders valuable information about the condition of themachinery. The old and conventional method of vibration assessment is not adequate to predict 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 for predicting the onset of defects, giving adequate time to plan and undertake preventive measures.

Spectrum analysis has some constraints in with respect to 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 Cepstral is the inversion of spectral in spectrum). The transmission of gear tooth meshing vibration from the tooth contact region to the shaft, through rolling element bearings and then through the gearbox casing can have an important influence on the measured vibration spectrum. In critical applications the measurement of the torsional vibration of the gear may be preferable. In a conventional frequency analysis of a spectrum the effects of the transmission path obscure the true source signature.It is also not possible to pinpoint the defects accurately where the problem is associated with more than one sideband and harmonic, as in the case of gas turbines, steam turbines and gearboxes on board ships and submarines. Transmission path effects are additive and can be separated in Cepstrum which also gives accurate detection of the periodic structure within 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,unlike in a spectrum.

As mentioned, gear vibration spectra commonly show sidebands of the meshing frequency and its harmonics. Such sidebands typically arise from the modulation of the tooth meshing waveform by the gear rotational frequency. For gearboxes in good condition the sideband level generally remains constant with time. Changes in the number and amplitude of the sidebands normally indicate deteriorationin condition. In the particular case of a local fault in one of the teeth, a localized modulation effect takes place once per revolution of the faulted gear. Several modulation phenomena may be present, each producing a different family of sidebands characterized by the same spacing in the spectrum, equal to the corresponding modulating frequency. As a

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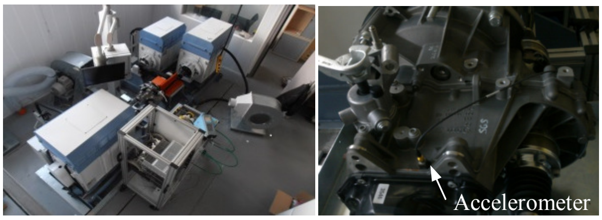
consequence, the sideband spacing contains diagnostic information, since it is related to the modulation source [6]. However, it can be difficult to distinguish and evaluate the sideband spacing by means of spectral analysis, due to the contemporary presence of several families of sidebands and other components. In order to overcome this problem, Cepstrum analysis can be employed. Various forms of Cepstrum exist, but all of them can be considered a spectrum of a logarithmic spectrum [6]. For applications in machine diagnostics, the power Cepstrum, is well suited and generally applied, as shown in the literature [1], [5]; it is defined as the inverse Fourier transform of the logarithmic power spectrum [5].

II. Description of the Test Set-Up

A. Experimental Set-Up

The measurements are conducted on an open loop test bed consisting of three dynamometric machines. The gearbox is screwed via a flange, which normally serves for assembly with the internal combustion engine, to the test stand. The complete clutch is mounted and operated on the shaft. The input shaft is driven via a belt drive. Original vehicle joint shafts are mounted on the output flanges. The gearbox is shifted and the clutch is operated with the aid of a shift robot. The shifting speed and shift force can be tuned for each gear. The completely newly conceived test stand can reproduce with high dynamics the data measured during real vehicle operation. However, for our purposes we performed the measurements in steady state regimes only.



Test rig arrangement Vehicle gearbox

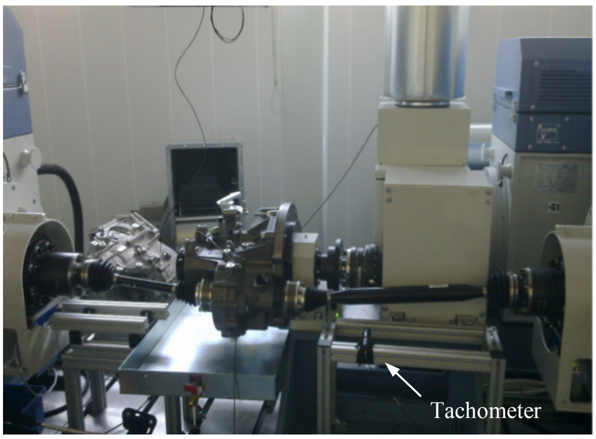


Fig.1The open loop test bed used for investigation of faults in an automotive gearbox

B. Investigated Gearbox

The gearbox used for our measurements is of the type most commonly used in modern small to mid-sized passenger cars with transversely mounted powertrain and front wheel drive; a five-speed gearbox with final drive gear and front wheel differential. The internal arrangement of gears, shafts and bearings is depicted in Fig. 2. One fault is artificially introduced into the gearbox: a dimple to imitate pitting damage on the pinion of the fifth speed mounted on the intermediate or secondary shaft. The gear with the introduced fault is marked in red in the Fig. 2. The fifth speed gear specifications are shown in Table I.

TABLE I
Fifth Speed Gear Specifications

No.	Modal parameter	Notation	Drive Gear	Driven Gear
1	Location in gearbox	--	Input shaft	Intermediate shaft
2	No. of teeth	Z	50	37
3	Youngmodulus (N/m^2)	E	21e10	21e10
4	Gear case	--	Healthy	Faulty (pitted)
5	Poisson's ratio	ν	0.3	
6	Transmission ratio	Rp	0.74	

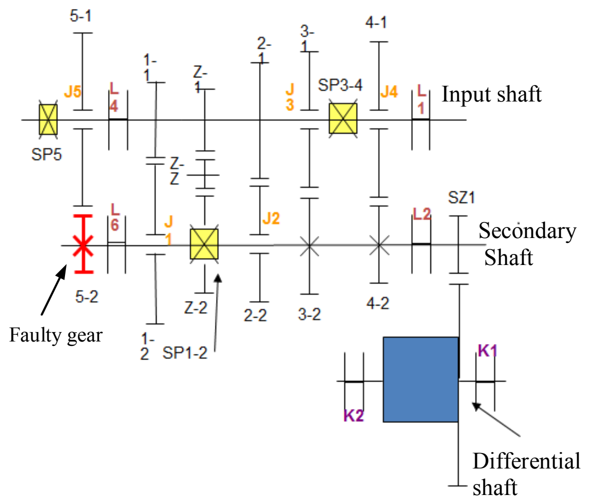


Fig. 2 Diagram of the investigated five-speed automotive gearbox, the highlighted gear is the faulty element

C. Description of the Artificial Damage

Fig.3 shows the pinion for fifth speed with damage on one tooth only. The mesh side of the tooth was damaged by grinding one a pit. The following figure depicts the artificially fabricated fault. The photos and measured data of the pit were acquired with the Video-Probe XLG3 from GE Measurement & Control Systems with the aid of 3D Phase Measurement. The total surface area of the pit is 4.58 mm^2. The gearwheel is treated as damaged if the surface of damage on one tooth is greater than 4% of the tooth surface. In our case the damage equals 3% of the tooth surface. This means there is a significant pit, but the pinion gear can't yet be treated as damaged.

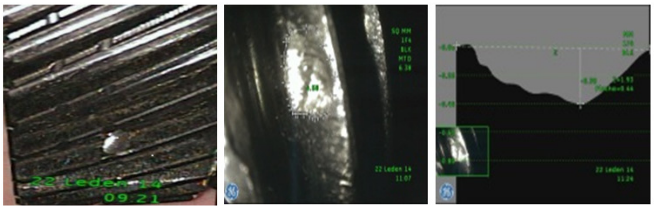


Fig. 3 Detail of the pitting damage created on one tooth only

III. Cepstrum Analysis

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 spectral and the Cepstral. A cepstrum is the forward Fourier transformation of the logarithm of a spectrum. It is therefore the spectrum of a spectrum, and has properties that make it useful in many types of signal analysis. One of its more powerful attributes is the fact that any periodicities, or repeated patterns, in a spectrum will be sensed as one or two specific components in the Cepstrum. If a spectrum contains several sets of sidebands or harmonic series, they can be confusing because of overlap. However, in the Cepstrum, they will be separated in a way similar to the way the spectrum separates repetitive time patterns in the waveform. Gearboxes and rolling element bearing vibrations are especially good candidates for Cepstrum analysis.

Cepstrum, which is an anagram of spectrum, is a nonlinear signal processing technique used to identify and separate harmonic families in the spectra of gearbox signals. Cepstrum is alsoapplied in echo cancellation and speech signal processing. Table II compares the terms used in the spectral and Cepstral analyses. The calculation of Cepstrum involves the inverse Fourier transform of the natural logarithm of a kind of spectrum. Exact definitions vary across the literature. Given a real signal x[n], different Cepstrum forms can be found:

$$C_{cplx} = \frac{1}{2\pi}\int_{-\pi}^{\pi}\log\left[X(e^{j\omega})\right]e^{j\omega n}\,d\omega \tag{1}$$

$$C_{real} = \frac{1}{2\pi}\int_{-\pi}^{\pi}\log\left|X(e^{j\omega})\right|e^{j\omega n}\,d\omega \tag{2}$$

$$C_{power} = \frac{1}{2\pi}\int_{-\pi}^{\pi}\log\left[XX^{*}\right]e^{j\omega n}\,d\omega \tag{3}$$

Since both the Fourier transform and the inverse Fourier transform are complex-domain processes, the cepstrum is complex if the phase information of the original time waveform is preserved. The complex cepstrum has the corresponding inverse complex cepstrum. In this case the time waveform can be reconstructed from a modified cepstrum. Therefore the complex cepstrum can be used for noise reduction and signal separation, such as echo cancellation. On the other hand, if the input of the inverse Fourier transform is real (no phase information), for example, a power spectrum, or the magnitude of the Fourier transform of the signal, the Cepstrum is real-valued. Even though the real-valued Cepstrum cannot be reconstructed back to the time domain, we still can "lifter" a harmonic family in the quefrency domain and obtain a liftered spectrum.

TABLE II
Comparisons of Terms Used in Spectral and Cepstral Analyses

Spectral analysis	Cepstral analysis
Spectrum	Cepstrum
Frequency (Hz)	Quefrency (second)
Harmonic	Rahmonic
Filter	Lifter

IV. Vibration Measurements

One nondestructive technique has been employed to record the gearbox during operation vibration acceleration generation. The test stand is equipped with three dynamometers; the input dynamometer serves as the internal combustion engine, the output dynamometers introduce the load on the flanges of the output joint shafts. A Brüel&Kjaer portable front-end type 3050-B-040 4channel input Module 50KHz analyzer is used. The speed is measured using a Tachometer Type MM360, and a tri-axial (TeltaTron type 4524B with measuring range 500 m/s^2)accelerometer is used to record the vibration acceleration signals, both mounted upon the gearbox case as shown in Fig.1. The vibration signal in vertical and radial terms is presented in this article. The sampling frequency used is 6.4 kHz and signals of 0.5 sec duration are recorded. Recordings were carried out at different operation conditions as shown in Table III.

TABLE III
The Sequences of Measurement at Different Operating Conditions (Load, Speed) for Healthy and Faulty Cases

No.	Input/output speed (rpm)	Input/output torque (Nm)	Gearbox Temp. °C
1	1000/322	50/155	Average 90
2	2000/645	100/310	
3	3000/960	130/402	
4	4000/1290		

V. Results and Discussion

Cepstrum enables detection of periodicities in quefrency domain usually as results of modulation. The frequency spectrum technique will not have information on whether changes come from the source or transmission path. Harmonics and sidebands in the spectrum represent the concentration of excitation energy caused by the rotation component, and they are typically used to detect any abnormality in the operation. Advantages of using the Cepstrum in gear damage identification in the situation of combined effects of the harmonics and sideband in the

Cepstrum appear as a small number of clearly defined rahmonic peaks; it is therefore easier to identify changes in the system. It is able to detect the presence and growth of a sideband and to extract the spectrum periodicity [5].

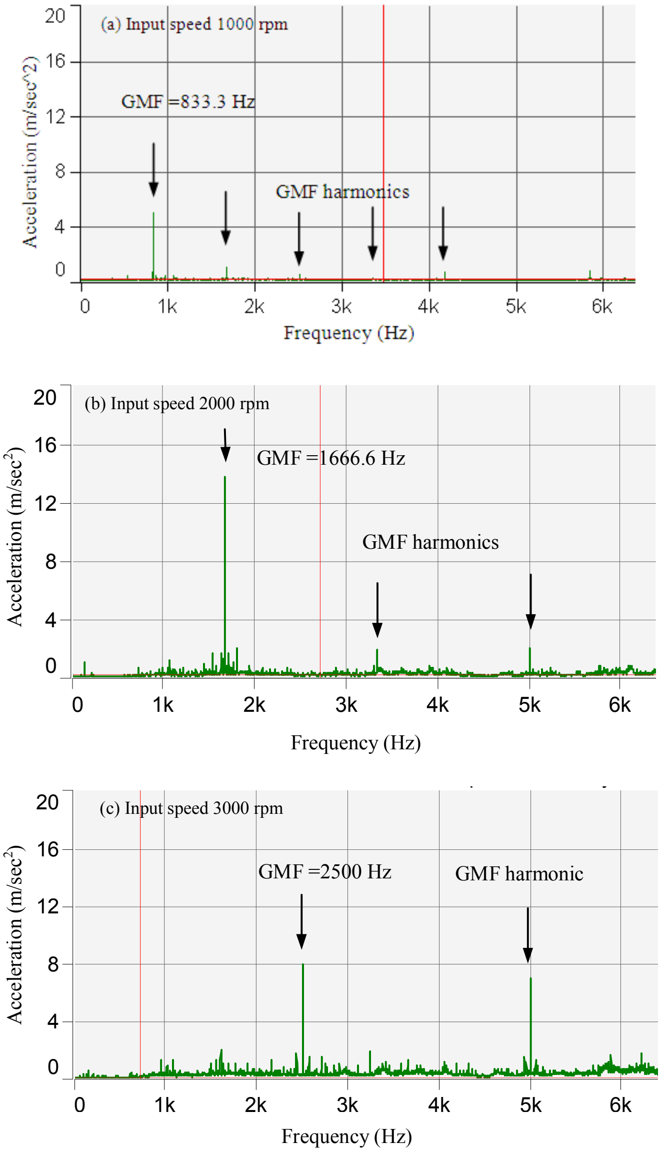


Fig.4 Frequency spectrum for the faulty gear (pitting of tooth) in fifth speed of 1000, 2000, and 3000 rpm, input load 130Nm.

The original non-stationary vibration signals with gear pit fault are displayed in Figs.4-6in terms of frequency, order spectrum and time domain, at different speeds and input/output loads 130/402 Nm. The result of applying a conventional spectral analysis method (FFT) to the specified non-stationary signal is shown in Fig.4.Fig.4 displays the FFT of the vibration signals with the faulty gear and the mesh frequency and its harmonics are shown the position of which depends on the rotation speed and number of gear teeth. It is clear that the resulting spectrum is significantly obscured by spectral smearing. In addition, traditional spectral averaging cannot be applied to the non-stationary signal. Fig.4 clearly shows that spectral smearing substantially affects the result of conventional analysis based on time sampling. Therefore, classical Fourier analysis has some limitation such as being unable to process non-stationary signals. Fig.5 shows the order spectrum at different input shaft speeds and input/output load 130/402 Nm.The mesh order for input shaft (50-teeth drive gear) is displayed at the 50th order and it harmonics.

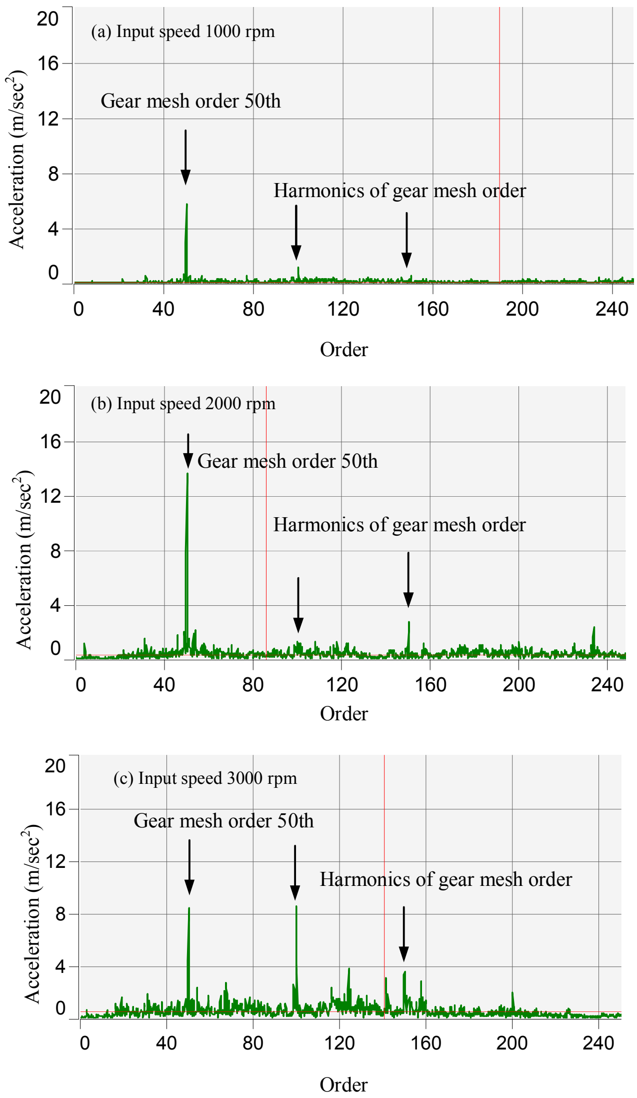


Fig.5Order spectrum for the faulty gear in fifth speed of 1000,2000,and 3000 rpm, input/output load 130/402 Nm

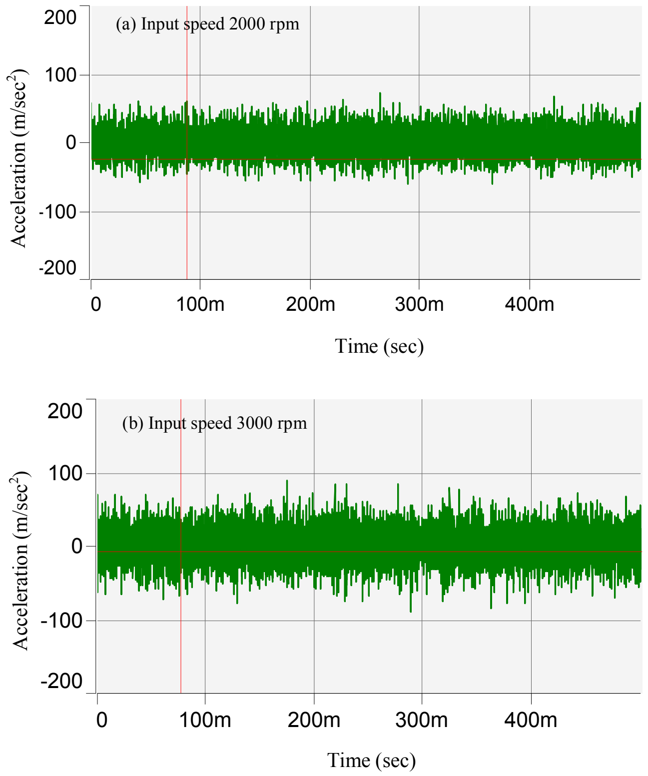


Fig.6Time domain for the faulty gear (pitting of tooth) in fifth speed at 2000, 3000 rpm, input/output load 130/402 Nm

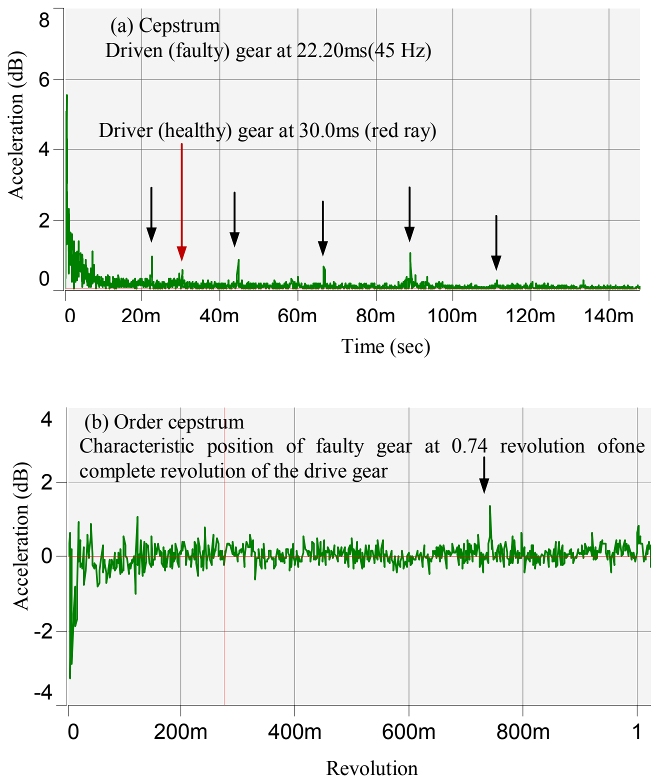


Fig.7Cepstrum analysis at input shaft speed 2000 rpm,and input/output loads 130/402 Nm

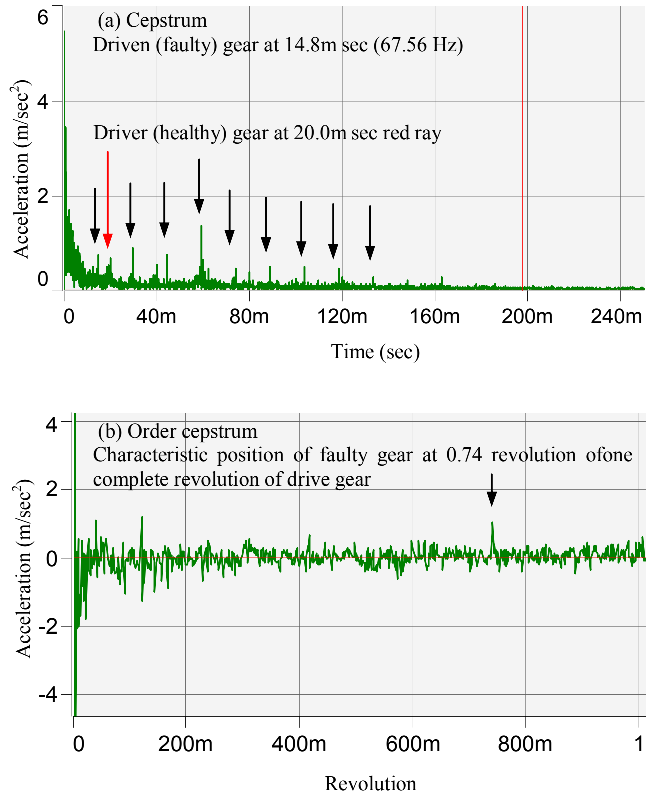


Fig. 8Cepstrum analysis at input shaft speed 3000 rpm, input/output load 130/402 Nm

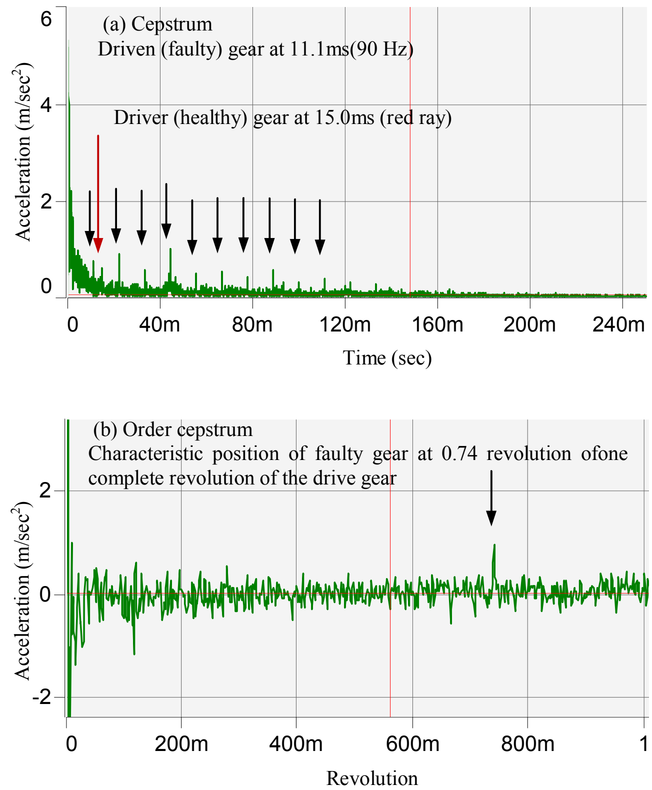


Fig.9Cepstrum analysis at input shaft speed4000 rpm, input/output load 130/402 Nm

Figs. 7 (a), 8 (a), and 9 (a) show how severe the damage of the driven gear is, by presenting the number of rahmonics of driven shaft rotation as the source of the problem. Cepstrum indicates periodicity at22.22 ms, which is 45 Hz, or rotation by the driven shaft for input shaft speed 2000 rpm and 14.8 ms,11.1ms,which is 67.56 Hz and 90Hz, or rotation by the driven shaft for input shaft speed 3000 rpm and 4000 rpm respectively.

The order cepstrum is depicted in Figs. 7 (b), 8 (b), and 9 (b). In the case of the order cepstrum, it can be seen that the characteristic order for a faulty gear, gear mesh ordersand its harmonics are represented in the order cepstrum. The simplicity of the order quantity representation can be put down to the ability of the order signal processing method to eliminate undesirable spectral smearing and modulation effects.

Figs. 7 (b), 8 (b), and 9 (b) demonstrate the advantage of the order cepstrum for the analysis of vibration signals generated at different input shaft speed. From Figs. 7to9, one can draw the conclusion that the order cepstrum can identify the characteristic order. Therefore, it can be used to detect the fault ina gear.

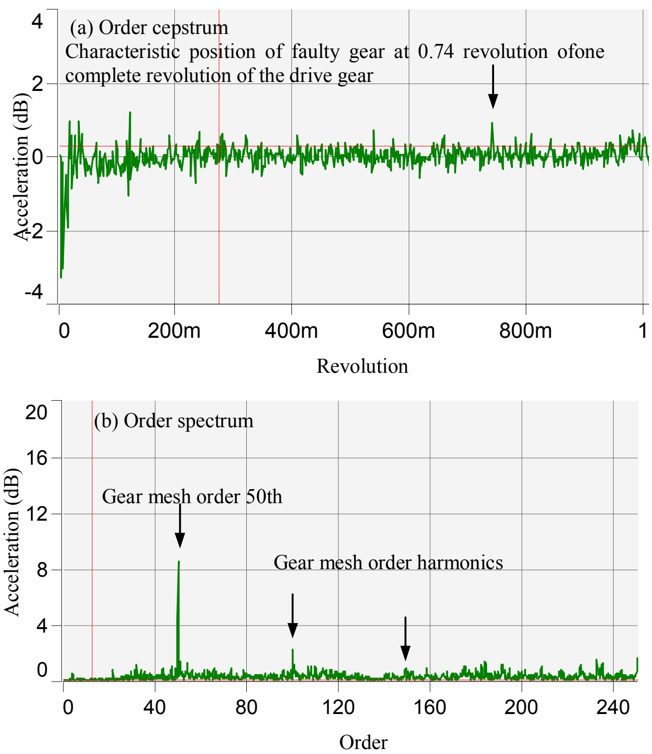


Fig.10Order cepstrum and order spectrum analysis at input shaft speed 2000 rpm, input/output load 50/155 Nm

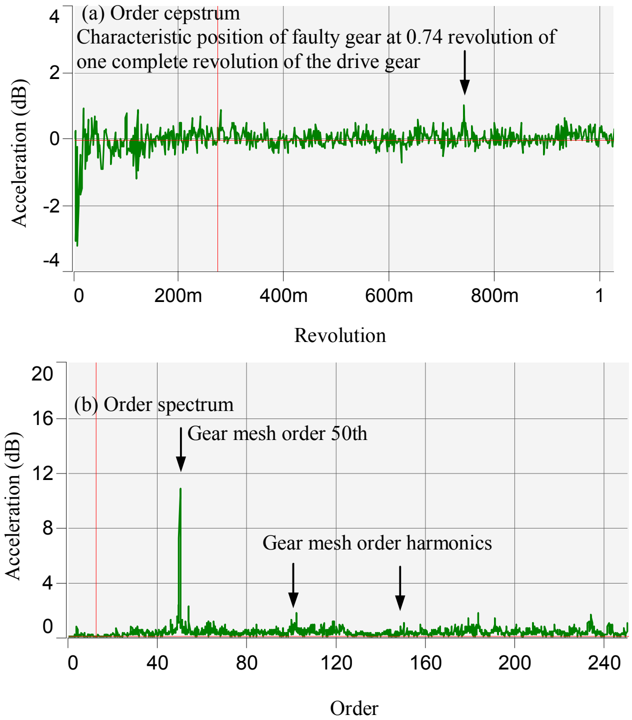


Fig. 11Order cepstrum and order spectrum analysis at input shaft speed 2000 rpm, input/output load 100/310 Nm

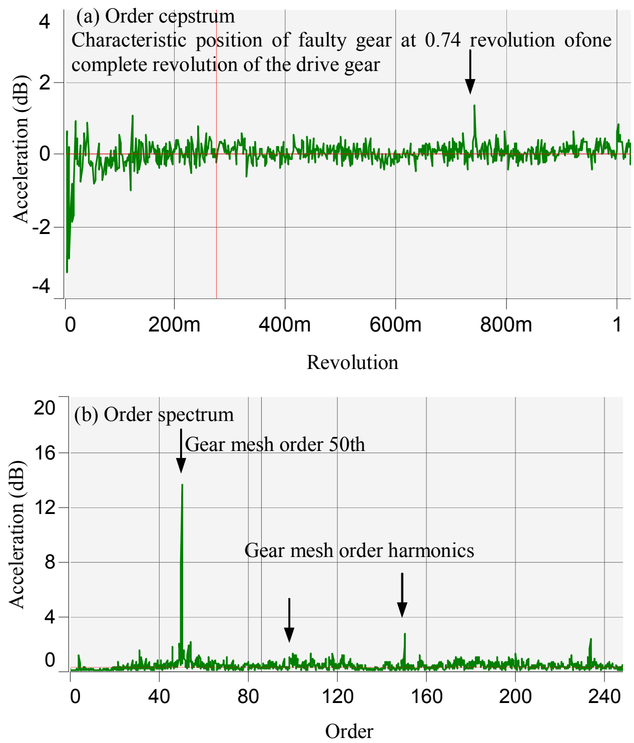


Fig. 12Order cepstrum and order spectrum analysis at input shaft speed 2000 rpm, input/output load 130/402 Nm

Figs. 10-12 show order cepstrum and order spectrum at input shaft speed 2000 rpm and different input and output loads from 50 Nm and 155 Nm, 100 Nm and 310 Nm to 130 Nm and 402 Nm respectively, as shown in Table II item 2.The effect of load is seen in the order spectrum Figs.10 (b), 11 (b), and 12 (b) as the amplitude peak increases at gear mesh order with increasing input and output load, and some harmonics appear. On the other hand, the order cepstrum remainslargelyunchanged from low to high loads. Therefore, one can draw the conclusion that the order cepstrum can identify the characteristic order of a faulty gear at both low and high load. Therefore, it can be used as a full fault diagnosis technique for gearboxes.

VI. Conclusion

Cepstrum analysis appears to be efficient for detecting changes not easily noticeable in the spectrum. A major benefit of using the Cepstrum technique would be earlier damage identification as changes clearer and easier to identify.

The order cepstrum can identify the characteristic order. Therefore, it can be used in full fault diagnosis of a vehicle gearbox.

The order cepstrum can identify the characteristic order of a faulty gear at low and high load.

Acknowledgment

This publication was supported by the European Social Fund within the framework of realizing the project “Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague”, Prague, Czech Republic, CZ.1.07/ 2.3.00/ 30.0034.

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