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Modern Vibration Signal Processing Techniques for Vehicle Gearbox Fault Diagnosis

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Abstract**—**This paper presents modern vibration signal-processing techniques for vehicle gearbox fault diagnosis, via the wavelet analysis and the Squared Envelope (SE) technique. The wavelet analysis is regarded as a powerful tool for the detection of sudden changes in non-stationary signals. The Squared Envelope (SE) technique has been extensively used for rolling bearing diagnostics. In the present work a scheme of using the Squared Envelope technique for early detection of gear tooth pit. The pitting defect is manufactured on the tooth side of a fifth speed gear on the intermediate shaft of a vehicle gearbox. The objective is to supplement the current techniques of gearbox fault diagnosis based on using the raw vibration and ordered signals. 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 output joint shafts. The gearbox used for experimental measurements is 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 results show that the approaches methods are effective for detecting and diagnosing localized gear faults in early stage under different operation conditions, and are more sensitive and robust than current gear diagnostic techniques.

Keywords**—**Wavelet analysis, Squared Envelope, gear faults.

I. INTRODUCTION

THE wavelet analysis is an effective tool for the detection of sudden changes in non-stationary signals. It has the property of time-scale localization, which is particularly useful in the analysis of vibration signals with short time transient phenomena, such as the SA generated by a faulty gear with a fatigue tooth crack. In this paper, the wavelet analysis is applied to the residual signal of gear meshing vibration [1].

The resonance demodulation works in a similar way to the commonly used narrow-band demodulation, but emphasizes a different frequency band. The former emphasizes the band associated with the structural resonance excited by the fault-induced impacts, whereas the latter focuses on the fault-induced high order modulation sidebands around the dominant gear meshing harmonic. For both approaches, the kurtosis value of the demodulated signal is normally used as an indicator of gear faults. A scheme of using the resonance demodulation technique for early detection of gear tooth cracks was presented by [2]. The objective of the resonance demodulation technique is to supplement the current techniques of gearbox fault diagnosis based on the synchronous signal averaging technique. It was focused on the fact that gear tooth crack produced vibration impacts that would excite the structural resonances when the cracked tooth was engaged. Using this scheme, the regular gear meshing harmonics were first removed from the synchronous signal average to generate the residual signal. The residual signal was then band-pass filtered around a structural resonance within the range of gear meshing harmonics. The band passed residual signal is demodulated to extract the features related to the crack induced sudden change in a complete revolution of the gear of interest. Resonance demodulation technique focuses on the analysis of the structural resonance excited by the impacts produced by the local gear fault. This can be achieved by utilizing the resonance demodulation technique (also known as the envelope technique) which has been extensively used in the diagnosis of rolling bearings. The structural resonance, in this case, can be seen as an amplifier to the low-energy impacts. A scheme of using the resonance demodulation technique [3] was discussed for the diagnosis of gear tooth crack.

A number of statistical measures can then be used on the demodulated signal as an indicator on the existence and status of gear fault. In the present work, the modern approaches are used for detecting and diagnosing localized gear faults under different operation conditions, and compared with current gear diagnostic techniques.

The Kurtosis is simply the normalized fourth moment of the signal. The moment is normalized to the square of the variance of the signal. The kurtosis is a statistical measure of the number and amplitude of peaks in a signal. That is, a signal that has more and sharper peaks will have a larger value [4].

$$Kurtosis = \frac{N\sum_{i=1}^{N}(x-\bar{x})^4}{\left[\sum_{i=1}^{N}(x-\bar{x})^2\right]^2} \tag{1}$$

where, $\bar{x}$: The mean value of signal; x: The signal in time domain; N: The number of data points.

II. DESCRIPTION OF THE TEST SET-UP

A. Investigated Gearbox

Gears are widely used in parallel axes drives where high speeds and power are involved and are used to transmit motion and power between parallel shafts when the application requires higher speeds and loads. The gearbox

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used for our measurements is 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. 1, a diagram of the investigated five-speed automotive gearbox.

In this paper, one fault is artificially introduced into the gearbox: It is a dimple which imitates a pitting damage on the fifth speed pinion mounted on the intermediate shaft. The gear with the introduced fault is marked in red on the Fig. 1. Fifth speed gear specification is shown in Table I.

TABLE I
FIFTH SPEED GEAR SPECIFICATION

No.	Modal parameter	Notation	Drive Gear	Driven Gear
1	Location in gearbox	--	Input shaft	Intermediate shaft
2	No. of teeth	Z	50	37
3	Young modulus (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	

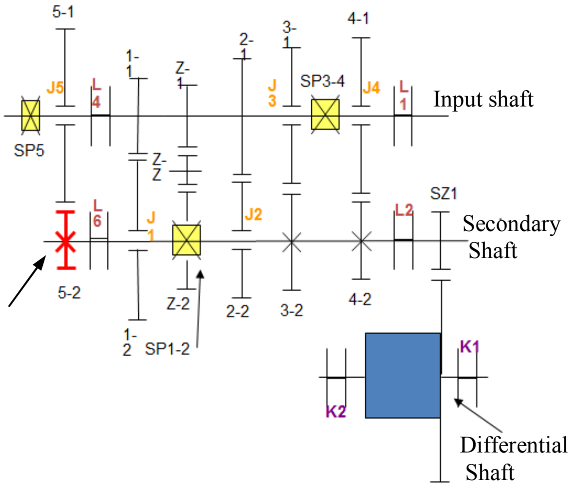
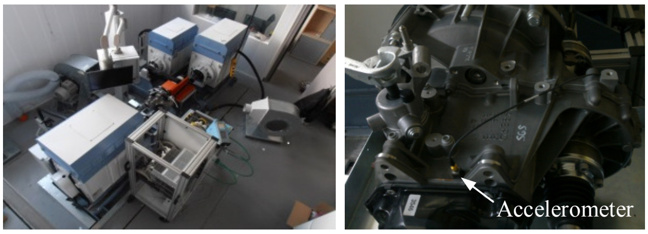


Fig. 1 Diagram of the investigated five-speed automotive gearbox, the highlighted gear is the faulty element

B. 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. Fig. 2 shows the real photo of arrangement layout of test rig components and indicates to the accelerometer and tachometer positions.



Test rig arrangement Vehicle gearbox

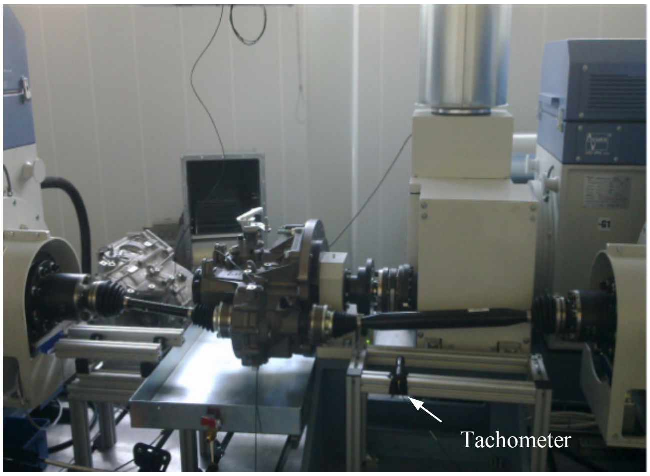


Fig. 2 The open loop test bed used for investigation of faults in an automotive gearbox

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 the present work, 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.

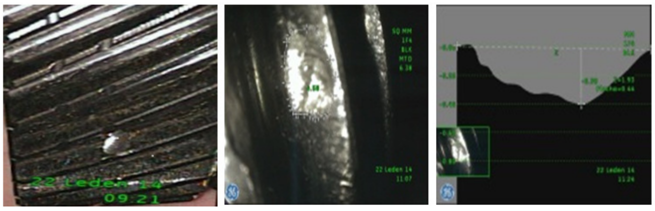


Fig. 3 Detail of the pitting damage created on one tooth only

III. MORLET WAVELET FILTER

A. Morlet Function

The continuous wavelet transform (CWT) is used to obtain the wavelet coefficients of signals [5]. The statistical parameters of the wavelet coefficients are extracted which constitute the feature vectors. The Morlet wavelet is one of the most popular non-orthogonal wavelets, the definition of Morlet is:

$$\psi(t) = \exp(\frac{\beta^2 * t^2}{2}) \cos(\pi t) \tag{2}$$

It is a cosine signal that decays exponentially on both the left and right sides. This feature seems very similar to an impulse. It has been used for impulse isolation and mechanical fault diagnosis through the performance of a wavelet denoising procedure. However, in practice, it is not easy to provide a proper threshold for wavelet denoising. This is can be avoided by using an adaptive wavelet filter instead of wavelet denoising [5].

B. Adaptive Morlet Wavelet Filter

A daughter Morlet wavelet is obtained by time translation and scale dilation from the mother wavelet, as described in the following formula [7]:

$$\psi_{a,b}(t) = \psi(\frac{t-b}{a}) = \exp[-\frac{\beta^2 (T-B)^2}{2a^2}] \cos[\frac{\pi(t-b)}{a}] \tag{3}$$

Where (a) is the scale parameter for dilation and (b) is the time translation. It can also be looked at as a filter. To identify the immersed impulses by filtering, the location and the shape of the frequency band corresponding to the impulses must be determined first. Scale (a) and parameter (β) control the location and the shape of the daughter Morlet wavelet respectively. As a result, an adaptive wavelet filter could be built by optimizing the two parameters for a daughter wavelet [5], [6]. Several researchers have reported on how to select a mother wavelet that adapts the best to the signal to be isolated. The method of (β) selection in a Morlet wavelet is based on maximum Kurtosis. Details of how to select (β) and (a) in a Morlet wavelet based on Kurtosis to make the mother wavelet match the signal to be isolated were provided in [6]. In this analysis, focus has been placed on finding the best wavelet filter (the daughter wavelet of a Morlet wavelet) instead of optimal wavelet reconstruction.

IV. SQUARED ENVELOPE ANALYSIS

The squared envelope analysis focuses on the analysis of the gearbox body resonance excited by the impacts produced by the local gear fault. This can be achieved by utilizing the resonance demodulation technique (envelope analysis) which has been extensively used in the diagnosis of rolling bearings.

The gearbox body resonance, in this case, can be seen as an amplifier to the low-energy impacts. In the present paper, a scheme of using the resonance demodulation technique [3] is discussed for the diagnosis of gear tooth pit.

The resulting signal is regarded as the squared envelope that describes the power of the envelope signal, to avoid the masking effect which is caused by the extraneous components introduced by rectification operation in the envelope analysis.

V. VIBRATION MEASUREMENTS AND RESULTS

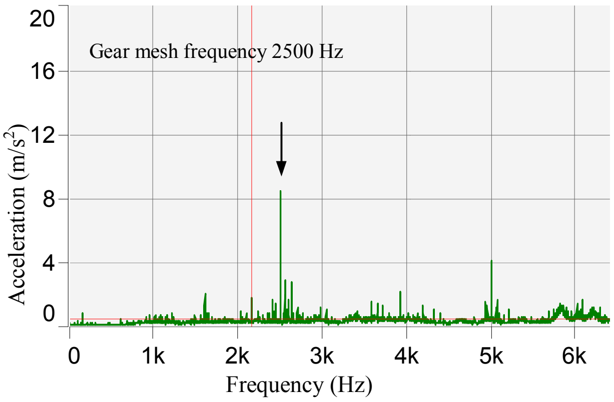
Significant effort was dedicated to the signal processing of the vibration waveforms acquired during the tests. The goal set a priori is to measure and calculate a number of parameters features extracted by the signals and check their behavior during the tests in order to identify the most promising ones that may be used for damage detection and condition monitoring of the gear system.

One non-destructive technique, vibration acceleration generation, was employed to record the gearbox during operation. The vibration signals are simultaneously measured from the casing of the damaged gearbox unit. A tri-axial (Telta Tron piezoelectric accelerometers type 4524B with measuring rang 500 ms^{-2}) accelerometer is used for recording vibration acceleration signals that mounted upon the gearbox case as shown in Fig. 2. The vibration signal in vertical and radial terms is presented in this article. The selected sampling frequency range is 6.4 kHz and signals of 0.5 sec duration. A Brüel & Kjær portable front-end type 3050-B-040 4channel input Module 50 kHz analyzer is used. Also, a tachometer type MM360 is used to measure the input shaft speed. Recordings are carried out at two cases, the first one at input shaft speed 3000 rpm and input shaft load 130 Nm and the second one at input shaft speed 3000 rpm and input shaft load 50 Nm. The analyses are limited to the frequency range 0-6.4 kHz which includes the most meaningful meshing harmonics. The digital signals are processed and analyzed by means of the Lab-Shop and MatLab software.

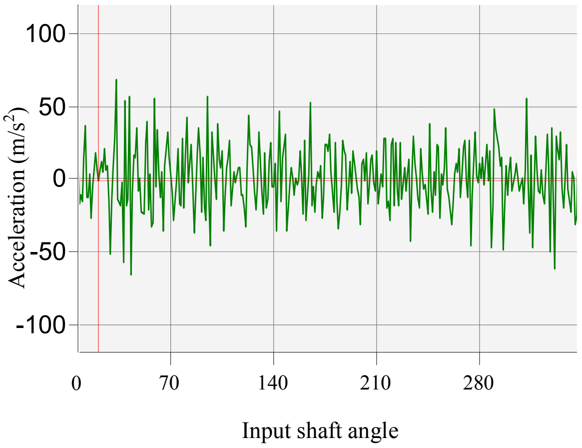
Time synchronous averaging is used as the common method for early detection of failure in gears: by synchronizing the sampling of the vibration signal with the rotation of a particular gear and evaluating the ensemble average over many revolutions with the start of each frame at the same angular position, a signal -called Time-Synchronous Average (TSA) is obtained, which in practice contains only the components which are synchronous with the revolution of the gear in question. Sufficient averages are taken and the TSA is approximated a truly periodic signal with periodicity corresponding to one revolution of the selected gear (wheel gear on input shaft). This method requires a reference signal for determining the angular position of the gear in question. The TSA of the experimental synchronized signals evaluated over 25 revolutions of the wheel [2] (i.e. input shaft gearwheel meshed with pitted pinion gear).

In this paper, the existing vibration data collected in real vehicle gearbox as shown the Fig. 2 at certain operation condition as mention before is used. Fig. 4 shows the measured vibration signal analysis and the corresponding spectrum and residual signal after de-nosing it by using CWT. From Figs. 4 (a) and 5 (a), it's clearly seen that the dominance of a gear mesh frequency related to the input shaft gear (50 teeth) at input shaft speed 3000 rpm or a gear concerned has 37 teeth and speed 4054 rpm. In Figs. 4 (b) and 5 (b), TSA of raw signal of input shaft (the input shaft gear has 50 teeth and

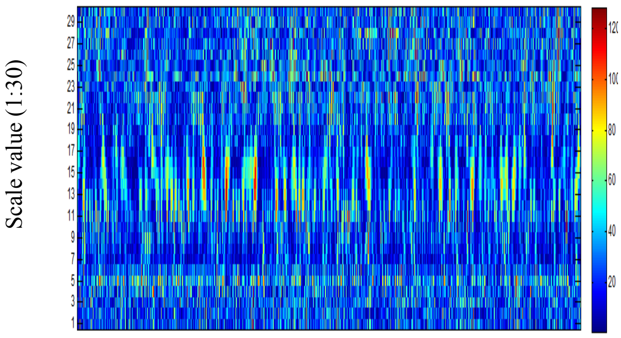
3000 rpm in fifth speed). The resonance can be excited by both gear meshing harmonics and the impacts produced by the pitted tooth. The difference between these two forms of excitations is that the resonant vibration produced by the meshing harmonics exists across the whole revolution of the gear and may be seen for healthy gears, whereas the pit-induced resonance is only a local phenomenon.



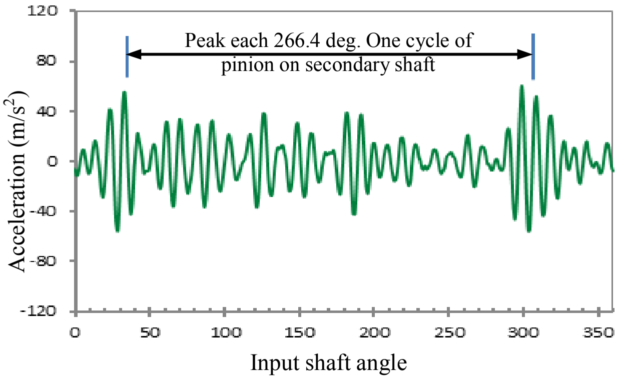
(a) Frequency spectrum of faulty gear



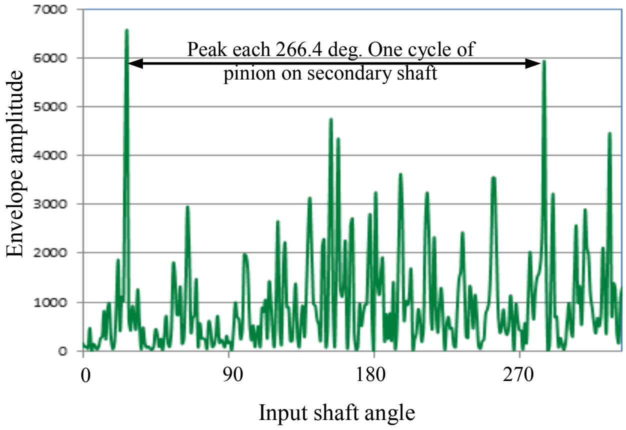
(b) The T.S.A of input shaft signal



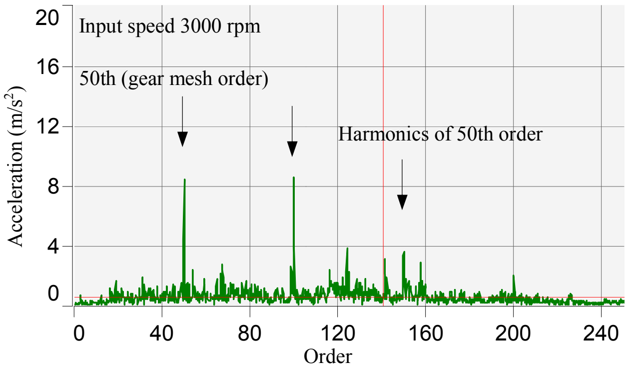
(c) The Wavelet map (β =0.6 and a =7)



(d) Residual signal (β =0.6 and a =7)



(e) Squared Envelope signal for TSA signal



(f) Order spectrum

Fig. 4 Analysis of gear meshing signal at input shaft speed 3000 rpm and input shaft load 130Nm

Therefore, the identification of the localized resonant vibration would be, in principle, valuable to the detection of gear-tooth pits. By examining the residual signals, some sudden changes are identified as indicated by the high frequency oscillations, as shown in Figs. 4 (d), (e) at about 25^{o} to 35^{o} and 290^{o} to 300^{o} of shaft angle (relative to the tachometer's triggering point) and this indicates to the concerning fault gear (37 teeth on secondary shaft that complete it cycle each 0.74 of input gear cycle) which indicates accurately to the faulted gear, along with some remaining gear meshing components.

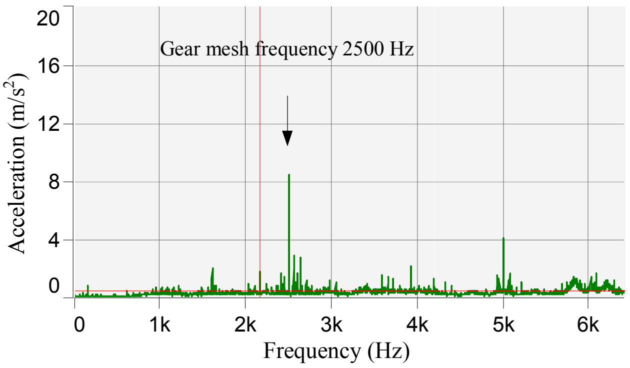
Despite these visual cues, at input shaft load 50 Nm the Kurtosis values of TAS of raw signal equals only 3.072 which is far below the generally accepted critical value of 4.5 [2], for the residual signal is 4.625. By investigating the squared envelope signal, Fig. 4 (e) has a distinct peak at around 25° to 35° and 290° to 300° of the input shaft angle in degrees as shown in Fig. 5 (e), the calculated Kurtosis value of squared envelope is 11.626 at same condition (low load) then the wavelet analysis and squared envelope have affected techniques in fault detection and diagnostic. Also, Figs. 4 (d), (e) in residual signal and the squared envelope signal have a distinct peak at around 25° to 35° and 290° to 300° of input shaft angle in degree. At high load, the calculated Kurtosis value reached to 6.892 for residual signal, and reached to 8.44 for same condition in the squared envelope signal, providing a clear indication of the local gear fault especially at low load. To evaluate the wavelet and squared envelope analyses, Kurtosis values are used as an indicator parameter feature and even more responsive to the fault. Assessment of the performance of the proposed methods is presented in Table II for the studied cases.

TABLE II
EVALUATION OF THE WAVELET AND SQUARED ENVELOPE ANALYSIS EFFECT AT INPUT SHAFT SPEED 3000 RPM

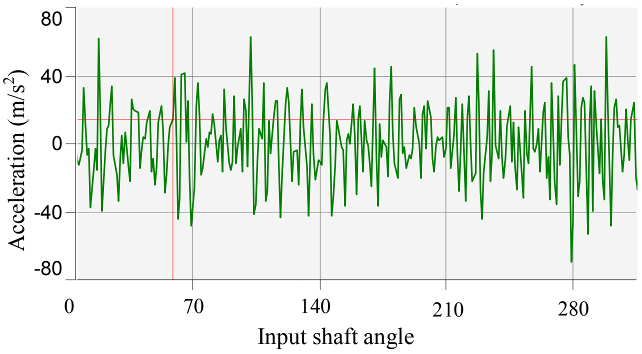
Input shaft Load (Nm)	Kurtosis T.S.A signal	Kurtosis residual signal	Kurtosis squared enveloped
130	3.269	6.892	8.44
50	3.072	4.625	11.626

By investigation of the Kurtosis values in Table II, the effectiveness of the proposed techniques in gear fault diagnosis are evidenced specially the squared envelope analysis at low load.

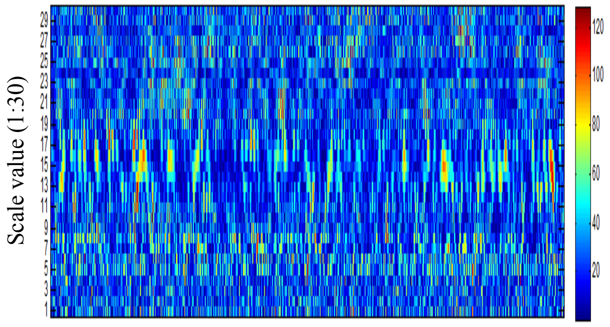
Figs. 4 (f) and 5 (f) show order spectrum at different load where the gears mesh orders (fifty orders) and its harmonics are significant that can be used in fault diagnosis during constant speed and variable speed (speed up or down).



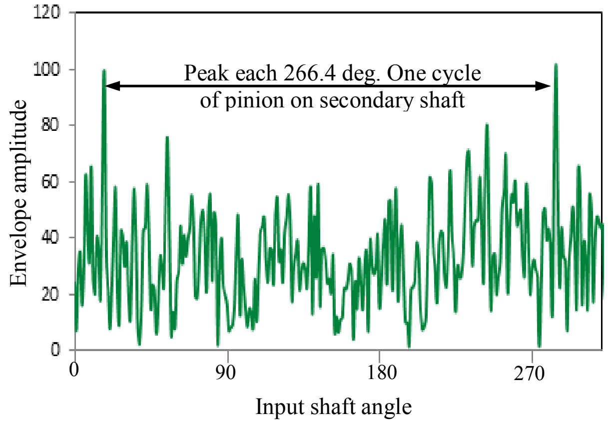
(a) Frequency spectrum (Hz) of input shaft gear



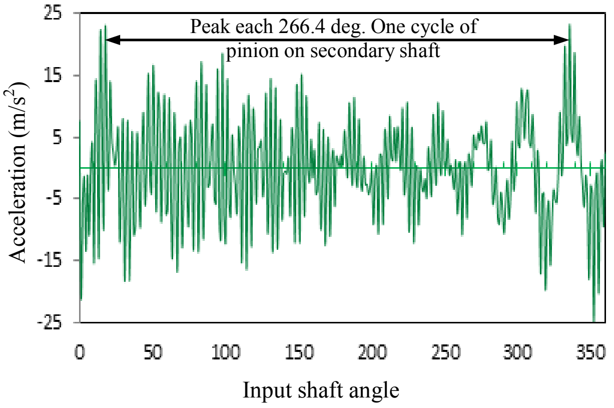
(b) The TSA of input shaft gear in degree (360°)



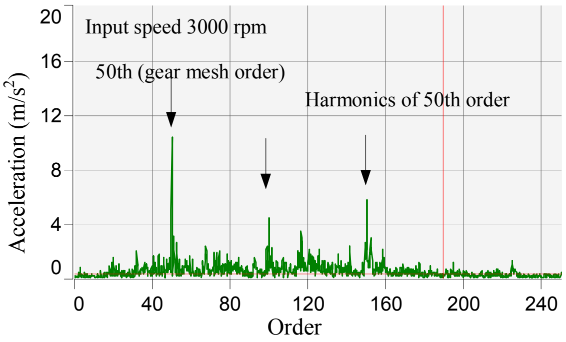
(c) The Wavelet map (β =0.1 and a =27)



(d) Squared Envelope signal



(e) Residual signal



(f) Order spectrum

Fig. 5 Analysis of gear meshing signal at input shaft speed 3000 rpm and input shaft load 50Nm

VI. CONCLUSIONS

This article used two Modern techniques associated with rotating machinery fault diagnosis: wavelet and squared envelope analyses. Both the wavelet and squared envelope analyses are useful tools to identify the fault frequencies and distinguish them from other frequency contents.

As faults localized in one tooth produce transient dynamic effects, the application of the WT appears well suited. This technique seems possible to localize the damaged tooth. The presented results show that the WT of the raw signals is practically insensitive to a gear pit, while the sensitivity of the WT of TSA signals is quite satisfactory. Thus, for a complete diagnosis, it is necessary to repeat the analysis with reference to each gear in the machine. Moreover, as the pit effects are evident only in some frequency ranges, a fault detection procedure would be strongly dependent on the choice of a proper cross-section in the WT map. This limit is overcome if the residual of the TSA signal is processed by the WT.

The analysis results presented in this paper have demonstrated that the wavelet analysis and squared envelope techniques provide an effective supplement to the current techniques of gearbox fault diagnosis based on synchronous signal averaging method. The kurtosis of the squared envelope signal is a robust indicator of gear tooth pits. This technique has some advantages over the current gear diagnosis techniques and is thus potentially a powerful tool for gear fault diagnosis.

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