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# **A procedure of vibration analysis from planetary gearbox under non-stationary cyclic operations for instantaneous frequency estimation in time-frequency domain**

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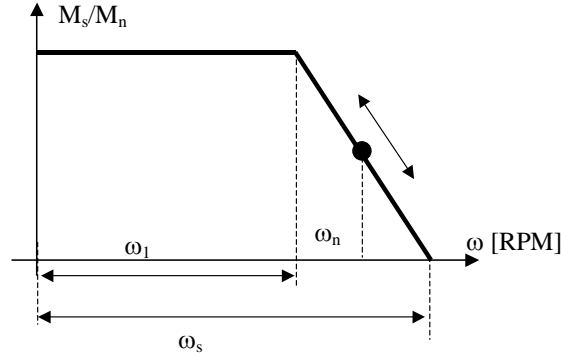
## **Abstract**

Condition monitoring of gearboxes via vibration analysis is a well-recognized approach in scientific literature and also in engineering practice. However, in many cases, the machines work under non-stationary operating conditions (load and speed variation), that often require specific signal processing and pattern recognition suitable for time varying systems. One of the key problems is to identify the variations of operating conditions (i.e. external load or rotational speed of input shaft in gearbox). The measurement of current consumed by electric motors or instantaneous speed obtained by processing of tachometer signal may be difficult or impossible in many industrial conditions. In such case, non-stationary load variations may be identified by extraction of information hidden in vibration signals. For example, it may be extracted from amplitude or frequency demodulations. Unfortunately, both approaches are difficult (or even impossible) for our machines due to complexity of design and wide range of load/speed variation. In order to avoid these constraints, new approach is proposed in this paper and exploited for complex, multistage gearboxes with planetary stage. Cyclic load variations are extracted from the instantaneous speed estimated via a time-frequency spectrogram of vibration signals. Algorithm for instantaneous frequency estimation of a single component via T-F maps has been developed by Millioz and Martin. In this paper, a procedure using this algorithm is proposed for estimating the instantaneous speed, and applied to vibration signals from planetary gearboxes.

## **1. Introduction**

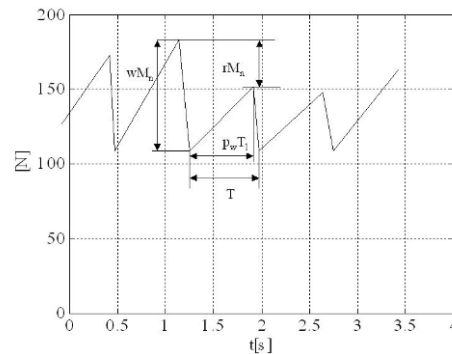
Condition monitoring of gearboxes via vibration analysis is a well-recognized approach in scientific literature and also in engineering practice. However, in many cases machines work under non-stationary operating conditions that influence amplitude and frequency content of vibration signals [1][2]. If there is no speed control system in drive unit

(motor/coupling/gearbox), change of external load will introduce change of input speed, Fig1. During normal operation, electric motor should run at speed range ( $\omega_1:\omega_s$ ), nominal speed  $\omega_n$  being usually in the middle, . The speed is smaller than  $\omega_1$  for run up or run down condition only. It is not the case considered here.



**Fig 1. Simplified characteristic of Electric Motor [5]**

Using this property it is possible to identify speed variations by processing of vibration signals. By tracking instantaneous frequencies, for example mesh frequency and its harmonics, it is possible to obtain information about input speed variations [3] [4]. In the application dealt in this paper, speed variations are quite strong and cyclic due to the nature of the digging process executed by a bucket wheel excavator – a machine used in mining industry (Fig 2a). Fig 2b shows the expected external load/speed profile, got from a theoretical model proposed by Bartelmus [5]. “T” denotes the period of a saw tooth cycle related to the digging of one bucket; “ $p_w$ ” is a parameter describing relative duration (in percents) of digging cycle, when load is increasing, after “ $p_w$ ” load is quickly decreasing and cycle is repeating. Each cycle may have different amplitudes depending on some factors such as geology, temperature, condition of buckets, so parameter “r” is a coefficient used to “randomize” amplitude of consecutive segments.



**Fig.2 Theoretical variation of external load in bucket wheel excavator during digging**

In order to estimate such speed profiles from real signals, it is proposed to use an automatic time-frequency segmentation algorithm developed by Millioz and Martin [16]. In this paper, we propose a procedure based on the mentioned algorithm able to provide reliable information about operating conditions. The procedure is based on automatic detection of the instantaneous frequency for specific mesh harmonics.

Other approaches based on amplitude or frequency demodulations are difficult to use. For example, frequency demodulation based on Hilbert transform is not convenient due to carrier frequency selection/extraction from multi-components signal. The methodology proposed by Bonnardot [19] and developed further by Combet [20] is able to demodulate

frequency for limited fluctuation of the speed (less than 1%). It requires carrier and bandwidth (around the carrier) selection that not contain any components disturbing phase of the carrier. In analysed case speed fluctuation is around 4% [6] so due to time varying load, complexity of the frequency content (multistage gearbox) and high reduction ratio (sidebands related to low speed shafts are very close to carrier for example output shaft rotation is 5rpm), time varying SNR etc., it is suggested to use other techniques as for example peak extraction in time – frequency domain.

An example of a spectrogram computed with a vibration signal from a planetary gearbox is shown in Fig3. It is easy to find similarity between expected load profile (Fig.2b) and instantaneous frequency for a several mesh harmonics,  $f=\{2200, 2700, 3100\}$ [Hz], Fig 3. Fig. 3 shows both amplitude and frequency modulation (peaks of amplitude harmonics 2600Hz marked by arrows).

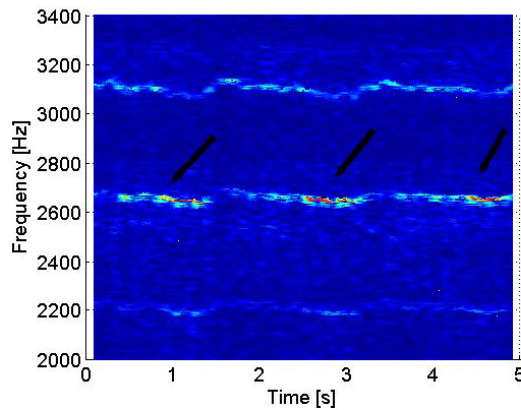


Fig 3. Example of time frequency map of planetary gearbox vibration under time varying cyclic load

## 2. Modelling of signals

In order to extract required information from vibration signal generated by gearbox, especially by multistage gearbox with planetary stage, working under time varying operating conditions, there is a need to understand frequency contents of vibration signal and phenomena that exist in mechanical system, i.e. sources of vibration and mechanisms of generating signals). In this section, a simple model of signal for a need of operating conditions identification will be formulated.

### 2.1 Planetary Gearbox vibration signal @ stationary load

Vibration signal generated by a gearbox, single stage - one gear pair, is described often as a sum of sinusoidal components

$$S_{gear}(t) = \sum_{i=1}^N A_i \cdot \sin(2 \cdot \pi \cdot i \cdot f_{mesh} \cdot t + \varphi_i) + n(t) \quad (1)$$

where

$S_{gear}$  - signal generated by gear pair,  $A_i$  - amplitude of  $i^{th}$  harmonic,  $f_{mesh}$  - mesh frequency,  $\varphi_i$  - phase of  $i^{th}$  harmonic,  $i$  - order of harmonic component,  $N$  – number of harmonics that can be detected in spectrum, usually  $N=5-6$  for fixed axis gearbox,  $N=8$  for planetary gearbox, depends on condition/cooperation/design of gear pair, SNR of the signal etc.,  $n(t)$  - a centered white gaussian noise

In fact, real vibration signals from multistage planetary gearbox are very far from this simple model. We have neglected frequency contents related to other stages, shafts, bearings, (according to our experience they have much lower energy), influence of transmission path etc. From detection point of view it can be treated as interference and it will be modelled as noise. However, for the application concerned in this paper, the planetary stage vibration is much stronger than from remaining stages so we neglect other sources. For more details related to gearbox modelling it is advised to study works done for example by [7], [8], [10], [9], [11] and other. This simple model is recalled here to help to understand in next section what will happen with gear pair vibration when time-varying operating conditions are applied.

## 2.2 Operating condition variation. Planetary Gearbox signal @ non-stationary load

A machine can work under constant or time-varying operating conditions. Time varying operating conditions may be related to external load variation, input speed variation or simultaneous speed and load variation.

- **Load variation** with constant speed affects amplitudes of the gearbox vibration response. If load variation is cyclic (periodic) it produces amplitude modulation of gear signal. Let's assume that source of modulation – according to Fig. 2,3 - is:

$$S_{LOAD}(t) = A(t) \cdot \text{sawtooth}(2 \cdot \pi \cdot f_{LOAD} \cdot t, \Delta) \quad (2)$$

where:

$S_{LOAD}(t)$  is external load profile ( signal describing variation of load),  $A(t)$  is an unknown value related to the parameters of digging (geology, environmental impact, operator' skills etc),  $f_{LOAD}$  – frequency of digging,  $f_{LOAD} = 1/T_{bucket}$   $\Delta$  - ratio,  $T_{bucket}$  -cycle of digging

Any periodic signal may be represented by a linear combination of harmonic components:

$$S_{LOAD}(t) = \sum_{i=1}^M A_i \cdot \sin(2 \cdot \pi \cdot i \cdot f_{LOAD} \cdot t + \phi_i) \quad (3)$$

The model of the signal generated by a gearbox may be as follows:

$$S_{gear@TVLC}(t) = (1 + S_{LOAD}(t)) \cdot S_{gear}(t) \quad (4)$$

$$S_{gear@TVLC}(t) = (1 + A(t) \cdot \text{sawtooth}(2 \cdot \pi \cdot f_{LOAD} \cdot t, \Delta)) \cdot \sum_{i=1}^N A_i \cdot \sin(2 \cdot \pi \cdot i \cdot f_{mesh} \cdot t + \phi_i) \quad (5)$$

- **Speed variation**, with constant load, affects frequency contents of the gearbox vibration response. If speed variation is cyclic (periodic) it produces frequency modulation of the gear signal. Let's assume that the source of modulation is the same as for AM.

$$S_{gear@TVLC}(t) = \sum_{i=1}^N A_i \cdot \sin(2 \cdot \pi \cdot i \cdot (f_{mesh} + A(t) \cdot \text{sawtooth}(2 \cdot \pi \cdot f_{LOAD} \cdot t, \Delta)) \cdot t + \phi_i) \quad (6)$$

Please note that  $f_{mesh}(t)$  is a function of  $t$  because if the input speed is time varying, the mesh frequency is varying, too. For a simple gear pair,  $f_{mesh}$  is a scaled version of the input speed.

$$f_{mesh} = f(\text{number\_of\_tooth}, \text{input\_speed}) \quad (7)$$

- In case of **simultaneous load and speed**, the gear-pair response can be modelled as a simultaneous AM/FM modulation:

$$S_{gear@TVLC} = (1 + S_{LOAD}) \cdot \left( \sum_{i=1}^N A_i \cdot \sin(2 \cdot \pi \cdot i \cdot (f_{mesh} + A(t) \cdot \text{sawtooth}(2 \cdot \pi \cdot f_{LOAD} \cdot t, \Delta)) \cdot t + \phi_i) \right) \quad (8)$$

If the modulating frequency is small (this is a case for the application dealt in this paper,  $T_{bucket} > 0.5$  [s]) it is difficult to extract component with carrier frequency in order to demodulate frequency, i.e. get information about source of modulation.

### 3. Instantaneous frequency estimation via time frequency analysis - theoretical background.

In this section, we describe a generic time-frequency segmentation algorithm and its application to planetary gearbox signals. We consider any kind of signal  $s[m]$  embedded in a centered white Gaussian noise  $n[m]$  of variance  $\sigma_n^2$ .

$$x[m] = s[m] + n[m] \quad (9)$$

$s[m]$  the signal to be segmented, contains all the non-stationary parts of  $x[m]$ , and may be either deterministic or stochastic,  $n[m]$  is a white Gaussian noise of unknown variance  $\sigma_n^2$ . Our goal is to identify the time-frequency points that contain a part of the  $s[m]$  energy. In order to do this, we use the Short Time Fourier Transform (STFT) as defined by

$$X_\phi[n, k] = \sum_{m=n-\frac{M_\phi-1}{2}}^{n+\frac{M_\phi-1}{2}} x[m] \phi[m-n] \exp\left(-2i\pi k \frac{m}{M_\phi + Z}\right) = X_\phi^r[n, k] + iX_\phi^i[n, k], \quad (10)$$

where:  $n$  and  $k$  are the time and frequency indexes respectively,  $\phi[m]$  an  $M_\phi$ -length window and  $Z$  the zero padding,  $K = M_\phi + Z$  are frequency bins,  $X_\phi^r[n, k]$  and  $X_\phi^i[n, k]$  are the real and imaginary parts of  $X_\phi[n, k]$  respectively.

#### 3.1. Signal detection

Given that the STFT is linear, all coefficients of the STFT of a white Gaussian noise  $n[m]$  have a complex Gaussian distribution. Consequently, the spectrogram coefficients, as defined by

$$S_{x,\phi}[n, k] = |X_\phi^r[n, k]|^2 = (X_\phi^r[n, k])^2 + (X_\phi^i[n, k])^2, \quad (11)$$

which have a  $\chi^2$  distribution with two degrees of freedom. In presence of signal  $s[m]$ , due to the linearity of the STFT, the time-frequency coefficients becomes:

$$X_\phi[n, k] = S_\phi[n, k] + N_\phi[n, k] \quad (12)$$

We have to discriminate points where  $S_\phi[n, k]$  is non-zero. Given that  $s[m]$  is unknown,  $S_\phi[n, k]$  is also unknown and may have a zero-mean. Consequently, we consider the second-order moment of (12):

$$E(X_\phi[n, k]^2) = \gamma_s[n, k]^2 + \sigma_n^2, \quad (13)$$

where  $\gamma_s[n, k]^2$  is the second order moment of  $S_\phi[n, k]$  only. We get the well-known result that a time-frequency coefficient containing signal has a higher second-order moment than coefficients containing noise only.

The distribution of the second-order moment of time-frequency coefficients containing signal is unknown. However, the distribution of the second-order moment of points containing noise only is a  $\chi^2$  distribution with two degrees of freedom. Consequently, a detection based on a Neyman-Pearson approach, allows to define a threshold  $t_{\sigma_n^2}$  given a

chosen false alarm probability  $p_{fa}$

$$t_{\sigma_n^2} / \text{Prob}(N_\phi[n, k]^2 > t_{\sigma_n^2}) = p_{fa} \quad (14)$$

$$t_{\sigma_n^2} = \sigma_n^2 \ln(p_{fa}^{-1}), \quad (15)$$

where  $\ln(x)$  is the natural logarithm. All time-frequency coefficients whose second-order moment is higher than this threshold will be detected as signal. The threshold  $t_{\sigma_n^2}$  (15) depends on the chosen false alarm probability, and the noise level  $\sigma_n^2$ , which has to be estimated.

### 3.2. Noise level estimation

To estimate the noise level, a Maximum Likelihood (ML) estimator is unbiased and optimal in case of noise only. The estimation  $\hat{\sigma}_n^2$  is

$$\hat{\sigma}_n^2 = \frac{1}{NK} \sum_{n,k} (X_\phi[n, k]^2), \quad (16)$$

where N and K are the number of time and frequency indexes respectively.

When signal  $s[m]$  is present, the estimator becomes biased

$$E(\hat{\sigma}_n^2) = \sigma_n^2 + \frac{1}{NK} \sum_{n,k} \gamma_s[n, k]^2 \quad (17)$$

The signal to segment results in an overestimation of the noise level. Unfortunately, given that this signal is unknown, its time-frequency location is also unknown. The idea is consequently to use an iterative algorithm: the noise level, at first overestimated, permits the determination of a first threshold (15). Some points containing signal are therefore detected. The next iterations re-estimate the noise level only on points which are non detected as containing signal. The noise level is less overestimated, leading to a lower detection threshold, and thus new points containing signal are detected.

### 3.5. Stop criterion

We need a criterion to determine if all non-detected points are noise only, in other words if all non-detected points have a complex Gaussian distribution.

To that end, we use the spectral kurtosis [12]  $SK(x)$  which is the kurtosis definition for a complex random variable:

$$SK(z) = \frac{E(z^2 z^{*2})}{E(z z^*)^2} \quad (18)$$

As real Gaussian random variable has the particularity to have a kurtosis equal to zero, complex Gaussian variables have a spectral kurtosis equal to zero. Consequently the algorithm stops when the spectral kurtosis of the non-detected points becomes smaller than a threshold  $t_{SK}$ , considering that the remaining points have a complex Gaussian distribution. To complete the algorithm, at each iteration we add a region growing algorithm [13], as in [14]. The point detected with the highest second-order moment is chosen as a seed for the region growing algorithm, labelled  $l$ . A search for other points detected is carried out in its 8-connectivity neighbourhood in the TFR, the same label is assigned to these points. The spectral pattern labelled  $l$  is thus created. When all neighbouring points are classified, a new seed is chosen among the remaining detected points, and a new pattern is created.

The main advantage of this region growing is the possibility to limit the number of points detected becoming segmented at each iteration. By a segmentation of only a proportion of  $p_{cand}$  points, one can avoid to classify small isolated high realization of Gaussian noise as signal. An analysis of the influence of the algorithm parameters  $p_{fa}$  (14),  $p_{cand}$  and  $t_{SK}$  may be found in [15] and [16]

In summary, the time-frequency segmentation proposed in this paper is an iterative process: at each iteration, the noise level is overestimated (17) due to the presence of signal; then this noise level permits the detection of some signal points (15). A region growing algorithm is applied to extract pattern from these detected points. The iterations are stopped when the remaining points have a Gaussian complex distribution, in other words when the spectral kurtosis of these points becomes smaller than the threshold  $t_{SK}$ .

### 3.4. Choice of parameters

We now apply this general segmentation algorithm to the particular case of planetary box signals. First, we have to choose the STFT parameters. A Hann window of 1023 points, an overlap of 511 points and 8192 frequencies is chosen, giving *a priori* the nicest time-frequency resolution of the modulated frequencies.

Then, the STFT is divided in several frequency bands, each one including only one frequency modulation. Two advantages are resulting: first, the hypothesis of white Gaussian noise has to be true only on a limited bandwidth; second, the algorithm deals with less points at a same time, saving time computation and memory.

Finally, we have to define segmentation parameters  $p_{fa}$  (14),  $p_{cand}$  and  $t_{KS}$  (See section 3.5)

The goal is to detect the frequency modulation, which is embedded in quite  $q$  low noise level, in a single continuous pattern. Consequently, a high probability of false alarm is sufficient to detect the signal. We set  $p_{fa} = 0.1$ . To get only one pattern, the proportion of candidates should be low to avoid creating useless new patterns. We set  $p_{cand} = 0.1$ . Finally, we wish to stop the algorithm as soon as the signal is detected: a high spectral kurtosis threshold is chosen,  $t_{SK} = 2$ . Following sections present the results of this segmentation on vibration signals coming from a planetary gearbox.



## 4. Procedure for speed profile identification by IF estimation based on T-F analysis - Application to real vibration signals (planetary gearbox)

From previous sections one may notice that the non-stationary operating conditions modulate the mesh frequencies and its harmonics in the same way. So the information extracted from each harmonic is the same. Moreover, for real signals with the already-mentioned complexity, each harmonic is embedded in a noise of different level according to the harmonic order and the estimation and detection proposed will necessary lead to some errors. Therefore, in order to minimize these errors and to get a more reliable detector, we propose to estimate the instantaneous frequency not from one harmonic but from an average of the less-noisy harmonics. In this section two real-world examples will be presented. First case is related to short vibration signal (5s) measured in a complex multistage gearbox with planetary stage on the input (complexity of the gearbox causes rich frequency content, time varying SNR, AM/FM modulation etc). Vibration signals that come from planetary stage overpower other sources. No tachometer signal is available. The task is to estimate the Instantaneous Frequency (IF) profile that will be similar to the expected load profile showed in Fig. 2b. Second case study is related to other multistage gearbox with planetary stage, the planetary stage being a second one. In this case, both vibration and tachometer signals were available. Duration of data is 60s. The task is to detect the global variation of operating condition from no load to heavy loaded gearboxes, we will ignore local cyclic variation of load. Quality assessment of estimation is done by comparison of estimated speeds: recalculated from instantaneous frequency (based on novel procedure) and from tachometer signal. More detailed information about gearboxes may be found in [17,18]

### 4.1. Case study 1 - planetary gearbox vibration data without tachometer signal

Fig4 shows the spectrogram of a planetary gearbox vibration signal with marked planetary stage mesh harmonics. As one can see, 8 harmonics with amplitude and frequency modulations are visible. Using algorithm described above we have obtained results showed in Fig5. Due to mentioned difficulties for some periods and harmonics, only the first harmonic is detected as a continuous function. Harmonic 8 is not detected probably because of the high Pfa, harmonics 4 and 5 are only detected on pieces whereas harmonics 2, 3, 7 and 6 are not far from a continuous function.

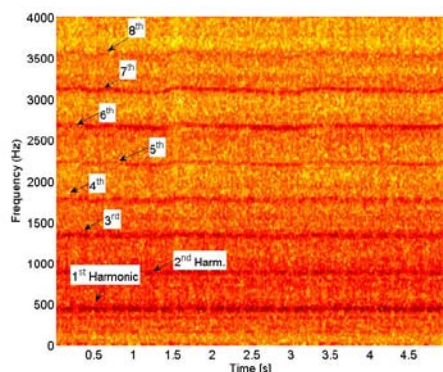


Fig.4. Case study 1 - Time Frequency Spectrogram of planetary gearbox vibration signal with marked planetary stage mesh harmonics

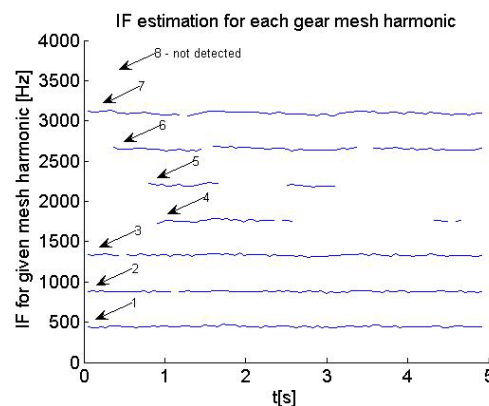


Fig.5. Case study 1 - Detection results for analysed signal (8 harmonics)

In order to compare results from different carriers, the detected IF of Fig.5 have been normalised as

$$IF_{normalised} = \frac{IF_{estimated}^{harmonic.order}}{harmonic.order} \quad (19)$$

Fig. 6 shows the 8 harmonics after normalisation. Fig7 shows the average of the 8 normalised IF estimated in Fig.5.

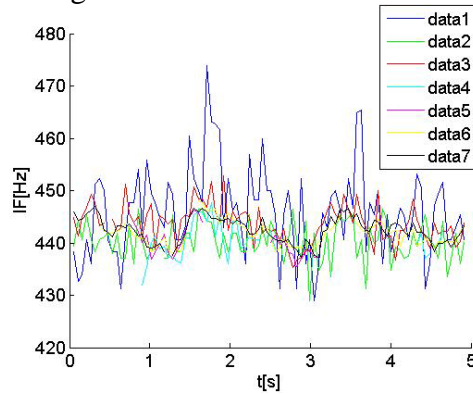


Fig.6 Case study 1 - Estimated instantaneous frequency variation Normalised according to fundamental harmonic

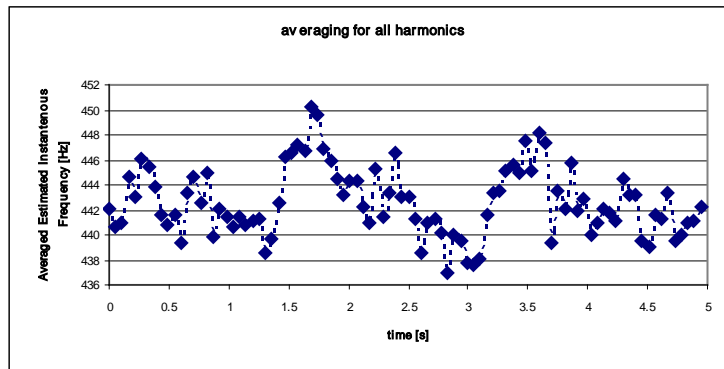


Fig.7. Case study 1 - Estimated normalised IF Averaged over 8 harmonics

From the fig 7 one may conclude that IF variation does not match to expected load/speed profile. In order to understand why results are not good as it was expected based on previous figures we have done a further analysis presented in next section.

#### 4.2. Case study 1 – estimated IF and variance

It was expected that results after normalisation should be satisfied, however the estimation has a high variance which essentially comes from the non-stationarity of the load, a digging process by the excavator, the noise of the signal and also the estimation errors of the spectrogram estimator.

The influence of the noise is much stronger for the lower harmonics. So, the idea is to reject harmonics 1-3 and to use only higher harmonics for the IF estimation. Fig.8.a,b show estimated IF averaged according to harmonics 1-3 and then 4-8. In fact Fig8a doesn't show any regularity in data, however Fig8b one may clearly find expected shape of data variation. It has been experimentally analysed how many and which harmonics should be used for further analysis. It has been noticed that if harmonics 1-3 are rejected results are better. Further rejection of harmonics does not affect results

significantly. As a criterion of harmonic rejection/acceptation we propose to use variance of instantaneous frequency, Fig 9

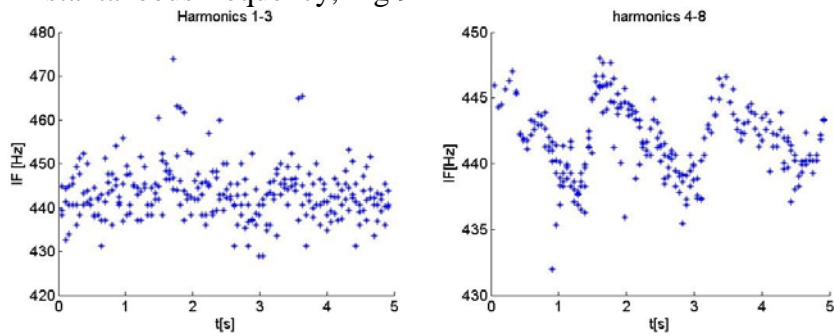


Fig.8 Case study 1 - Estimated instantaneous frequency variations normalised with the fundamental harmonic averaged with : a) harmonics 1-3, b) harmonics 4-8

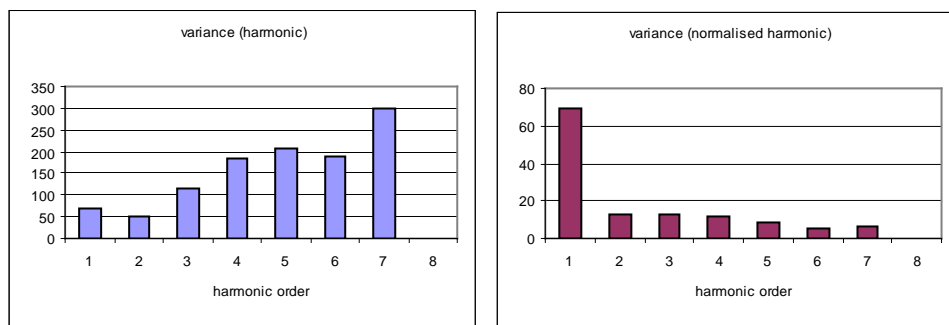


Fig. 9 Variance as a function of harmonic order a) detected harmonic frequency, b) normalised frequency

#### 4.3. Case study 1 – an improved processing

For a further improvement of the signal to noise ratio (SNR) of the final estimated profile, a simple moving average has been used. In statistics, a moving average, also called rolling average, rolling mean or running average, is a low pass filter . A moving average is commonly applied upon time series data to smooth out short-term fluctuations and highlights longer-term trends or cycles. A result of smoothing is showed in fig 10.

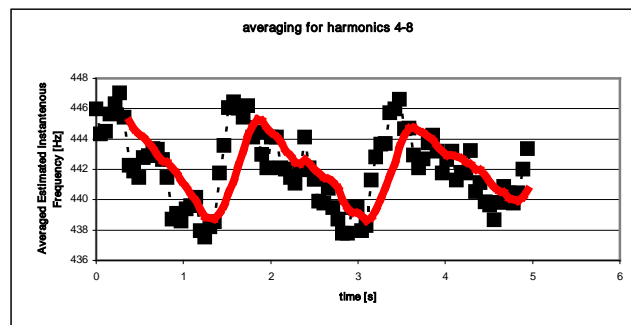


Fig.10. Case study 1 – IF estimation results: smoothed, averaged and normalized frequencies based on harmonics 4-8

#### 4.4. Case study 2.- Planetary gearbox vibration data with tachometer signal

In this experiment, both vibration channels and auxiliary channels (current, tachometer) were available. In the analysed signal, it is possible to find two characteristic periods. During 0-30 [s], the gearbox has been working without load, whereas the rest of the time

the gearbox has been working with a usual time-varying load value. Based on the tachometer signal, a speed profile has been estimated and used for comparison with the result estimated by the approach proposed, fig11,12.

**Procedure:**

- 1st step – segmentation of nearly 60s signal into 11 segments (5s each segment – please note that due to computation complexity it may be technically difficult to obtain STFT for whole 60s signal)
- 2nd step – the same detection procedure as for gearbox 1
- 3rd step – 11 partial results put in one vector related to whole signal
- 4th step – “recalculation” of IF (mesh component) to Instantaneous Speed (input shaft). It is done by simple formula that takes into account input speed, numbers of teeth (transmission ratio). In fact it is inverse calculation as one usually performs in order to find mesh frequency

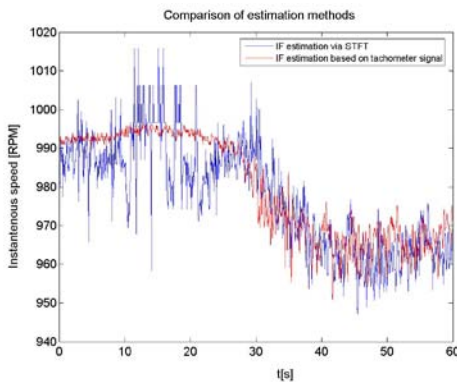


Fig.11 Comparison of IF estimation methods (red – based on tachometer signal, blue -based on vibration processing in TF domain)

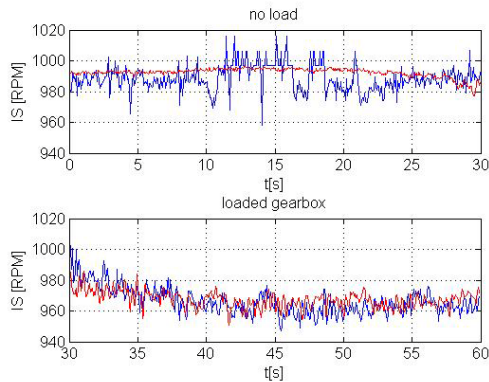


Fig.12 Detailed analysis of the estimation results (0-30[s] is unloaded gearbox, 30-60 is loaded gearbox)

One can notice two parts:

- 0-30s – no loaded machine, bigger frequency, problematic detection due to poor SNR –no loaded gearbox → small amplitudes of mesh components
- 30-60s – loaded gearbox – better SNR, quite similar results to tachometer based speed profile

**Error of estimation definition**

In this case, the tachometer signal is available so it is possible to define estimation error Absolute error in RPM (fig13a) is

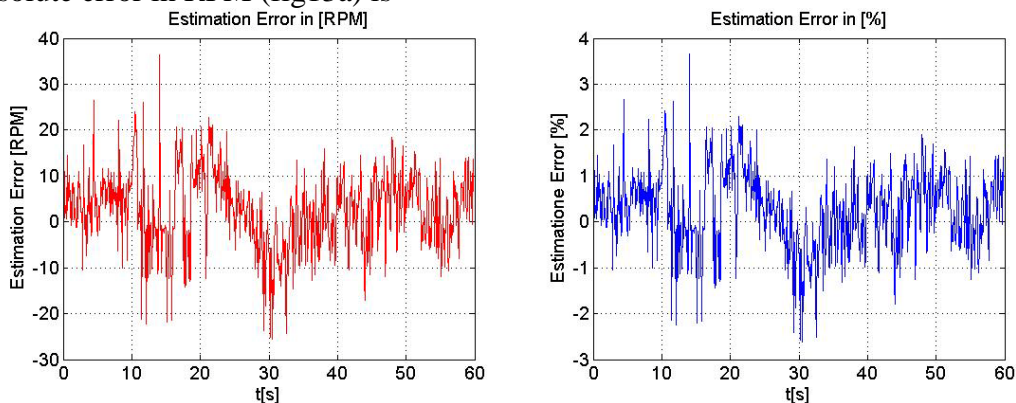


Fig.13 Estimation error: a) in RPM, b) in percents

$$E = IS\_tachometer - IS\_spectrogram \quad [\text{RPM}] \quad (20)$$

relative error (referred to tachometer data) (Fig12b)

$$Er = \frac{IS\_tachometer - IS\_spectrogram}{IS\_tachometer} * 100[\%] \quad (21)$$

## 5. Conclusions. Future work

During the condition monitoring of machines, it is crucial to know whether a machine works under constant or time varying operating conditions (TVLC). If TVLC exists it has to be identified as auxiliary data for diagnosis process. If usage of additional channels (current, tachometer, etc) is not possible TVLC may be estimated by vibration analysis. A novel procedure for instantaneous speed estimation using vibration signal only has been proposed in this paper. The approach proposed here uses an automatic segmentation algorithm in time frequency domain. First, a detection of the instantaneous frequency for a specific number of mesh harmonics is proposed. After normalisation, the estimation is averaged in order to improve the variance. Finally, a simple moving average is applied in order to reduce the time fluctuations. The proposed approach has been successfully applied to real vibrations issued from a complex gearbox with planetary stage. Two cases have been considered; first the estimation obtained are very similar to the expected load/speed profile. For the second case, a tachometer signal was available, which has allowed the comparison of the results to a speed profile obtained by tachometer signal processing. Two criteria have been proposed in order to assess estimation. The maximum relative error is less than 4% for unloaded gearbox, and is around 1% for fully loaded machine error. These errors are satisfactory for condition monitoring purposes.

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