Nearly real-time monitoring of gearbox vibration signal using DWT

Niola V., Quaremba G., Avagliano V.

Department of Mechanics and Energetics
University of Naples “Federico II”
Via Claudio 21, 80125, Napoli, ITALY
vincenzo.niola@unina.it http://niola.dime.unina.it/

Abstract – Gearbox diagnosis is challenging in engineering because the vibration signals from a gearbox are complex. The spectral analysis carried out for monitoring the mechanical transmission has a substantial limitation for realizing a real-time monitoring process. To overcome this shortcoming, it was decided to introduce a nearly real-time technique that, while maintaining a high specificity, is able to provide greater sensitivity for detecting significant variations of vibration signal. That kind of approach, as will be discussed in this paper, should earlier detect dynamical irregularity inside the gearbox. The aim is to perform a nearly real-time monitoring in order to stop the duration test faster than the methods reported in our previous papers.

Key-Words: - Duration test, Signal processing, Gearbox monitoring, Wavelet Transform.

1 Introduction

Both the industrial and the academic attention focused on the study and development of vibrational signal processing in order to detect the presence of defects and to prevent catastrophic gears failure.

From a mechanical point of view, an anomalous behaviour can be induced, for instance, by material properties or by specific geometry of some mechanical components which can take several positions or conditions of critical equilibrium, during the working process, due sometimes to early and irregular wear phenomena producing anomalous vibration.

Generally, anomalous vibration does not show a clear pattern or a particular frequency, especially if a long time series is observed.

Additionally, many systems exhibit nonlinear behaviour, i.e. quasi-periodic vibration, where two or more incommensurate periodical signals show an irrational ratio of their respective frequencies.

In this case non-periodic signal can always be decomposed into the sum of harmonic periodic functions such as

\[ x(t) = C_1 \sin(\omega_1 t + \phi_1) + C_2 \sin(\omega_2 t + \phi_2) \]  

where \( \frac{\omega_1}{\omega_2} \) is an irrational number.

At DiME (Dipartimento di Meccanica ed Energetica), we are developing methods and techniques for monitoring vibration signal which, taking the advantage of decomposing the signal by means of the wavelet transform, make the monitoring and diagnostic sensitivity more effective. The new algorithm allows to stop earlier the duration-test in order to enable a careful inspection inside the gearbox.

2 Wavelet Transform and monitoring Indicators

The proposed method is based on the principle of decomposing vibration signal through the wavelet transform (WT) [1-3]. The word wavelet is used in mathematics to denote a kind of orthonormal bases in \( L^2(\Omega) \) with remarkable properties.

Wavelets allow to simplify the description of a complicated function in terms of small number of coefficients. Often there are less coefficients necessary than in the classical Fourier analysis. Wavelets are adapted to local properties of functions greater than the Fourier basis.

Note that the vertical axis in the next figures denotes always the dimensionless level, i.e., the partition of the time axis into finer and finer resolutions.

Let \( \psi(t) \) be the mother wavelet, the daughter wavelet will be

\[ \psi_{a,b}(t) = \psi\left(\frac{t-b}{a}\right) \]  

where \( a \) is the scale parameter and \( b \) is the time translation. By varying the parameters \( a \) and \( b \), we can obtain different daughter wavelets that constitute a wavelet family. Wavelet transform is to perform the following operation
where \( \psi \) stands for complex conjugation. Recall that a wavelet \( \psi \) (mother wavelet) and a function \( \phi \) (father wavelet) such that
\[
\{ \phi_k \}, \{ \psi_k \}, k \in \mathbb{Z}, j = 0, 1, 2, \ldots, N
\]
is a complete orthonormal system [4]. By Parseval theorem, for every signal \( s \in L^2(\mathbb{R}) \), it follows that
\[
s(t) = \sum_{k} a_{j_k} \phi_{j_k}(t) + \sum_{j=j_0} d_{j_k} \psi_{j_k}(t). \tag{5}
\]
In particular, the decomposition of signal \( s(t) \) performed by means of the Discrete Wavelet Transform (DWT) is represented by the detail function coefficients \( d_{j_k} = (s, \psi_{j_k}) \) and by approximating scaling coefficients \( a_{j_k} = (s, \phi_{j_k}) \) [5].

In summary, wavelets offer a frequency/time representation of data that allows us time (respectively, space) adaptive filtering, reconstruction and smoothing. The coefficients obtained as described above were used for the construction of two kind of indicators: Periodogram \( W(T) \) and Form Factor \( FF \).

### 2.1 – Periodogram
The periodogram allows to evaluate both the trend of the period of signal and possibly the onset of new frequencies. This index is defined as
\[
W(T) = \frac{1}{2} \left( A^2 + B^2 \right) \tag{6}
\]
where
\[
A = 2 \sum_{i=1}^{a} x_i \cos \frac{2 \pi i}{T} \tag{7}
\]
and
\[
B = 2 \sum_{i=1}^{a} x_i \sin \frac{2 \pi i}{T} \tag{8}
\]
\( x_i \) is the time series, \( T \) is the range over the signal is isolated.

Therefore, the evolution of such a diagram could help to determine the existence or not of a significative period, strong to the variance showed by the signal.

### 2.2 – Form Factor
The Form Factor is defined as follows
\[
FF = \frac{H_{\text{mean}}}{H} \tag{9}
\]
where \( H = H_{\text{max}} - H_{\text{min}} \) is the distance from the highest peak to the deepest valley showed by signal \( s(t) \), \( H_{\text{mean}} \) is the compensation straight averaged line, i.e., the straight line chosen as the \( x \) axis which minimizes the sum of squared deviations of signal \( s(t) \) from it.

Furthermore, it should annul the integral
\[
\int_0^l s dx = 0 \tag{10}
\]
where \( s \) is the signal under study and \( l \) is its length. Note that if the signal is mostly "flat" then \( H \) will tend to zero vice versa \( H \) will tend to 1.

### 3 Trials
Regarding the test-rig used for the monitoring, the new procedure employs the same components described in our previous works [6-7]. The accelerometer signals were sampled at frequency of 4096Hz. The rotation speed during the dynamic test-run was settled at 2500 rpm, which corresponds to a meshing frequency of roughly 458Hz. In all the signals we see the carrier, corresponding to the third harmonic of meshing frequency and the relative modulation frequency as Fig. 1 shows with reference to 3 time segments belonged to Run11, randomly selected.

The acceleration signals were processed using specific algorithm and procedures in order to characterize the onset of the anomalous wear phenomenon. The wavelet used was the "gaus1" [2], scale 1 is equivalent to roughly 800Hz. Each accelerometer segment (hereinafter named as Run) is of 10000 points, equivalent to 2.44s. Finally, synchronous time average is an effective way to remove noises from periodic signals. Accordingly because the signal of interest is periodic and noises are random, the noises will tend to zero when the number of periods tends to infinity. So, assuming true the above concept, in this paper we used the geometrical averaged time period for processing the vibration signal. In many cases we can compare it to a "natural filter" of denoising.
Note that the scale frequency (819Hz) of wavelet was chosen in order to analyze deeply the left sideband nearly the second order of the meshing frequency (917Hz).

Below are the diagrams of the indices described in the par. 2.1 and 2.2: periodogram and form factor, Figs.3 and 4 respectively.

Fig. 1 - Spectral analysis with reference to Run11, baseline

Now let us start with the description of monitoring process by showing the strength of the technique proposed. Fig. 2 shows time evolution of wavelet coefficients (gaus1, 819Hz, scale 1) with reference to three time segments of RUN11 randomly selected obtained during the durability test.

Fig. 2 - Run11 - Wavelet coefficients, scale 1

The three time segments processed belong to Run11. They were assumed as baseline. Because they show three patterns quite similar, at that time the analysis of indexes does not suggest to stop the duration test.

Recall that typical defects of gears (such as cracks and craters) cause a modulation of vibration signal mainly affecting the sidebands of frequency spectrum.

Regarding the wear, it is the major cause of failure for a particular type of gear wheels characterized by high sliding speed.

The effects of wear can be found in a variation of the load distribution and vibration behaviour with
consequences on the lifetime of gear. It is well known that the material removed is proportional to the contact pressure and to the relative sliding speed of the mechanical components as well as with reference to material itself and environmental conditions.

In the case of two gears, we must determine the time evolution of contact pressure and local sliding speed on tooth side throughout the meshing process. Unfortunately, these determinations are not always easy. Usually, there is a general increase of meshing stiffness with the progress of wear and a tendency to a limit curve. In particular, there is a mechanical adjustment towards higher value of stiffness during the first phase of wear, in correspondence to teeth in contact. Consequently we observe a gradual increasing of the contact area to greater stiffness in the remaining angular portion, with the exception of the area around the primitive circle where the wear is negligible.

Such a behaviour is due to teeth bending. In fact, when the wear affects the central area then the contact interests a larger surface. Therefore, in the subsequent dynamical analysis we tried to highlight, by amplifying (i.e. using FF index), the effects induced by static transmission error due to progressive changes of flank profile. In this case there is a disappearance or angular displacement of direct teeth drive when one tooth is worn with flattening of the stiffness curve on values corresponding to the single meshing gear tooth.

The above consideration can be observed from the trend of the periodogram that, after an initial rise, decreases with the progress of wear, indicating an adjustment of meshing conditions (running-in) Figs. 3 and 4.

This happens up to 15% of the duration test, where, as it will be explained in the following, a significative change of FF shape was observed. As we will show later, the modification of FF will remain constant during the prosecution of test-run (this means that the change observed is not due to a pure transient phenomenon). This new situation, as we show in the following, will require the interruption of duration test.

Let us examine the 15th test cycle (Run15): Fig 5 shows the time evolution of wavelet coefficients while Figs. 6 and 7 illustrate the relative periodogram and form factor respectively.

In particular, Fig. 7 well points out the onset of the anomaly: the third time segment of signal (between 670000 and 680000 unit of time), belonging to Run15, shows a pattern significantly and definitively different from the two previous ones.

Because that is symptomatic of the occurrence of an anomaly it was necessary to stop the test. A comparison of test cycles performed shows more clearly the reason of the interruption of test.
The condition that suggests the interruption of duration test is highlighted by Fig. 8 reported below. It shows the comparison of two patterns obtained by interpolating the wavelet coefficients, calculated from Run11 and Run13 each of one geometrically averaged on 101 periods, by means of spline.

This means that a functional, mechanical and consequently vibratory, change internally to the gearbox was happen. Consequently we stopped the duration test in order to allow a careful inspection for understanding the reasons that led to the change of pattern morphology. This is necessary if we want to re-design a more reliable gearbox.

Fig. 10 shows the time progress of wear and its consequence in terms of mechanical vibration. Recall that when FF tends to 1 this means the co-presence of several different frequency, due to the progressive wear propagation of gears, becomes more relevant and significative. What said above is well represented in the Fig. 10.

The arrow, inside the box-figure, shows the direction of wear increasing and the corresponding increment of FF index.

The correlated increasing of entropy is illustrated in the Fig. 11 where for each time segment is reported the entropy values (i.e., the log log log energy of squared signal).

It is quite evident why the test-run was stopped. In fact by comparing the patterns of two series of wavelet coefficients belonging to Run11 and Run15 it is clear the different dynamical vibration(Fig.8). Such a difference can not be ascribed to a transient phenomenon. In fact the comparison between the pattern of Run13 vs Run15 (Fig. 9) shows the persistence of a new shape of vibration signal (different if compared to the one showed by Run11).
We can observe the stability of vibration during the Run11, taken as basic signal. The major variation occurs during the Run13, in occasion of the onset of anomalous wear. The trend related to the Run15, confirms the gradual anomalous wearing process, although less in terms of absolute value. The wearing process producing new frequency indeed increases also the entropy of the mechanical system.

6 Conclusion
An effective procedure for monitoring the wear development during the duration test of a gearbox is showed. It takes into account the effects induced on the vibrational signal by a pair of gears of a gearbox. The wavelet coefficients calculated from the vibration signal, were used for calculating two different indicators. The results of the laboratory tests on the wear process are in good agreement with those found in the literature.

From a dynamical point of view, wear causes a variation of meshing stiffness and the modification of tooth profile and consequently the increasing of static transmission error and therefore a significative modification of the vibration spectrum.

The test results, when the operating conditions are constant, show the consequence of running-in. The clearance generated by the wear is well illustrated by the diagrams relative to the proposed indicators. Hence they could be used to perform a diagnosis assessment on the entity of gear wear.

It is also evident that the technique described above is more effective if compared to what we described in [6,7]. In fact, it allows to stop the test-run at 15% and not roughly at the end of duration test.

This represents an important advantage: in fact the mechanical transmission can be inspected at the beginning of defects which after a short time leads to breakage. In this way we can study the onset problem namely when it appears.

It is fundamental to observe, for instance, the "signs" left on the gears involved during the abnormal working condition.

All the above considerations support the monitoring technique presented and the advantage of stopping instantly the duration test, i.e., when the first anomalous vibration signal occurs.

References