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# **DETECTION OF A GEAR COUPLING MISALIGNMENT IN A GEAR TESTING DEVICE**

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## **Abstract**

On the gear testing device of the LIS laboratory (Grenoble, France), a total of 20 signals are synchronously recorded including shaft acceleration signals in several positions, torque, rotation speed, optical encoder signal of both shafts and currents and tensions of the non-synchronous training motor. After about 3500 hours of using this device, the driving gear shaft broke at the gear coupling position with the training motor shaft, which created an impressive helicoidal crack. This failure could be due to a flexion strain caused by a misalignment of the two shafts, but this fault was not detected before. In this paper we compare results of different signal processing methods for the detection of this fault. Particularly, we use the phase spectrogram whose advantage is to be able to highlight a slight phase modulation in signals that is not detectable on the amplitude spectrogram. We also attempt to detect the fault using spectral analysis, a non-stationary modelling based on Prony's model and comparison of signals recorded at different times before the crack: the acceleration signals, the torque, and the torsional vibration signal obtained from the shaft encoder signal. The detection results are compared and discussed between the different methods.

## **1. INTRODUCTION**

In rotating machinery rotor misalignment is known to generate vibration problems. It is measured that about 60 per cent of faults was caused by misalignment [Li 01]. The moment created by a misalignment in a gear coupling is quite complex but its fluctuations occur at twice the shaft speed [Dewell 84]. Thus, the presence of the 2 times shaft speed vibration is known to be an indicator of a misalignment.

Furthermore, coupling misalignment does not significantly alter the 1x vibration response but the 2x vibration response is clearly a characteristic signature of misaligned shafts [Sekhar 95]. Misalignment initially affects the 1x response but in the case of severe misalignment, a 2x component appears in the response [Jordan 93]. So an increase of the 2x shaft speed vibration corresponds to an increase of the misalignment. The physical source of these effects may be modelled as a rotor bend for the 1x response and as a rotor asymmetry for the 2x response [Sinha 04].

In this paper, different signals measured on our gear testing device are analysed in order to attempt to find criteria for an early detection of faults that could appear in the gear coupling. Two signal processing methods are used. The first method takes advantage of the non-stationarity of the observed measured. It is based on a classical spectrogram followed by a time-frequency tracking of one harmonic modulation. Then a spectral analysis of the extracted modulation yields interesting parameters for supervising a running system. The second method takes advantage of a known model of the observation and proposes the tracking of local model parameters. In this paper, we aim at studying time-frequency local approaches.

The proposed methods actually do not need data means or synchronous measures. Results are presenting on the gear testing device of the lab (GOTIX bench of LIS-Grenoble France).

In this paper, we focus on the results and references are given for going insight the methods we do not describe. We first describe the experiment and we analyse the torsional vibration and the torque signals after synchronous averaging. We then use the frequency spectrogram for analysing slight frequency modulations in the acceleration signals. A time-frequency Prony analysis is finally applied in order to track the evolution of Prony's parameters.

## 2. DESCRIPTION OF THE EXPERIMENT



*Fig.1: Left: gear testing device, middle: tested gears, right: cracked gear coupling. The gear coupling that links the training motor shaft to the gear shaft appears in the lower right corner of the middle figure.*

The gear testing device of the LIS laboratory (Grenoble, France) is used to study and develop new signal processing methods adapted to the early detection of a crack or the wear of the tested gears. Twenty signals are synchronously recorded on this device: accelerations at the bearing positions of the shafts, torque, rotation speeds, encoder signals and tachometer signals of both shafts and currents and

tensions of the non-synchronous training motor. The sampling frequency is 25 kHz except for the encoder and tachometer signals (100 kHz). This device (fig.1) has been running for 3500 hours when the gear coupling that links the motor shaft to the gear shaft suddenly broke, creating an impressive helicoidal crack of the gear shaft at its coupling position (fig.1 right). This appears while we were testing new gears for 300 hours under normal load conditions. The gear coupling has never been changed for the 3500 hours. GOTIX testing device is described on our website (<http://www.lis.inpg.fr/english/research/projets/aproj21.htm>) where all data can be loaded. Only one personal identification is required.

### **3. FIRST OBSERVATIONS**

#### **3.1. Torsional vibration signal**

The torsional vibration signal of the shaft is obtained by phase demodulating the shaft encoder signal [Sweeney 96]. The encoder signal is first band-pass filtered around the carrying frequency ( $1024 \times 12.3 = 12.6 \text{ kHz}$ ). The band-pass filter is chosen of width  $\pm 8 \text{ kHz}$ , which allows high modulation frequency analysis. The spectrum of the torsional vibration is rich in harmonics: it contains harmonics of the driving shaft speed (12.3 Hz) of the driven shaft speed (46.7 Hz, gear ratio is  $57/15 = 3.8$ ), and also harmonics of the 50 Hz (current frequency). The time waveform of the vibration is so complex to analyse. In order to retain the driving shaft synchronous components only and to filter other components, we perform a synchronous averaging based on the tachometer signal of the driving shaft. Figure 2 shows the torsional vibration at time 3200h averaged on 125 rotations of the shaft (25 times the gear coincidence period). The main harmonics are the 1x shaft speed, 57x (gear frequency) and also 18x and 78x. These two last harmonics are likely to be due to the motor constitution.

In order to detect a fault that could appear in the gear coupling, we computed the averaged torsional vibration at different instants from 3200h (beginning of the new test) to 3465h (a few hours before the crack), but we did not find particular evolution of the time waveform and of the main harmonic amplitudes. Since a misalignment fault is characterised by an increase of the second harmonic, we plotted the evolution of the 2x frequency modulation amplitude and compared it to the fundamental one (figure 3). The 2x modulation slightly increases at 3385h and 3455h, which could be an indicator of a misalignment fault. We also plotted the 2x/1x amplitude ratio that may be more valuable for the detection.

#### **3.2. Torque signal**

As for the torsional vibration signal, the torque is perturbed by harmonics of the driven shaft frequency and of the 50 Hz frequency. We so performed a synchronous averaging in order to retain the driving shaft harmonics only. The averaged and zero-mean torque at time 3200h is shown on figure 4: the 18x shaft speed harmonic is here preponderant, which confirms that this component must be due to the training motor. The 1x and 57x are also present.

We computed the averaged torque at different instants from 3200h to 3465h, and we plotted the evolution of the 1x and 2x shaft speed modulation amplitudes (figure 5). The 2x modulation turns out to decrease at the end of the experiment, unlike the torsional vibration. The torque seems here to be difficult to interpret for the detection of a fault.

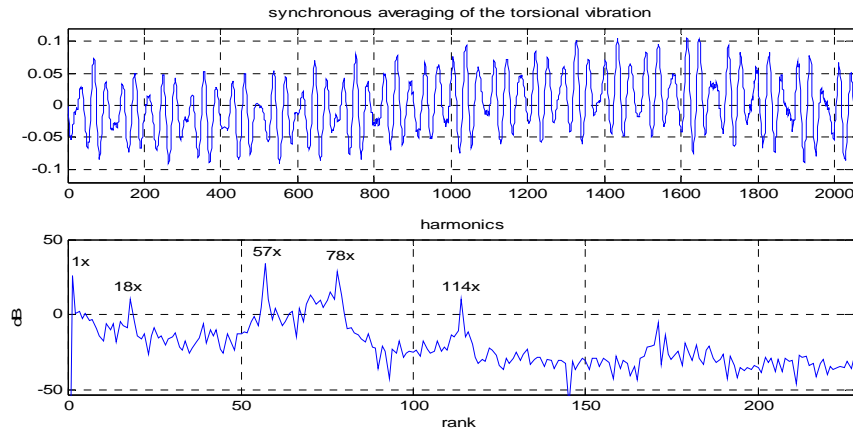


Fig.2: Synchronous averaged torsional vibration signal at 3200h and its harmonics: main harmonics are 1x shaft speed, 57x (gear frequency), 18x and 78x.

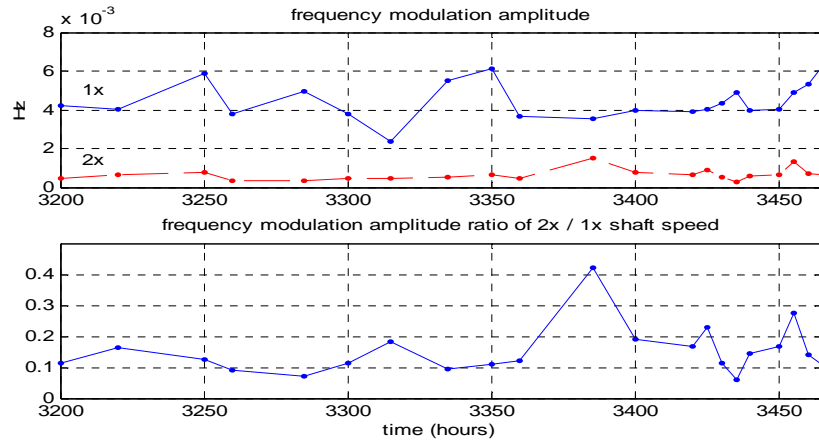


Fig.3: Evolution of the 1x and 2x shaft speed frequency modulation amplitudes estimated from the torsional vibration signal. The 2x modulation slightly increases at 3385h and 3455h (crack is at 3485h).

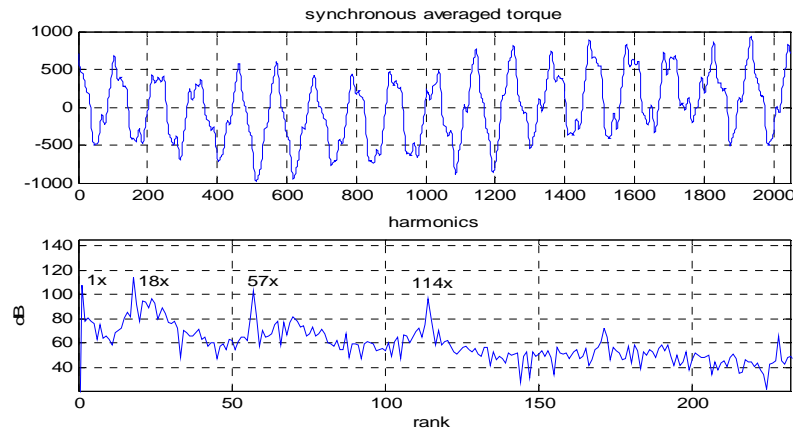


Fig.4: Synchronous averaged torque at 3200h and its harmonics: main harmonics are at 1x shaft speed, 18x, 57x (gear frequency).

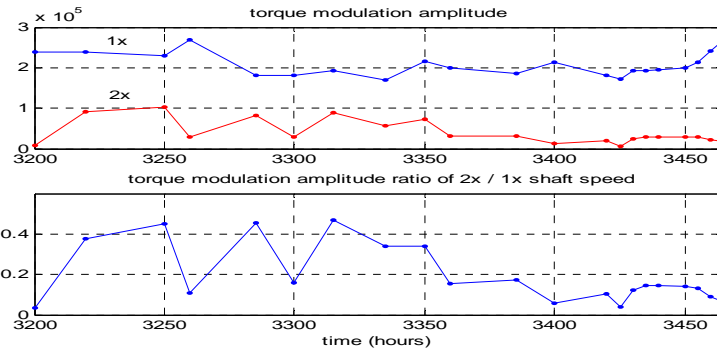


Fig.5: Evolution of the 1x and 2x shaft speed modulations of the torque.

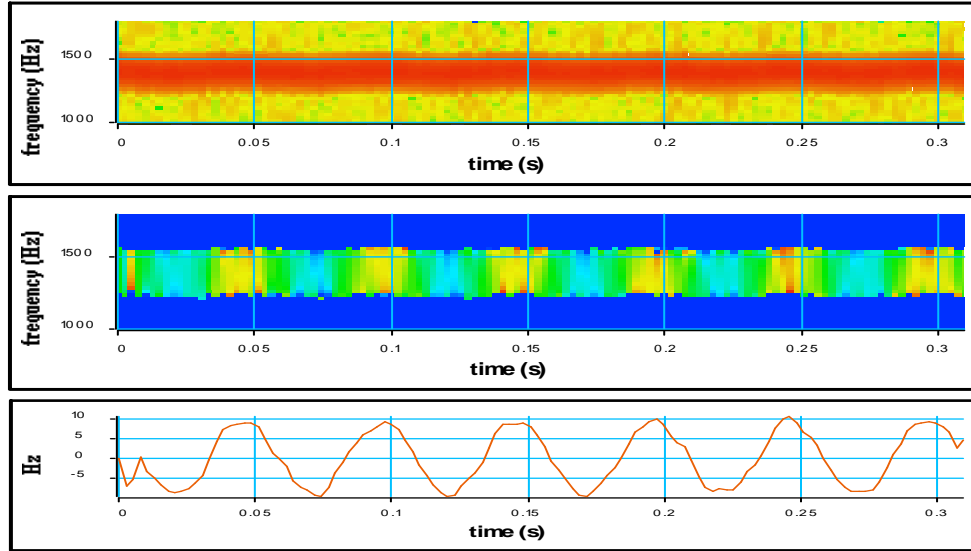
#### 4. ACCELERATION ANALYSIS BY THE FREQUENCY SPECTROGRAM

##### 4.1. The frequency spectrogram

On the well known power spectrogram, only the amplitude of the short-time Fourier transform (STFT) is shown. Thus, a slight frequency modulation may not be clearly visible on the power time-frequency plane. The frequency spectrogram [Léonard 00] was developed as a complement to the power spectrogram. It exploits the phase information of the STFT.

The frequency spectrogram is simply computed by the phase difference of the STFT between two consecutive segments divided by the time shift between the segments. Furthermore, its sensibility can be increased by applying an integer gain to the result. The advantage is to be able to highlight a slight frequency or phase modulation that does not clearly appears on the amplitude spectrogram. Figure 6 shows the power and frequency spectrograms of a simulated frequency modulated sinusoid. The slight modulation is not evident on the power spectrogram itself but is better visible on the frequency spectrogram. A cut can then be applied on it at the modulated frequency in order to recover the modulation signal. This modulation can

actually be recovered by tracking the maxima position of the power spectrogram, but this needs to highly interpolate the frequency axis in order to limit quantization [Léonard 00]. Thus, the frequency spectrogram permits to decrease the calculation time for recovering a frequency modulation. It also has the advantage to be more visual in a first analysis.



*Fig.6: top: power spectrogram of a simulated frequency modulated sinusoid, middle: frequency spectrogram, bottom: modulation signal recovered by a cut of the frequency spectrogram. Signal to noise ratio is 10dB.*

#### 4.2. Analysis of the acceleration signals

We applied the frequency spectrogram to the two acceleration signals denoted by CH5 and CH6 which are the closest to the gear coupling. CH5 measures vertical acceleration and CH6 measures horizontal and radial acceleration, both at the bearing of the gear shaft near the coupling. The acceleration signals are dominated by the harmonics of the gear frequency (700Hz).

We measured the frequency modulation of the second gear harmonic at 1400Hz which here stronger than the fundamental. The rotation period of the driving shaft corresponds to around 2032 samples. In order to track a modulation within the rotation period, a size of 512 samples was chosen for the spectrogram gliding window. Once the modulation signal is recovered by a cut of the frequency spectrogram at 1400Hz, a spectral analysis can be applied on it. Figure 7 shows the spectrum of the modulation signal of acceleration CH6 at the beginning of the new test (3200h) and before the crack (3465h). By comparison of these two spectrums, the frequency modulation amplitudes of the 1x shaft speed (12.3Hz) and of the 2x clearly evolved from 3200h to 3465h: the 2x becomes higher than the 1x at 3465h. Figure 8 shows evolution of these harmonics. A fault seems to appear at 3300-3350h due to an increase of the 2x/1x amplitude ratio. It also increases just before the crack (3465h) for signal CH6.

The originality of the approach is the extraction of the modulation signal in the



time-frequency plane followed by a spectral analysis in order to estimate the evolution of the modulation amplitude versus time.

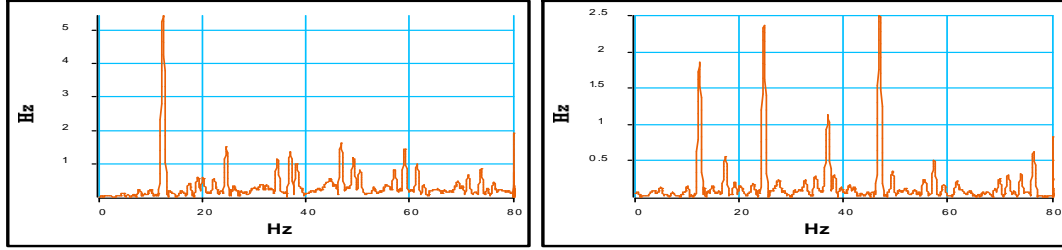


Fig.7: Spectrum of the modulation signal obtained from the frequency spectrogram of acceleration CH6 at time 3200h (left) and 3465h before the crack(right).

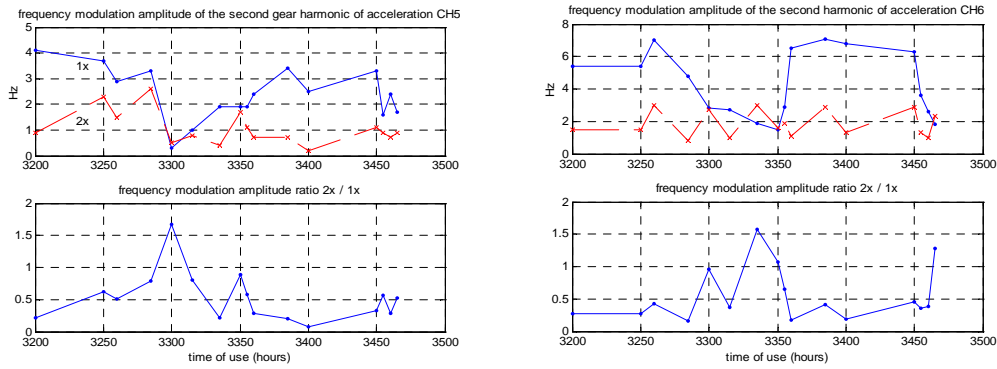


Fig.8: Frequency modulation amplitude at 1x and 2x shaft speed of the 2<sup>nd</sup> gear frequency harmonic (1400Hz) for accelerations CH5 (left) and CH6 (right).

## 5. PRONY ANALYSIS

We finally performed a time-frequency Prony analysis [Martin 04] to the synchronous averaged acceleration signals CH5 and CH6. We observed the evolution of the Prony parameters (frequencies, dampings, amplitudes and phases) versus the time of analysis. The main evolution was observed for the damping parameter. Figure 9 shows evolution of the mean value and of the standard deviation of the estimated damping parameter. Damping is often higher for a cracked structure.

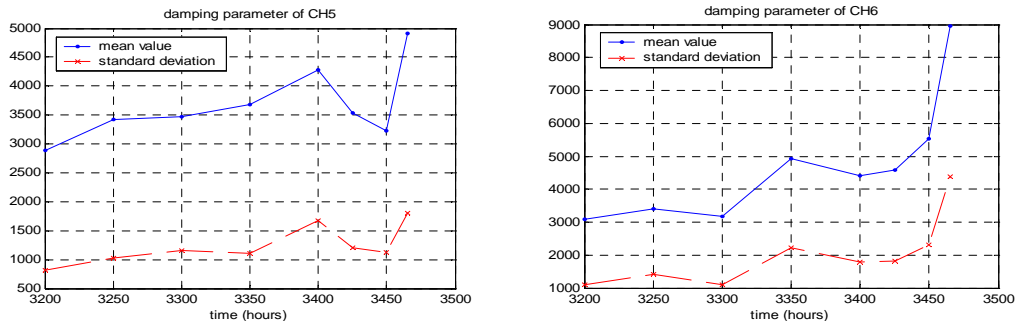


Fig.9: Evolution of the mean value and standard deviation of the damping parameter of Prony analysis applied to the averaged acceleration signals CH5 and CH6.



## 6. CONCLUSION

In a diagnostic and surveillance purpose, this paper presents two signal processing approaches in order to attempt to find criteria for early fault detection. The frequency spectrogram is interesting in order to demodulate frequency modulations when the modulation frequency is not known and/or apt to change before the occurring of a crack. The only *a priori* knowledge is the modulation bandwidth, whose choice is not critical. The algorithm is simple with a low computation cost. The Prony analysis is a local estimation of model parameters and is suitable for detecting the modification of shocks induced in a system. In our experimentation, the tracking of the damping factor seems to be decisive. Contrary to the first one, this method has a higher computation cost.

The proposed methods have been tested on GOTIX bench of LIS-Grenoble. We observed from time 3200h (beginning of experiment) to 3465h (before the crack) an increase of the 2x shaft speed modulation amplitude in the torsional vibration signal and in the acceleration signals close to the gear coupling. This could be an indication that the misalignment increased in the gear coupling, and the friction between the teeth due to the created moment finally led to the crack of the shaft in the coupling.

Both approaches are working in time-frequency space and can be applied to all observations including harmonic modulations or shocks. They are adapted for tracking changes in a great amount of data. The next step now is to deduce a detection algorithm. Works are in progress in that way trying to define a detector, which will not be sensitive to the choice of a threshold, as in [Hory 02].

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