Diagnosis of belt drives based on cyclostationary approach

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Abstract

This work aims to develop tools for diagnosis of belts. The problem of belt tension has been privileged. The study is based on analysis of accelerometric signals and signals coming from strain gauges. If spectral analysis techniques hardly shows this type of defect, the cyclostationary properties that we highlight can bring relevant information to characterize noise belt and therefore the impact of tension it. For the analysis of the second-order cyclostationarity, we privileged the analysis envelope technique in suitable frequency bands. This method allows to overcome the difficulty of the prior deletion of the contribution in the first-order, absent in the exploited band. The double accelerometric signal and strain gauge analysis allows to highlight the interest of this last type of measure not used so far for this type of application. The gauge can give very many non-discernible information, with clarity, from measurements collected on the accelerometer, this is all the more remarkable in the low frequencies where the accelerometric sensor is visibly less sensitive. We present in this work any prior synchronous analysis of the methodology used to obtain the cyclostationary contribution on signals from an experimental test bench provided for this purpose.

Keywords :
Belt defects, vibration signal diagnostic, rotating machines, envelope analysis, accelerometer, strain gauge, cyclostationarity, discrimination

1 Introduction

Nowadays, the belts are very widespread. They are found in miniature machines and products to the general public (cameras, washing machines, …). Transportation and industrial sector (conveyors, agri-food) are the areas using the more this type of transmission. The belt is cheap, flexible and generates little noise. Manufacturers are constantly seeking to improve its performance in terms of power transmission. They modify the structure to balance load distribution and reflect on new materials of manufacturing may increase life expectancy. The research is also used in dynamic terms, in particular in order to limit the phenomena of harmful vibrations [1].

A running belt is prone to all kinds of damage. There are four vibration patterns [2] disrupting its operation (Fig.1): vertical (a), linear (b), torsional (c) and transverse (d). The modes can be limited by introducing in the transmission of tensioners. The installation tension plays an important role on the life of the belt. It can also change the frequencies of the system and the natural frequency of the belt to cause resonance or the output of the belt from the pulleys trough [3]. Investigations have shown a link between the amplitude of transverse vibration and stiffness of the belt. This stiffness decreases naturally with the uptime, and then stabilizes. Thus, the loss of upcoming rigidity may be inherent in the presence of any defect in the compression of the belt layer. Results indicate the possibility of making a diagnosis of defective belts from the transverse vibration [4]. We propose to study vibration and deformation of the landings to diagnose belt defects. A test bench was developed for this purpose. Accelerometers and strain gauges have been implemented to provide the measures

In the field of vibration diagnosis, the traditional tools of signal processing are often based on the assumption of stationarity. However, in practice, the actual physical processes are non-stationary. Analysis of the temporal evolution of these processes reveals the presence of repetitive patterns. This pattern assumes the existence of a cycle of base commonly encountered in rotating machines. If the operating parameters are constant (temperature, speed, etc.), the process can then be considered to be cyclostationary. In most cases, the vibratory process from rotating and alternative machines is cyclostationary. This property is also checked for signals of belts.

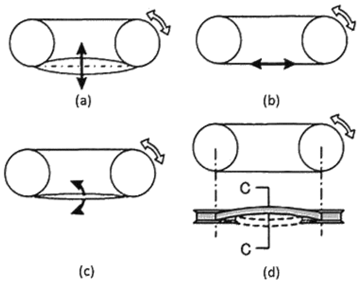


Figure 1: Vibration patterns.

We present in this paper firstly a reminder on the cyclostationnarity. Then, we give the tools implemented to exploit this property, including the analysis of envelope technique. We describe the test bench and all instrumentation as well as the spectral analysis of the accelerometric sensors and strain gauges. The last part shows the results of cyclostationary analysis.

2 Cyclostationarity

The cyclostationarity is widely studied in the field of Telecommunications [5]. Its effectiveness has proved also in blind source separation, identification in modal analysis [6], mechanics [7] and more recently for the diagnostics of machines for machining [8].

$x(t)$ is, a signal random cyclostationary. $x(t)$ will said first-order cyclostationarity (CS1), if its first-order moment (its expectation $m_x(t)$) is periodic of T period, i.e. if:

$$m_x(t) = E[x(t)] = m_x(t+T) \tag{1}$$

with $m_x(t)$ the average statistics of all.

$x(t)$ will said second-order cyclostationary (CS2), if its second-order moments are periodic. The $R_x(t,\tau)$ autocorrelation function of the signal is periodic of T period such as:

$$R_x(t,\tau) = E[x(t)x^*(t-\tau)] = R_x(t+T,\tau+T) \tag{2}$$

where $x^*(.)$ is the conjugate transpose $x(.)$.

A signal to both first-order cyclostationary and second-order cyclostationary is told cyclostationary wide-sense. A cyclostationary signal is CSn, if all its moments of n-order are periodic. The n-order cyclostationarity implies the cyclostationarity to the lower orders.

3 Envelope analysis

Envelope analysis (Fig. 2) is a diagnostic method that is widely used for the study of defects in bearings. This procedure [9] requires filter a signal in high frequencies $[f_1, f_2]$., for example around a resonance. This avoids the step of deleting the first-order cyclostationary contribution (periodic part) which is mainly present at low frequency. The resonance produces a natural amplification. Then, the filtered signal is demodulated, prior to its translation in the frequency band $[0, f_2 - f_1]$. A stage of zero-padding is applied. We get an analytical signal by inverse Fourier transform. The analytical signal module is extracted to study its envelope or its Fourier transform.

It has been shown in [10] that:

$$\int_{\Re} S_x(f,\alpha)df = \lim_{W\to\infty}\int_{-W/2}^{W/2} E\left[x(t)^2\right]e^{-j2\pi\alpha t}dt \qquad (3)$$

This means that the Fourier transform of the signal envelope corresponds to the integral of the spectral correlation function, along the axis of the frequencies. The spectral correlation function is the dual transformed of Fourier, in t and α, the correlation (according to equation (2)) function such as:

$$\int_{\Re} S_x^{\alpha}(f) = S_x(\alpha, f) = \iint R_x(t,\tau)e^{-j2\pi\alpha t}e^{-j2\pi f\tau}dt\,d\tau = \iint R_x(\alpha,\tau)e^{-j2\pi f\tau}d\tau \qquad (4)$$

The cyclostationarity analysis can therefore be based on the Fourier transform of the square of the envelope signal. If the study of its spectrum exhibits periodic frequency rays, then the signal will be considered second-order cyclostationary.

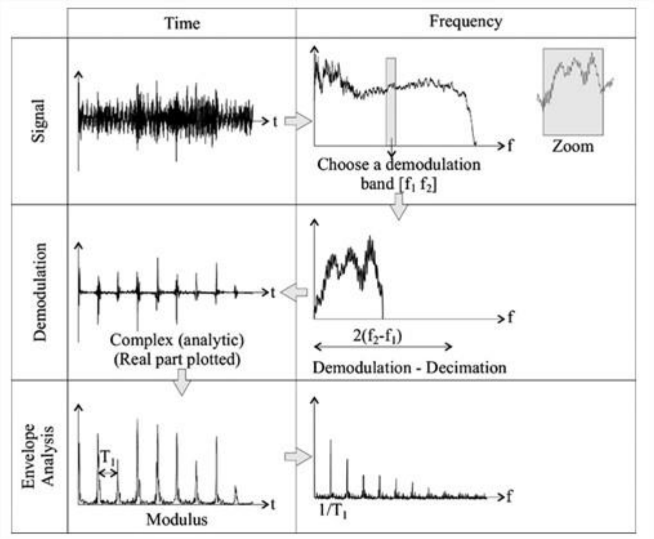


Figure 2: Envelope analysis [9].

4 Test-rig

We have created a test bench incorporating a belt transmission (Fig.3). We work sith a V-belt. An idler is installed between the two pulleys. It severely limits the belt beats that generate harmful vibrations to the system.

Two optical encoders (resolution of 4096) collect the angular information on each pulley. They are connected to a frequency divider. An acquisition card performs the essential steps to collected vibration signal pre-processing. It also provides a recording of signals during 60 seconds for example, according to different sampling rates. We chose 1600 Hz. The selected frequency is relatively high compared to the frequencies of study. This is voluntary for a good comparative study of our sensors. Four channels of acquisition are available for simultaneous recording.

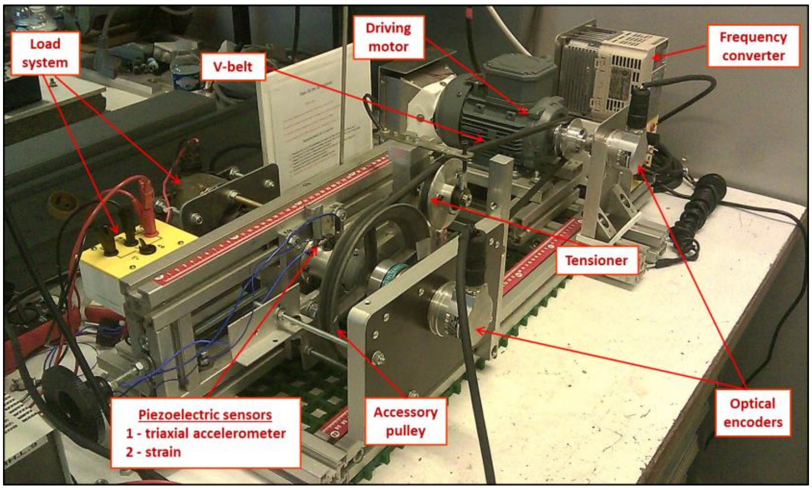


Figure 3: Test bench created at LASPI [1].

A triaxial piezoelectric accelerometer 356B21 (sensitivity of 9 mV/g) and a uniaxial piezoelectric strain gauge 740B02 (sensitivity of 50 mV/με) are positioned on the shaft of the accessory pulley. We focus our study only on the triaxial piezoelectric accelerometer signals in the transverse direction (i.e. parallel to the shaft of the accessory pulley and perpendicular to the plane of rotation of the belt) and the uniaxial piezoelectric strain gauge. The accelerometer is sensitive to vibrations of a structure while the strain gauge reacts to bending suffered by the landing.

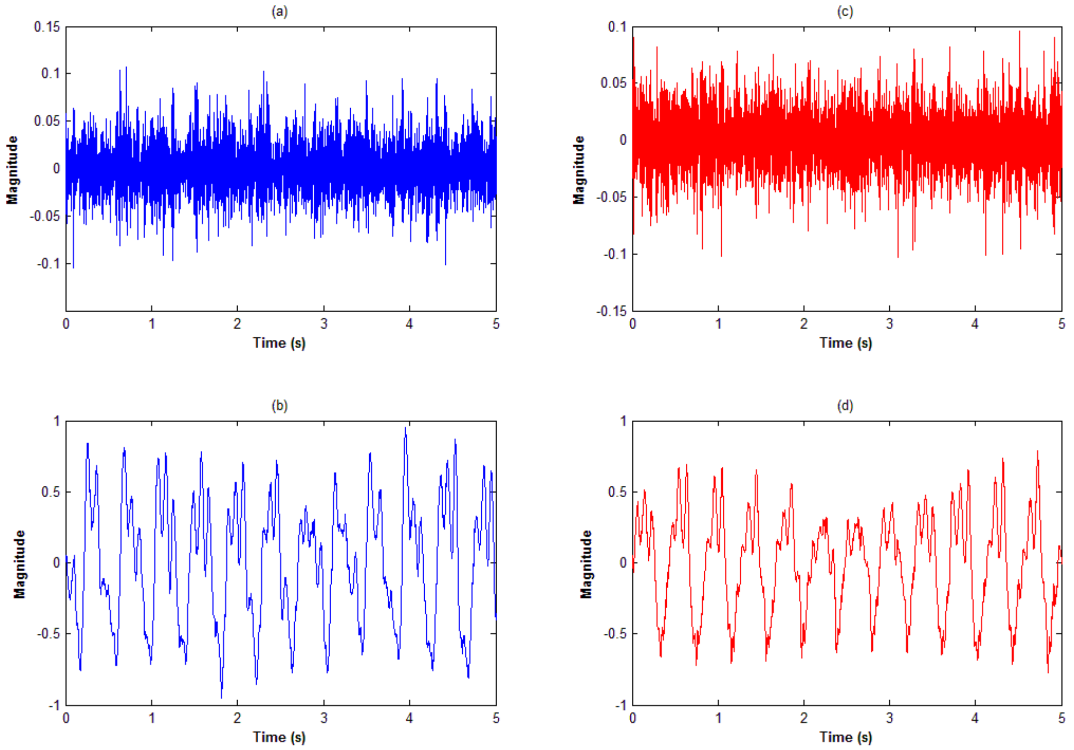
We seek to show that the gauge signals are as rich (and even more) information than those of the accelerometric signals. Time or frequency representations could facilitate statistical treatments. In a second step, we show the second-order cyclostationary for belt signals. This aspect is then used to discriminate the behaviour of a tight belt (normal operation) to that of a slightly relaxed belt (abnormal operation). The belt was moderately rounded.

5 Traditional analysis

5.1 Time analysis

Our transmission system is composed of four elements in rotation such as motor (crankshaft pulley) running at 6.8 Hz (0.14 s), a tensioner to 5.8 Hz (0.17 s), an accessory pulley at 2.45 Hz (0.4 s) and a belt at 0.96 Hz (1.04 s). Therefore, this study is done at slow speed. It is worth noting that in this configuration, the belt which naturally behaves like a vibrating, is subject to weak beats whose frequency is around 0.3 Hz (3.33 s). In the following figures, we will represent the vibration signals of the tight belt in blue and the vibration signals of the belt slightly relaxed in red.

Different time views (Fig.4) are observable on 10 seconds of acquisition. (Fig. 4) (a)-(c), we have the accelerometric signals in (Fig.4) (b)-(d) the gauge signals. It is difficult to give an opinion on the accelerometric signals in two operating conditions. On the gauge, however, we clearly see a repetitive cycle that corresponds to the rotation of the accessory pulley (0.4 s). In this case, there is a regularity in the two types of operation of the belt Amplitudes differ: between [-1,1] for the tight belt and [-0.8,0.8] for the slightly relaxed belt. Accelerometric signals are complex but those of the gauge display representation more simple that could facilitate a better time analysis. It would be possible to work on a form indicator (variance, kurtosis, etc...) for temporal diagnosis.



5.2 Frequency analysis

A frequency analysis is made from spectra of signals (Fig. 5 and Fig. 6). In the very low frequencies (Fig.5), the main frequency peaks of the accelerometer correspond to rotations of the accessory pulley (2.45 Hz) and its harmonics (2x2.45, 3x2.45,... Hz). These peaks (including harmonics) are modulated by more small-amplitude peaks related to the frequency of beating of the belt (2.45 ± 0.3, 2x2.45 ± 0.3, ...Hz). The gauge shows off those same peaks but also the peaks of the beat frequency of the belt (0.3 Hz), as well as the frequency and harmonics respective half of the belt (0.96/2, 2x0.96/2,... Hz), belt (0.96, 2x0.96, ...Hz), and lower the tensioner (5.8, 2x5.8,...Hz) and motor (6.8, 2x6.8,... Hz). However, the frequencies of rotating elements having harmonics are slightly more spread, in the case of the tight belt.

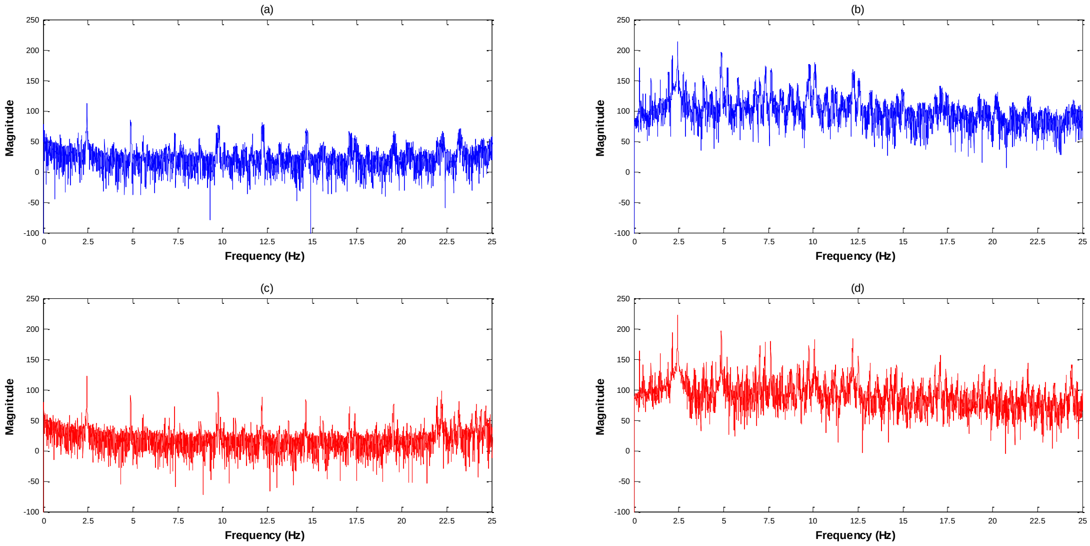


Figure 5: Signals spectra of the accelerometer (a)-(c) and gauge (b)-(d) in the band [0-25] Hz, tight belt in blue and slightly relaxed belt in red

Areas of resonance (Fig. 6) with the accelerometer and the gauge for the two workings of the belt are virtually the same, around the center frequencies 90 Hz, 175 Hz, 375 Hz, 575 Hz. There is a slight amplification of resonances for the gauge with the slightly relaxed belt signals (Fig.6)(b)-(d). Resonances are well observable on the accelerometric signals (Fig.6)(a)-(c). If we want to study a particular rotating element, it may be appropriate to extract the desired peaks (those of the belt for example) from the gauge signal. On the other hand, the analysis of signals from rotation of the pulley may be more suitable with the accelerometer, because they are less polluted by the other rotating elements. In all cases, make a clear comparison of tense belt and slightly relaxed belt signals is apparently not easy from a study of the spectra because they are very similar.

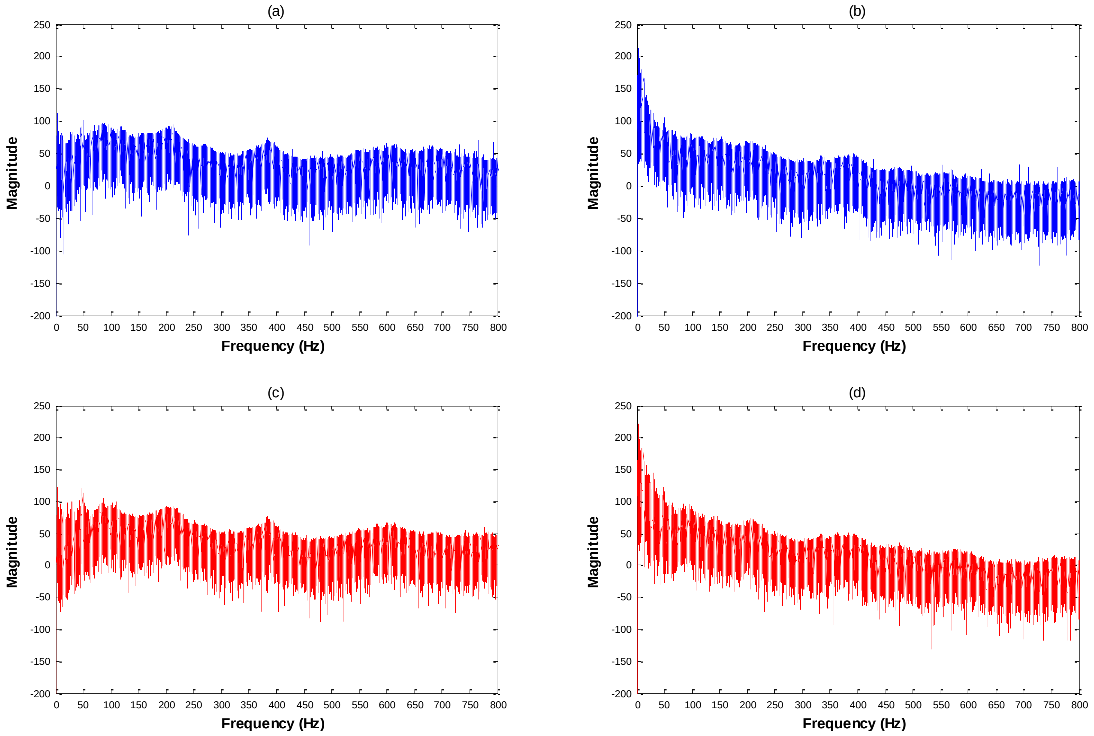


Figure 6: Signals spectra of the accelerometer (a)-(c) and gauge (b)-(d) in the band [0-800] Hz, tight belt in blue and slightly relaxed belt in red.

The spectral coherence between the accelerometer and the gauge for the tight belt (Fig.7) (a)-(c) and slightly relaxed belt (Fig.7) (b)-(d), indicates a good correlation for the study of the accessory pulley rotations and its harmonics (2.45 ± 0.3, 2x2.45 ± 0.3,... Hz), in the very low frequencies (band [0.50] Hz), considering the slightly relaxed belt. In general, the spectra differ and tend to conform to a certain extent around resonances

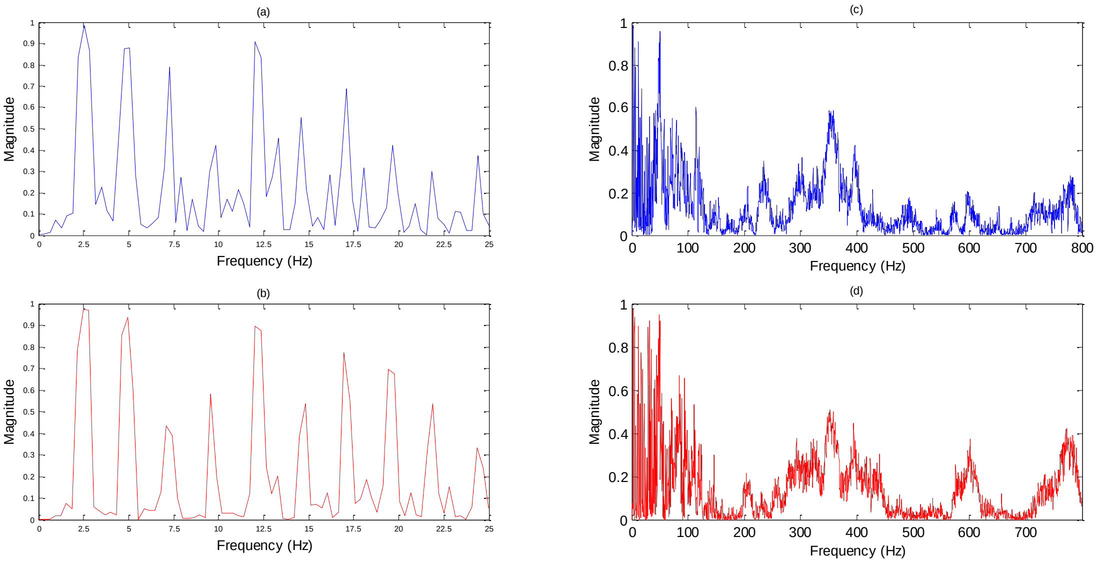


Figure 7: Spectral coherence functions between the accelerometer and the gauge, (a)-(c) signals belt tight blue and (b)-(d) slightly relaxed red belt.

6 Cyclostationary analysis

We do filtering in the frequency band [330,430] Hz, around an area of resonance with no peaks (Fig. 8). Then, we perform an envelope analysis from the demodulated signal.

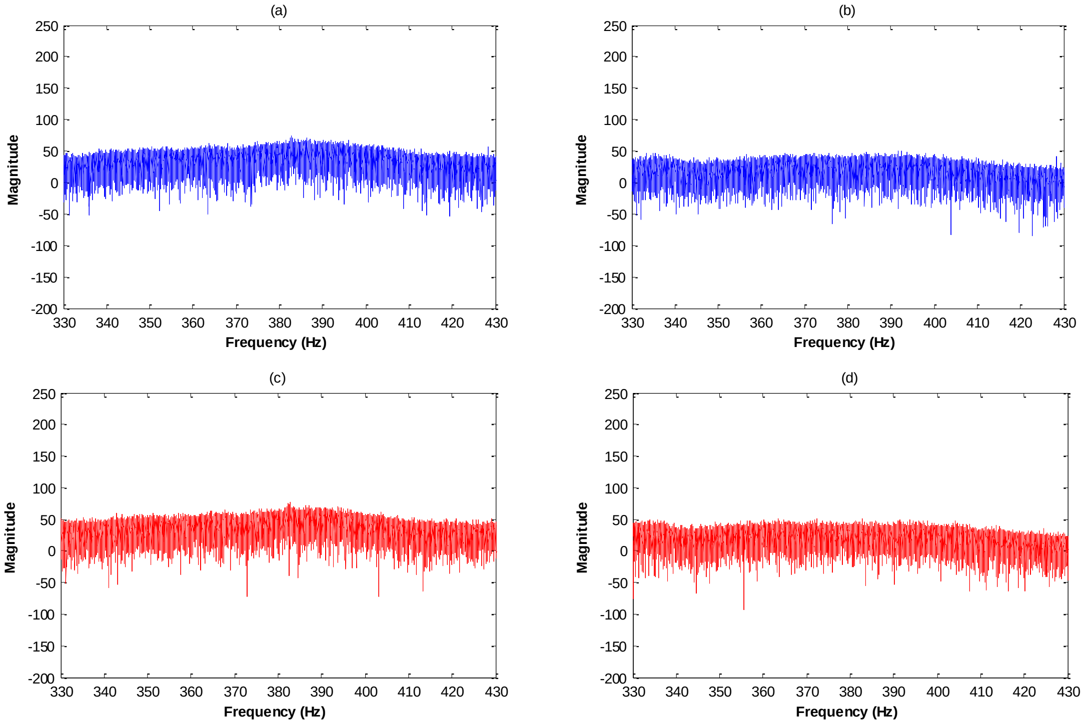


Figure 8: Signals spectra of the accelerometer (a)-(c) and gauge (b)-(d) in the band [330-430] Hz (resonance zone), tight belt in blue and slightly relaxed belt in red.

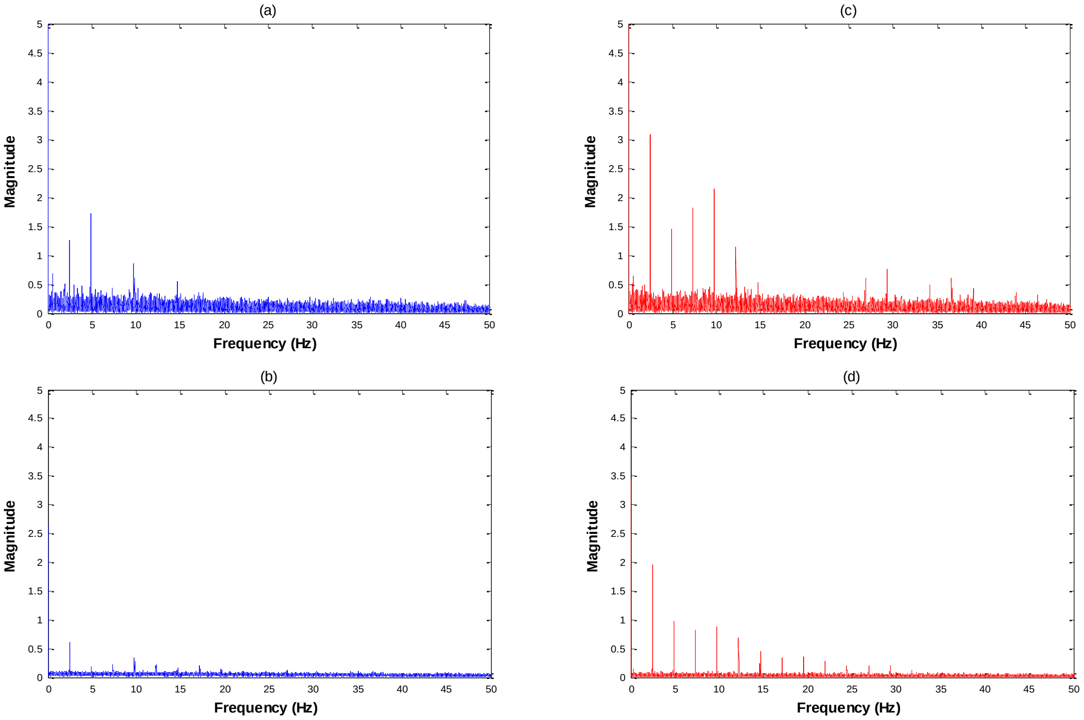


Figure 9: Spectra of the square of the envelope after filtering in the band [330,430] Hz, for the accelerometer (a)-(c) and gauge (b)-(d) signals, tight belt in blue and slightly belt relaxed in red.

Indeed, the spectra of the Envelope (Fig. 9) have periodic peaks at the frequency of rotation of the accessory pulley (2.45 Hz). These results inform us that belt signals are second-order cyclostationary and cyclic frequency is the rotation of the accessory pulley. This second-order cyclostationarity is less visible on the signals of the tight belt compared to the slightly relaxed belt. Therefore, the loss of tension in the belt appears be vibration signals of increasingly second-order cyclostationary. Peaks in the spectrum of envelope in the case of the tight belt are more spread in width and disappear after 20 Hz. The amplitudes in the case of slightly relaxed belt are practically doubled and disappear after 40 Hz. Fluctuations in speed to the level of the accessory pulley exist and are significant in the case of transmissions with a slightly relaxed belt. We can also observe that the measurement with strain gauge have less mode than accelerometric analysis, the spectral signature of the envelope is more regular.

Conclusion

This work is devoted to the diagnosis of slow speed belt transmissions. A test bench allowed to test different configurations of transmissions. If the temporal and frequency conventional analysis shows very little difference between a tight belt and a slighty relaxed belt, the second-order cyclostationary analysis provides an indicator suitable for this type of defect. Moreover, the join analysis of the accelerometer and strain gauge shows that strain gauges provide as relevant as the accelerometric sensor image picture. They can be more efficient in low frequency for applications at low speed. This work is an early study, it is now necessary to calibrate the indicator to the belt tension. Work has also been undertaken to diagnose belt wear, this indicator also provides interesting information on this issue.

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