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FAULT DETECTION IN CILINDERS OF THE INTERNAL COMBUSTION ENGINE USING THE CHOI-WILLIAMS DISTRIBUTION OF ACOUSTIC SIGNALS

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Abstract. *Faults in Internal Combustion Engines (IC engines) could be detected using signal processing techniques applied to the acoustic data measured experimentally. The detection and the diagnosis techniques of the faults in IC engines are important tools to be used in the Quality Control of the IC engines assembly line and in the condition monitoring. In this context, the objective of this work is to purpose a methodology of the detection and diagnosis of faults in cylinders of the IC engines using the time-frequency analysis of acoustic signals measured with the engines in operation. Usually, the signals measured in the IC engines have transient components that are difficult to identify by using the conventional spectral analysis. Hence, the acoustic signals will be processed to the time-frequency domain using the Choi-Williams Distribution in order to detect the transient components produced by the faults in the cylinders of the IC engine. The results proved that the time-frequency analysis provided by the Choi-Williams Distribution has applied to acoustic signal may be used as a powerful technique to be used in the detection and diagnosis of faults in IC engines.*

Keywords: *acoustic signals, fault detection, internal combustion engines, time-frequency distributions*

1. INTRODUCTION

The Internal Combustion Engines (IC engines) are largely employed as propulsion system of vehicles. The major role of the IC engines is provide the torque and rotation, that is, the mechanical power for the traction of a vehicle. Nowadays, as the automotive industry, as the academia are interested in the development of the techniques for the identification of faults in IC engines (Delvecchio et al., 2018). For example, during the inspections of quality control of the vehicles in an assembly line, it is interesting the early diagnosis of faults in the IC engines. Furthermore, during the cycle life of the IC engine, usually sensors and instrumentation are board in the vehicle in order to detect faults without the necessity of the disassembly of the system.

In this sense, there are in the literature several works about the identification and classification of faults in the IC engines by using the signal processing techniques applied to the experimental vibro-acoustic signals (Randall, 2011; Delvecchio et al., 2018). Randall (2011) presents several signal processing techniques and types of the sensors to be used in the measuring of the vibra-acoustic data and the detection of faults in the IC engines. Chen et al. (2016) have proposed a faults classification system in pistons using Neural Networks of vibration signals measured in IC engines. Since the acoustic and vibration signals measured in the IC engines are nonstationary, usually the time-frequency analysis is applied in order to identify the transient components caused by the faults in engines (Antonino-Daviu et al., 2017). More recently, Delvecchio et al. (2018) have published a tutorial that summarizes the state-of-art of research about the several signal processing techniques, instrumentation and some methods for the and classification of faults in IC engines.

In this work, it will be applied the Choi-Williams Distribution (CWD) as a time-frequency representation for the detection of faults in cylinders of the IC engines. Usually, faults in IC engines generates transient signals which are difficult to detect by using the conventional spectral analysis, such as, the Power Spectrum or the Power Cepstrum. Hence, in this work, it will be employed time-frequency analysis of the signals measured in the IC engines. Since the acoustic signals measured in the IC engines have several components, the CWD may provide a time-frequency map with more details when compared to the others time-frequency representations, as for example, the Short Time Fourier Transform, Continuous Wavelet Transform or the Wigner Distribution (Cohen, 1995).

2. VIBRO-ACOUSTIC SIGNALS GENERATED BY INTERNAL COMBUSTION ENGINES

IC engines have several components and subsystems, such as, the cylinders, crankshaft, fuel pump, valves, etc. Because all these elements work simultaneously, it is difficult to detect faults in the IC engines due to complexity of the noise that is generated during the measuring of the signals. Usually, it is employed vibration signals and/or acoustic signals for the fault detection in the components of the IC engines (Delvecchio et al., 2018). In the case of faults in the cylinder from IC engine, the acoustic signals are more sensitive to the presence of the transients components generated by the pulses caused by the fault (Delvecchio et al., 2018). Hence, in this work, it will be employed the Choi-Williams Distribution to the acoustic signals measured in the IC engine with one damaged cylinder.

The table 1 describes the more common types of faults that can occur in cylinders from IC engines (Delvecchio et al., 201). It can be seen in this table, that for defect detection in pistons from IC engines, it recommended the analysis of the acoustic and vibration signals for most cases. Moreover, the signals generated by faults in IC engines are transient and cyclostationary. In these situations, the time-frequency analysis is the more recommended technique for the detection of the transient events produced by faults in the IC engines.

Table 1. Characterization of the signals measured in the IC engines caused by faults in pistons (Delvecchio et al., 2018).

IC engine subsystem	Fault	Signal temporal characteristic	Path	Technique	Signal
Piston	Misfire	Transients	Structure-borne	Cyclostationarity time-frequency analysis	Vibration or Acoustic signals
Piston	Knock	Transients	Structure-borne	Cyclostationarity time-frequency analysis	Vibration or Acoustic signals
Piston	Piston slap	Transients	Structure-borne	Cyclostationarity time-frequency analysis	Vibration or Acoustic signals
Piston	Bearing cap with wear	Transients	Structure-borne	Cyclostationarity time-frequency analysis	Vibration
Piston	Connecting rod with uncorrected screw preload	Transients	Structure-borne	Cyclostationarity time-frequency analysis	Vibration

3. SIGNAL PROCESSING TECHNIQUES

3.1 Power Spectrum

A simple manner of identifying faults in IC engines is to apply the Power Spectrum (PS) to the acoustic signals. If the PS is applied to the IC engines, it measures the frequency energy density of the acoustic signal. Therefore, by using the PS, the signal analyst may verify what signal components have more energy in the frequency domain. By definition, the PS is the Fourier Transform (FT) of the Autocorrelation Function of the signal, x(t). The Autocorrelation Function, R(τ), is given by (Randall, 2011):

$$R(\tau) = E[x(t)x(t+\tau)] \tag{1}$$

where the symbol τ represents the delay time and the symbol E[] is the expected value of the product between x(t) and x(t+τ). The PS is defined by:

$$PS(f) = \frac{1}{2\pi}\int_{0}^{\infty} R(\tau)e^{-j2\pi ft}\,dt \tag{2}$$

where j is the pure imaginary and f represents frequency in Hz. By using the PS, the signal analyst may compare the increase in the amplitude of the signals components measured in the IC engines and to predict faults in their subsystems.

However, the PS is not able to represent the duration and the occurrence in the time domain of the transient components caused by faults (Cohen, 1995).

3.2 Power Cepstrum

The Power Cepstrum is a signal analysis tool used to identify the presence of the amplitude modulation in the signals components, such as, echoes or signals that have a repetition pattern in the time domain (Randall, 2011). By applying the Power Cepstrum to the acoustic signals, the analyst could identify the repetition period of the amplitude modulation components generated by the faults in the IC engines (Randall, 2011). The Power Cepstrum, C(t), is defined as the Inverse Fourier Transform of the logarithm of the Power Spectrum given by (Randall, 2011):

$$C(t) = IFT[\log(X(f)] \tag{3}$$

where the operator IFT denotes the Inverse Fourier Transform and X(f) the signal measured in the IC engine in the frequency domain. After Randall (2011), the Autocorrelation Function may also be used to identify the amplitude modulation of the components of the acoustic and vibration signals caused by faults in the mechanical systems. In the case of the Autocorrelation Function, it is simply the IFT of the PS without the presence of the logarithm inside of this operator. However, by using the Power Cepstrum or the Autocorrelation Function, the analyst is not able to identify what frequencies are present in the signal and how these frequencies change with the time.

3.3 Choi-Williams Distribution

The time-frequency representations are signal analysis tools able to extract the transient components, such as, the frequency and amplitude modulation and impulsive signals generated by the faults in IC engines. In this context, they have several advantages when compared to conventional spectral analysis or the Cepstrum analysis. The Short Time Fourier Transform (STFT) and the Continuous Wavelet Transform (CWT) are linear time-frequency representations that can be used to detect transient components produced by the defects in IC engines. Nevertheless, the quadratic time-frequency distributions, as for example, the Wigner Distribution (WD) and the Choi-Williams Distributions (CWD) may display a time-frequency map with more details if compared to the STFT and the CWD (Cohen, 1995). Therefore, in this work, it will be applied the CWD to the acoustic signals measured in the IC engines in order to identify faults in the cylinders.

The Wigner Distribution (WD) is a generalization of the Spectral Density Function (PS) has defined in the equation (2). The WD is an energy density function model in both time and frequency domains. Hence, by applying the WD to the vibration signal measured of a mechanical system, it is possible to identify when and how the frequencies components are changing with respect to the time. In the WD, the Autocorrelation Function is calculated for each time instant τ, by considering the signal samples in the past and the future. Instead of equation (1), the Autocorrelation Function in the WD is defined by (Cohen, 1995):

$$R(t,\tau) = \int_0^\infty x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)d\tau \tag{4}$$

where the symbol * denotes the conjugate complex of the analytic signal x(t). The Wigner Distribution, WD(t,f) is the Fourier Transform of the Autocorrelation Function, R(t,τ),

$$WD(t,f) = \frac{1}{2\pi}\int_0^\infty R(t,\tau)e^{-j2\pi ft}dt \tag{5}$$

The main drawback of the WD is the presence of interference cross-terms in the time-frequency plane (Cohen, 1995). For example, if the vibration signal is the sum of two components, $x(t) = x_1(t) + x_2(t)$, the WD of x(t) is:

$$WD[x(t)] = WD[x_1(t)] + WD[x_2(t)] + 2\,\mathrm{Re}\{WD[x_1(t)x_2(t)]\} \tag{6}$$

where $2\mathrm{Re}\{WD[x_1(t)x_2(t)]\}$represents the cross-term between the two signal components, $x_1(t)$ and $x_2(t)$. In fact, for each pair of components, there is always a cross term in time-frequency distribution (Cohen, 1995). These cross-terms are considered as "undesirable artificial components" caused only by the quadratic nature of the WD. Hence, for a multi-component vibration signal, the interference terms may difficult the interpretation of the signal components.

The Choi-Williams Distribution (CWD) is a quadratic time-frequency representation able to attenuate the cross-terms for multi-component signals (Choi and Williams, 1989). For the formulation of the CWD, it is necessary to discuss the concept of the Ambiguity Function (Cohen, 1995) defined by:

$$A(\theta,\tau)=\int_{0}^{\infty} x\left(t+\frac{\tau}{2}\right)x^{*}\left(t-\frac{\tau}{2}\right)e^{j\omega t}\,dt \tag{7}$$

where ω is the frequency in rad/s and θ is the frequency in the ambiguity domain. The ambiguity domain is a different manner of interpreting the signal components in the time-frequency plane. In this domain, the cross-terms will always be localized in the regions far from the origin of the ambiguity domain. On the other hand, the signals components or auto-terms are always placed on the axes of this domain. Using this idea, Choi and Williams (1989) have proposed a function in the ambiguity domain as follows:

$$\phi(\theta,\tau)=\exp\left(\frac{-\theta^{2}\tau^{2}}{\sigma}\right) \tag{8}$$

where σ represents a parameter of suppressing of interference terms in the CWD. In the signal analysis context, the function ø(θ,τ), called kernel, can be defined by any mathematical equation that the analyst desires. According to this concept, it is possible to filter the cross-terms between the several signal components, by using the Characteristic Function Formulation, M(θ,τ) (Cohen, 1995):

$$M(\theta,\tau)=\phi(\theta,\tau)A(\theta,\tau) \tag{9}$$

and any time-frequency representation can be derived from the two-dimensional Fourier Transform of M(θ,τ):

$$C(t,\omega)=\frac{1}{4\pi^{2}}\int_{0}^{\infty}\int_{0}^{\infty} M(\theta,\tau)e^{-j\theta t-j\tau\omega}\,d\theta d\omega \tag{10}$$

which yields the Cohen's general class, C(t,ω), a manner of generalizing all linear and quadratic time-frequency representations. By inserting the Choi-Williams kernel has defined by the equation (8) in the equations (9) and (10), one has the Choi-Williams Distribution (1989):

$$CWD(t,\omega)=\frac{1}{4\pi^{3/2}}\int_{0}^{\infty}\int_{0}^{\infty}\frac{1}{\sqrt{\tau^{2}/\sigma}}\,x\left(t+\frac{\tau}{2}\right)x^{*}\left(t-\frac{\tau}{2}\right)\exp\left[-j\tau\omega-\sigma(t-\tau)^{2}/\tau^{2}\right]dt\,d\tau \tag{11}$$

which will be applied to the vibration response of some mechanical systems have considered in this work. Hence, if the signal has several components, the cross-terms will be suppressed and some of desired properties of WD will be preserved. A serious disadvantage of the CWD is the high computational cost has required in the calculation of the time-frequency matrix in the discretized form of the equation (11). If the vibration signal does not have several frequency components, it may be more appropriate to use the WD instead of the CWD.

4. MEASUREMENT AND PROCESSING OF THE ACOUSTIC SIGNALS

The acoustic signals were measured in the IC engine from the vehicle Volkswagen® Saveiro 2012. These signals were obtained with the IC engine by operating to the rotation in about 950 rpm (15,83 Hz) and in the approximated temperature of the 90 ºC. For the measuring, the IC engine was tested in a room with the objective of filtering the external noise. In the acquisition of signals, it was used a microphone from PCB® manufacturer and a data acquisition board from National Instruments®. For the acquisition of acoustic data, it was used a sampling frequency de 51200 Hz and the signals in the time domain were discretized with 768000 points.

5. ANALYSIS OF THE RESULTS

Figure 1 shows the acoustic signals in the time domain, spectrum and Cepstrum measured for the IC engine without faults. In this case, the signal is noisy and does not present no significant component caused by the damaged cylinder. However, for the Cepstrum of acoustic signal measured for the IC engine with fault illustrated in the Fig. 3, it is observed in the time of 0,0151 s a component probably caused by the amplitude modulation due the fault. The time of 0,0151 s corresponds to the inverse of the rotation frequency of IC engine (1/15,83) and divided by 4, since that the engine has 4 cylinders. The amplitude of this component (0,90) is larger than the amplitude for the signal without defect (0,48) which proves that the faulty cylinder generate an amplitude modulation.

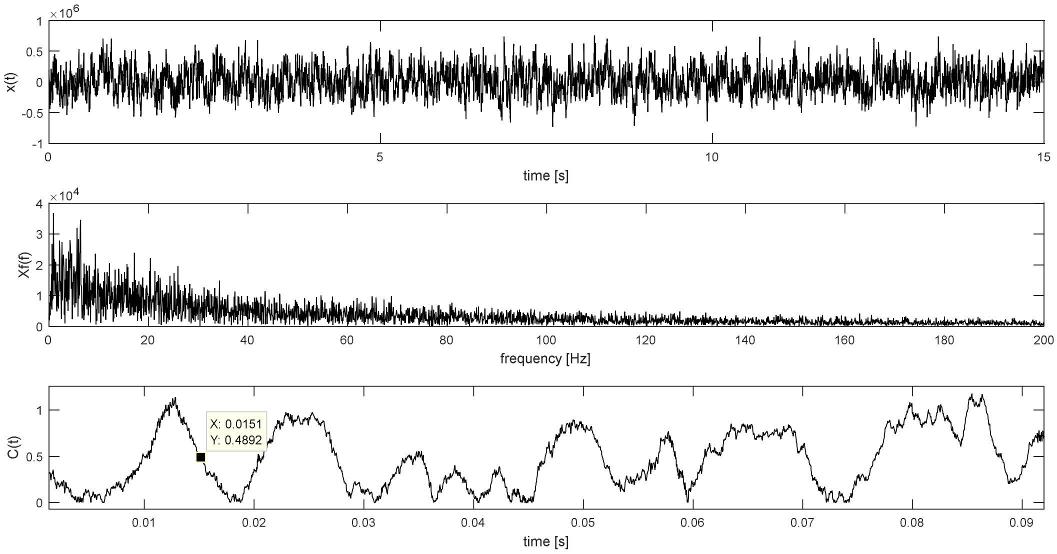

Figure 1. Acoustic signal measured in the time domain, spectrum and cepstrum for the internal combustion engine without fault.

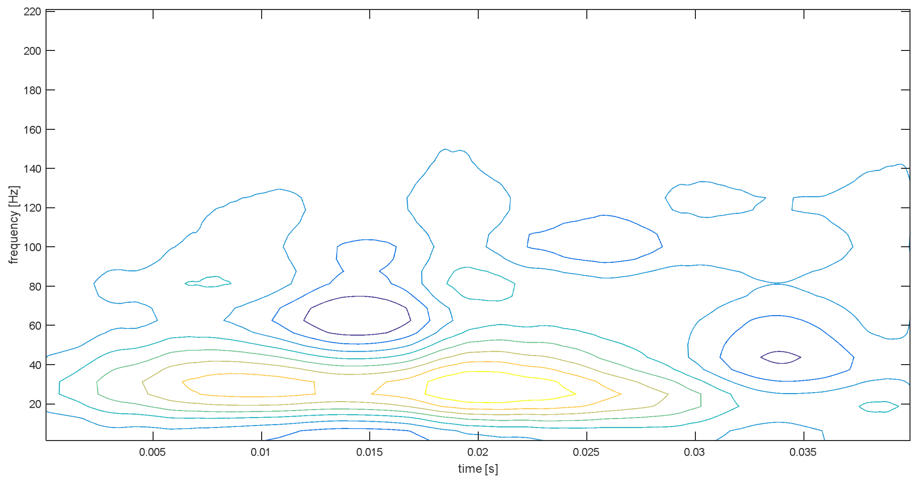

Figure 2. Choi Williams Distribution for the internal combustion engine without fault in the cylinder.

The Choi-Williams Distribution of the acoustic signal shown in the Fig. 4 displays two transient components in about 0,015 s and 0,035 s probably produced by the faulty cylinder from IC engine. These components are spaced with the approximated time of 0.015 s that is equals to the repetition time of the amplitude modulation component caused by the damaged cylinder. On the other hand, the Choi-Williams Distribution of Fig. 2 for signal measured in the IC engine without fault does not display these repetition pattern due to noise caused by the healthy engine components.

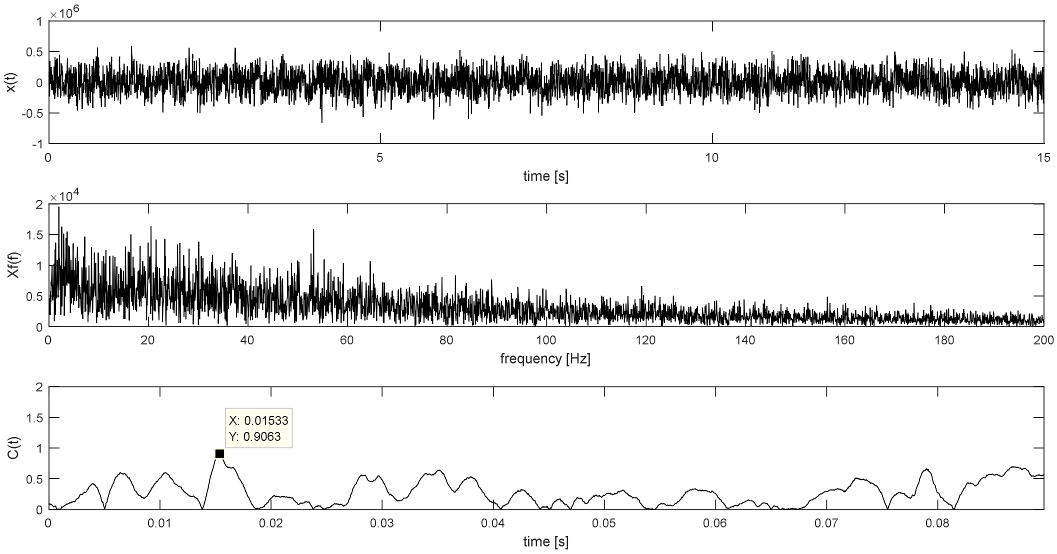

Figure 3. Acoustic signal measured in the time domain, spectrum and cepstrum for the internal combustion engine with fault.

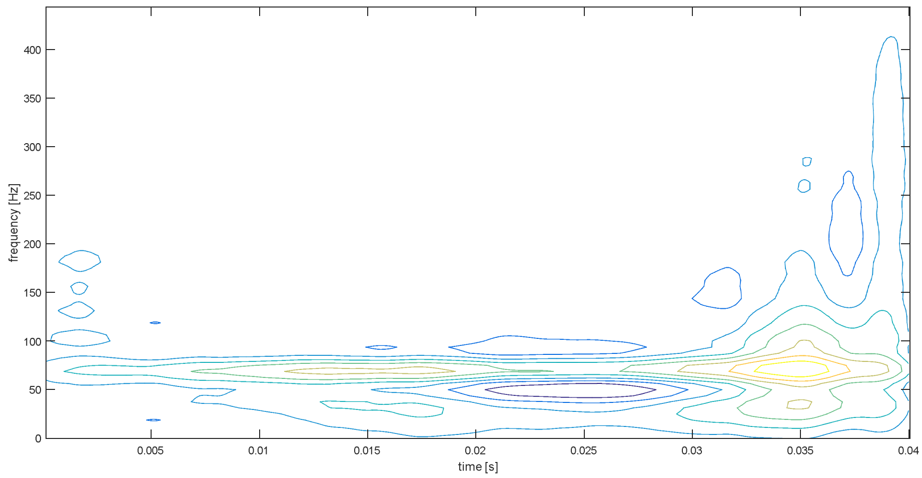

Figure 4. Choi Williams Distribution for the internal combustion engine with fault in the cylinder.

6. CONCLUSIONS

In this work, it was applied the Choi-Williams Distribution in acoustic signals measured in the Internal Combustion Engines (IC engines) in order to detect faults in pistons. Moreover, the Power Spectrum and the Power Cepstrum were also applied to the acoustic signals for detecting the frequency components and the amplitude modulation pattern caused by the defects in the pistons. For this purpose, the acoustic signals were measured in the IC engine without fault and another engine with fault in the piston. The acoustic signals were measured inside the room in order to filter the external noise generated by other sources. Since the noise present in the signals measured in the IC engine is very high, it was not possible to identify the components frequency caused by the faults by using the Power Spectrum. However, the Power Cepstrum displayed the period of the repetition caused by the amplitude modulation due to the fault in the pistons of the IC engine.

In the literature, it is recommended the use of time-frequency analysis for detecting the transient components produced by faults in the IC engines. Since the signals are ciclostationary, the more used techniques are the Short Time Fourier Transform, the Continuous Wavelet Transform and the Wigner Distribution. The Wigner Distribution may provide a more detailed time-frequency representation of the signal measured in the IC engine. Nevertheless, the cross terms produced by the Wigner Distribution may difficult the analysis and the identification of the components caused by the fault. In this sense, the Choi-Williams Distribution proved to be an efficient technique in the detection the transient components generated by the faults in the pistons of the IC engine.

7. ACKNOWLEDGEMENTS

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