On the use of cyclostationary indicators in I.C. engine cold test quality control

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ABSTRACT

The aim of this research is to process the I.C. engine vibration signal in cold conditions by using cyclostationary tools.
This type of analysis is needed in order to detect and diagnose irregular operations for quality control purposes. In particular, two faults artificially introduced one by one in the engines have been considered: piston assembled inverted and connecting rod without a bearing cap.
The originality of this paper mainly concerns the use of vibration measurements for the quality control of engines in cold conditions to diagnose assembly faults.

1. INTRODUCTION

Nowadays, the main part of engine manufacturers tests their engines by means of a "hot test", i.e. a test in which the engine is firing. On the other hand, recently, some companies have introduced a "cold test" instead of the hot test. The essential difference between these two methods is that the hot test aims at verifying the engine performance, while the cold test aims at verifying the anomalies by means of torque, pressure and vibration measurements. It is worth noting that by using the hot test only the main anomalies could be detected, while in the cold test the fault detection is more precise and effective, since no noise and vibration due to the firing are added.

Concerning the cold test technology, a previous paper [1] has shown the ability of different vibration signature analysis in extracting correct indicators for the condition monitoring procedure. In these works, the authors gave also emphasis to the use of some cyclostationarity tools applied to one specific assembly fault (i.e. connecting rod with incorrectly tightened screws).

The present research focuses on the use of some cyclostationary indicators very well suited for a simple and fast quality control investigation at the end of the assembly line. Particularly two new faulty conditions have been investigated (i.e. piston assembled inverted and connecting rod without a bearing cap).

Since vibration of reciprocating machinery (i.e. internal combustion engines, compressors) is complex and difficult to analyze, the literature on diagnostics of these machines is quite rare.
However most of the work in literature, concerning the above-mentioned strategies, refers to engines in firing condition. Kimmich et al. proposed a model-based diagnosis method [1]. Jean-Hugh Thomas et al. developed a diagnostic method to detect engine knock using pattern recognition with wavelet networks [3]. Molinaro et. al. used some pattern recognition detectors, such as cepstral coefficients and amplitude histograms, in order to improve knock recognition in spark engines [4]. Li et al. used the Independent Component Analysis to decompose noise signals into a number of independent components and, consequently, study each individual component separately [5]. Some approaches have been introduced by

applying the measurement of instantaneous angular speed for detection of fuel leakage in engines in firing [6]. Yang et al. use the instantaneous angular speed to detect faults relating to the gas pressure in the cylinder [7].

Cyclostationarity is a novel field of research developed in mechanics by Antoni [8]-[14] who proposed a methodology based on the properties of cyclostationarity applied to the malfunctions in engines in firing conditions (advance and delay of injections, misfires and knocks). Zouari et al. [15] applied the cyclostationary modeling to signals measured from reciprocating compressors .

This paper tries to answer the following questions:

- ✓ Are the vibration measurements obtained from the cold tests useful in detecting assembly faults in diesel engines?
- ✓ Is it possible to assess a fast and reliable monitoring procedure to make a correct pass/fail decision at the end of the engine assembly line?
- ✓ Is the cyclostationarity approach an effective technique to diagnose malfunctions (not common in literature) in engines by means of the analysis of vibration signals carried out in a non-combustion state?

The structure of the paper is the following. Section 2 introduces some cyclostationary theoretical background. Section 3, after describing the experimental apparatus and the tested faulty conditions concerns the application of Indicator of Cyclostationarity (*ICS*) and Degree of Cyclostationarity (*DCS*) in order to detect the presence of the fault. Finally, Section 4 shows the cyclostationary model capabilities in localizing the specific tested assembly faults.

2. CYCLOSTATIONARY INDICATORS

2.1 – Wigner-Ville Spectrum and Mean Instantaneous Power

Non-stationary signals can be defined as signals which satisfy a non-property, i.e. they do not satisfy the property of stationarity. It is not possible to define a general theory which treats non-stationary signals. The non-stationary behavior of each signal has to be individually evaluated. Time-frequency analysis can be considered a useful tool to analyze the amplitude and frequency non-stationarities within a signal. Moreover, the envelope analysis is effective to study the non-stationarities due to the energy variation within a signal.
In that case that a signal presents periodic energy variations and synchronous with the machine cycle a particular class of non-stationary signals can be defined: the cyclostationarity signals.
The theory of the cyclostationarity is developed by Gardner [16] in the telecommunication field and by Antoni in the mechanical field for the diagnosis of rotating machines. Moreover McCormick et al. gave their contribution in treating signals from rotating machines as cyclostationary [17].
Mathematically, a signal $x(t)$ that satisfies the periodicity of the first two moments, can be considered as a wide sense cyclostationary process:

first order cyclostationarity

$$m_x(t) = E\left\{x(t)\right\} = m_x(t+T) \tag{1}$$

second order cyclostationarity

$$R_{xx}(t_1,t_2) = E\left\{x(t_1)x^*(t_2)\right\} = R_{xx}(t_1+T,t_2+T) \tag{2}$$

where $E\left\{\cdot\right\}$ stands for the expected value and *T* is the time period.

Since this periodicity is linked with the existence of a basis cycle [12] in rotating machinery, it is more convenient to refer to a cyclic period θ in the angular domain.
Therefore, the equations (1) and (2) can be expressed in the angular domain as follows:

$$m_x(\vartheta) = E\left\{x(\vartheta)\right\} = m_x(\vartheta + \theta) \tag{3}$$

$$R_{xx}(\vartheta_1, \vartheta_2) = E\left\{x(\vartheta_1)x^*(\vartheta_2)\right\} = R_{xx}(\vartheta_1 + \theta, \vartheta_2 + \theta) \tag{4}$$

Each cycle can be considered as a realization of a random process. In order to do so, each realization must begin at an identical angular position.
Then, it is possible to compute an ensemble average (i.e. the average amplitude for a given angle ϑ). that we can define as Time Synchronous Average (i.e. TSA). The TSA permits to extract the "periodic part" (first cyclostationarity order) of the signal and so it is an estimation of the $m_x(\vartheta)$ as follows:

$$\hat{m}_x(\vartheta) = \frac{1}{N}\sum_{i=0}^{N-1} x(\vartheta + i\theta) \tag{5}$$

where $N\theta$ is the length of the signal, N the number of cycles within the signal.
The quantity

$$WVS_x(\vartheta, f) = E\left\{FT_{\tau\to f}\left\{x\left(\vartheta + \frac{\tau}{2}\right)\cdot x\left(\vartheta - \frac{\tau}{2}\right)^*\right\}\right\} = FT_{\tau\to f}\left\{E\left\{x\left(\vartheta + \frac{\tau}{2}\right)\cdot x\left(\vartheta - \frac{\tau}{2}\right)^*\right\}\right\} \tag{6}$$

defines an angular-frequency energy distribution (*FT* refers to the Fourier Transform and *E* is the "ensemble averaging operator") for cyclostationary signals known as the Wigner-Ville Spectrum (WVS).
It can be noted that, the WVS is related to the expected value of the Wigner Ville Distribution (WVD).
The main advantage of the WVS over the WVD is that it helps in reducing interference terms.

Antoni [8] interprets the WVS (under the assumption of non-negativity) as the Probability Density Function (PDF) of the frequency random variable ν vs. the angular position variable ϑ.
Because of this, the WVS can be described by its "spectral" moments.
The nth spectral moment is defined as:

$$m_n^x(\vartheta) = \int_0^\infty WVS_x(\vartheta, \nu)\nu^n d\nu \tag{7}$$

Antoni proves [18] that the spectral moments can be obtained from the following formulation

$$m_n^x(\vartheta) = (2\pi j)^{-n}\frac{\partial^n \ln K}{(\partial\tau)^n}(\vartheta, 0) \tag{8}$$

where *K* is the autocovariance function of the analyzed signal.
The estimated sampled Mean Instantaneous Power (MIP) can be obtained directly from the angular sampled signal:

$$\hat{m}_0^x[m] = \left\langle \left| X_a[m] \right|^2 \right\rangle_N^I \qquad m = 0,...., N-1 \tag{9}$$

with X_a the analytic signal where $\left\langle |\cdot| \right\rangle_N^I$ means averaging over *I* cycles of length *N* samples of a single measurement.

2.1 – Degree and Indicator of Cyclostationarity

In this paper the cyclostationary approach has been primarily taken into account for the estimation of two useful metrics: Degree of Cyclostationarity (*DCS*) and Indicator of Cyclostationarity (ICS_{nx}), both outlined in [19]. Both indicators try to quantify the distance of a cyclostationary process from the closest stationary process having a similar power spectral density. In particular ICS_{1x} and ICS_{2x} give an indication of the presence of first-order and second-order cyclostationarity components within a signal.
The *DCS* metric is defined as [14]:

$$DCS^{\alpha} = \frac{\left| SC_x^{\alpha}(f) \right| df}{SC_x^{0}(f) df} \tag{10}$$

with $SC_x^{\alpha}(f)$ the spectral correlation density of a signal *x(t)*.
A valid estimator of the indicator ICS_{nx} is proposed in [19]:

$$ICS_{nx} = \sum_{\alpha \neq 0} \frac{\left| \widehat{C}_{nx}^{\alpha}(0) \right|^2}{\left| \widehat{C}_{2x}^{0}(0) \right|^n}, \; n = 1, 2. \tag{11}$$

where α is the cyclic frequency and $\widehat{C}_{nx}^{\alpha}(0)$ is the cyclic cumulant calculated at lag zero and cyclic frequency α. The cyclic cumulant can be estimated as following:

$$\widehat{C}_{1x}^{\alpha} = N^{-1} DFT\left\{ x(k) \right\}(\alpha) \tag{12}$$

$$\widehat{C}_{2x}^{\alpha}(0) = N^{-1} DFT\left\{ x_c^2(k) \right\}(\alpha) \tag{13}$$

where *x(k)* is the TSA signal, $x_c(k)$ is the residual signal obtained after subtracting the TSA from the original angular signal, $DFT\left\{ x(k) \right\}(\alpha)$ is the *N*-point Discrete Fourier Transform of the discrete signal *x(k)* calculated at frequency α. Further details about the background theory of the cyclic cumulants can be found in [19].
The *DCS* and *ICS* indicators basically have the same physically meaning. Nevertheless they show some different peculiarities:

- ✓ DCS^{α} does not depend by the number of averages performed in order to obtain TSA; since ICS is calculated for TSA (ICS_{1x} and residual signal (ICS_{2x}), its value depends on the number of averages performed;
- ✓ the DCS^{α} is calculated for each cyclic frequency α; on the other hand the *ICS* value, being a summation over a cyclic frequency range, depends on the number of cyclic frequencies selected;

- ✓ since it requires the calculation of the spectral correlation density, the DCS^{α} is not so straightforward to compute; on the other hand the ICS value is faster and easier because its implementation is based on FFT algorithm.

Although its higher complexity the *DCS* has been implemented because of the low number of averages available to perform TSA, thus affecting the ICS reliability. Moreover it has been verified if the *DCS*, directly derived from spectral correlation density, could supply more useful information about the fault periodicity than the ICS metric.

3. EXPERIMENTAL APPARATUS

Experimental investigations are carried out on a 2.8 dm^3 diesel engine produced by VM Motori, 4-cylinder 4-stroke with four-valve-per-cylinder, turbocharged with an exhaust-driven turbo-compressor. The measurements are carried out in cold conditions (without combustion) while the engine crankshaft is driven by an electric motor via a coupling. The cyclostationary analysis has been carried out on signals extracted at 1000 rpm in order to process a higher number of cycles to perform the TSA since the duration of the acquisition time is fixed. The acceleration signal is measured by means of a piezoelectric general purpose accelerometer (MTN 1020; frequency range: 2-13 kHz) mounted on the engine block (turbocharger side) close to the bearing support of the crankshaft. The sample frequency is 14 kHz and the acquisition time is 2 s.

A tachometer signal with 360 pulse/rev is used to measure the angular position of the crankshaft. During the acquisition, the acceleration signal has been resampled with an angular resolution of 1 degree. The TSA has been computed over 16 averages, each corresponding to two crankshaft rotations (720º), in order to respect the periodicity of a 4-stroke engine. It has to be remarked that since the acquisition time is fixed to 2s the number of averages is therefore fixed.

The signal measured in healthy conditions can be assumed as the superposition of periodic components due to crankshaft rotation, piston motion, valve activities and the pressurization of the cylinders.

The faulty conditions under observation are the following:

- Inverted piston (IP1 engine) – Figure 1 (a). The piston is assembled inverted, with a non correct positioning of the valve sites. This wrong assembly does not permit the correct correspondence between the valve plates and the valve sites. Since the exhaust valve site area is larger than the intake valve site one, the exhaust valves hit their non-correspondent intake valve sites. The piston inverted is the number 1.
- Connecting rod without a bearing cap (RC4 engine) – Figure 1 (b). The absence of the bearing cap permits higher clearances between the rod and the crankpin. These higher clearances cause the hit of the piston against the valve plates. The faulty rod is connected to the piston 4.

4. CONDITION MONITORING PROCEDURE

The adopted condition monitoring procedure considers the use of cyclostationary tools in order to detect and diagnose the presence of the assembly fault. Therefore not only the healthy condition of an engine could be verified but, if a faulty condition is recognized, the procedure permits to localise the fault within the engine kinematics.

The time vibration signal is firstly synchronously resampled. The synchronous average (TSA) of an healthy engine is shown in Figure 2 (a). The TSA signal is evaluated over two crankshaft rotations because, as a matter of fact, the periodicity of a 4-stroke engine is of two crankshaft rotations. This synchronous average completely depicts the nature of the signal. In fact, one can see that the signal period is mainly characterized by four impulse responses that are linked to the pressurization of each cylinder (indicated as 'Press.').
Observing Figure 2 (b) and (c) depicting the 5th cycle of the residual and its MIP respectively it can be noted that the non-deterministic part is quite irrelevant showing that the healthy signal is mainly characterized by first order cyclostationarity.

Moreover Figure 3 depicting the DCS computed on the residual signal points out that the energy flow of the vibration residual signal in healthy conditions follows the cyclic order 2. This means that even it is not clear in Figure 2 (b) the release of turbolence due to the pressurizations happens 2 times each revolution of the crankshaft and gives some second order cyclostationary content. This DCS trend, where only the turbulence during pressurization is present like a source, can be assessed as a reference pattern representing the healthy condition.

Observing the TSA signal obtained for the faulty IP4 engine (see Figure 4 (a)), it can be noted that it is superabounded by two marked spaced peaks. These two peaks are due to the impacts of the valve plates against their non correspondent valve sites. It has to be remarked that the first hit happens during the pressurization of the faulty cylinder when all the valves are closed (see 'Press 1' in Figure 4 (a)). Since the number of averages performed for TSA calculation is not so high (i.e. 16), such a strong impulse response can be also observed in the residual signal. The low number of averages also affects the pressurization events indicated as 'Press 4' and 'Press 2' that can be recognized within the residual signal (see Figure 4 (b)). The second hit appears 360 degrees later the previous one when the intake valves are opened. Since the randomness due to the pressurization is not so relevant here, the second hit can be mainly observed within the TSA signal that estimates the deterministic contribution to the whole signal.
Based on these achievements, we may say that the IP4 signal is dominated by first order cyclostationarity: The physical explanation of this can be related to the high deterministic nature of the IP4 fault that causes impacts of the piston again the valve sites at the same angular position in each engine work cycle.
This is confirmed by the values assumed by ICS_{1x} and ICS_{2x} indicators reported in Table 1. Concerning the IP1 engine both indicators are higher than the ones assumed by the healthy signal. Moreover the ICS_{1x} is more relevant than the ICS_{2x} confirming the first cyclostationary nature of the IP1 faulty.
It has to be remarked that the TSA permits to localize the fault within the engine kinematics, the ICS indicator is only plenty for a pass/fail decision procedure.
The *DCS* calculated on the residual and depicted in Figure 5 shows that its energy flow mainly following the cyclic order 1 and its harmonics. This is because the release of energy due to the piston impact happens one time each crankshaft revolution.

Finally, the Wigner-Ville Spectrum (WVS) of the residual signal is computed in order to obtain a better angular localization of the events. The results are shown in Figure 6. As previously explained, two clearly vertical lines concerning the mechanical fault appears within the distribution. In addition further engine events are shown in the WVS. In particular the vertical lines at about 295º, 474º, 655º and 115º are related to the closure of the intake valves of the cylinders 3, 4, 2 and 1, respectively. The two vertical lines around 373º and 396º are related to the opening of the first cylinder output valves and to the pressurization of the third cylinder, while the vertical lines at about 12º and 36º correspond to the opening of the fourth cylinder output valves and to the pressurization of the second cylinder.
The WVS can be considered as a useful tool in order to understand which is the frequency range interested by the fault. However it has to be remarked that here the frequency range is not really considered since the monitoring procedure only seeks to detect and diagnose the presence of a fault.

Concerning the second fault condition, i.e. rod without bearing cap, all the same previous analyses are carried out: firstly the signal is synchronously resampled, secondly the residual signal and the mean instantaneous power have been calculated. The synchronous average is shown in Figure 7 (a): one can notice that four lower acceleration peaks can be linked to the pressurization of each cylinder.

In addition it can be noted a big variation in the synchronous average related to the hit of the connecting rod of the cylinder 4 when the opening of the intake valves of the cylinder 4 happens at the beginning of the intake stroke. This fact is proven in [1] to be theoretically happening at 26 degrees after the TDC of the cylinder 4; this event may be due to the impact of the piston against the intake valves that are being opened. After analyzing the valve displacement diagram (not reported here), it can be assessed that, at this angular location, the high clearance between the piston and the valve is lower then the bearing thickness. Since the presence of high clearance the angular position at which the impact occurs slightly changes at each engine cycle. This phenomenon justifies the second order cyclostationary properties of this faulty signal. It can be also observed that the duration of the impulse response is greater than 40 degrees because of the high

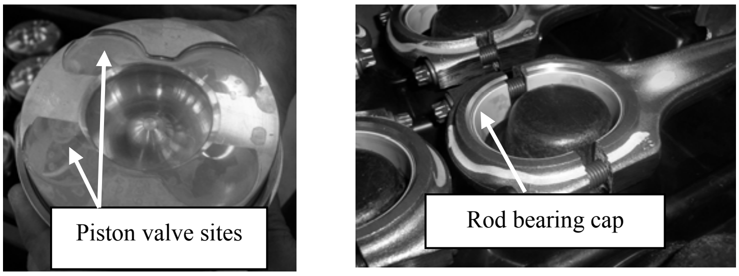
severity of the impact: the number of averages performed is not enough to remove its contribution from the non-deterministic part of the signal. As a consequence, the residual signal of the RS4 engine 8 (in Figure 7 (b) its 5^{th} cycle is depicted) is quite significant.
In order to get a better localization of the fault position, the mean instantaneous power of the residual signal has been computed. Figure 7 (c) points out the presence of the fault 26 degrees after the TDC of the cylinder 4 at the beginning of the intake stroke confirming the results achieved by analyzing the time synchronous average.
Concerning the ICS_{1x} and ICS_{2x} (see Table 1) indicators they show higher values than the healthy signals. The ICS_{2x} , showing a higher value than the corresponding ICS_{1x} , confirm the relevance of the second order cyclostationary peculiarity of the IP4 fault condition.
The *DCS* depicted in Figure 8 confirms the presence of second order cyclostationarity component, showing the strong periodicity of the 0.5 order caused by the happening of one impact each engine cycle.

5. CONCLUDING REMARKS

This paper deals with the application of some cyclostationary signal processing tools in order to analyse the vibration signals collected on a cold test of I.C. engines.
It could be concluded that:

- ✓ vibration measurements can be useful in detecting assembly faults in I. C. engine cold tests at the end of the assembly line;
- ✓ all the applied cyclostationary indicators show good sensitivity to both tested faults; this seems to be in coherence with the physics of vibration captured from an engine block in cold conditions;
- ✓ on one hand the cyclostationary modelling of the signal permits to define some indicators that can be able to detect the presence of a fault (i.e. *DCS* and *ICS*); on the other hand this approach permits to precisely localize the fault within the engine kinematics supplying a sort of diagnostic tool.

We have demonstrated that the cyclostationary indicators are well suited for the problem in hand and of very practical concern. They can be used in a automatic diagnosing systems since it is possible to avoid the implementation of 3-dimension tools like *SCD* or time-frequency calculations.



(a) (b)

Figure 1. Mechanical devices involved in 2 faulty conditions under study.

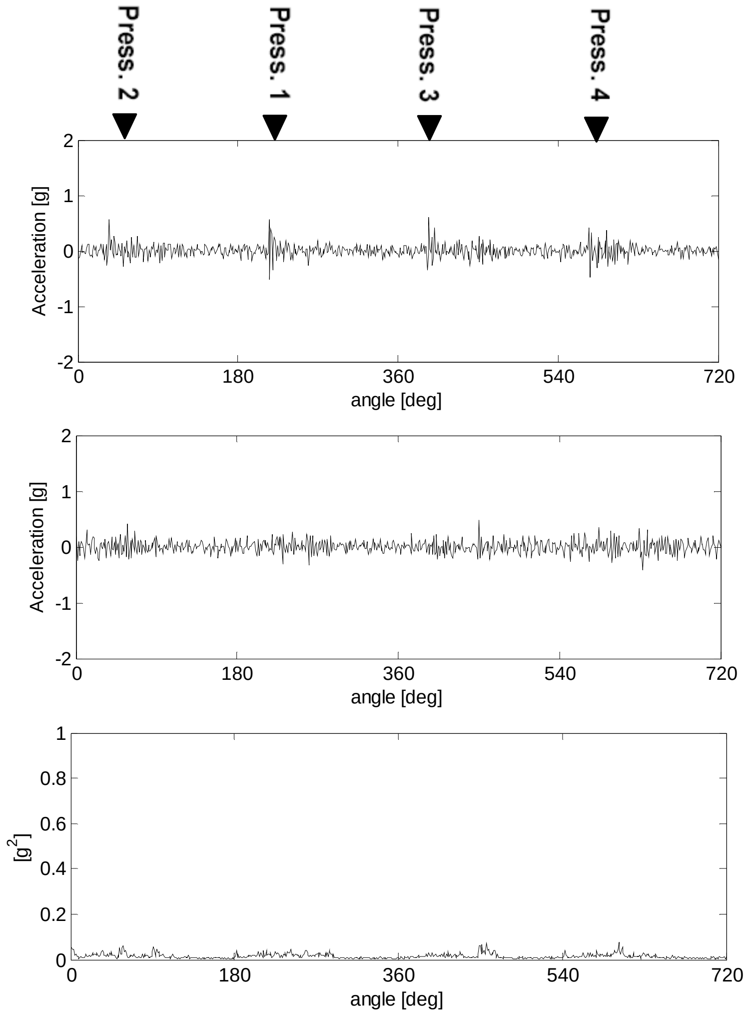


Figure 2. Healthy engine: (a) time synchronous average, (b) residual signal (5th cycle), (c) Mean Instantaneous Power of the residual signal.

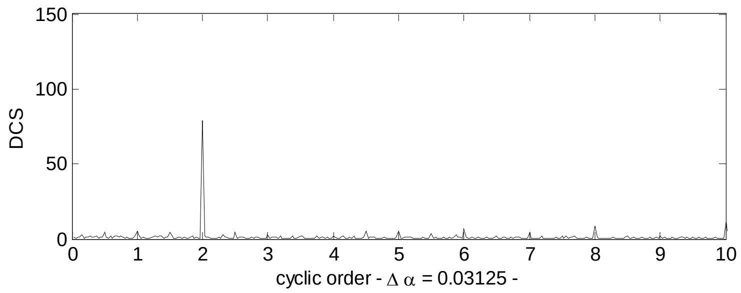


Figure 3. Healthy engine: DCS plotted in the cyclic order range 0-10.

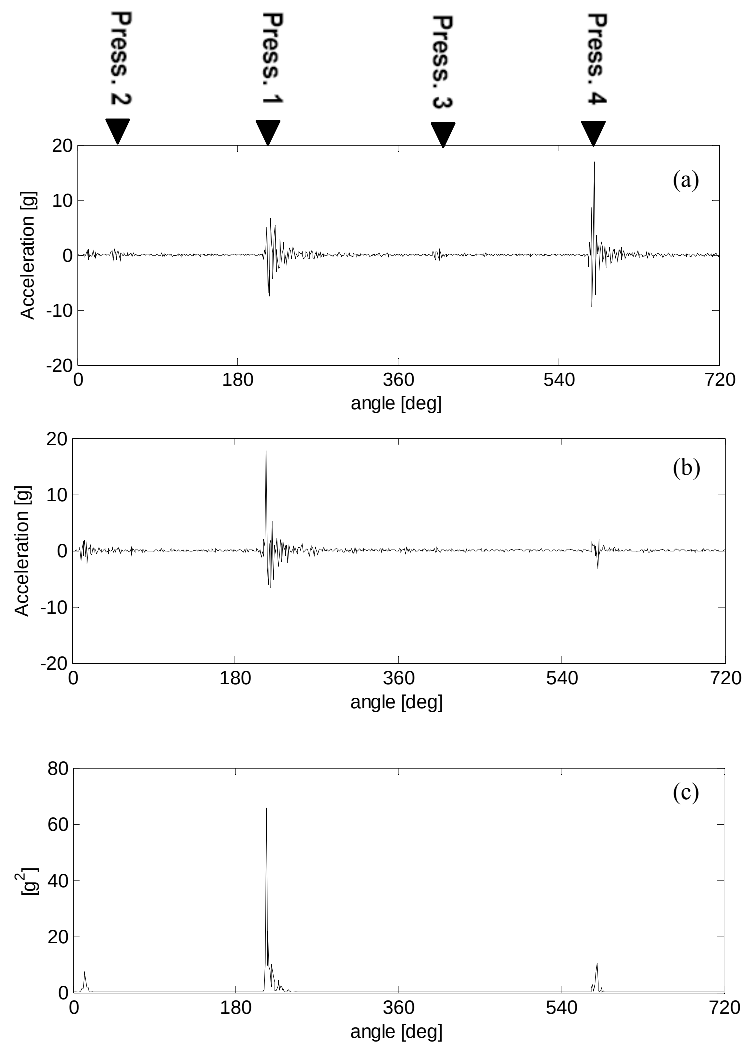


Figure 4. IP1 engine: (a) Time Synchronous Average, (b) residual signal (5^{th} cycle), (c) Mean Instantaneous Power of the residual signal.

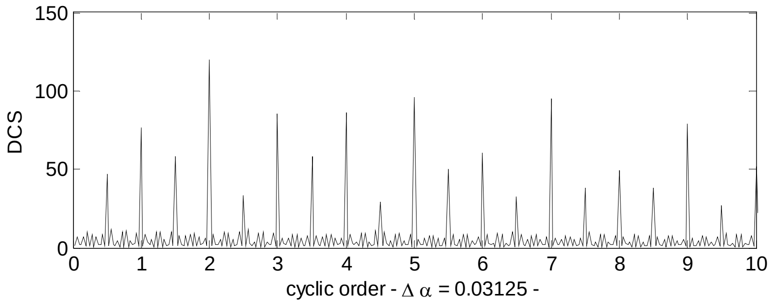


Figure 5. IP1 engine: DCS plotted in the cyclic order range 0-10.

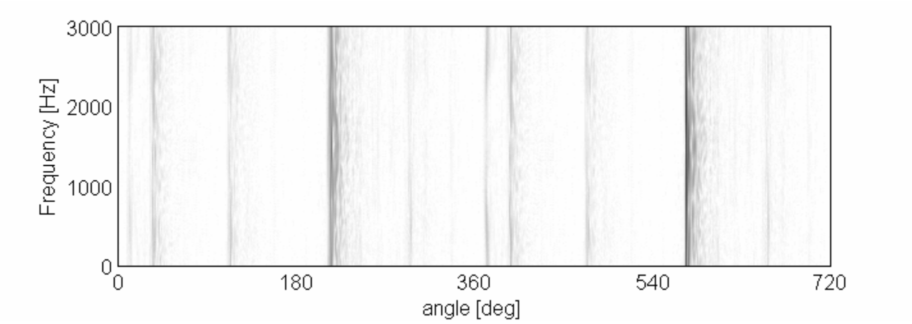


Figure 6. IP1 engine: Wigner Ville Spectrum of the residual signal.

Table 1 – ICS mean value at 1000 rpm.

Engine	ICS mean value in the range 0-10 cyclic order 1000 rpm	
	ICS_{1x}	ICS_{2x}
Mean + 3 Sigma for normal engines	0.04	2.10
Faulty IP1 engine	**43.91**	13.76
Faulty RC4 engine	15.26	**18.20**

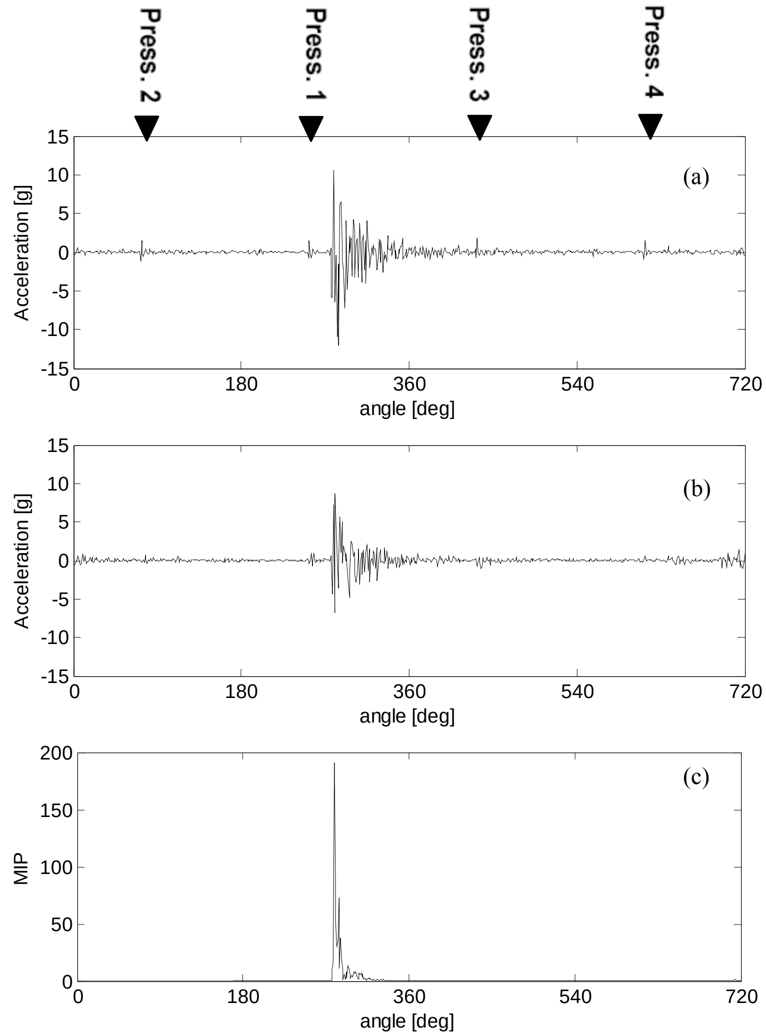


Figure 7. RS4 engine: (a) Time Synchronous Average, (b) residual signal (5th cycle), (c) Mean Instantaneous Power of the residual signal.

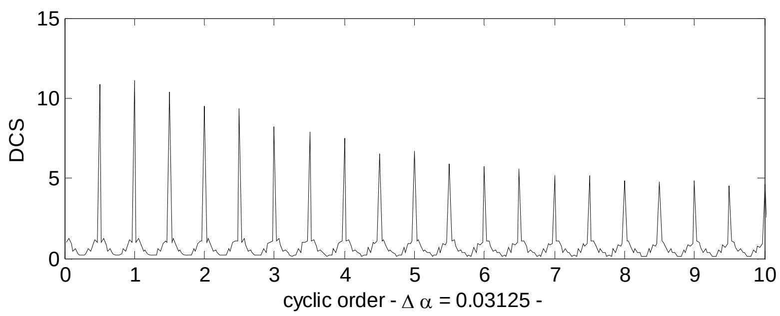


Figure 8. RS4 engine: DCS plotted in the cyclic order range 0-10.

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