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DIESEL AND GAS ENGINES DIAGNOSIS BASED ON INSTANTANEOUS ANGULAR SPEED ANALYSIS

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Continuous monitoring of pistons engines (diesel or gas) performance is critical for early detection of fault developments in an engine before it goes into a functional failure. Instantaneous angular speed (IAS) analysis is one of a few non-intrusive condition monitoring techniques that could be applied for such tasks. This method needs only a non-intrusive speed sensor (magnetic or optical) signal to assess in details the mechanical behaviour of an engine and diagnose injection, compression, or valve state defaults, and bearings/moving parts damages. The method is able to point out the exact cylinder which is in defect using additional order tracking speed sensor (TDC or cam). The technique is more suitable and efficient for mass industry deployments than other non-intrusive methods such as vibration and acoustic emissions. A combination of instantaneous angular speed analysis based on Hilbert transform associated with order analysis and statistical moments is used and give detailed and robust diagnosis. The system is used on a cogeneration plant to monitor GE/JENBACHER gas engines, emergency diesel engines, fleet locomotives, and military/ferry boats. It is also currently tested on emergency diesel engines in EDF nuclear power plants.

Keywords: engines, instantaneous angular speed, diagnosis

1. Introduction

Diesel engines may be affected by numerous defects associated with combustion, injection valves, cylinder / piston assembly ... In order to predict the occurrence of these defects, a method based on a non-intrusive measurement of the instantaneous angular speed (IAS) is proposed[1,2,3,4]. In a first step, the principle of the method is described, with in particular a presentation of the defect indicators that are evaluated. In a second step, an example of diagnosis is given for a diesel engine in which known defects has been purposely created.

2. IAS analysis

Several techniques that belongs to signal processing are used. In time domain they are the FIR filters and the Hilbert transform. In the frequency domain there is the Fast Fourier transform and related amplitude and phase. The input signal is built from a wheel with evenly space teeth and an appropriate sensor (usually a magnetic or optical sensor).

2.1 Time domain

The Hilbert transform of a function (or signal)*u(t)* is given by:

$$H(u)(t) = \text{p. v.} \int_{-\infty}^{\infty} u(\tau)h(t-\tau)\, d\tau = \frac{1}{\pi}\ \text{p. v.} \int_{-\infty}^{\infty} \frac{u(\tau)}{t-\tau}\, d\tau \tag{1}$$

Where *p.v* is the Cauchy principal value and *t* the time. The Hilbert transform is use to detect speed variation and flexion shafts.

The finite impulse response is used to filter the time signal. It is used to filter the signal in some frequency area and to select frequencies at orders or ½ orders. The time filtering is then a convolution of the signal with the FIR filter:

$$y[n] = \sum_{i=0}^{N} b_i \cdot x[n-i] \tag{2}$$

Where *x* is the input signal, *y* the filtered signal and b_i the filter

With a combination of order analysis, the frequency is tracked all along the signal.

2.2 Frequency domain

The Fourier analysis is used to convert a time domain signal to a representation in the frequency domain. The corresponding discrete Fourier transform is defined by:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi kn/N} \qquad k = 0, \dots, N-1. \tag{3}$$

Where x_n is here a real value and the X_k a complex value.

The Order Frequency analysis corresponds to a Fourier analysis that focus on harmonics of the rotation speed. Up to 20 orders are used with the tracking of amplitude, phase and derivated value all along the signal.

3. Reciprocating engine dynamic

The torque provided by the rod-crank system of a piston engine is not constant; it can be broken down for each cylinder into two terms: the torque related to inertia, and the torque related to gas effect

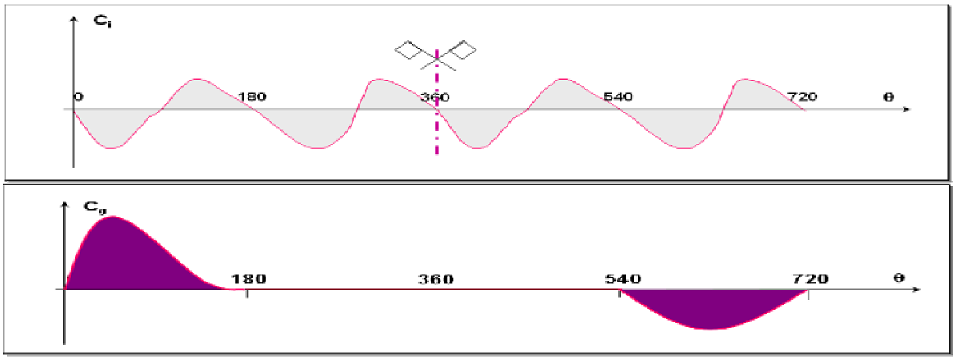


Figure 1: torque related to inertia (above), and torque related to gas effect (below)

For the complete engine, results are torque waves that depend on the number of cylinders. The torque variations can be decomposed into harmonics of the engine cycle, which means multiples of two crankshaft revolutions, or 720 °: so 1 engine cycle = 2 revolutions of crankshaft rotation= 720°. The relative importance of these harmonic depends on the angular position of the crank, the relative position of the cylinders (on line or V etc…) And, of course, the firing order. These harmonics are all terms of tensional excitations of the engine components.

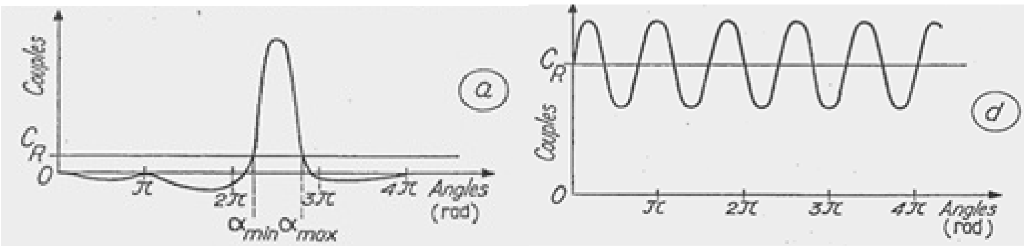
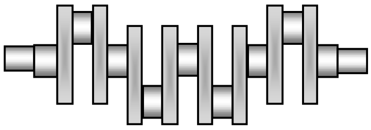


Figure 2: torque variations for: (a) one cylinder engine; (d) 6 cylinders engine

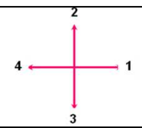
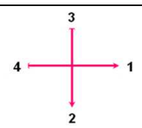
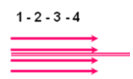
Manufacturers seek to master the dynamic behaviour of organs and thus to minimize the sources excitation. This can be done by cancelling or minimizing the amplitude of certain harmonic components as shown on the 4 cylinders engine example on the right



The ignition is supposed to be regular; there is an explosion every 180 ° of crankshaft rotation. The order of ignition is supposed to be 1-3-4-2. We can then determine the anglesof rotation of the-crankshaftbetweenthe explosion in thecylinder 1 andthe other cylinders: $\alpha_{12}=3\pi$, $\alpha_{13}=\pi$, $\alpha_{14}=2\pi$.

From thesedata, we can see that in thisconfigurationsomeharmonicsare in opposition (the amplitudes are subtracted) and offset, others coincide (in the same direction the amplitudes are added); so we call major harmonics the ones the amplitudes are added. Examples are given in **Table 1** below.

Table 1: examples of phases between cylinders for a 4 cylinders engine for different harmonics

Harmonic Order	Phases between cylinders	
0.5	$\alpha_{12}=1.5\pi$, $\alpha_{13}=0.5\pi$, $\alpha_{14}=\pi$	
1	$\alpha_{12}=3\pi$, $\alpha_{13}=\pi$, $\alpha_{14}=2\pi$.	
1.5	$\alpha_{12}=4.5\pi$, $\alpha_{13}=1.5\pi$, $\alpha_{14}=3\pi$	
2	$\alpha_{12}=6\pi$, $\alpha_{13}=2\pi$, $\alpha_{14}=4\pi$	

In this particular example the first major harmonic is the order 2 of the revolution of the crankshaft rotation or the order 4 of the engine cycle (explosion cycle). The further calculation shows that we the harmonics where the amplitudes are added (same direction) correspond to the order 2 and their multiple (H4-H8 etc ...)

Table 2: Major torque harmonics for each type of engine and each type of motion

Engine type	vertical	lateral	front	rear	torsion
L4	2-4-6				2-4-6-8-10
L6	6				3-6-9-12
V6	6		1-2-4	1-2-4	3-6-9-12
V8	4	2-4-6			4-8-12
V12	6-12	12			6-12

4. Diagnostic indicators

The evolution of the instantaneous acyclic and its harmonic decomposition are based on demand for any cycle in the measurement sequence. It is possible to trace the envelope instant acyclic and its harmonic decomposition in any time sample recording values.

All frequency demodulated signals are analysed in time domain cycle/cycle (0-720°: 4 strokes engine; or 360° for a 2 strokes engine). Any impulsive effect even if it happens in a very short time is captured with a given relationship to the mechanical/ gas effect.

All sudden events that happen in each cycle will be captured by applying Kurtosis calculations which is the fourth order statistical moment:

$$K = \frac{E(X-\overline{X})^4}{[E(X-\overline{X})^2]^2} \tag{4}$$

The sudden event may correspond to friction, material degradation, assembly irregularity due to overstress. In our case it is applied on the angular displacement, angular velocity, and angular acceleration. As soon as such event occur, the Kurtosis (not normalized) will go up to 3.

All frequency demodulated signals are analyzed in time frequency domain cycle/cycle (0-720°: 4 stroke engine; or 360° for a 2 stroke engine). Any distortion or instability is seen and related to its behavior.

There are 2 global indicators: one is called “MECHANICAL HEALTH”, the other one is called “ENGINE EFFICIENCY”. In VIB360, they are shown as colors, from green (good) to red (bad), as shown on **Figure 3** below.

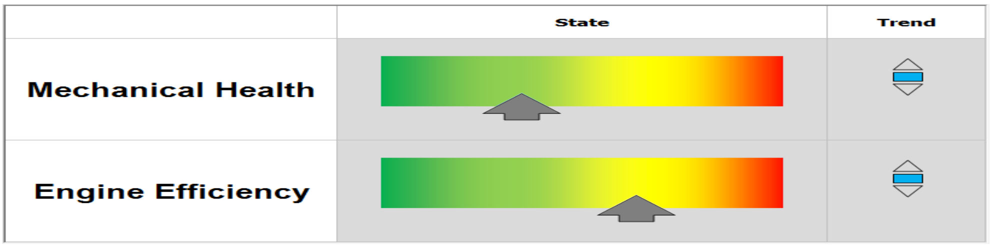


Figure 3: main indicators as they appeared in VIB360

“MECHANICAL HEALTH” is calculated from a combination of some details indicators (such as stresses, cylinder pressure variations...), and a time value of the irregular statistical indicator to quickly identify the presence of instant irregularities (pulse) generated by damage. This indicator gives the mechanical behavior of the important components (all crankshaft’s main components). It is an indication about the overall condition of the engine**. It can be seen as a value indicating the wear in the engine, which is not related to the combustion**. Its value is between 0 and 1, and the engine should alert and stop if it tends to 1.

“ENGINE EFFICIENCY” is an indicator having an impact on efficiency and cost of operation. The engine could run with a bad efficiency. A damage of an engine is not in consideration by this indicator; only gas effect operation (injection, combustion, compression).It is calculated by combining the use of the harmonic distribution/and regularity applied on each cycle (0-720°) acyclic angle displacement signals. **It is an indication how efficiently the engine is running. This has, among others, effects on the operation cost of the engine.**

Associated with these 2 global indicators, details indicators are also evaluated, and some of them are associated with a single identified cylinder (see **Figure 4** below).

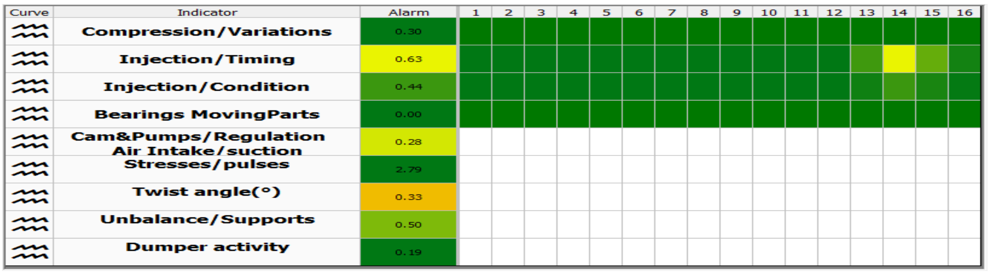


Figure 4: detailed indicators as they appeared in VIB360

"COMPRESSION/VARIATIONS" gives a picture of the temporal regularity of the compression in all cylinders; some engines have irregular delays by construction, and of course the compression regularity that is affected by poor compression (delays between cylinders compressions, worn or defective valve train components). The deviation in the compression stroke of one or more cylinders can be detected. If its value is bad, one should check the backlash of piston rings and/or valves (in-/or outlet); and/or oil pressure defect

"INJECTION TIMING" indicates the temporal settings of the injection, but it gives no information that the injectors have to be replaced. The injection timing plays one of the most important roles in determining engine performance. This indicator shows more or less uniform distribution of cylinder pressure during combustion phase of the cylinders. If the pressures in all cylinders are more or less the same the value of the indicator tends to be zero (no significant difference). The value tends to 1 if the cylinders pressure difference is significant (for example the fuel injection is poor in one or more cylinders). All analysis is done on each cycle (720°).The deviations of abnormal amount of fuel injection per cylinder are detected. If the value of this indicator is bad,one should check the fuel gear rack. It could also be caused by overpower, valves defect, or oil pressure defect.

"INJECTION CONDITION" gives information if the injector has to be replaced. Injection can be seen as the stability/equality between all explosions (ignition system deficiencies, defective fuel injection valve, peak firing pressure unbalance, worn or scored liners...). It is calculated using the 0.5 order harmonic which gives the situation of the resultant pressure irregularity of the cylinders. It provides information about the quality of the ignition. If injection condition indicates problems, one should check all other indicators that indicate problems as well, it could be located also in the fuel pump, injector… This leads specifically towards the problem.

"BEARINGS/MOVING PARTS" is the image of the dynamic behavior of the bearings of all moving parts (crankshaft, condors, pistons, damaged connecting rod and wrist pins, damaged bearings, The indicator value goes from 0 (good condition) to 1 (bad condition). This indicator could also be influenced by the damper reaction behavior (reaction to poor coupling, and/or high speed/load). It is based on the calculations of the applied 4th statistical moment on the angular displacement, velocity, and acceleration. It provides an indication of the status of the bearings and other moving parts of the engine, measured per cylinder over multiple revolutions. If the value of this indicator is bad, one should check all bearings and moving parts in the engine (per cylinder). The status per cylinder should indicate in which cylinder the problem occur.

"CAM & PUMPS/ REGULATION/AIR INTAKE/ SUCTION" gives information when the crankshaft is disturbed externally (such as regulation, fuel/lub/water pumps faults, intake/exhaust port or bridge wear, turbocharger defects, excessive exhaust emission factors,...). It is calculated on the derivative of the angular acceleration.If the value of this indicator is bad, one should check the driven components within the engines: pumps, cams…

"STRESSES" identifies the presence of crankshaft twist that introduces a misalignment in bearings axes (mechanical stress on bearings). It generates irregularities on the crankshaft by sudden pulses in each operating cycle. It is calculated on the result of the applied 4th statistical moment on the angular acceleration. It is an indicator of mechanical fatigue and/or misaligned bearings.

“CYLINDER PRESSURE VARIATIONS” shows in the cylinders a variation in the pressure (acceleration/deceleration). It gives the impact that the power on the crankshaft is different for each cylinders. It usually results from in a non-smooth movement of the crankshaft (damper instability reaction, horsepower discrepancies...). It is calculated by estimating impulsive effects on the angular velocity.It is also an indicator of a malfunction of the damper, or rubber coupling damage, lack of necessary effective pressure in a cylinder.

“UNBALANCED/SUPPORTS” gives the information about the global movement of the engine (excessive frame vibration, foundation or grout damage, poor supports,).It is calculated on the harmonic distribution mainly the order 1 related to the rotation frequency of the crankshaft.

“DAMPER” is the image of the dynamic behavior of the damper, whether it is active (at certain speed there is not enough crankshaft twist to be activated); or it is active within its own resonant designed frequency (so it filters all tensional vibrations to avoid harmful frequency situation, means breaking crankshaft parts). The indicator shows whether it is full active (green color) or partially active (yellow or red color). This indicator could also be influenced by the damper reaction behavior (reaction to poor coupling, and/or high speed/load).It is calculated using the energy of the major harmonic (cycle gas harmonic) with respect to the resonant damper imposed harmonic (supposed to introduce a phase delay when excited and amplified). It also provides an indication of the status of the coupling.

“TWIST ANGLE” gives the information of the crank angle variation caused by the twist of the crank shaft (excessive level such as above 0.3° could be caused by the defects described above such as “INJECTION CONDITION”.

“IGNITION SYSTEM” is the image of the dynamic behavior of the regularity of the ignition system, mainly the spark plugs. It is calculated by using the harmonic distribution. It also provides an indication of the state of the spark plugs.

5. Analysis on a V16 diesel engine: injectors fault diagnosis

On a V16 diesel engine dedicated to energy production, a passive VR sensor has been temporarily installed on the flywheel (as shown on **Figure 5** below) and connected to the VIB360 Analyzer unit. The flywheel has 142 teeth.Additionally a second channel was enabled for the existing active VR sensor at the CAM. The measuring equipment was installed just outside the test cell doors.

The operators enabled test scenarios using the existing engine management system.Various engine running condition sequences of about 1 minute each have been captured for analysis. Raw signals were successfully produced and recorded.

The signal from the CAM gear wheel produced a signal comprising the timing pin pulse, but also a pulse from the cut out holes (see **Figure 5** below). A software engineer subsequently extracted the timing pin pulse to obtain cylinder specific information, using National Instrument data acquisition (NI4432) and the VIB360 Software analysis.

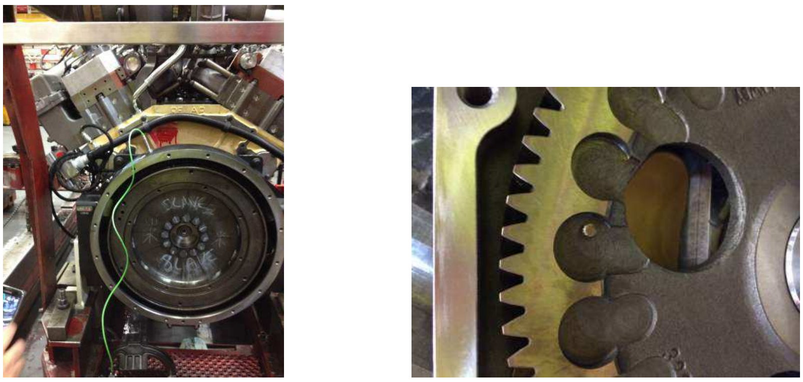


Figure 5: views of the passive VR sensor (left) and the CAM gear wheel (right)

Different tests has been conducted for different configurations of the diesel engine, defined by the rotation speed and the load.

Table 3: list of tests conducted on the V16 engine

Test	Rotation speed	Load	Created defect
Test 1	1900 RPM	8400 NM	no defect
Test 2	1900 RPM	9400 NM (full load)	defect on cylinder 10
Test 3	1000 RPM	4000 NM	no defect
Test 4	1000 RPM	4000 NM	defect on cylinder 6

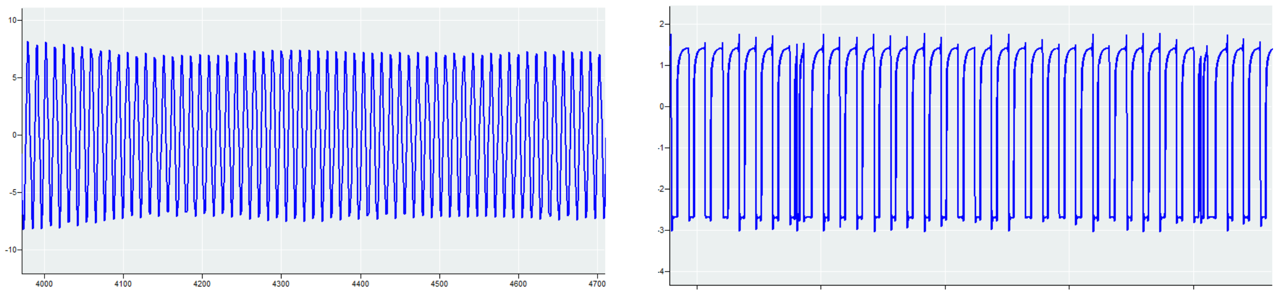


Figure 6: raw signals from the flywheel (142 teeth, right) and the CAM (24 holes, left) rotation speed sensors

From these raw signals can be extracted the dynamic angular displacement (DAP), the Kurtosis on angular velocity (KAV), and the Kurtosis on angular acceleration (KAA). During test 2, a defect has been created on the injector of the cylinder 10 between the 10th and the 60th seconds.

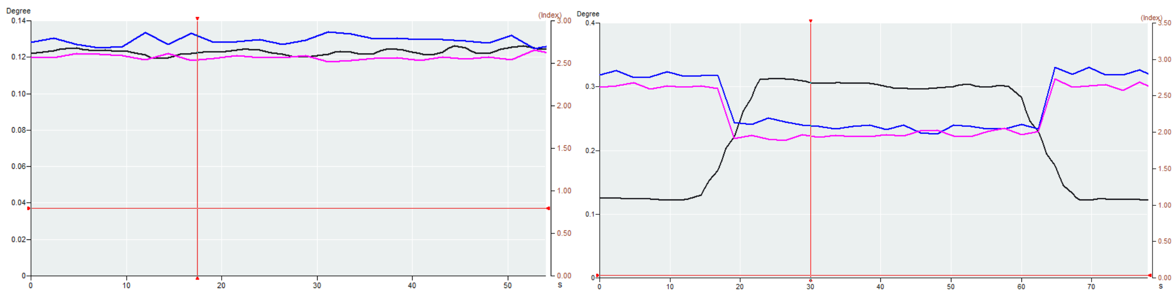


Figure 7: DAP (black), KAV (blue), an KAA (pink)for test 1 (left) and test 2 (right)

On **Figure 8**are shown the details indicators calculated by VIB360 software for test 1 and test 2. The injection defect is clearly identified during test 2 on the right cylinder.

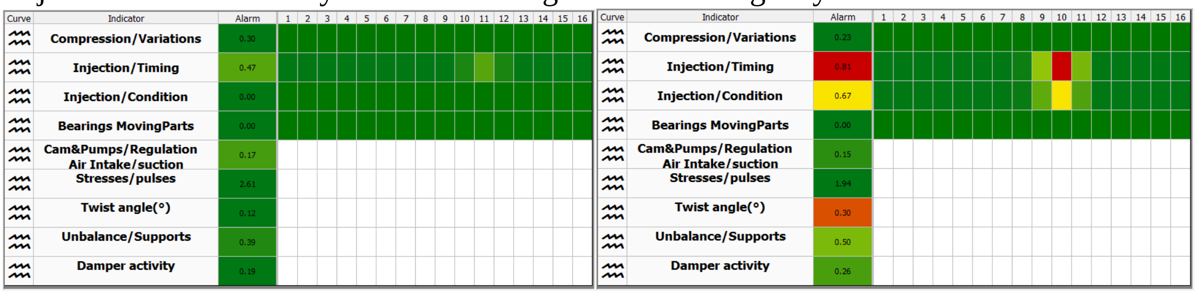


Figure 8: details indicators for test 1 (left) and test 2 (right)

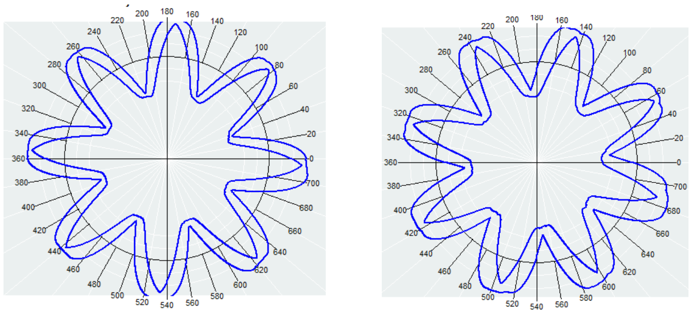


Figure 9: speed variation during 2 crankshaft revolutions (720°) for test 3 (left) and test 4 (right)

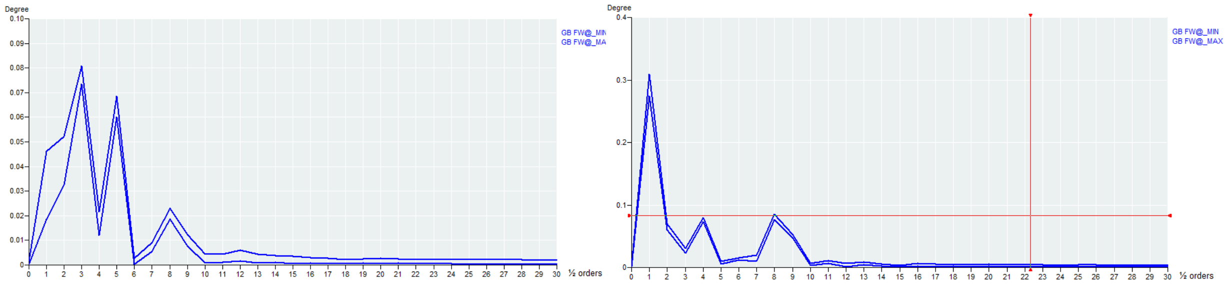


Figure 10: first 30 harmonics of the engine cycle for test 3 (left) and test 4 (right)

On **Figure 10** are shown the first 30 harmonics of the engine cycle (2 crankshaft revolutions), computed from speed variation during 2 crankshaft revolutions (720°) for both test 3 and test 4 (see **Figure 9**).

For test 3, it shows the existing 8^{th} harmonic order (related to the engine cycle V16 operation without damper full operation because not necessary) and the 5^{th} harmonic order related to engine cycle (very low amplitude due to damper): this is a normal dynamic response of a V 16 engine. Harmonic 1 corresponds to the irregularity in cylinder pressure.

For test 4, it shows the existing 1^{st}harmonic order dominant (related to the engine cycle injector defect: irregularity in cylinder pressure) and the 8^{th} harmonic related to major harmonic cycle of V16 engine, and 5^{th} related to damper exciting frequency operation. Similar results are also observed for test 1 and test 2.

6. Conclusion

A method for monitoring diesel engines based on a non-intrusive measurement of angular velocity was presented. This method permits the evaluation of defect indicators that cover a large part of the problems encountered by a diesel engine. The system is used on a cogeneration plant to monitor GE/JENBACHER gas engines, emergency diesel engines fleet locomotives, and military/ferry boats. It is also currently tested on emergency diesel engines in EDF nuclear power plants.

REFERENCES

1 Jean-Louis Ligier and Elian Baron, Acyclisme et Vibrations : Applications aux Moteurs Thermiques et aux Transmissions, *Edition Technip 1 et 2*.

2 Guy Louradour and Bernard Gironnet, Vibrations et Vitesses Dangereuses de Torsion de Lignes d'Arbres.

3 Julius S Bendat, Non Linear System Analysis From Random Data.

4 Christian Lalanne, Vibrations et Chocs Mécaniques.