

Vibration-Based Analysis for Detecting Turbocharger Blade Defect on High-Power Diesel Generator

Metaga Jeremi Sogoba, Badié Diourté, Moussa Magara Traoré

Ecole Nationale d'Ingénieurs Abderhamane Baba TOURE (ENI-ABT), Bamako, Mali

Email: infos@eni-abt.ml

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Abstract

This study is concerned with 12-MW capacity turbochargers on diesel power generators. These are generators equipped with 18 cylinders. Our previous studies [1] showed that the processing of vibration signature collected from a power generator is very complex, insomuch the dominant vibration remains the one originating from explosion frequency in the diesel generator cylinders, with a fairly high number of cylinders. This vibration drowns out all other possible vibrations, which can expose defects. The study at hand is focused on turbochargers with 20,940 rpm, while the rotation speed in the diesel engine is 600 rpm only. With the turbocharger rotating at very high speed, it results in severe mechanical constraints on the rotor shaft in the turbocharger and its related organs (turbine blades). The wear of turbine blades can result in breakdowns in the turbocharger. This article is an attempt to early detect defaults in turbine blades based on vibration signature that can be experimentally determined. We noted in our investigations that a diesel engine and its turbochargers do not bear the same mechanic loads. While the diesel engine is the seat of violent shocks brought about by explosions in cylinders, the turbochargers are driven by the action of exhaust gas from explosions, without being affected by explosion shocks. The study found that explosion frequency in the diesel engine cylinders, which disrupted the vibration signals in the diesel engine and alternator, did not impact on the vibration signals in the turbocharger. We experimentally determined, following several campaigns of measurements, a vibration signature on the turbochargers under study, which corresponds to a defect in turbine blades.

Keywords

Vibration Signature, Fast Fourier Transform Method (FFT), Turbocharger, Turbine Blades

1. Introduction

We undertook this study as a result of repeated breakdowns in turbochargers on some power generating sets, to early detect causes of the breakdowns. Chief among them is the wear of turbine blades. During the normal functioning of the turbocharger the blades are likely to wear out over time. If the worn-out blades are not replaced in time breakdowns can occur on the turbocharger, which led us to determine the global vibration level of the turbochargers under investigation. The global vibration level is measured according to a standardized threshold, or obtained experimentally [2]. The wear of turbine blades occurs in global vibration level above the reference threshold. To detect the defect, the signals are interpreted with the help of signal processing methods [3]. The signals collected from the turbochargers are stationary [4]. There are many methods for signal processing. For the purposes of this study, Fast Fourier Transform (FFT) has been selected, for it is easy to implement and can be efficiently applied for processing stationary signals. Thus, we determined a vibration signature corresponding to the wear of the turbine blades. We found that the explosion frequency of the diesel engine does not disturb the spectra collected on the turbochargers.

2. Method

Signals collected on diesel generating sets are mostly cyclostationary [5] [6]. The first studies on cyclostationary signals can be traced back to the 1950s. In telecommunications, cyclostationarity received much attention, in particular since the 1980s; its use in mechanics appeared more recently, though [7]. A power generating set is characterised by the frequency of a rotating crankshaft and the frequency of explosions in the diesel engine cylinders. Disruptions may occur when the two frequencies are overlaid. These result in random cyclic signals; in other words, these are cyclostationary signals.

A random process is strictly cyclostationary with period T , if its probability density being periodic of period T .

$$P_x(t) = P_x(t + nT), \quad \forall (t, n) \in \mathbb{R} \times \mathbb{Z} \quad (1)$$

Period T is called cyclic period.

A random process is solely stationary, if its probability density is invariant by time translation.

$$P_x(t) = P_x(t + \Delta t), \quad \forall (t, \Delta t) \in \mathbb{R}^2 \quad (2)$$

Turbochargers on a diesel generator are insulated from mechanic shocks resulting from explosions in the diesel engine cylinders, which explains why the signals produced by the turbochargers are stationary. These signals can be properly processed using Fast Fourier Transform method. This method is obtained from discrete Fourier transform. Fast Fourier Transform (FFT) is an algorithm for calculating discrete Fourier transform (DFT). We selected this algorithm for its efficiency. On the one hand, it is an algorithm that makes possible filtering by

altering the spectrum, and using the inverse transform (finite impulse response filter), on the other hand. A discrete Fourier transform of T size (number of samples) is given by the formula:

$$X(k) = \sum_{t=0}^{T-1} x(t) e^{\left(-2\pi j \frac{kt}{T}\right)} \text{ avec } k = 0, \dots, T-1 \quad (3)$$

For example, $t = 2n$ if t is even and $t = 2n + 1$ if t is odd. We arrive at the rapid Fourier transform (FFT). $X(k)$ is then written [8] [9]:

$$X(k) = \sum_{n=0}^{N-1} x(2n) e^{\left(-2\pi j \frac{k2n}{T}\right)} + \sum_{n=0}^{N-1} x(2n+1) e^{\left(-2\pi j \frac{k(2n+1)}{T}\right)} \quad (4)$$

2.1. Determining Explosion Frequency in Diesel Engine

Explosion frequency is an important parameter for diesel generators since the primary source of vibration is related to this frequency. It is determined based on the crankshaft positioning and the number of cylinders in diesel engine. The frequency of explosion is given by the following formula:

$$F_{\text{expl}} = \frac{\text{number of explosions per cycle}}{\text{number of turns per cycle}} \quad (5)$$

$$f_0 = \frac{1}{\text{turn}} \quad (6)$$

$$F_{\text{expl}} = \frac{\text{number of explosions per cycle}}{2} f_0 \quad (7)$$

with f_0 : rotation frequency of the diesel engine.

The diesel engine under study has 18 cylinders (Table 1). Explosion occurs 2 by 2, or 9 explosions per cycle. Following the formula (7), explosion frequency is 45 Hz.

2.2. Measures

Measurements were carried out on a diesel power generator at Balingue plant, belonging to the public energy utility of Mali. The instruments that have been used for measurements included a 100 mv/g-sensitivity accelerometer, a signal collector with 12,800 line capacity, and signal processing software. Measurements were made at standard measurement points (Figure 1) by fitting the

Table 1. Characteristics of the power generating set investigated.

Characteristics of the Power Generating Set	
Operating mode	Basic operation
Type of engine	4X18V38B
Engine output power	12.150 Kw
Engine rotation speed	600 rpm
Rotation direction	Counter-clockwise
Fuel	HFO
Turbocharger rotation speed	20.940 rpm

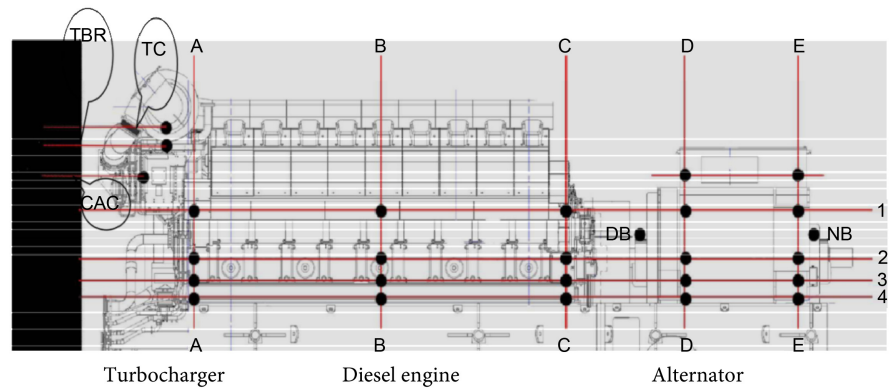


Figure 1. Configuration of measurement points.

accelerometer at these points, while the generator was running at full capacity (11 MW). We selected 6 measurement points on the turbochargers 8 measurement points on the diesel engine, and 8 measurement points on the alternator. On each measurement point, 3 measures were performed following 3 directions: axial, radial vertical and radial horizontal.

3. Results

3.1. Global Vibration Level Analysis

Tables 2(a)-7(a) show the global vibration level of the turbocharger with worn-out blades. **Tables 2(b)-7(b)** show the global vibration level of the turbocharger with healthy blades.

It has been noted that the whole range of the diesel engine vibration levels are below the permissible limit of 45 mm/s for the diesel side (**Table 2** and **Table 3**). As for the alternator, the limit is 20 mm/s. All the measurements on the alternators are below this limit (**Table 4** and **Table 5**).

As no measurement on the diesel and alternator reaches these limits (45 mm/s and 20 mm/s), the vibration status of the diesel engine and alternator is sound [10] [11].

On the other side, the maximum vibration measured on the turbochargers was 20.8 mm/s in side A (**Table 6**) and 22.5 mm/s in side B (**Table 7**) compared to a limit of 18 mm/s in the first measurement campaign. That has led us to undertake investigations in an attempt to pinpoint what was causing this abnormal vibration. After the turbochargers have been repaired, we obtained a vibration of 16.5 mm/s, at the same measurement point (**Table 7**).

3.2. Spectral Analysis

We can see that on the faulty turbocharger where turbine blades are worn out [Figure 2(b)], the spectrum [Figure 2(a)] is different from the spectrum [Figure 3(a)] of the healthy turbocharger [Figure 3(b)]. These spectra are obtained in frequency domain. Their occurrence is linked to the state of the turbocharger [12]. If a break occurs, it manifests itself in a separate spectral typology. This indicates

Table 2. Vibration level of the diesel engine side A.

(a)

Measurement Points												
Parameters	1aAX	1aRH	1aRV	2aAX	2aRH	2aRV	3aAX	3aRH	3aRV	4aAX	4aRH	4aRV
Acceleration (m/s^2)	6.66	3.54	7.29	1.80	0.895	1.81	2.41	2.19	2.80	0.682	0.512	0.558
Velocity (mm/s)	10.7	9.50	17.8	4.82	9.27	11.3	5.20	7.70	8.88	2.90	4.95	7.98
Unbalance f_0 (m/s^2)	0.0029	0.012	0.0059	0.0031	0.015	0.0089	0.0016	0.0074	0.0048	0.0012	0.013	0.0077
Alignment H2 (m/s^2)	0.0057	0.031	0.024	0.0056	0.016	0.017	0.0040	0.039	0.019	0.010	0.017	0.018
Alignment H3 (m/s^2)	0.0029	0.012	0.012	0.0079	0.0026	0.015	0.0047	0.012	0.017	0.0057	0.012	0.011

(b)

Measurement Points												
Parameters	1aAX	1aRH	1aRV	2aAX	2aRH	2aRV	3aAX	3aRH	3aRV	4aAX	4aRH	4aRV
Acceleration (m/s^2)	6.54	3.74	8.29	1.85	0.852	2.04	2.71	2.30	2.45	0.719	0.537	0.599
Velocity (mm/s)	11.1	10.2	21.1	5.16	9.86	12.4	6.28	8.42	8.22	3.47	5.04	8.67
Unbalance f_0 (m/s^2)	0.0024	0.016	0.0048	0.0028	0.012	0.010	0.0023	0.0089	0.0041	0.00049	0.011	0.0099
Alignment H2 (m/s^2)	0.0082	0.031	0.021	0.0052	0.013	0.016	0.0054	0.038	0.014	0.011	0.014	0.016
Alignment H3 (m/s^2)	0.0065	0.014	0.0059	0.0062	0.0025	0.013	0.00090	0.010	0.012	0.0044	0.012	0.012

Table 3. Vibration level of the diesel engine side B.

(a)

Measurement Points												
Parameters	1bAX	1bRH	1bRV	2bAX	2bRH	2bRV	3bAX	3bRH	3bRV	4bAX	4bRH	4bRV
Acceleration (m/s^2)	8.44	5.40	8.51	1.92	0.867	1.69	2.94	2.37	2.99	0.849	0.604	0.700
Velocity (mm/s)	13.8	11.8	20.3	4.74	8.97	12.4	6.65	8.50	10.2	3.41	4.94	9.75
Unbalance f_0 (m/s^2)	0.0026	0.011	0.0060	0.0027	0.015	0.020	0.0023	0.0073	0.0066	0.0011	0.0016	0.020
Alignment H2 (m/s^2)	0.0076	0.034	0.018	0.0061	0.017	0.017	0.011	0.041	0.017	0.012	0.0069	0.014
Alignment H3 (m/s^2)	0.013	0.011	0.011	0.0068	0.0026	0.0055	0.0076	0.0075	0.010	0.0084	0.0079	0.0038

(b)

Measurement Points												
Parameters	1bAX	1bRH	1bRV	2bAX	2bRH	2bRV	3bAX	3bRH	3bRV	4bAX	4bRH	4bRV
Acceleration (m/s^2)	7.32	6.04	9.49	1.94	0.855	1.85	3.69	2.75	3.08	0.949	0.570	0.668
Velocity (mm/s)	12.4	13.3	23.4	4.84	9.72	12.7	8.41	9.60	10.8	3.59	4.88	9.80
Unbalance f_0 (m/s^2)	0.0035	0.012	0.00074	0.0034	0.013	0.020	0.0019	0.0098	0.0010	0.0014	0.0023	0.019
Alignment H2 (m/s^2)	0.0054	0.033	0.025	0.0027	0.013	0.014	0.0086	0.041	0.020	0.0069	0.0056	0.011
Alignment H3 (m/s^2)	0.0081	0.012	0.018	0.0069	0.0036	0.011	0.0075	0.012	0.012	0.0084	0.014	0.0023

Table 4. Vibration level of the alternator side A.

(a)

Measurement Points												
Parameters	5aAX	5aRH	5aRV	6aAX	6aRH	6aRV	7aAX	7aRH	7aRV	8aAX	8aRH	8aRV
Acceleration (m/s ²)	0.485	0.580	0.297	0.445	0.494	0.249	1.64	0.553	0.766	0.770	0.500	0.929
Velocity (mm/s)	10.8	16.1	7.18	12.3	14.1	11.8	4.99	7.98	6.63	4.54	6.13	11.9
Unbalance f0 (m/s ²)	0.023	0.014	0.013	0.026	0.017	0.056	0.013	0.0059	0.025	0.0099	0.0082	0.052
Alignment H2 (m/s ²)	0.034	0.0069	0.033	0.033	0.034	0.028	0.014	0.008	0.024	0.014	0.0075	0.037
Alignment H3 (m/s ²)	0.021	0.013	0.027	0.025	0.016	0.011	0.0088	0.014	0.024	0.0070	0.025	0.036

(b)

Measurement Points												
Parameters	5aAX	5aRH	5aRV	6aAX	6aRH	6aRV	7aAX	7aRH	7aRV	8aAX	8aRH	8aRV
Acceleration (m/s ²)	0.514	0.609	0.409	0.477	0.573	0.323	0.901	4.37	0.523	0.898	0.569	0.924
Velocity (mm/s)	12.5	14.0	11.1	13.2	14.9	13.7	4.87	11.5	6.87	5.02	6.64	12.7
Unbalance f0 (m/s ²)	0.026	0.012	0.014	0.026	0.016	0.058	0.011	0.0016	0.023	0.0092	0.0067	0.052
Alignment H2 (m/s ²)	0.045	0.0062	0.032	0.038	0.032	0.026	0.017	0.0016	0.018	0.017	0.0088	0.033
Alignment H3 (m/s ²)	0.037	0.029	0.018	0.033	0.020	0.0069	0.010	0.018	0.036	0.0074	0.043	0.039

Table 5. Vibration level of the alternator side B.

(a)

Measurement Points												
Parameters	5aAX	5aRH	5aRV	6aAX	6aRH	6aRV	7aAX	7aRH	7aRV	8aAX	8aRH	8aRV
Acceleration (m/s ²)	0.533	0.646	0.308	0.502	0.481	0.262	1.94	0.563	0.825	1.01	0.533	0.946
Velocity (mm/s)	13.9	15.0	6.96	13.5	14.0	12.1	5.11	8.36	6.99	4.54	6.39	12.9
Unbalance f0 (m/s ²)	0.025	0.014	0.0056	0.023	0.017	0.056	0.0087	0.0056	0.024	0.0057	0.0066	0.058
Alignment H2 (m/s ²)	0.043	0.0078	0.036	0.037	0.033	0.027	0.015	0.0086	0.026	0.014	0.0095	0.033
Alignment H3 (m/s ²)	0.055	0.015	0.029	0.015	0.018	0.0060	0.0020	0.014	0.022	0.0039	0.026	0.015

(b)

Measurement Points												
Parameters	5aAX	5aRH	5aRV	6aAX	6aRH	6aRV	7aAX	7aRH	7aRV	8aAX	8aRH	8aRV
Acceleration (m/s ²)	0.668	0.584	0.364	0.537	0.562	0.330	1.12	0.673	0.812	0.809	0.550	0.885
Velocity (mm/s)	18.4	13.4	10.0	14.6	14.9	14.1	4.35	8.70	8.73	4.56	6.90	13.9
Unbalance f0 (m/s ²)	0.025	0.011	0.0034	0.023	0.012	0.060	0.0040	0.0065	0.027	0.0053	0.0059	0.062
Alignment H2 (m/s ²)	0.046	0.0075	0.031	0.038	0.034	0.025	0.0087	0.0099	0.026	0.014	0.0097	0.027
Alignment H3 (m/s ²)	0.071	0.019	0.013	0.0081	0.024	0.0025	0.0054	0.018	0.026	0.0081	0.035	0

Table 6. Vibration level of the turbocharger side B.

(a)

Measurement Points									
Parameters	TbAX	TbRH	TbRV	BbAX	BbRH	BbRV	CbAX	CbRH	CbRV
Acceleration (m/s^2)	13.8	7.19	8.72	3.38	2.46	3.76	5.50	6.66	4.38
Velocity (mm/s)	19.4	12.6	22.5	6.64	9.66	8.02	9.00	9.44	9.43

(b)

Measurement Points									
Parameters	TbAX	TbRH	TbRV	BbAX	BbRH	BbRV	CbAX	CbRH	CbRV
Acceleration (m/s^2)	17.5	10.2	15.7	2.58	3.66	4.33	4.10	3.23	2.31
Velocity (mm/s)	14.9	12.7	16.5	10.3	6.35	8.46	10.1	6.91	7.83

Table 7. Vibration level of the turbocharger side A.

(a)

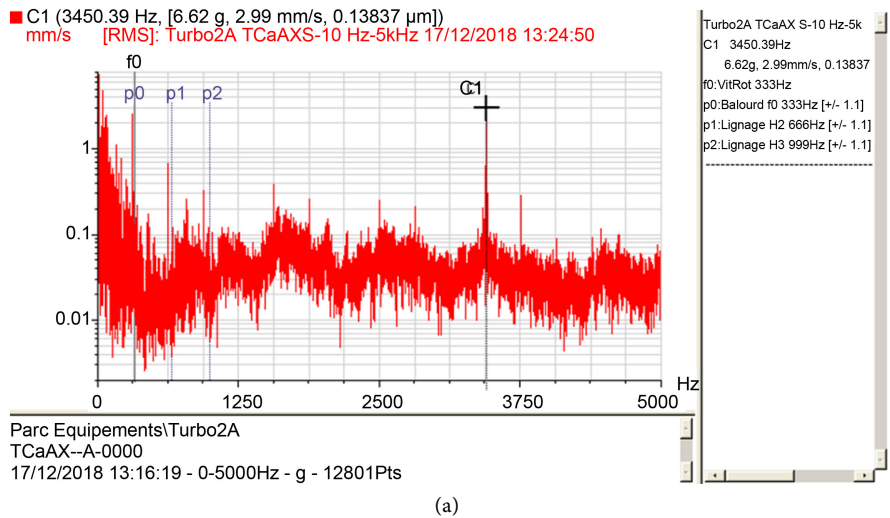
Measurement Points									
Parameters	TaAX	TaRH	TaRV	BaAX	BaRH	BaRV	CaAX	CaRH	CaRV
Acceleration (m/s^2)	14.0	9.28	7.17	3.22	2.83	4.19	3.86	6.70	4.50
Velocity (mm/s)	14.8	10.8	20.8	4.95	9.82	7.85	8.43	9.50	9.54

(b)

Measurement Points									
Parameters	TaAX	TaRH	TaRV	BaAX	BaRH	BaRV	CaAX	CaRH	CaRV
Acceleration (m/s^2)	11.4	9.25	7.15	2.53	3.99	2.91	7.12	2.41	3.89
Velocity (mm/s)	12.7	11.1	17.3	9.97	5.72	7.78	10.3	6.46	7.87

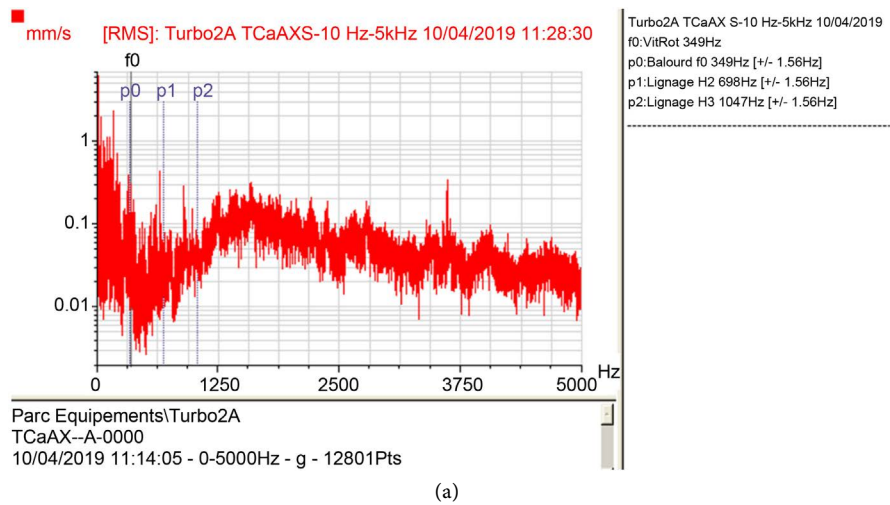
that turbochargers, while part of the diesel engine, are fully insulated from the mechanical shocks originating from the diesel engine cylinders. They work like a usual rotating machine. The Fast Fourier Transform method, in frequency domain, correctly applies to turbochargers for power generating set. As a consequence, the spectral analysis enabled us to obtain relevant results. High vibration at frequency C1:3478.51 Hz has been detected in the turbine wheel. It has 39 blades and turns at 349 Hz.

4C1:13.9 kHz corresponds to almost 39 times the rotation speed of the turbine wheel (13.6 kHz). This shows that 4 out of the 39 blades are worn out. On dismantling the turbocharger, we, indeed, found that out of the 39 blades in the turbine wheel 4 were worn-out. We found that the signals collected from the diesel engine and alternator are cyclostationary and carried by explosion frequency in the diesel engine cylinders. On the other hand, the signals collected from the turbochargers are stationary and insulated from explosion frequency, at 45 Hz. This frequency is no more the dominant one. In our previous studies, the spectra collected from the diesel engine and alternator of the diesel power generators



(b)

Figure 2. Defective turbine blade.



(b)

Figure 3. Healthy turbine blade.

were constantly carried by the explosion frequency in the diesel engine (**Figure 4** and **Figure 5**). These spectra did not change, in frequency domain, even with a defect.

4. Discussion

The measurement points on the turbocharger part were in places where the temperature was very high. This constraint has led us to repeat the same measures several times to ensure the accuracy of these measures. We found relevant results from the Fast Fourier Transform method. However, it is possible to improve these results by testing other methods. In perspective, we intend to test the time-frequency method on high power diesel generators and compare these results with those found with the Fast Fourier Transform method (FFT).

5. Conclusions

The explosion frequency in diesel engine has no impacts on the turbochargers. They work as a usual rotating machine. Therefore, it was possible to analyse the

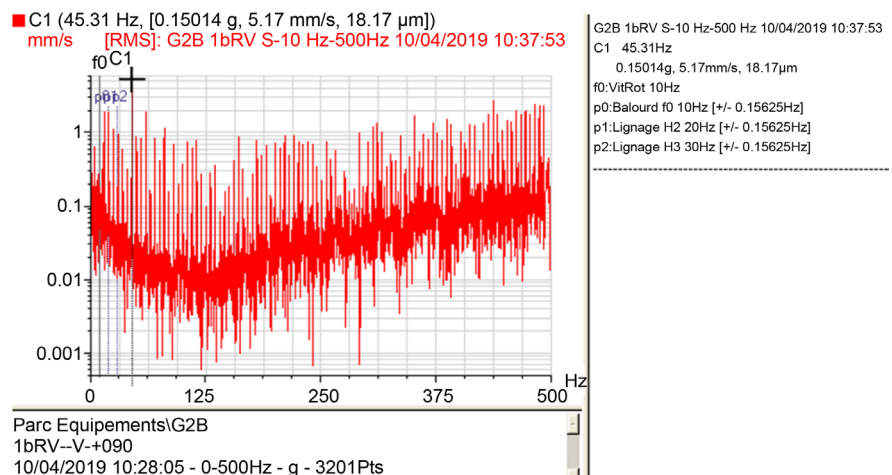


Figure 4. Spectra of diesel engine.

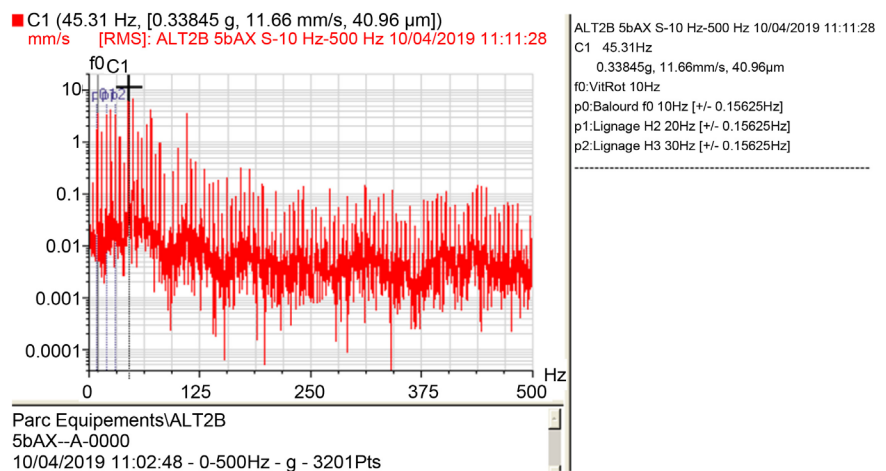


Figure 5. Spectra of alternator.

signals collected with the help of Fast Fourier Transform method in frequency domain. The vibration signature changes according to the sound health or the defect in the turbocharger. On the other hand, our previous studies have shown that the vibration signature of a power generating set along the diesel part and the alternator part does not change, even with a defect, in terms of frequency domain. This vibration signature was always born by the explosion frequency in the diesel engine.

The study found that explosion frequency in the diesel engine cylinders, which disrupted the vibration signals in the diesel engine and alternator, did not impact on the vibration signals in the turbocharger.

Through experiment, we determined a vibration signal corresponding to an actual defect in the turbocharger turbine, including detecting the defect, the cause of the defect, as well as the extent and severity of the given defect (wear of 4 blades).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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