Vibration Analysis-Based Diagnosis of High-Power Diesel Generator Turbocharger

Metaga Jeremi SOGOBA, Badié DIOURTÉ, Lamissa DIABATÉ

Abstract**:** ***The diesel engine of a high-power generator is equipped with two turbochargers. These are mounted on the gas exhaust above the diesel engine. Most investigative studies on vibration analysis of diesel power generators typically focused on the main bearing line in the diesel engine, on alternator rotor [1]. Turbochargers, however, play a very important role in the working of diesel engine. This article reports a study on the turbochargers of high-power diesel generator. 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. Despite its limitations in diesel engine diagnosis, FFT method is adequate for a correct diagnosis of turbochargers. As a result, following several campaigns of measurements we experimentally defined minimal admissible vibration values for turbochargers, and we detected a defect in bearing among the turbochargers tested.***

Keywords: Diesel generator, FFT method, high-power, turbocharger, vibration.

I. INTRODUCTION

High-power diesel generators are designed for regular electricity supply. An incident resulting in unplanned shutting down of the power generator is highly detrimental to electricity availability for consumer. From 2012 to 2014, we identified 5 major incidents involving turbochargers on high-power diesel generators operated by the electricity company of Mali. These incidents brought to a halt the generators for a long period of time, with significant deficits in electricity production. Our investigations were carried out at 3 different steam plants. One of the steam plants under investigation experienced a 60-percent deficit in electricity production from its full capacity due to faulty turbochargers.

This study seeks to provide a diagnosis of turbochargers through vibration analysis. This approach is currently a control method and is widely used for monitoring industrial facilities [2], [3], [4], [5], [6], [7]. This study started in 2012. From 2012 to 2014, we failed to arrive at any relevant findings on turbochargers. Starting from 2015, we found out that the turbochargers on one of the high-power diesel engines were isolated from the diesel engine explosion shocks. In effect, FFT method is efficiently applicable for these kinds of machines, while our previous studies showed that FFT method has limitations with regards to interpreting signals collected from the diesel engine. The diesel engines signals are cyclostationary, while the turbocharger signals are stationary.

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II. FFT METHOD

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 size T (number of samples) is given by the formula:

$$X(k) = \sum_{t=0}^{T-1} x(t)\, e^{\left(-2\pi j \frac{kt}{T}\right)} \qquad \text{For } k = 0, \ldots\ldots, T-1 \qquad (1)$$

Under the formula t = 2n if t is even and t = 2n + 1 if t is odd, we obtain the discrete Fourier transform (FFT). X(k) is then written [9,10]:

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

If $N = \frac{T}{2}$, let us spell out the sequences:

$$t = 0, \ldots, 2N-1 :\ x_{2N}(t) = x(t) \qquad (3)$$

$$n = 0, \ldots, N-1 :\ x_N^0(n) = x(2n) \qquad (4)$$

$$n = 0, \ldots, N-1 :\ x_N^i(n) = x(2n+1) \qquad (5)$$

$$k = 0, \ldots, 2N-1 :\ X_{2N}(k) = X(k) \qquad (6)$$

With these notations, "(2)" becomes:

$$X_{2N}(k) = \sum_{n=0}^{N-1} x_N^0(n)\, e^{\left(-2\pi j \frac{kn}{N}\right)} + \sum_{n=0}^{N-1} x_N^i(n)\, e^{\left(-2\pi j \frac{kn}{N}\right)} e^{\left(-\pi j \frac{k}{N}\right)} \qquad (7)$$

In the second summation of the right-hand side term of "(7)", factor $e^{\left(-\pi j \frac{k}{N}\right)}$ does not depend on n. The calculation is then for $k = 0, \ldots, 2N-1$

$$X_{2N}(k) = \left[\sum_{n=0}^{N-1} x_N^0(n)\, e^{\left(-2\pi j \frac{kn}{N}\right)}\right] + e^{\left(-\pi j \frac{k}{N}\right)} \left[\sum_{n=0}^{N-1} x_N^i(n)\, e^{\left(-2\pi j \frac{kn}{N}\right)}\right] \qquad (8)$$

If $0 \le k \le N-1$,

One can see in the two expressions in square brackets the discrete Fourier transforms for sample sequences with even number $x_N^0(n)$ and samples with uneven number $x_N^i(n)$ which we call $X_N^0(k)$ and $X_N^i(k)$.

For $k = 0, \ldots, N-1$

$$X_{2N}(k) = X_N^0(k) + e^{\left(-\pi j \frac{k}{N}\right)} X_N^i(k) \qquad (9)$$

If $\omega = e^{\left(-\pi j \frac{1}{N}\right)}$, then:

$$X_{2N}(k) = X_N^0(k) + \omega^k X_N^i(k) \tag{10}$$

The corresponding calculations are shown in figure 1.

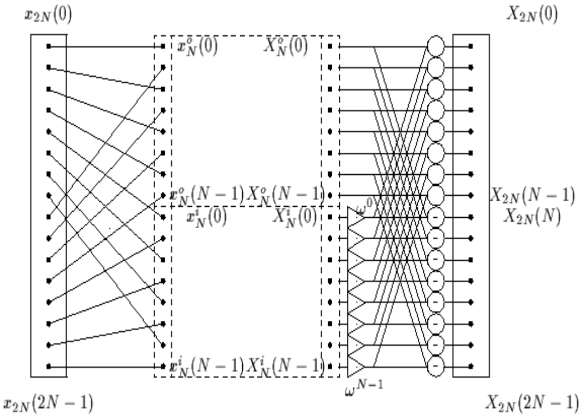

Figure 1. FFT Calculation Sequence Diagram

III. STUDY CONDUCT

Figure 2 is the diagram of standard measurement points [8]. Measurements were carried out by fitting the acidometer at these points.

A. Experimental Conditions

Measures are performed on generating set running to maximum capacity. The measurement points are allocated between the side A and side B of the generator:
Side A: left side back to the alternator,
Side B: right side back to the alternator.
Measurement points are selected following the ISO standard 8528-9. There are 3 measurement points: bearing TC, bearing TBR, and bearing CAC. There are 4 measurement points on the diesel component: bearing 1, bearing 2, bearing 3, and bearing 4; similarly, there are 4 measurement points on the alternator: bearing 5, bearing 6, bearing 7, and bearing 8.
For each measurement point measures are taken in three positions: axial (AX), radial vertical (RV), and radial horizontal (RH).
The following parameters are measured for each measurement point:

- Overall acceleration level expressed in of m/s^2;
- Overall velocity level expressed in mm/s;
- Peak extract to rotating speed in mm/s;
- Peak extract to harmonics H2 and H3 in mm/s.

B. Findings Presentation and Analysis

A turbocharger is an air-fuel supply system for diesel engine. Gas exhausts are directed towards the turbine wheels of the turbocharger in order to set it in rotation. When the rotor turns at high speed up to 20 times, the rotation speed of the diesel engine pumps in fresh air for supercharging the diesel engine with fresh air.
Insomuch we could not make significant fndings on the turbochargers we stopped conducting our study on the turbochargers from 2012 to 2014.
In 2015, we resumed our investigation on the turbochargers, and we found out that explosion shocks in diesel engine do not have impacts on the turbocharger vibrational state. The turbochargers turn at a rotating speed up to 20 times the rotation speed of the diesel engine. Thus, their kinematic properties are widely different from the diesel engine's properties. Taking these characteristics into account led us to relevant results.

- *Measures*

Turbochargers *Diesel* *Alternator*

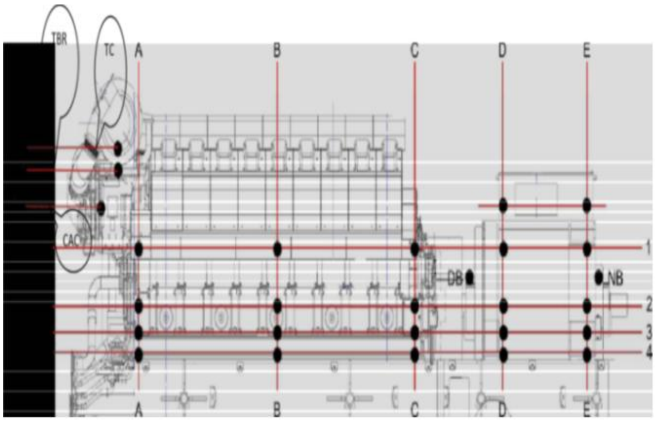

Figure 2. Configuration of Standard Measurement Points on Power Generating Set

Two major incidents happened at the power station SOPAM. They occurred on turbochargers, putting out of work 2 diesel generators, as a result. Our investigations were then focused on the turbochargers on the diesel power generator n°1 (G1) at the station. Table 1 shows the characteristics of G1.
The diesel generators at SOPAM have a diesel engine that turns at 500 tr/mn with turbochargers that turn at 13 000 tr/mn, or 26 times the rotation speed of the diesel engine. Tables 2 and 3 show the values for measurement parameters in monitoring the turbochargers' Side A and Side B, on diesel power generator n°1 (G1).

Table 1. Characteristics of G1

Site	SOPAM
Power station operating mode	Basic operation
Type of engine	5X16ZAV408
Engine output power	11200 Kw
Engine speed	500 tr/mn
Rotation direction	Counter-clockwise
Fuel	HFO
Turbochargers	13 000 tr/mn

Table 2. Monitoring Parameters of Turbo1 Side A

VEP	TCaAX	TCaRH	TCaRV	TBRaAX	TBRaRH	TBRaRV	CACaAX	CACaRH	CACaRV
Ng:Accélération	0.709	0.789	0.877	0.415	0.306	0.589	0.531	0.633	0.808
Ng:Vitesse Vibrato	7.42	8.12	6.93	5.87	3.91	4.19	4.69	3.49	4.45
Balourd F0	0.059	0.021	0.118	0.073	0.119	0.084	0.185	0.047	0.117
Lignage H2	0.028	0.054	0.064	0.129	0.032	0.069	0.073	0.159	0.062
Lignage H3	0.030	0.048	0.067	0.022	0.015	0.075	0.044	0.026	0.079
Divers 5000 Hz	8.23	7.71	7.64	5.90	4.27	4.48	4.80	3.66	5.72

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Table 3. Monitoring Parameters of Turbo1 Side B

VEP	TCbAX	TCbRH	TCbRV	TBRbAX	TBRbRH	TBRbRV	CACbAX	CACbRH	CACbRV
Ng:Accélération	1.20	1.08	1.42	0.496	0.286	0.609	0.488	0.614	0.819
Ng:Vitesse Vibrato	7.23	5.50	7.13	6.38	3.78	4.66	4.84	3.69	5.49
Balourd F0	0.071	0.019	0.185	0.106	0.058	0.057	0.150	0.133	0.113
Lignage H2	0.172	0.073	0.136	0.213	0.064	0.282	0.197	0.296	0.412
Lignage H3	0.065	0.030	0.100	0.032	0.019	0.035	0.034	0.146	0.058
Divers 5000 Hz	8.75	6.22	7.26	6.55	3.91	5.06	4.87	3.89	6.89

C. Diagnosis

The diesel power generators at the power station SOPAM have diesel engines equipped with 16 cylinders that explode 2 by 2 or 8 explosions per cycle. The explosion frequency is 33.33 hz. The turbochargers on these generators have roller bearings.

❖ *Bearing Functional Diagram*

The function of bearing is to allow the rotation of the main shaft while shifting its load towards the mounting, with the minimum frictions possible. Another function of the bearing is to position the shaft in the bearing housing. Figure 3 shows the functional diagram of bearing, and Figure 4 shows its transfer function.

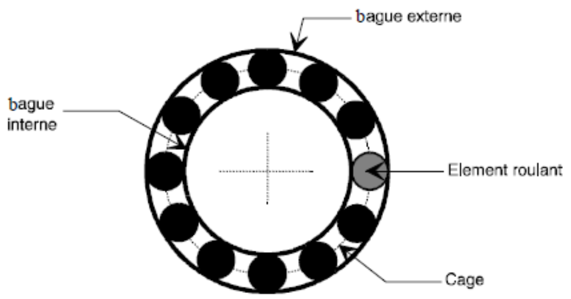

Figure 3. Bearing Functional Diagram

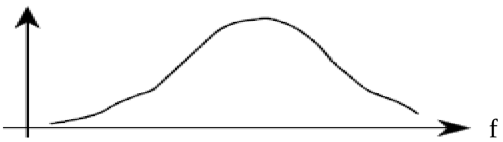

Figure 4. Bearing Transfer Function

❖ *Analysis*

We found out that explosion frequency in diesel engine does not have impact on spectral vibrations measured on the turbochargers. In contrast, in our previous studies on the diesel and alternator components, the main vibration was located at explosion frequency level. Figure 5 shows the spectrum from side A, and Figure 6 from side B. We performed the measurements on 26 May 2015. The follow-up measurements were planned to take place 2 months later on, in continuous operation, that is to say on 26 July 2015. We do not have standardised precise indicators on the turbochargers with regards the standards available to us (IS/ISO standard 8528-9, ISO standard 10816-1). Therefore, we proceeded to experimentally determine indicators. On the 25 of June 2015, exactly after 1 month in continuous operation, the turbocharger on side B broke down over a defect in bearing, while the one on side A revealed no defect. This breakdown happened before the planned date (26 July 2015) for the second measurement campaign. Indeed, we looked at the vibrational sate of the turbocharger side B, on the basis of the first series of measurements, as a benchmark for thresholds. Typically, defects on turbocharger are either in bearings or wheels of the turbocharger. A wear suffered by the blades shows in the turbocharger rotation frequency or in a harmonic at this level. Measures show that vibration levels are not high at rotation frequency and at harmonics of rotation frequency. On the other hand, the defect in bearing detected on the turbocharger (side B) on G1 appeared with increased overall acceleration level. Defects in bearing are observable with overall acceleration level (Table 3). We can see that the spectrum of the turbocharger in good working order (Figure 5) is comparable to the curve for bearing transfer function (Figure 4). The spectrum pointer shows 0.1 mm/s. By contrast, the spectrum of the faulty turbocharger runs away from the bearing transfer curve (figure 6), thus showing a degraded state of the bearing. Table 4 [11] shows the thresholds experimentally defined, in taking the measures from the faulty turbocharger as a benchmark for thresholds.

Table 4. Experimentally defined values (OL: Overall level)

Engine speed tr/mn	Turbocharger Speed tr/mn	OL at speed Turbocharger mm/s	OL in acceleration Turbocharger m/s^2
≤ 500	≤ 13 000	18	4

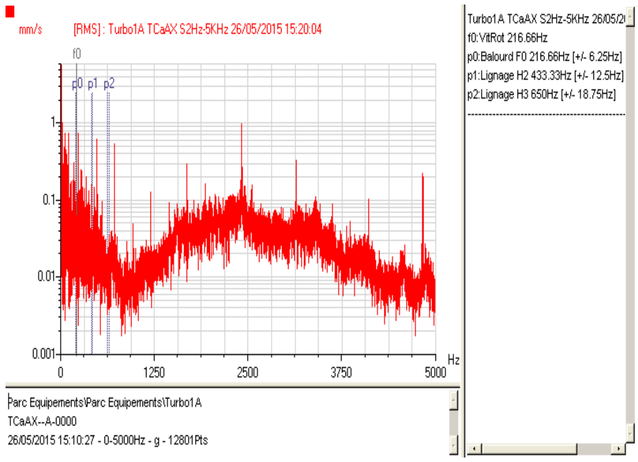

Figure 5. G1 Turbocharger Spectra on Side A

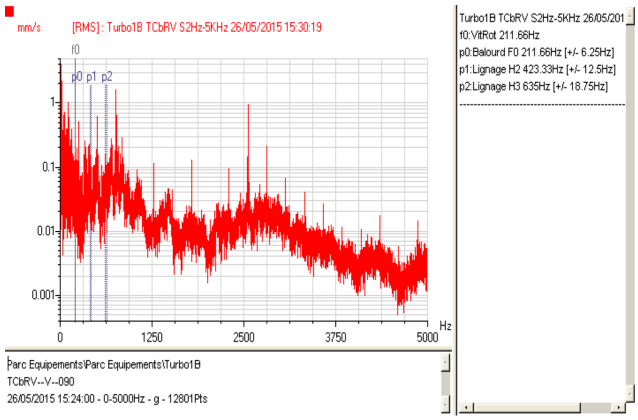

Figure 6. G1 Turbocharger Spectra on Side B

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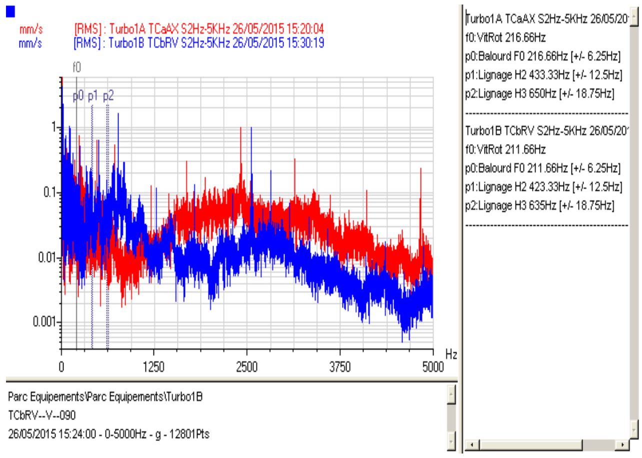

Figure 7. Turbocharger Spectra on Sides A and B

IV. CONCLUSION

This study focused on diagnosis of high-power diesel generators through vibration analysis. We were interested in the power station SOPAM in Mali because of the numerous incidents that occurred on turbochargers mounted on diesel generators at this station. We carried out a diagnosis on the turbochargers of the diesel power generator n°1 (G1). We found that the turbochargers do not suffer from shock explosions in the diesel engine. For this reason, the signals collected have been efficiently analysed with the help of FFT method. Our analysis focused on the bearings. We found that the spectrum of the turbocharger on G1 side A is comparable to the curve for a bearing transfer function (Figure 5). This turbocharger is in good working order. On the other hand, the spectrum of the turbocharger side B, which broke down, runs away from transfer function characterizing bearings. Therefore, we can draw the conclusion that if there is a defect in bearing the spectrum runs away from the transfer function assigned to bearing. Figure 7 shows an overlay of the two conditions: acceptable condition in red, and poor condition of bearings in blue.

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