INVESTIGATION ON CHARACTERISTICS OF TURBOCHARGER VIBRATION USING DIGITAL SIGNAL PROCESSING TECHNIQUE

Article history
14th June 2023
Received in revised form
22nd October 2023
Accepted
23rd October 2023
Published
1st December 2023

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Abstract

High-speed rotating machinery such as a turbocharger is always subject to imperfection that causes strong vibrations. The problem is that there is no way of knowing the root causes of these vibrations by just using our five senses. This problem is significant since unattended heavy vibrations on a turbocharger may lead to permanent damage and a high cost to fix them. The purpose of this study is to investigate the vibration characteristics of a running turbocharger using the Digital Signal Processing (DSP) method, hence identifying the sources of such vibration profiles. In this context, DSP is the process of taking vibration signals that have been digitized and then mathematically manipulating them. Usually, it involves converting time domain data into frequency domain using Fast Fourier Transform (FFT). To identify the causes of turbocharger vibrations, a literature review was done by studying past research of the same methodology. An experiment was conducted by running the machine at different speeds and operating conditions across the choke, regular, and surge conditions. Vibrational data was obtained by mounting a piezoelectric accelerometer onto the compressor housing. The data was then later post-processed using MATLAB to execute FFT. The result shows high energy peaks at various frequencies associated with an unbalanced rotor, oil whirl, looseness, misalignment, and surging noise. On this basis, it is concluded that the vibrational data of a turbocharger can be identified using DSP.

Keywords

Turbocharger, Vibration, Fast Fourier Transform, Digital Signal Processing

1.0 Introduction

Turbochargers are a vital class of turbomachinery intended to increase the power of internal combustion engines. Turbocharging is a way to increase the power output of an engine by introducing air into the engine cylinder with a higher density than ambient. This can be achieved by a compressor driven by a turbine. The engine's hot exhaust gas boost is used to drive the turbine. The advances in rotordynamics analysis using up-to-date computation technology have made the dynamics of turbochargers' rotor-bearing systems a rich area for investigation.

To date, vendors worldwide are still looking for ways to have more dynamically stable turbochargers for their business and customer satisfaction. More contributions are needed for optimum design stability while assuring continued low-cost production.

2.0 Literature Review

Based on a textbook journal by Nguyen-Schafer (2012), the unbalanced response (also forced vibration response) traverses the resonances at the first, second, third, or higher critical speeds. The critical speeds are the rotor rotational speeds at which the rotor *eigenfrequencies* equal the *rotor frequency*. The unbalanced responses are harmonic vibrations with the rotor frequency, with a frequency order of 1X.

According to Nguyen-Scafer (2012), The rotor vibration response results from superimposing the harmonic unbalanced excitation on the sub-synchronous components, i.e., the inner and outer oil whirl vibrations. The self-excited frequency components have irrational frequency orders from 0.25X to 0.70X for the inner oil whirl and from 0.1X to 0.3X for the outer oil whirl. The whirl frequency orders depend on the rotor speed and the oil temperature.

Artur Andrearczyk (2020) has researched the operating characteristics of a turbocharger compressor with components manufactured by multiJet printing technology. Experimental tests were conducted at high rotational speeds up to 100,000 rpm with the reference material, which is the original aluminium compressor wheel and a polymer wheel. Analysis of material strength and vibration during operation are recorded and compared. A modified automotive turbocharger was subjected to experiments on a test stand. Rotation looseness is usually caused by excessive clearance between the rotating and stationary elements of the machine, that is, between the rotor and the bearing sleeves. Therefore, it exhibits an inconsistent cluster of frequency characteristics at orders between 2X and 4X.

On the other hand, Steven Bamberg (2017) developed a reliable methodology that accurately predicts compressor surges. The simulation at the surge point shows a dominant oscillation at about 7.46 kHz, which is interpreted as an indicator of surge onset in the sector model. Considering the running speed, the surge spike is at 1.95X times the shaft order speed. Hence, it can be confirmed that the surging condition exhibits frequency components at the super-synchronous region.

3.0 Methodology

This project will use the Digital Signal Processing (DSP) method to analyse the characteristics of the turbocharger vibrations on the frequency spectrum. DSP takes real-world signals like voice, audio, video, temperature, pressure, or, in this case, vibrations that have been digitised and then mathematically manipulated. The FFT is a computational tool that facilitates signal analysis through digital computers, such as power spectrum analysis and filter simulation. It is a method for efficiently computing the discrete Fourier transform of a series of data samples referred to as a time series (Cochran et al., 1967)

Figure 1: Overall methodology flowchart of this project

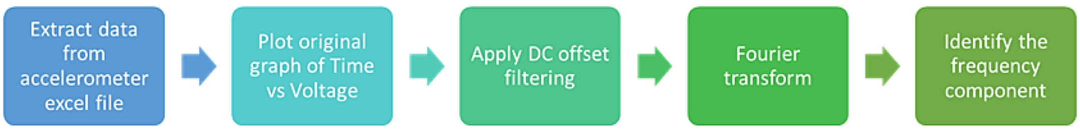

Figure 2: Flowchart of the MATLAB code to carry out the frequency analysis

The accelerometer used to record the vibrational data is Endevco brand Model 2226C. The output signal from the accelerometer is in Volts. The signal conditioner used in this experiment is an Endevco brand Model 123. Model 123 is a new microprocessor-controlled 3-channel signal conditioner for Piezoelectric (PE) or Integrated Electronic Piezoelectric (IEPE) sensors.

An accelerometer screw mounting adapter had to be designed to attach the sensor to the compressor body and obtain vibrational data without adhesives. The dimensions of the accelerometer were precisely measured and designed using SOLIDWORKS software. The material used to fabricate the adapter was aluminium.

For this experiment, the turbocharger will be operated at four different speeds: 60krpm (5 points), 90krpm (8 points), 105krpm (9 points), and 120krpm (9 points). At each speed, multiple points representing different operating conditions of the turbocharger will be taken. The first point of every speed will start near the choke line, while the last point will end across the surge line. 15,000 data samples were taken in 1 second and recorded for 10 seconds.

Figure 3: Position of the accelerometer within the adapter mounted on the turbocharger compressor.

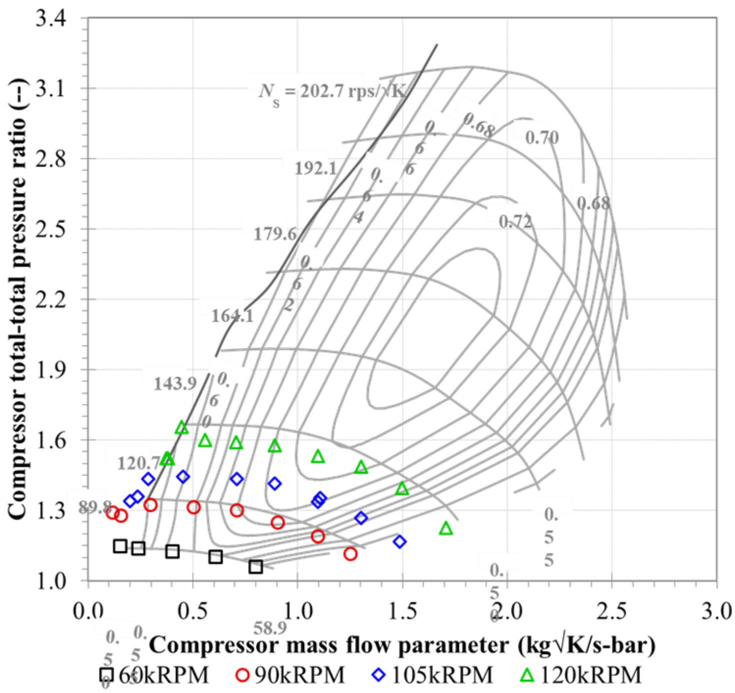

Figure 4: Compressor map for the turbocharger that will be tested and the position of points that will be taken.

RESULTS AND DISCUSSION

4.1 Analysis of Signals of Ambient Sound

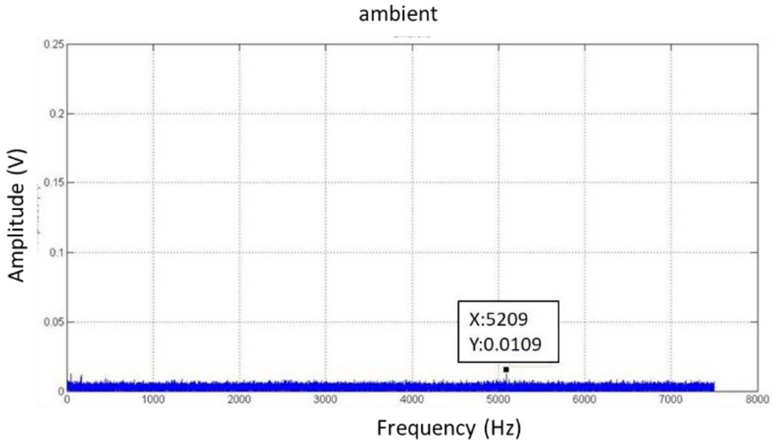

Figure 5: FFT plot of ambient sound

The signal seems to be at a consistent amplitude of around 0.01V and less. This trend can later be spotted in the FFT plot during the operation of the turbocharger to identify it as an ambient sound profile.

4.2 Analysis of Signals of Ambient Sound

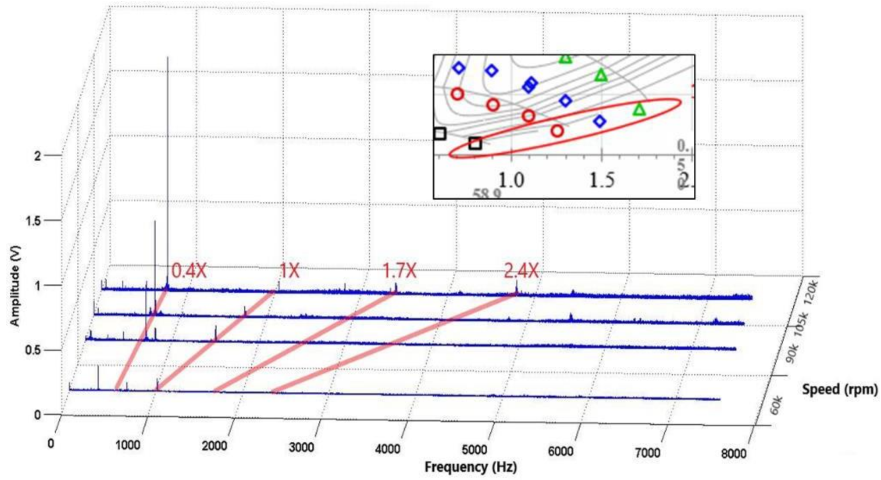

Figure 6: Waterfall diagram of each speed at point 1

The 1X component is always present across all speeds at a constant amplitude. This is caused by the unbalanced rotor. For sub-synchronous vibrations, all speeds have a dominant 0.4X spike with an increase in amplitude as the speed increases. This profile is associated with oil whirls. However, at the super-synchronous region, spikes at 1.7X and 2.4X were present at 120krpm. These spikes have no trend throughout the speed and only exist at high running speeds.

According to the result of research by Andrearczyk (2020) in Figure 2.8, some spikes tend to exist along the super-synchronous region at high speeds due to looseness and misalignment. These spikes do not have a trend and can be categorised as non-dominant random noise excited by high speed.

4.3 Analysis of Signals of Normal Operating Conditions

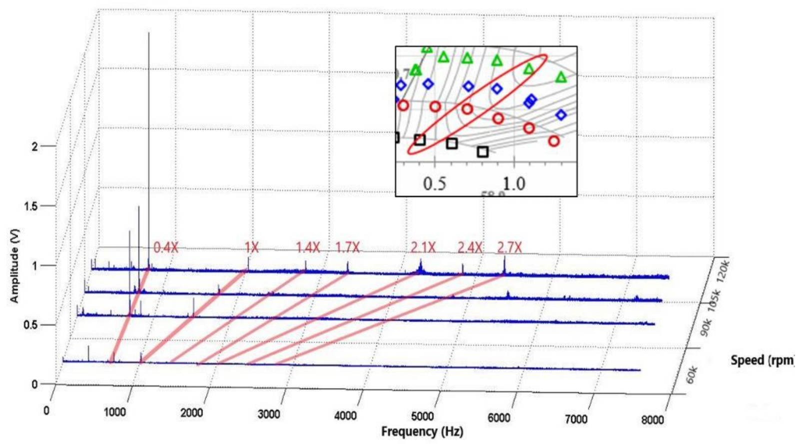

Figure 7: Waterfall diagram of each speed at midpoint

The 1X component is always present across all speeds at a constant amplitude. This is caused by the unbalanced rotor. For sub-synchronous vibrations, all speeds have a dominant 0.4X spike with an increase in amplitude as the speed increases. This profile is associated with oil whirls.

However, at the super-synchronous region, there are many spikes at 1.4X, 1.7X, 2.1X, 2.4X and 2.7X at 120krpm only. These spikes have no trend throughout the speed and only exist at high running speeds. These spikes do not have a trend and can be categorised as non-dominant random noise excited by high speed.

4.4 Analysis of Signals at Surge Conditions

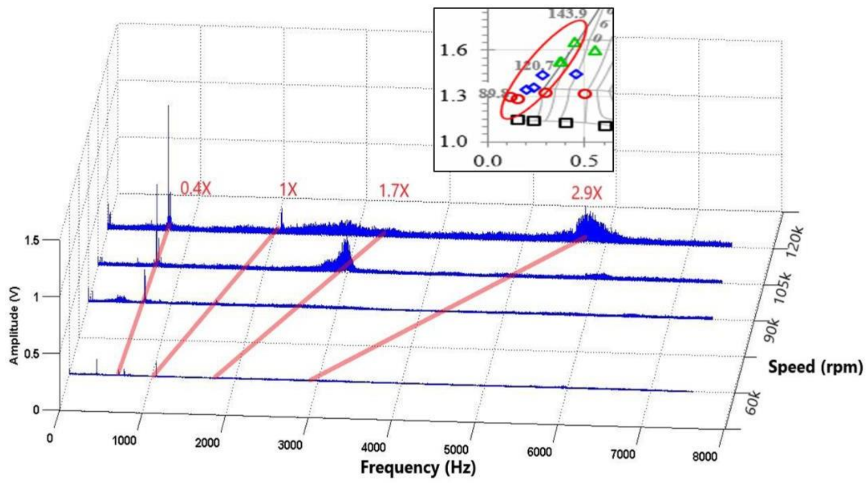

Figure 8: Waterfall diagram of each speed at the last point

For synchronous vibration caused by an unbalanced rotor at 1X, it is evident at 60krpm, 90krpm, and 120krpm. However, at the speed of 105krpm, the 1X spike is very subtle and hidden. This is unusual, but other studies have experienced the same result (Ali Alsaeed, 2015). For the sub-synchronous features, the oil whirl component of 0.4X is consistently trending across all speeds and conditions. Furthermore, there is one high spike at frequency order of 1.7X at 105krpm speed. The last point of all operating speeds represents the surge condition. Therefore, it can be confirmed that the profile is only caused by surging.

To further clarify, Bamberg (2017) has reported that frequency profiles caused by surging can exist at super-synchronous regions as high as 1.96X and above. This can also be caused by a high-frequency sound heard during the turbocharger experiment operating at this speed at surging. Another possibility is that the considerable noise at that 1.7X order is the cause of the disappearance of the 1X order since the surging spike has much higher energy. Another high energy spike at a higher frequency that can be noticed is the one along the 120krpm speed, denoted at 2.9X at speeds of 120krpm. It can also be confirmed that it is excited by the surging condition.

Conclusion

In a nutshell, the objectives of this project were successfully achieved. The unbalanced responses are harmonic vibrations with the rotor frequency, with a frequency order of 1X. For sub-synchronous vibrations less than 1X, oil whirl components can be easily recognised by frequency orders between 0.4X and 0.48X. Mechanical looseness and misalignment can cause super-synchronous vibrations which are more than 1X.

Lastly, turbocharger surging conditions exhibit tremendous energy profiles at 1.95X or more. Secondly, vibrational data of the turbocharger using experimental testing was successfully obtained. From the raw accelerometer data in Volts, the data was passed through a signal conditioner to amplify the signal. Labview was used for data acquisition at a set sampling rate and exported in a readable Excel file. Turbocharger vibration characteristics were successfully analysed using the digital signal processing method. The output data obtained from the experiment was imported to MATLAB software, where FFT is executed and plotted accordingly to show frequency trends across certain speed and running conditions.

Acknowledgments

The author would like to acknowledge the Ministry of Higher Education Malaysia (MoHE) for funding this research –under the registered program cost centre: #R.J130000.7809.4L893

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