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NHV Analysis Report

Ride Handling and NVH | ACHA6003

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1 Introduction

Noise, Vibration, and Harshness (NVH) analysis is a critical aspect of modern engineering, particularly in the automotive and mechanical systems industries, where understanding and mitigating unwanted vibrations and sound emissions are key to improving performance, durability, and user experience. This report explores NVH concepts by analysing two distinct mechanical systems: the Ryobi R18PI-0 high-pressure handheld inflator and a 1.6L Ford Sigma engine.

The study employs advanced measurement tools, including microphones, accelerometers, and tachometers, to capture vibration and acoustic data under varying operating conditions. Using DewesoftX software for data analysis, Fast Fourier Transform (FFT) and Order Tracking (OT) graphs are generated to identify key frequencies and their sources. The findings focus on phenomena such as natural frequencies, and cylinder deactivation effects, providing insights into the relationships between operational changes and NVH performance.

Excessive NVH not only impacts machinery performance but can also negatively affect human health and comfort. Prolonged exposure to high levels of noise can lead to hearing damage, stress, and cognitive fatigue, while vibrations transmitted through equipment can cause discomfort and, in severe cases, musculoskeletal disorders. (Rahimimoghadam et al., 2023) Addressing these NVH issues is essential for ensuring operator well-being and compliance with occupational health standards in industries and consumer environments. By addressing these challenges, this analysis offers a comprehensive understanding of NVH dynamics and its implications for both mechanical systems and human users.

2 Investigation of NVH Concepts (Task 1)

2.1 Choice of Mechanical System

The mechanical system selected for this investigation is the Ryobi R18PI-0 (*Figure 1*), a high-pressure handheld inflator. To understand its dynamic behaviour, the system was disassembled and analysed for potential sources of excitations.



Figure 1 - Ryobi R18PI-0 (Ryobi Limited, 2022)

2.2 System Teardown and Analysis

The Ryobi R18PI-0 employs a HRS540S-5044F brushed DC motor as its primary driving mechanism. DC electric motors have a ripple effect due to the nature of their construction. The way the brushes interact with the commutator segments creates periodic short circuits, generating high-voltage pulses that reduce armature impedance, increase current, and produce distinct current ripple waveforms (Abacan *et al.*, 2019).

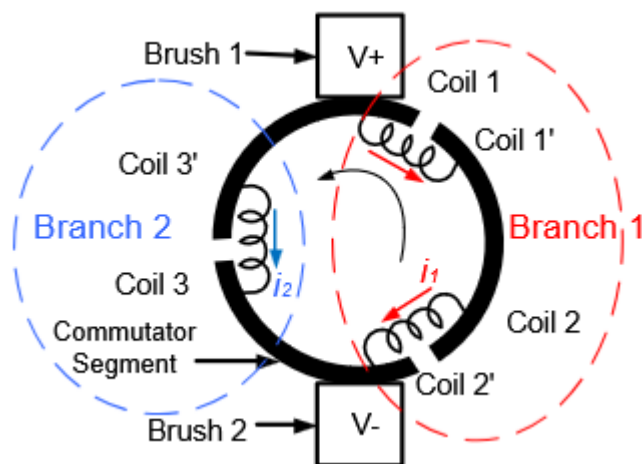


Figure 2 - Brushed DC Motor Diagram (Abacan *et al.*, 2019)

These ripples can be calculated by using *Equation 1*.

$$\text{No. of Ripples}_{\text{per revolution}} = \text{No. of Brushes} \times \text{No. of Commutator Segments}$$

Equation 1 - Calculating Ripple Effect in Brushed DC Motors (Abacan et al., 2019)

The HRS540S-5044F motor is sealed, preventing full disassembly without risking its functionality. Based on external observations, it has 5 commutator segments. Assuming the standard configuration for brushed DC motors, it likely operates with 2 brushes, substituting these factors into *Equation 1*:

$$\text{No. of Ripples}_{\text{per revolution}} = 2 \times 5 = 10$$

Using the operating speed of 18,000 RPM, the frequency of the ripple effect can be determined.

$$\text{Frequency} = \frac{18000 \text{ rpm} \times 10 \text{ Ripples}_{\text{per revolution}}}{60} = 3000\text{Hz}$$

Equation 2 - Frequency Equation (Cadence PCB Solutions, 2020)

The motor transmits motion to a 10-tooth gear, which is in mesh with a 46-tooth gear, producing a gear ratio of 4.6:1. This larger gear drives a crank-slider mechanism, converting the rotational motion into linear motion to operate the reciprocating piston, as seen in *Figure 3*.

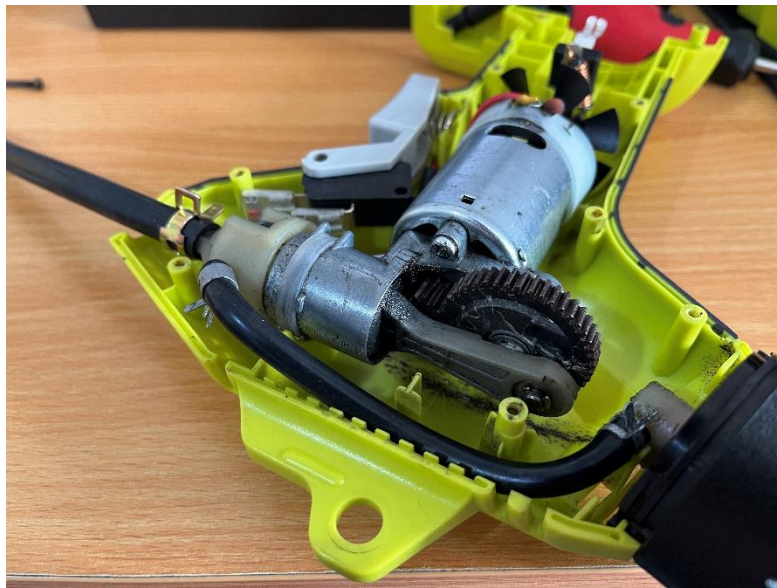


Figure 3 - View of Components Inside

Here's an overview of the system in relation to the primary excitor:

Table 1 - System Overview

Component	Description	Frequency	Order
DC Motor Main Shaft	Operates at 18,000 RPM as per technical documentation.	300 Hz	1 st
DC Motor Ripple	Produces 10 electrical ripples per revolution.	3000 Hz	10 th
Gear Pair	Gear ratio 4.6:1, reducing speed to 3,913 RPM.	65.22 Hz	0.22 nd
Piston	Completes one stroke per revolution of the large gear.	130.44 Hz	2 nd
Air Pulses	One intake and one exhaust event per piston cycle.	130.44 Hz	2 nd

2.3 Component Harmonic Resonance

Natural frequency refers to the rate at which a system oscillates naturally when displaced from its equilibrium position and left to vibrate freely, without the influence of external forces. It is an intrinsic property determined by the system's mass and stiffness. (Lim, A., 2018)

For example, in a simple harmonic system, the natural frequency can be expressed mathematically as:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Equation 3 - Natural Frequency Equation (PCB Design Resources, 2023)

Where k is the stiffness (spring constant), and m is the mass. This relationship indicates that increasing stiffness or reducing mass raises the natural frequency, while reducing stiffness or increasing mass lowers it. (PCB Design Resources, 2023)

In engineering applications, it is critical to ensure that the natural frequencies of components do not align with the excitation frequencies during operation. When an external force matches a system's natural frequency, harmonic resonance can occur, leading to amplified oscillations that may result in additional stresses and ultimately can end in component failure. For example, poorly designed systems subjected to resonance have historically caused catastrophic failures, as seen in the Tacoma Narrows Bridge collapse of the 1940s. (SimScale, 2023)

With harmonic resonance in mind, here's an analysis of its potential effects within the mechanical system under discussion:

- **Motor Shaft and Ripple Effects**

The motor shaft operates at 300 Hz, with ripple at the 10th order (3000 Hz). If these frequencies align with the natural frequencies of the motor housing or nearby components, resonance could amplify vibrations, potentially leading to increased wear, noise, or failure of connected mounts and bearings.

- **Gear Pair Interaction**

The gear pair introduces a fundamental frequency of 65.22 Hz due to the gear ratio and tooth meshing. If these align with the natural frequencies of the product's housing or frame, the vibrations can result in accelerated fatigue or even cracks in supporting structures.

- **Crank-Slider Mechanism**

The reciprocating motion of the crank-slider mechanism creates a dominant frequency at 65.22 Hz, with additional harmonics from the piston's acceleration profile. Resonance in the connecting rod or slider could cause excessive oscillations, reducing the efficiency and lifespan of the mechanism.

- **Air Pulses**

Air pulses occur at 130.43 Hz. If the pressure waves synchronize with the natural frequencies of the air chamber or ball valve, resonance may cause oscillations that reduce valve sealing performance or lead to rapid valve degradation.

- **Structural Components**

The entire system's casing, its mounting structures, or fixtures could resonate at frequencies matching any of the identified excitation sources. This can intensify noise profiles, reduce operational stability, compromise the structural integrity, or loosen and degrade fixtures over time.

2.4 Mechanical Vibration and Acoustic Air Pressure Wave Measurement

2.4.1 Mechanical Vibration

To measure mechanical vibrations, the most commonly used device is a piezoelectric accelerometer, which detects oscillations and converts them into an electrical signal. Accelerometers are highly sensitive devices capable of capturing vibration frequencies, amplitudes, and phase data. They can measure displacement, velocity, or acceleration depending on the frequency range and application. For example, low-frequency vibrations often use displacement measurements, while higher frequencies are better represented through acceleration data. Advanced accelerometers are frequently integrated into systems with digital processing tools, such as Fast Fourier Transform (FFT) analysers, to diagnose system health and predict failures. (Fluke Corporation, n.d.)

2.4.2 Acoustic Air Pressure

To measure acoustic air pressure, devices such as microphones are commonly employed. Microphones are transducers, which means they convert acoustic energy (sound) into electrical energy.

There are two primary types of microphones: dynamic and condenser.

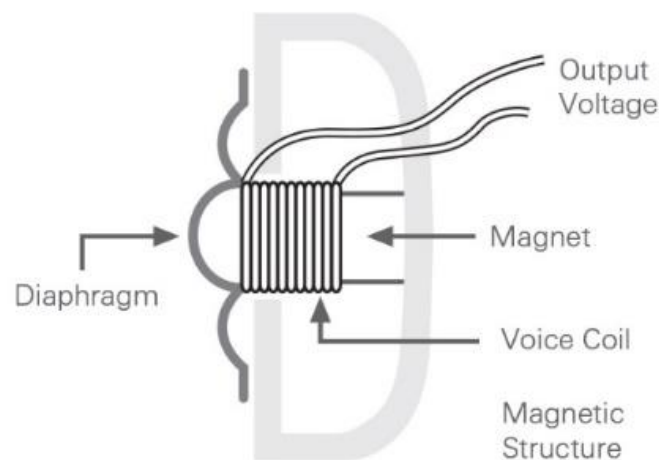


Figure 4 - Dynamic Microphone Diagram (Audio-Technica, n.d.)

Dynamic microphones operate similarly to speakers but in reverse. They have a diaphragm that moves with sound pressure, causing a coil attached to the diaphragm to move within a magnetic field, generating an electrical current.

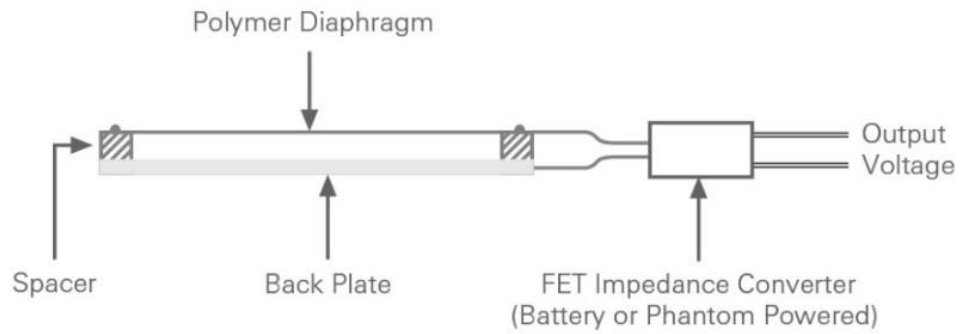


Figure 5 - Condenser Microphone Diagram (Audio-Technica, n.d.)

Condenser microphones, on the other hand, utilize a thin diaphragm that acts as one plate of a capacitor, with a fixed backplate forming the other. The diaphragm's movement in response to sound pressure changes the capacitance, which is then converted into an electrical signal. (Audio-Technica, 2023).

3 Analysis of Measured NVH Data

The analysis conducted on a 1.6L Ford Sigma engine was conducted using a comprehensive testing setup, as shown in Figure 6. To capture the engine's performance, five distinct sensors were employed. A microphone (AI1) was placed close to the engine to record the sound emitted during testing. To measure vertical and lateral vibrations, two piezoelectric accelerometers (AI2 and AI3) were positioned on the rocker cover. A fourth accelerometer (AI4), also of the piezoelectric type, was installed on a safety shroud around the radiator to monitor additional vibrations. To track the engine speed, a non-contact tachometer was used to measure the flywheel's rotation.

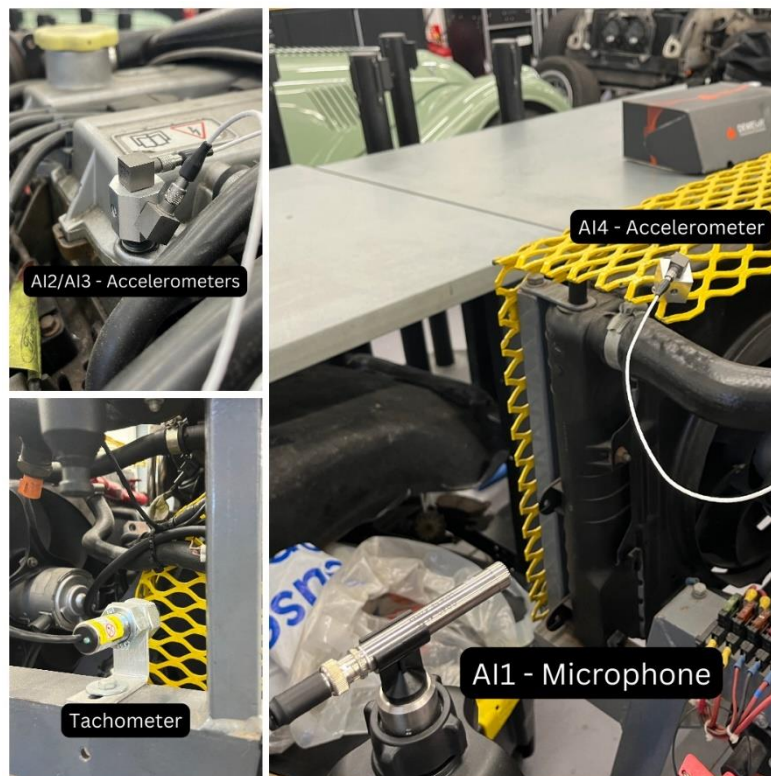


Figure 6 - Sensor Test Setup

The test procedure involved a full engine sweep, starting from idle speed, ramping up to maximum RPM, and then returning to idle. The first test was conducted by gradually releasing the throttle cable, allowing the engine to decelerate progressively. In the second test, the throttle was released suddenly, and the engine was allowed to settle on its own. After completing these two tests, the impact on NVH levels of running the 4-cylinder engine on less cylinders was investigated by sequentially disconnecting each injector and performing the same two test runs.

3.1 Order Locked Analysis

The data collected during testing was analysed using DewesoftX software, resulting in the generation of Fast Fourier Transform (FFT) and Order Tracking (OT) graphs for detailed evaluation.

3.1.1 Separate Orders Identification

Using the data collected from AI1, a focus was observed on the frequencies corresponding to the 2nd and 36th orders, as illustrated in Figure 7. The 2nd order frequencies are associated with events occurring twice per crankshaft revolution, which aligns with the expected behaviour of intake and exhaust air pulses.

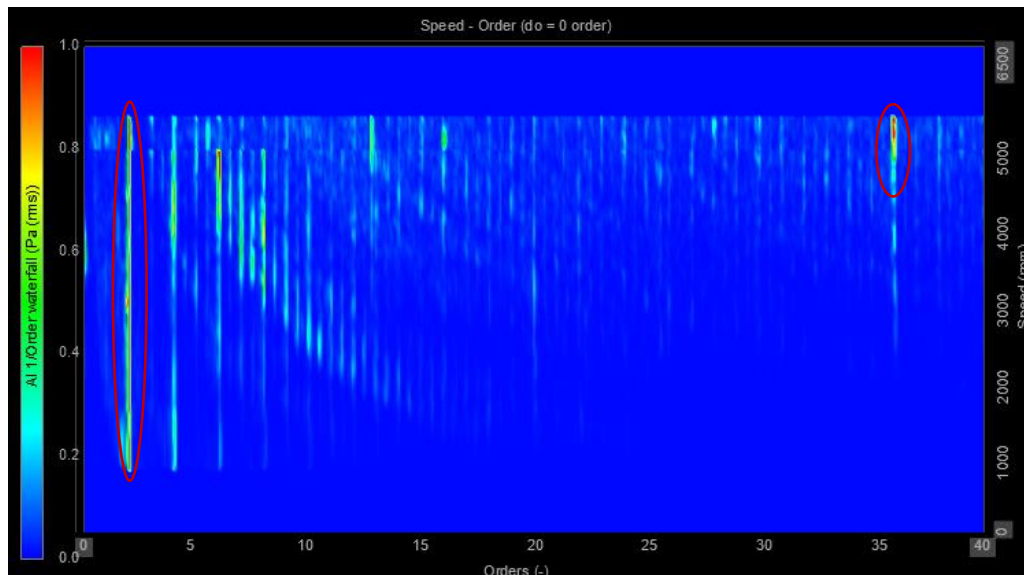


Figure 7 - AI1 OT Graph

The higher frequencies observed at the 36th order may correlate to the operation of the camshaft gear, which is believed to have 36 teeth. This suggests a connection between these frequencies and the interaction between the camshaft gear and the cambelt during operation.

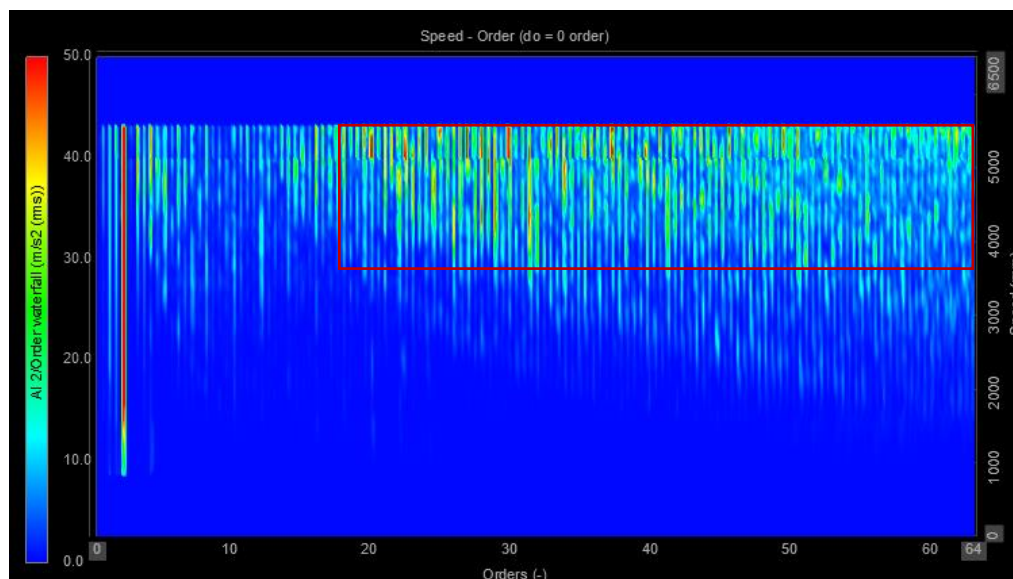


Figure 8 - AI2 OT Graph

Figure 8 and Figure 9 display the vertical and horizontal vibrations recorded during testing, with notable emphasis on the 2nd order frequencies, which stand out prominently in both directions. Vertical vibrations become more intense beyond the 16th order, particularly at higher RPMs (above 3000 RPM). Conversely, lateral vibrations are more concentrated below the 20th order, while still maintaining a pronounced presence at higher RPMs. This pattern could indicate the influence of specific structural or operational factors at these orders.

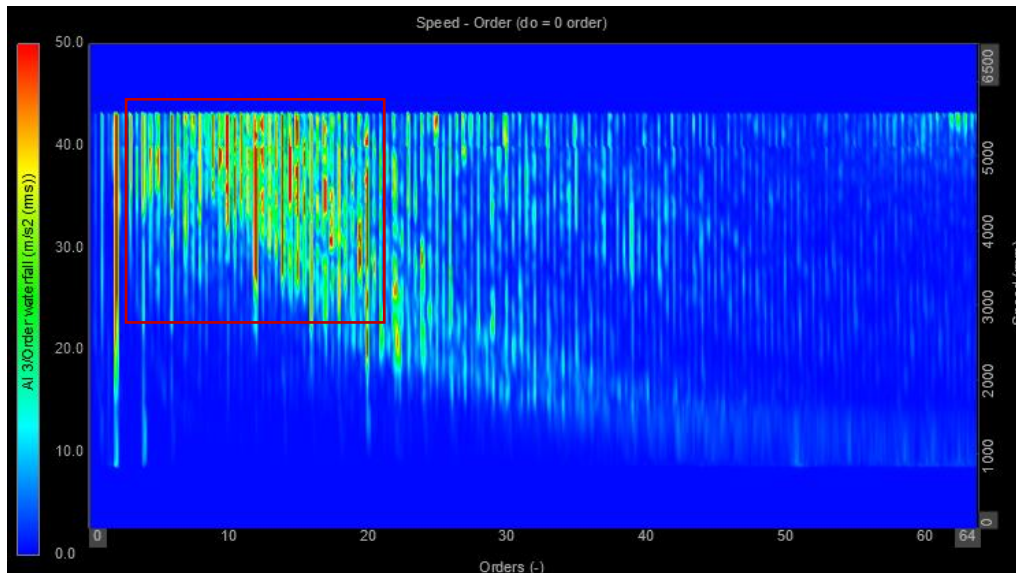


Figure 9 - A13 OT Graph

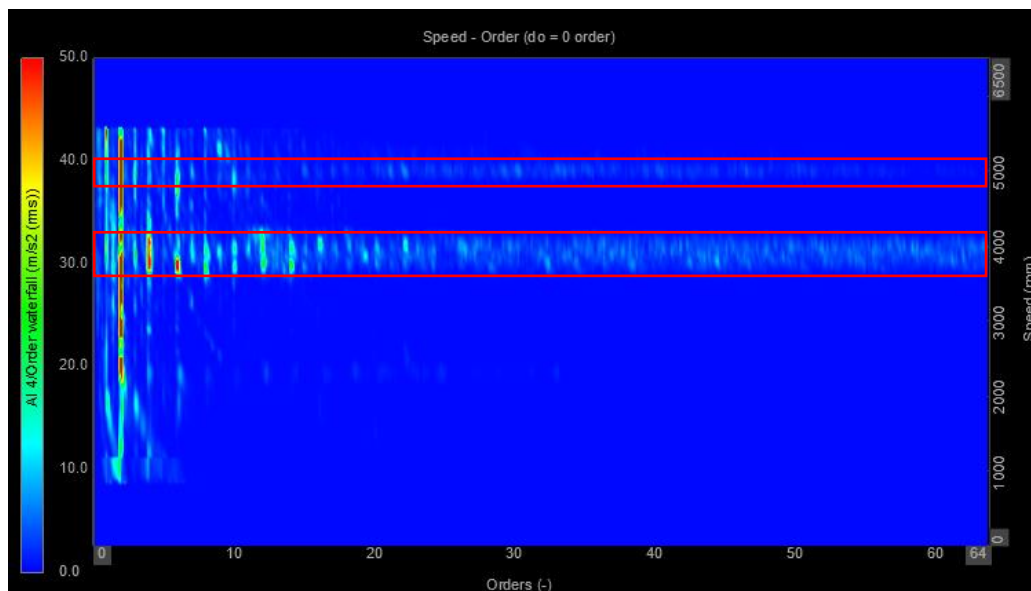


Figure 10 - A14 OT Graph

Figure 10 illustrates data captured from the accelerometer placed on the radiator mesh guard. The results suggest that the component exhibits a natural frequency resonance near 4000 RPM, with a less pronounced resonance reappearing faintly around 5000 RPM. These observations indicate potential

vibrational amplification at these speeds, due to the engine operating near the radiator guard's natural frequencies.

3.1.2 FFT Waterfall Plots

A 2D FFT waterfall plot is used to analyse the frequency content of signals over time or other reference variables, such as rotational speed (RPM). In DewesoftX, this plot is commonly used in applications like NVH analysis to examine how noise or vibration frequencies evolve under varying conditions, such as engine acceleration or deceleration. (Dewesoft, 2023)

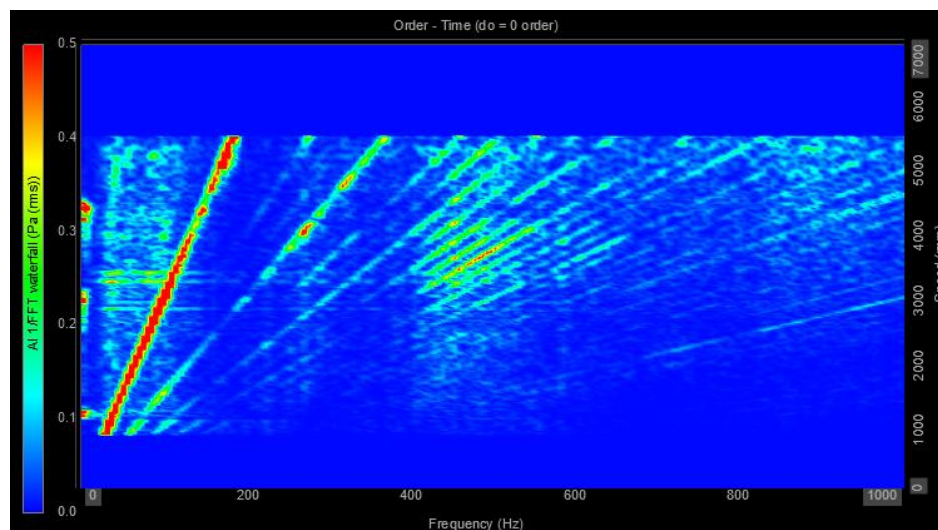


Figure 11 - AI1 FFT Waterfall

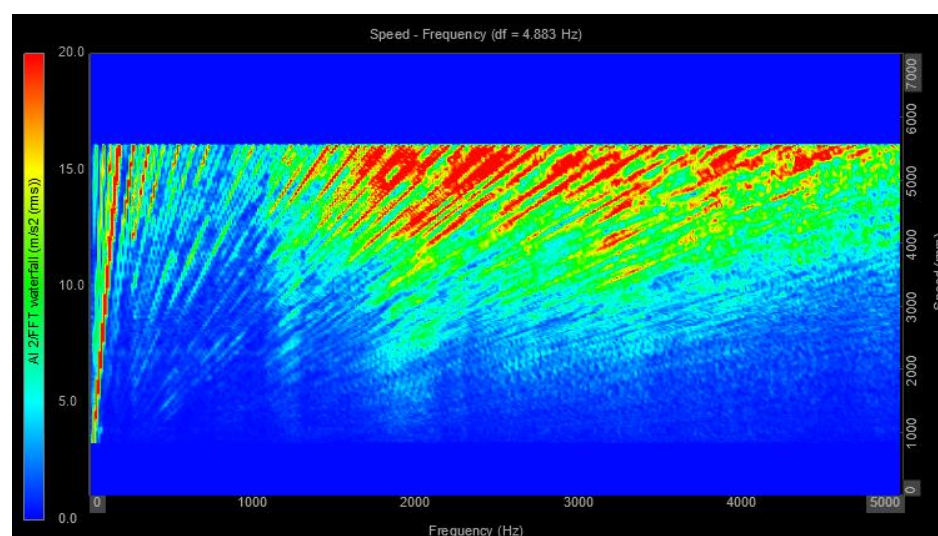


Figure 12 - AI2 FFT Waterfall

Vertical vibrations, as recorded by AI2, were most pronounced at engine speeds above 4000 RPM and frequencies exceeding 1000 Hz.

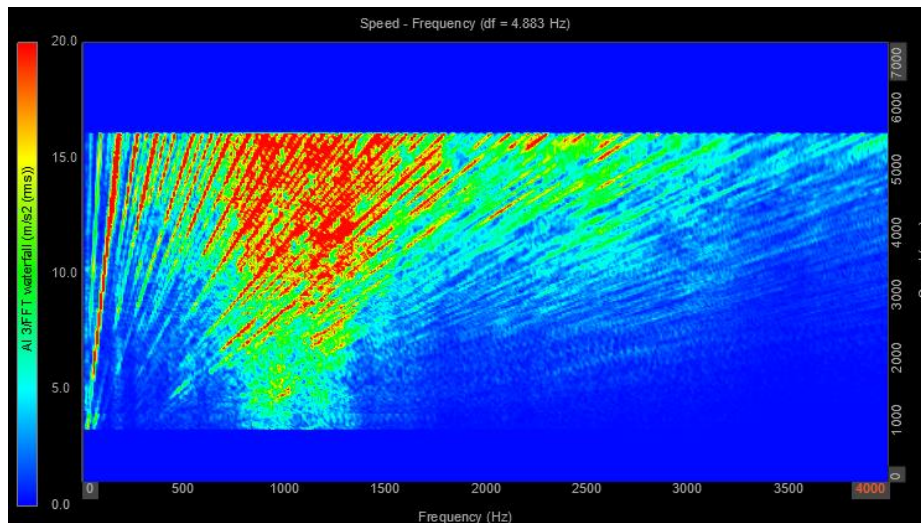


Figure 13 - AI3 FFT Waterfall

Lateral vibrations were predominantly concentrated in the upper half of the RPM range, occurring at frequencies below 2000 Hz. The highest excitation levels reached approximately 20 m/s².

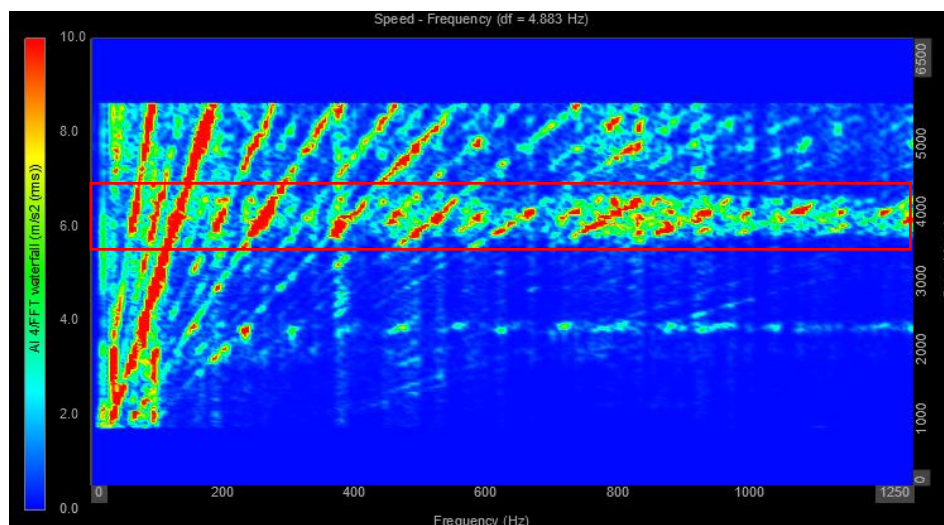


Figure 14 - AI4 FFT Waterfall

AI4 data, once again, highlights resonance occurring near 4000 RPM, which is indicative of the natural frequency of the radiator shield guard.

3.1.3 FFT Analysis (Cylinder Deactivation)

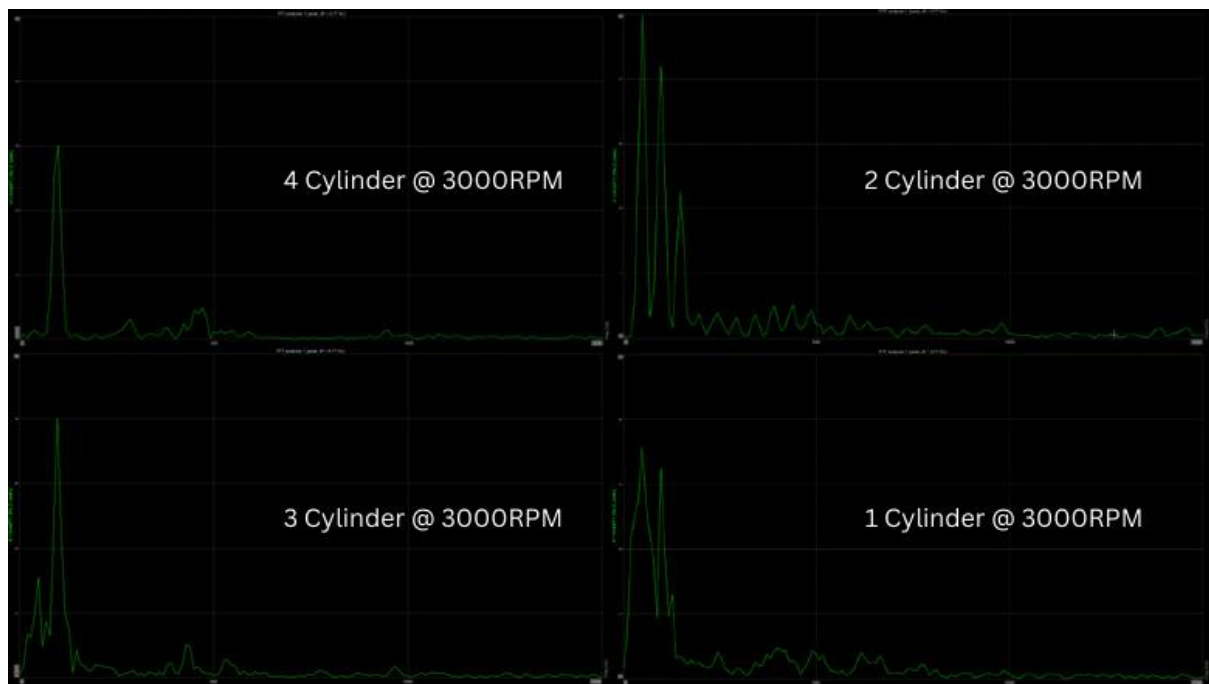


Figure 15 - AI1 FFT Graphs @ 3000rpm

Figure 15 compares AI1 data captured from the testing running different numbers of active cylinders, highlighting the variation in acoustic pressure levels and frequency response under these conditions.

When operating with all four cylinders, the system peaked at 3 Pa around the 100 Hz frequency range. Reducing operation to three cylinders increased the pressure amplitude to a peak of 4 Pa, while two-cylinder operation further amplified this to a maximum of 5 Pa. Conversely, single-cylinder operation exhibited a slight reduction in peak pressure, reaching only 3.5 Pa, though all configurations consistently peaked in the 100-150 Hz frequency band. These trends suggest that cylinder deactivation significantly influences the amplitude of the pressure waves, possibly due to changes in intake and exhaust dynamics or combustion stability under varying loads.

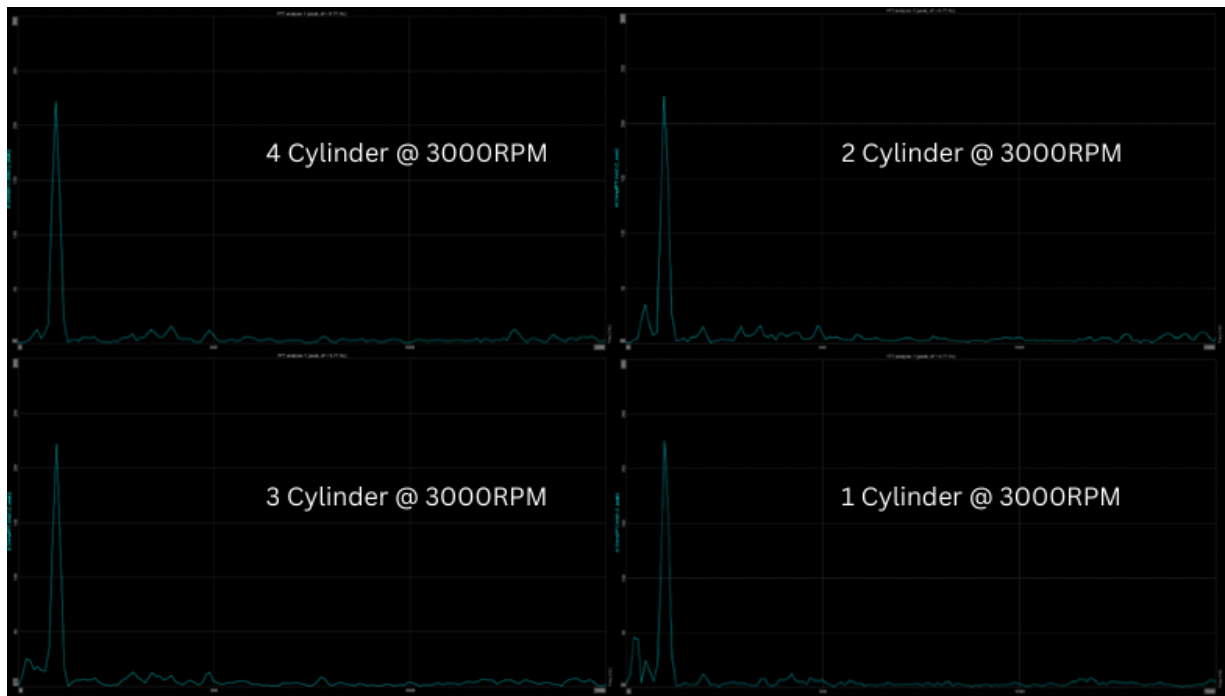


Figure 16 - AI2 FFT Graphs @ 3000rpm

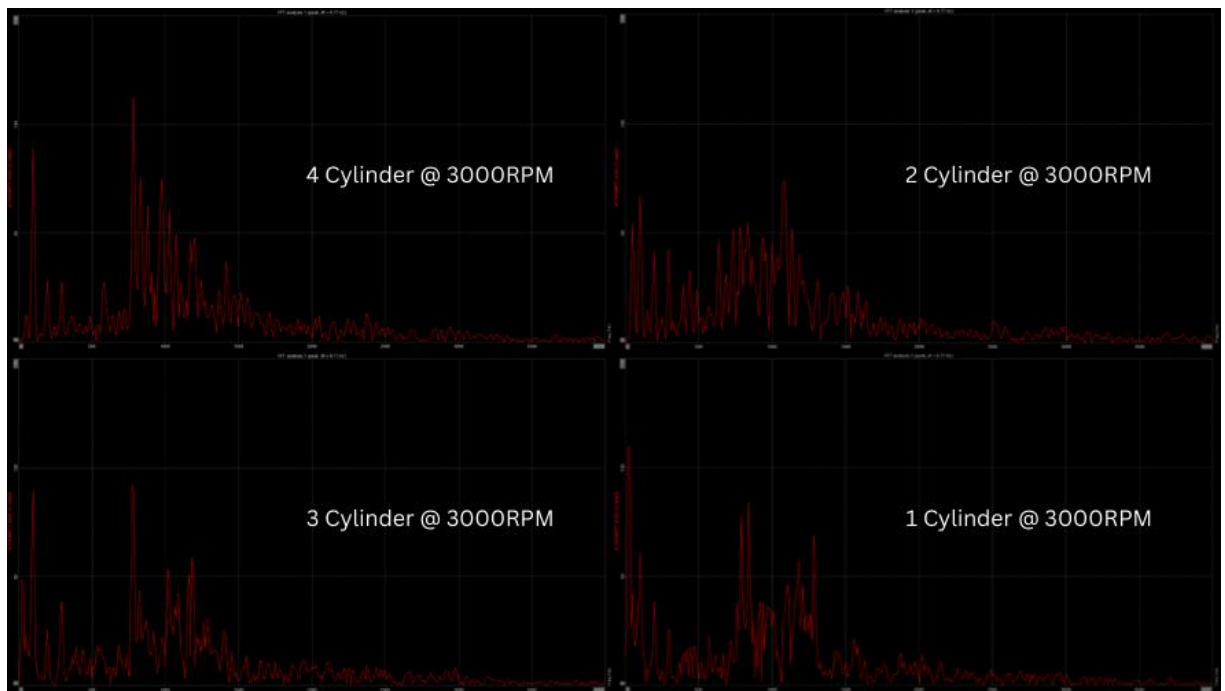


Figure 17 - AI3 FFT Graphs @ 3000rpm

Figure 16 and Figure 17 present the vertical and horizontal vibration measurements, respectively, from the engine under the various cylinder configurations tested.

The vertical vibrations across all configurations maintain a relatively uniform peak of approximately 225 m/s^2 within the 100-150 Hz frequency range, suggesting consistent harmonic characteristics in this direction regardless of the number of active cylinders.

Conversely, the horizontal vibrations exhibit a clear dependency on cylinder configuration. In the four-cylinder configuration, the peak amplitude reaches 100 m/s^2 at a frequency of 750-800 Hz. However, as cylinders are deactivated, both the amplitude and the frequency range evolve. Three-cylinder operation shows reduced amplitudes with vibrations spreading up to 1000 Hz. Two-cylinder operation extends the range further to 1500 Hz, while single-cylinder operation covers nearly 2000 Hz. This increase in frequency range with fewer cylinders indicates changing resonance and excitation characteristics, possibly due to the reduced damping effect and altered load distribution in the engine.

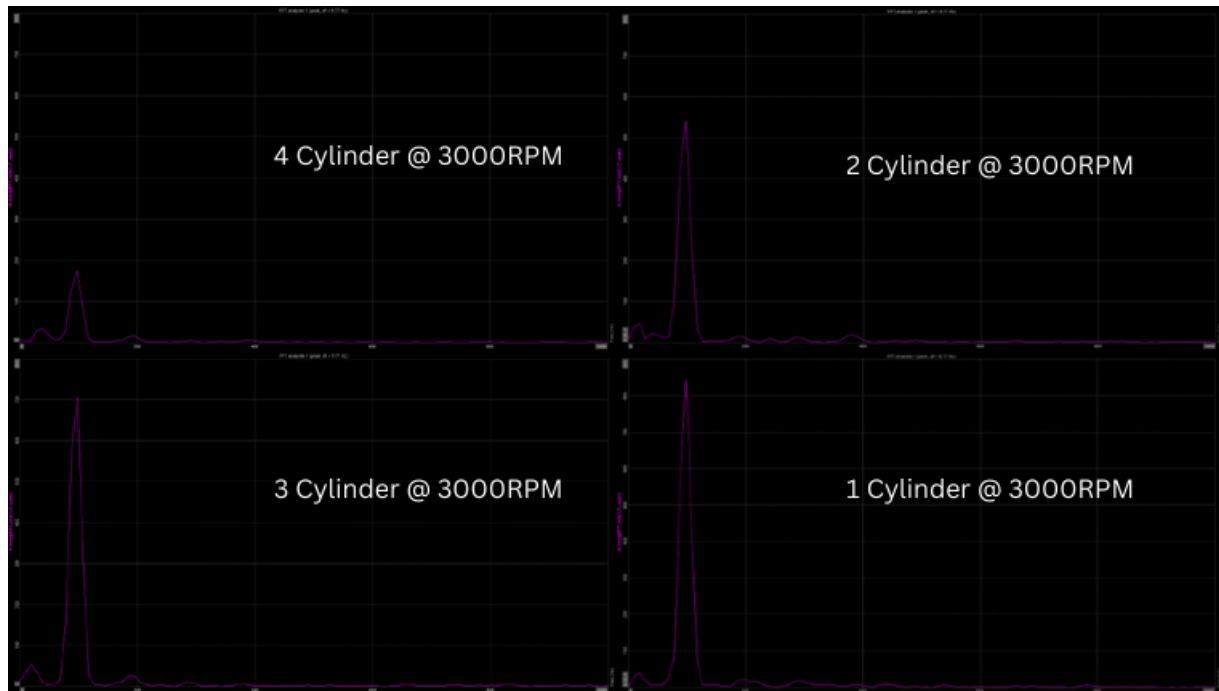


Figure 18 - A14 FFT Graphs @ 3000rpm

4 Conclusions

This report has explored the NVH characteristics of two mechanical systems, providing valuable insights into the sources and behaviours of noise and vibration. Through detailed testing and analysis using tools like accelerometers, microphones, and DewesoftX software, key frequencies and their associated components were identified, shedding light on subjects such as harmonic resonance, excitation orders, and the impact of operational changes like cylinder deactivation.

The findings emphasize the importance of NVH analysis in diagnosing and addressing performance issues in mechanical systems. Understanding the interaction of various components and the influence of design choices allows for better, quieter, smoother, and more efficient systems. This analysis highlights the role of NVH in optimizing system reliability and user experience.

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