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Wales Institute of Science & Art



NVH Analysis

Ride Handling & NVH ACHA6003

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1 Introduction

In the automotive sector, the analysis of noise, vibration and harshness (NVH) is used in testing components, diagnosing mechanical issues, and improving the occupant experience.

The human hearing range spans from 20 Hz to 20 kHz with different pitches within that range being perceived at different volume levels, hence the use of weighting curves. The occupant's experience can be improved by making changes to the vehicle structure to prevent or mitigate unwanted noises, mainly in the 30 to 4000 Hz range. Refining the sounds of the car is intended to uphold or improve the occupant's perception of the brand image (Wang, 2010). It is vital to analyse the sounds the occupants will hear within the vehicle as high levels of noise for long periods of time can be damaging to hearing (World Health Organisation, 2022).

NVH analysis can also be used in influencing driver behaviour by altering the engine sound heard by the occupants, for example adapting the sound to one that drivers are more familiar with, so they are more aware of when to change gear (Sontacchi *et al.*, 2016).



Figure 1 – An artificial head with microphones to record the sounds an occupant hears (Continental Engineering Services, no date).

Cold testing at the manufacturing end-of-line stage uses NVH analysis to identify issues which deviate from the expected vibration signature such as improperly fitted components, damaged components, or incorrect timing (Polytec, 2023). NVH analysis is also used to find the natural frequencies present in the system, this is crucial as resonant vibrations can lead to fatigue failure of components due to the cyclic loading with high amplitudes. Modal testing is utilized to find the natural frequencies of a structure by exciting the structure with a known force and measuring the response of the structure (Dewesoft, 2021).

In this report, equipment used for recording noise and vibrations is researched, an analysis of a mini compressor is performed to determine the orders that may be present, and NVH analysis of an engine under various operating conditions is performed to find resonant frequencies and assess the effect of engine malfunction on the NVH produced by the engine.

2 Equipment

A dynamic microphone converts the pressure from a sound wave into an electrical signal by using a diaphragm connected to a coil, with the coil surrounding a magnet. When the sound wave contacts the diaphragm, the diaphragm is moved by the pressure of the sound wave at the sound waves frequency. The coil moves with the diaphragm resulting in a current being induced in the coil from the movement of the magnetic field. This creates an electrical signal representing the frequency and amplitude of the sound wave (Rennie and Law, 2019b).

Piezoelectric microphones function similarly however instead of moving through a magnetic field, the electrical signal is created from the diaphragm imparting a force onto the piezoelectric material, creating a potential difference on the surface of the crystal. The change in potential difference is the amplitude of the signal, and the rate of change in potential difference over time corresponds to the frequency of the signal (Rennie and Law, 2019a).

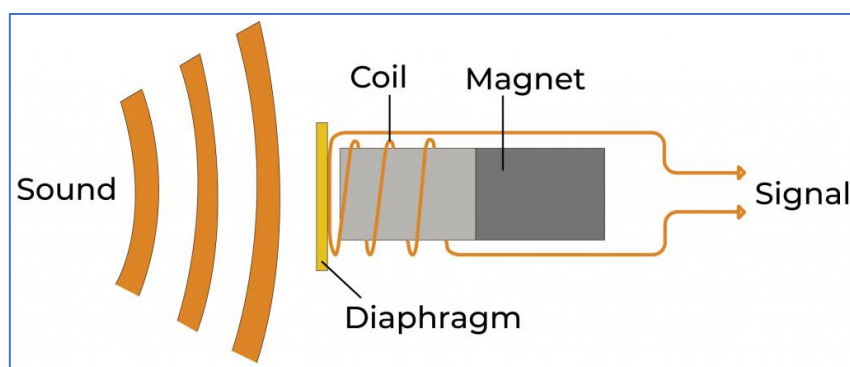


Figure 2- The internals of a dynamic microphone (soundref.com, 2023).

A piezoelectric accelerometer is used to measure the acceleration of a mass. When measuring vibrations this acceleration comes from the force exerted on the mass by each vibration. The acceleration of the mass exerts the same force onto the piezoelectric crystal causing a change in internal stress, generating a voltage via the piezoelectric effect (ni.com, 2023).

Integrated electronics piezoelectric (IEPE) microphones and accelerometers have an integrated circuit to amplify the charge generated by the piezo electric material, reducing the output impedance, making it less susceptible to signal loss and electromagnetic interference over the length of the cable (Levinzon, 2015).

A hall effect tachometer uses a magnetic field to measure the speed of rotation of a component. As the magnetic field moves around the hall effect sensor, the sensor generates a voltage due to the Hall

effect. This voltage relates to the position of the magnet, and then difference in voltage over time is related to the rotational speed. The rotational speed can also be measured using a laser tachometer, which is made up of a laser and a light sensor. A fixed point on the rotating component is made to change the amount of light reflected at the sensor, which is then recorded. The time between voltage spikes allows for the calculation of rotational speed.

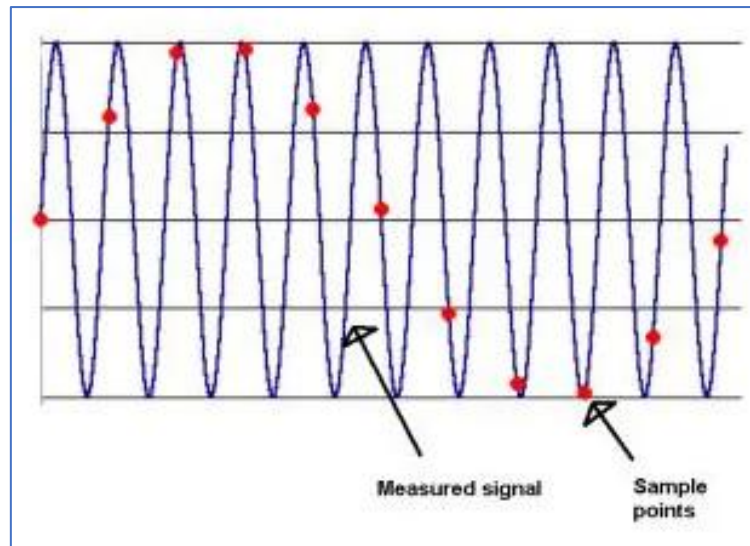


Figure 3 - Example of aliasing occurring due to sample rate being too low (Herres, 2015).

According to the Nyquist-Shannon sampling theorem, the sample rate of the sensor must be at least twice the frequency of the sampled frequency. Having a sample rate that is less than 2 times the sampled frequency will cause aliasing, causing the signal to be incorrectly interpreted (Brandt, 2011).

The signals from the microphones and accelerometers are sent to a Data Acquisition device (DAQ) for conversion to digital and are synchronised by time. During this process the signal is filtered to remove unwanted frequencies (Dewesoft, no date). A Fast Fourier Transform (FFT) is used to separate the recorded signal into individual sine waves representing each frequency and the amplitude of each frequency.

3 Generation of Order-locked Analysis

A 12 V DC portable compressor (Figure 4) was disassembled to analyse the possible excitation orders. The compressor was comprised of a brushed DC motor, connected to a piston via the main shaft with a bearing at each end, and 1 in the wall between the motor and the piston. The commutator had 12 segments which would contact 2 brushes per revolution therefore the commutator may produce vibrations in the 6th order.



Figure 4 - Disassembled compressor

The piston (Figure 5) reciprocates from bottom-dead-centre (BDC) to top-dead-centre (TDC) and returns to BDC for every revolution of the main shaft and it has a counterweight to cancel out vibrations. The counterweight will maintain a constant rotational velocity however the velocity of the piston will change at a different rate resulting in a 2nd order vibration occurring.

The bearings are all identical and have a 19 mm OD, a 7mm ID, and ball diameter of 6mm. The ID rotates with the main shaft. Due the difference in circumference of ID and OD, at a motor speed of 1500 Hz a ball would travel around the outer race with a frequency of 553 Hz, a vibration from this would be in the order 0.368. The ratio between ID and ball diameter means each ball rotates between the races with a frequency of 1750 Hz, assigning vibrations caused by them to be in the 1.167th order.

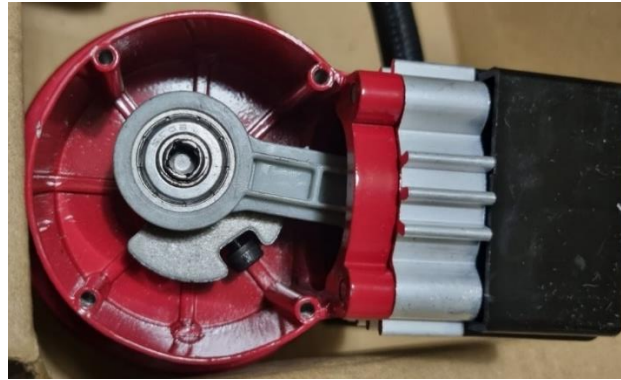


Figure 5 - Piston side of the compressor

When moving from TDC to BDC air is drawn into the cylinder through an intake valve, and then from BDC to TDC it is compressed and forced through the exit valve. Both events occur at the same frequency as the main shaft rotation, making them both produce 1st order vibrations; however, they will occur out of phase with each other.

Table 1 – Possible excitation orders

Component	Order	Operating Frequency (Hz)	Details
Main Shaft	1	25	Frequency at 1500 rpm
Commutator-Brush Contact	6	150	12 segments contacting brush twice per rev
Piston	2	50	Vibration due to conrod inclination
Air Valve	1	25	Air intake & exit once per rev
BB Outer Race	0.368	9.2	Order = If outer race damaged; $f = \text{outer race frequency} * n \text{ balls}$
BB Rotation	1.167	29.175	If ball damaged; $f = 2 * \text{ball bearing rotations (1 for inner race, 1 for outer race)}$

Table 1Error! Reference source not found. shows the possible excitation orders for the various components in the compressor. Ideally the components in the compressor should be designed with a natural frequency that is not excited by any of the frequencies experienced during operation. Damage to a bearing race or a single bearing ball could result in a frequency as specified in the details section.

4 Engine Operation NVH

4.1 Methodology

The testing setup for the NVH analysis of a 1.6 L Ford Sigma engine can be seen in Figure 6. A total of 5 sensors were used to gather data on the NVH characteristics of the engine during operation. AI1 was a microphone positioned near the engine to capture the sound. Vertical and lateral vibrations were recorded by AI2 and AI3 respectively, which were IEPE accelerometers positioned on the cylinder head cover. AI4 was an IEPE accelerometer positioned on a safety grill surrounding the radiator. A non-contact tachometer was used to determine the frequency of rotation of the flywheel to use as the reference for engine speed. The sensors were all recording at 20 kHz and were connected to a Dewesoft data acquisition system.

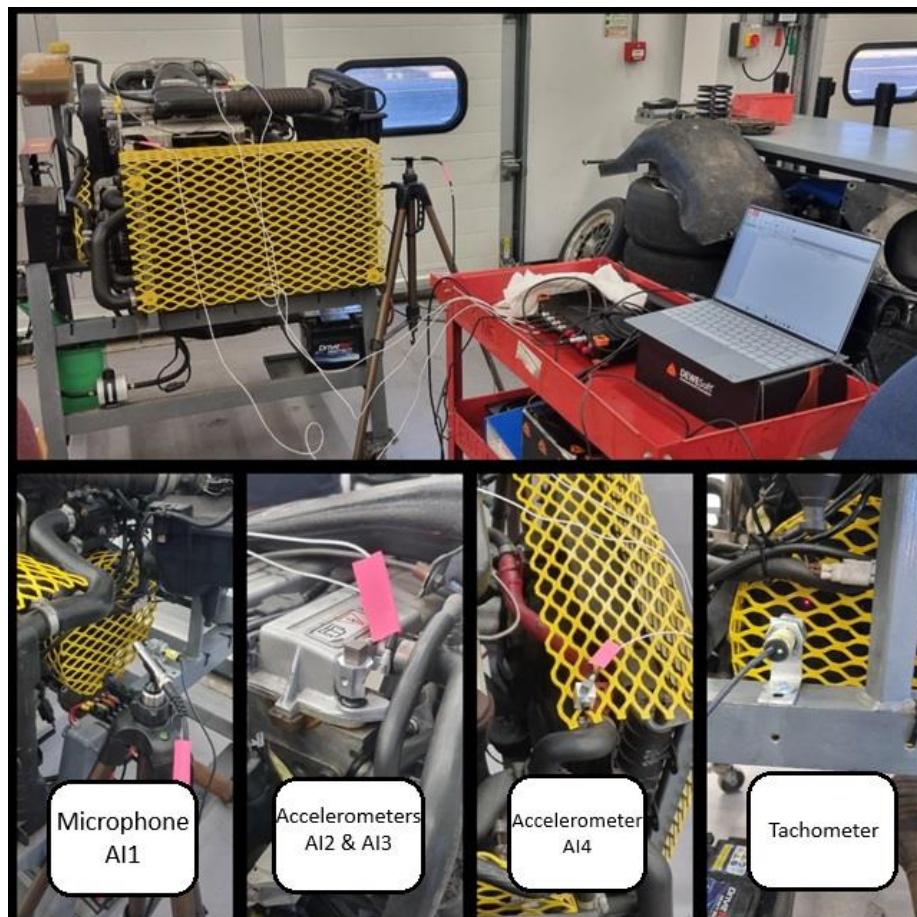


Figure 6 - Setup for the engine testing.

The engine speed was increased from idle up to the maximum rpm, maintaining this speed for approximately 1 second, followed by coasting to return to the idle engine speed. The tests were repeated twice before a sparkplug was disconnected and the test was repeated. This gave 2 sets of

data for the cylinder firing on 4 cylinders, 3 cylinders, and 2 cylinders. The engine was not able to operate with only 1 cylinder firing. The engine was not operating against any external load. Table 2 shows the sensor details including their position and orientation.

Table 2 - Sensor details

Sensor Name	Sensor Type	Measurements Taken, Location
AI1	IEPE Microphone	Sound Pressure, facing towards engine on flywheel side of engine
AI2	IEPE Accelerometer	Vertical Vibrations, on head cover
AI3	IEPE Accelerometer	Lateral Vibrations, on head cover
AI4	IEPE Accelerometer	Vertical Vibrations, on radiator guard
CNT7	Laser Tachometer	Engine speed, at flywheel

4.2 Analysis

The data recorded in the testing was used to generate FFT waterfall diagrams and order tracking by plotting the recorded frequencies in the frequency domain, using DewesoftX (2023). The frequency of rotation of the crankshaft is considered to be the fundamental frequency.

4.2.1 Order Tracking

Plotting the data in the frequency domain shows the variations in magnitude of excitement of each order relative to engine speed. In Figure 7, the 2 most significant orders seen are orders 2 and 36. The 2nd order corresponds to events occurring twice per crankshaft revolution, this is likely to be the exhaust and intake sound.

The noise at the 36th order was only distinctly recorded by AI1. At engine speeds above 6000 rpm the sound recorded at the 36th order produced the highest sound pressure, ranging from 1.7 up to 2.8 Pa rms, compared to the 2nd order sound at the same engine speed ranging from 2 to 2.2 Pa rms. From its order it could be assumed that the component in the 36th order could be a component connected to the crankshaft via the timing belt or the teeth of the timing belt contacting and releasing from the crankshaft and camshaft gears. In the audio recording, the 36th order frequency sweep and increasing volume with engine rpm was noticeable and became harsh around an engine speed of 6000 rpm.

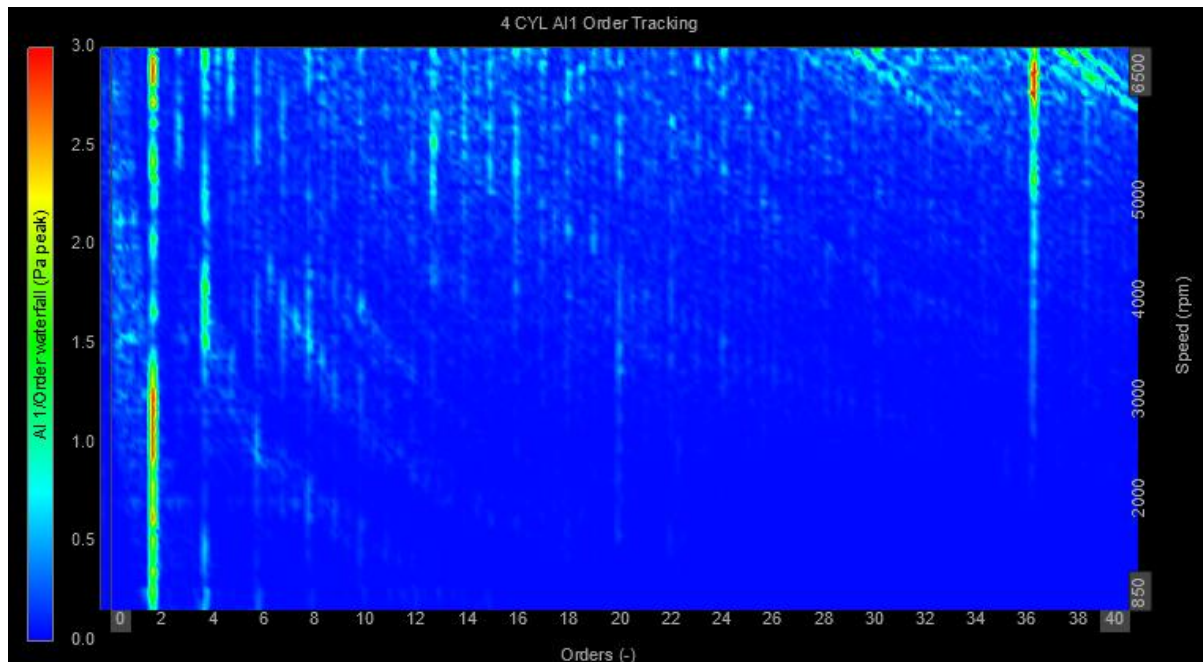


Figure 7 – AI1 Order Tracked results.

The plot for AI1 was the only plot in which the 36th order was distinct. The order tracking plot for AI2, seen in Figure 8, shows the presence of many harmonics from order 13.5 up to order 40, with some excitement of order 36, suggesting that the excitement at this frequency is caused by vertical vibrations.

Figure 7 also shows orders occurring at 0.5, 1, 2, 3, and 4. The camshaft rotates at half the frequency of the crankshaft meaning it would produce vibrations in order 0.5. The vibrations at order 1 can be attributed to crankshaft torsion due to the inertia from the reciprocation of the piston and connecting rod. The 2nd order vibration originates due to the inclination of the conrod. The 3rd and 4th order are also inertia forces generated by the piston movement (Martyr and Plint, 2007).

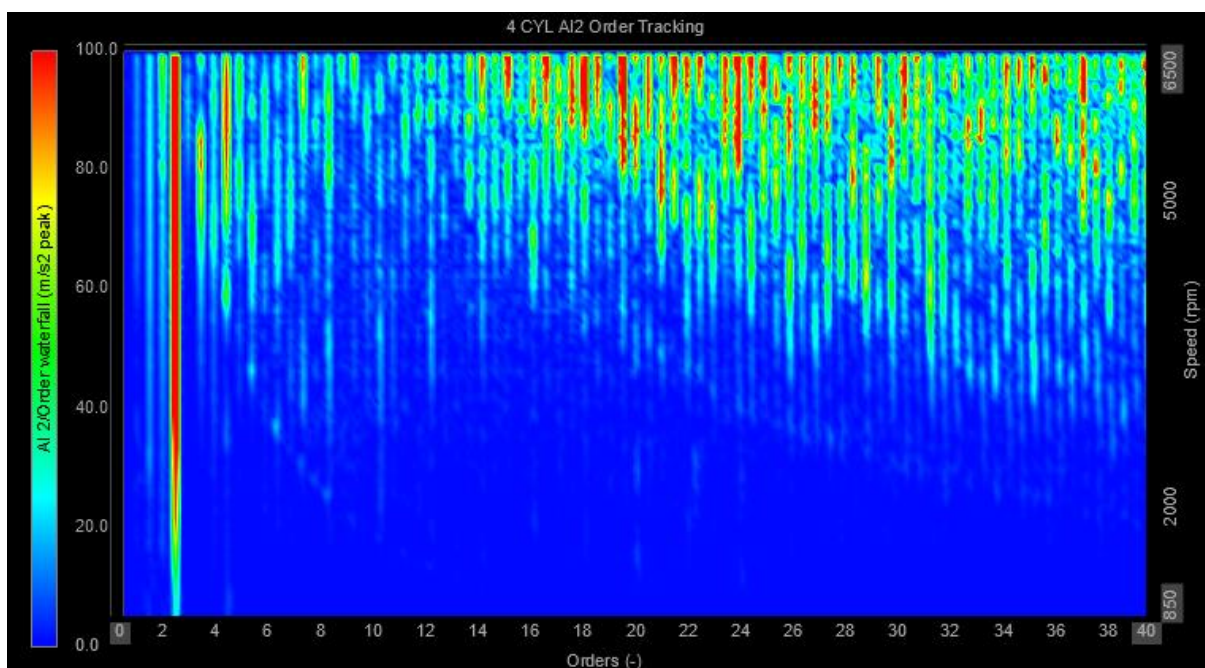


Figure 8 – AI2 Order Tracked results.

Comparing the order plots for AI2 and AI3 (Figure 8, Figure 9) highlights differences between the vertical and lateral vibrations present in the engine. Except for orders 0.5 through to 4, most of the excitations in the vertical axis are present at order 14 and above, whereas laterally they continue from the 4th order up to order 16 at 6500 rpm. The curves of higher vibration intensity with a constant frequency, spanning from higher orders at low engine speeds across to lower orders at high engine speeds, suggests there is a resonance occurring. The resonant frequencies are more apparent in the FFT waterfall plots shown later.

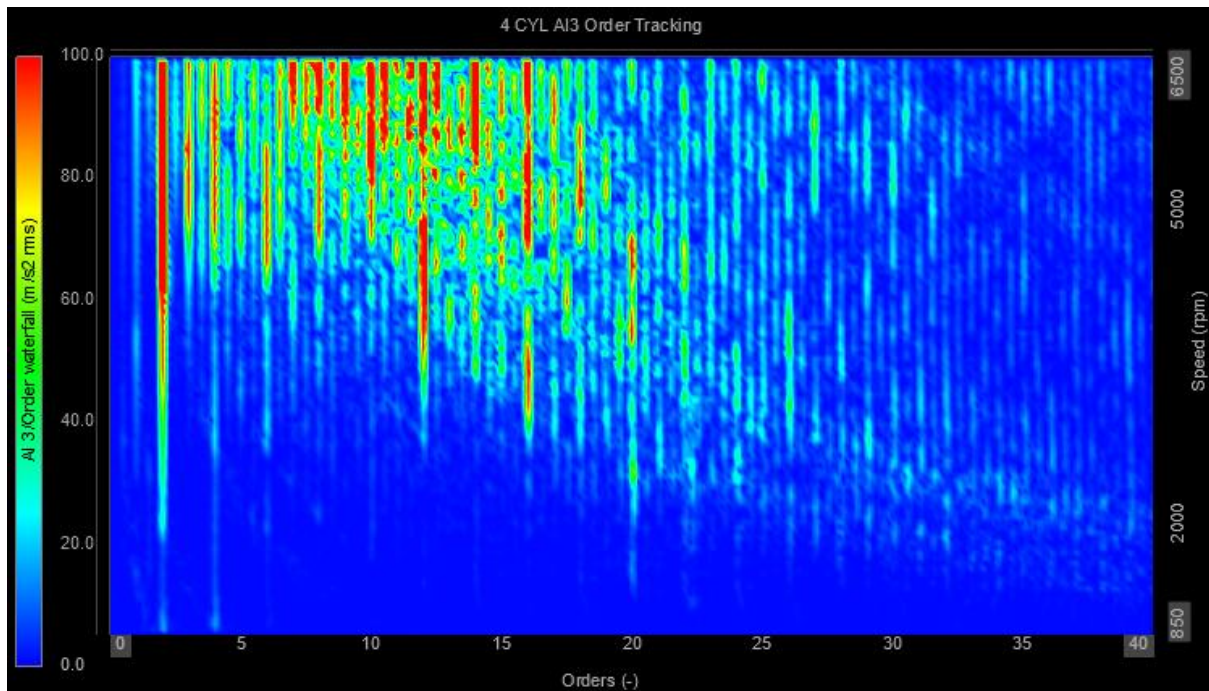


Figure 9- AI3 Order Tracked results.

The data from AI4 shows several lines of resonance that are similar to the previous signals but appear at lower frequencies, this suggests the natural frequency of the radiator guard, or components in contact with it, is lower than the natural frequency of the affected components at the engine head cover. The excitation of the 2nd order is at a similar level to the level seen in AI2 and AI3, however the 1st order vibrations appear to be affected by resonance at engine speeds of 6500 rpm.

There is an excitement across a large range of frequencies around engine speeds of 4100, 5200, 5900, and 6500 rpm. This may be related to the excitement seen in the data from AI1.

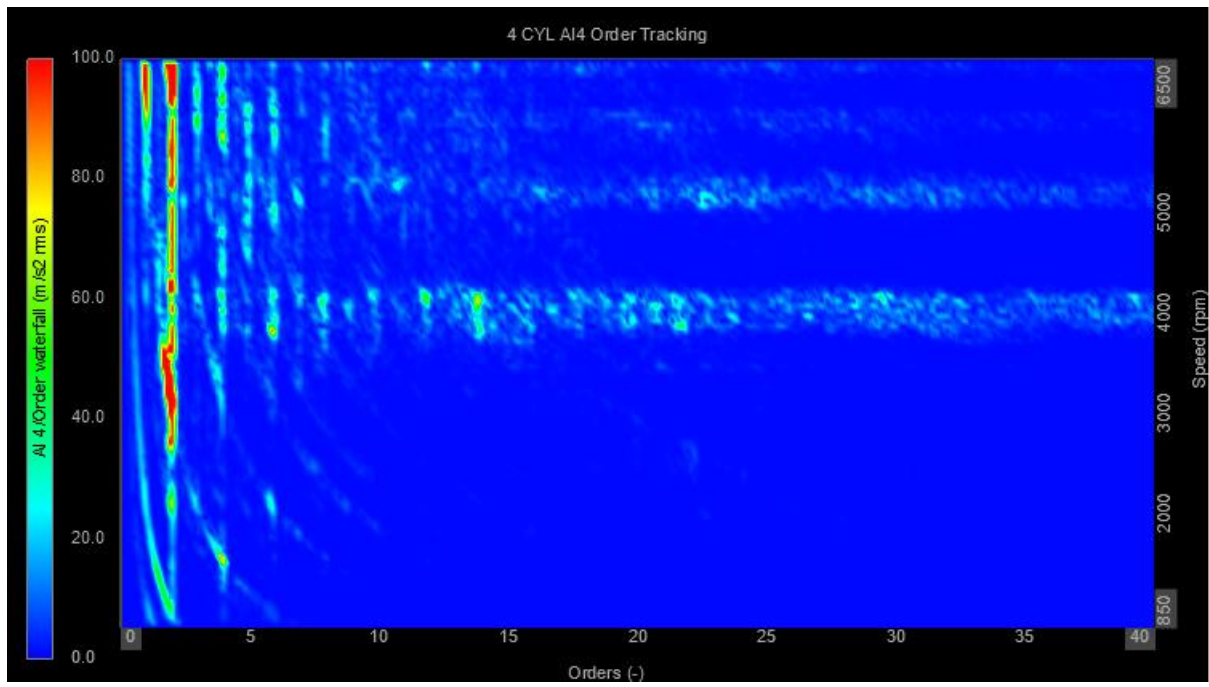


Figure 10- AI4 Order Tracked results.

4.3 FFT Waterfall plots

FFT Waterfall plots were made to locate frequencies where resonance was occurring to determine the natural frequencies of the system. In Figure 11 the natural frequencies result in louder sounds at higher orders at low frequencies, however it is harder to determine the natural frequencies at high frequencies due to the lack of orders above them. The resonance appears to spread across a wider range of frequencies, perhaps due to distortion of the sound.

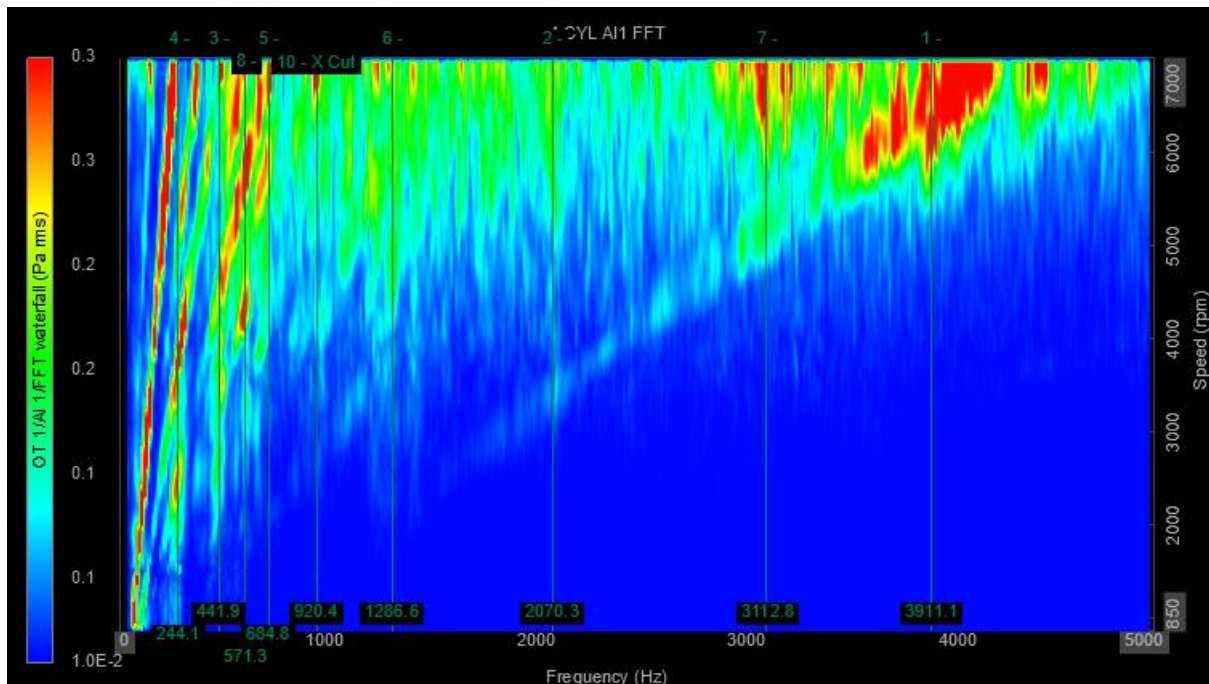


Figure 11 - A11 FFT Waterfall.

In Figure 12 resonances can be seen occurring at a frequency of 267, 391, 747, 1207, 1326, and 2000 Hz. Looking closer at the low frequency range it appears there is possibly resonance at a frequency around 130 Hz (Figure 13) however it only appears to be significant at engine speeds over 4000 rpm. It is not seen in the coast down for the same test, the resonance seems to only appear once the 2nd order vibrations become much larger. It could be related to the horizontal lines seen in the A14 results in Figure 10.

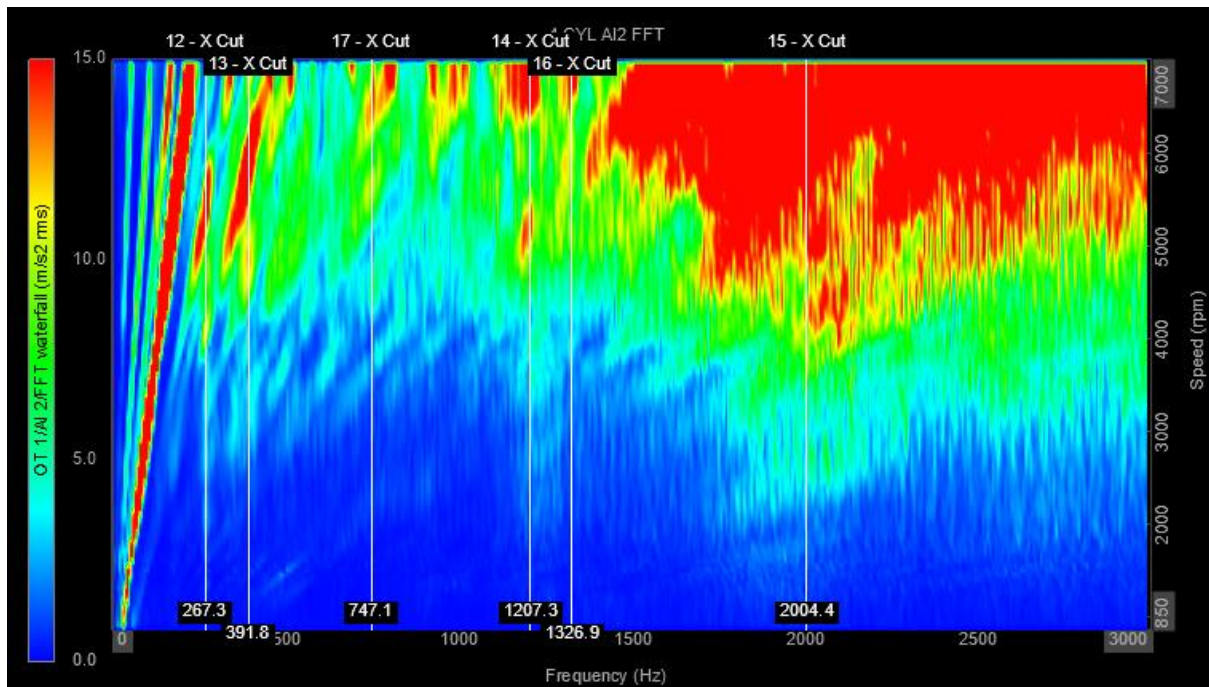


Figure 12 - FFT Waterfall of AI2 data from engine run up test.

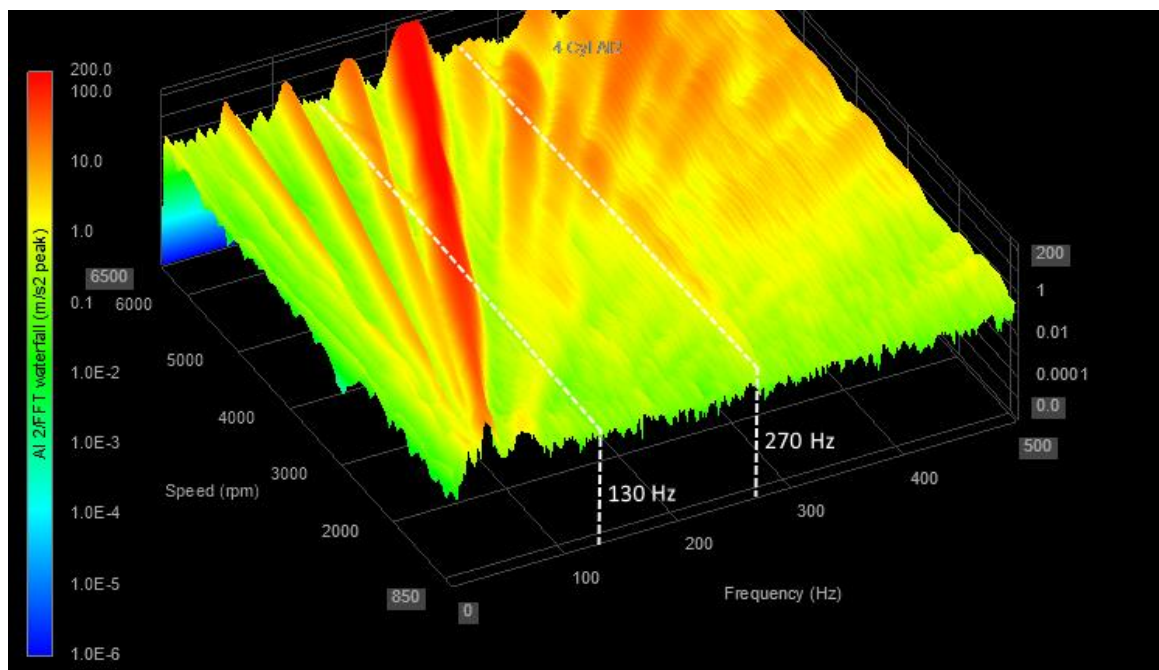


Figure 13- AI2 3D FFT Waterfall showing low frequency resonance.

The lateral vibrations recorded by AI3 showed had similar resonant frequencies to AI2 (Figure 14) which is to be expected. There was a large amount of excitation particularly between 891 and 1326 Hz, most likely due to there being 3 natural frequencies situated around this point.

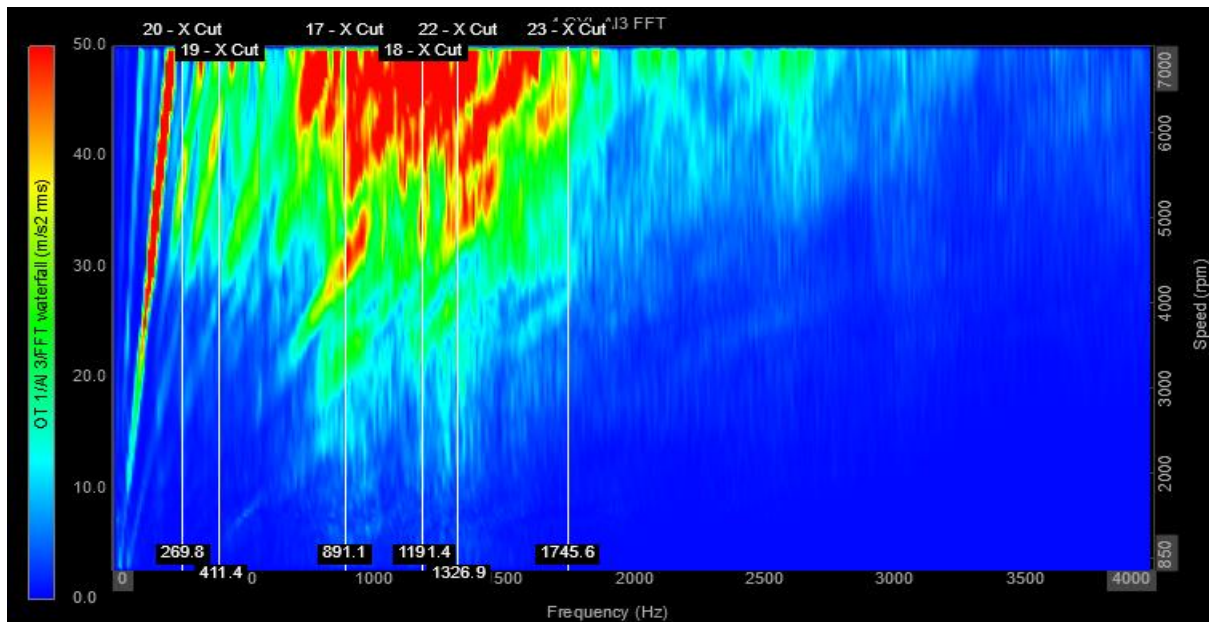


Figure 14 - A13 FFT Waterfall.

The FFT Waterfall generated from the A14 data (Figure 15) showed different resonant frequencies to the data from the other sensors. The lower natural frequency of the radiator guard is likely due to it having a larger shape with less stiffness than the head cover and components around the head cover. The excitation of the order 2 frequency was dampened between the engine and the radiator guard, so the magnitude of vibration was generally lower except at frequencies around 100 Hz and 205 Hz. Perhaps one of those is the natural frequency of the frame entire assembly was mounted to. A resonant frequency of 17 Hz can also be seen when the frequency scale of the graph is lower.

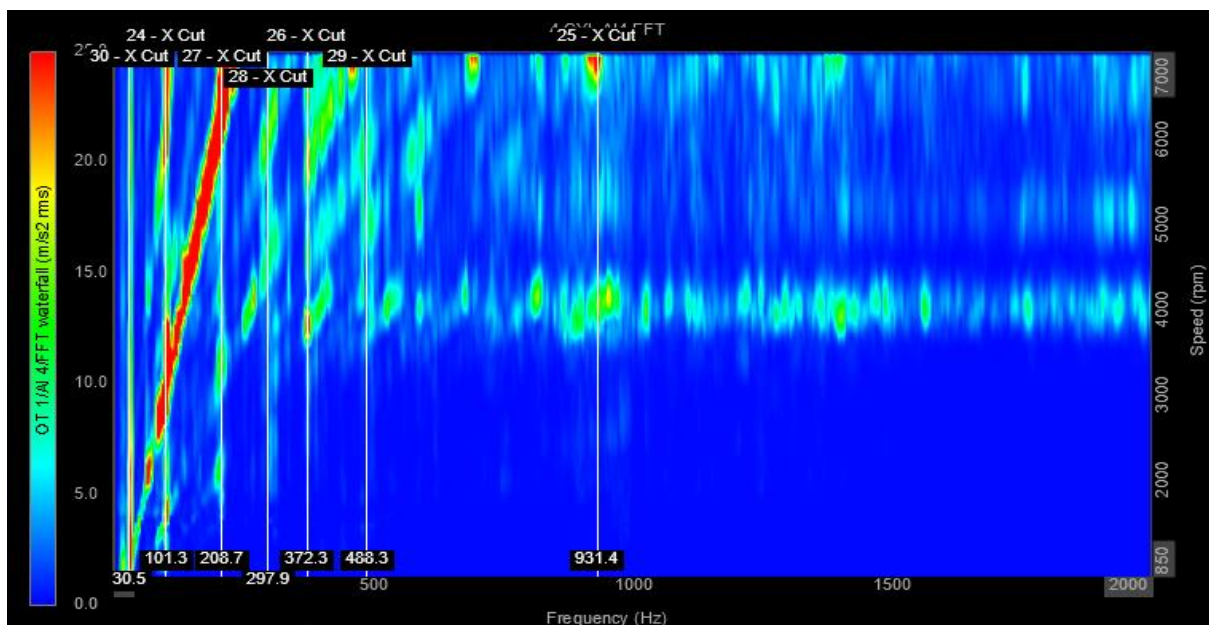


Figure 15 - AI4 FFT Waterfall.

4.3.1 Operational Cylinders FFT comparison

Running on a different number of cylinders had a substantial impact on the sound of the engine (Figure 16). At 4 cylinders the 1st order sounds were minimal however once only 3 cylinders were firing the 1st order sounds, at 50 Hz, were nearly as loud as the 2nd order sounds. Running on 2 cylinders make the 1st order sounds louder than the 2nd order, without weighting to account for human perception of different frequencies. A peak around 1800 Hz can be seen representing the 36th order.

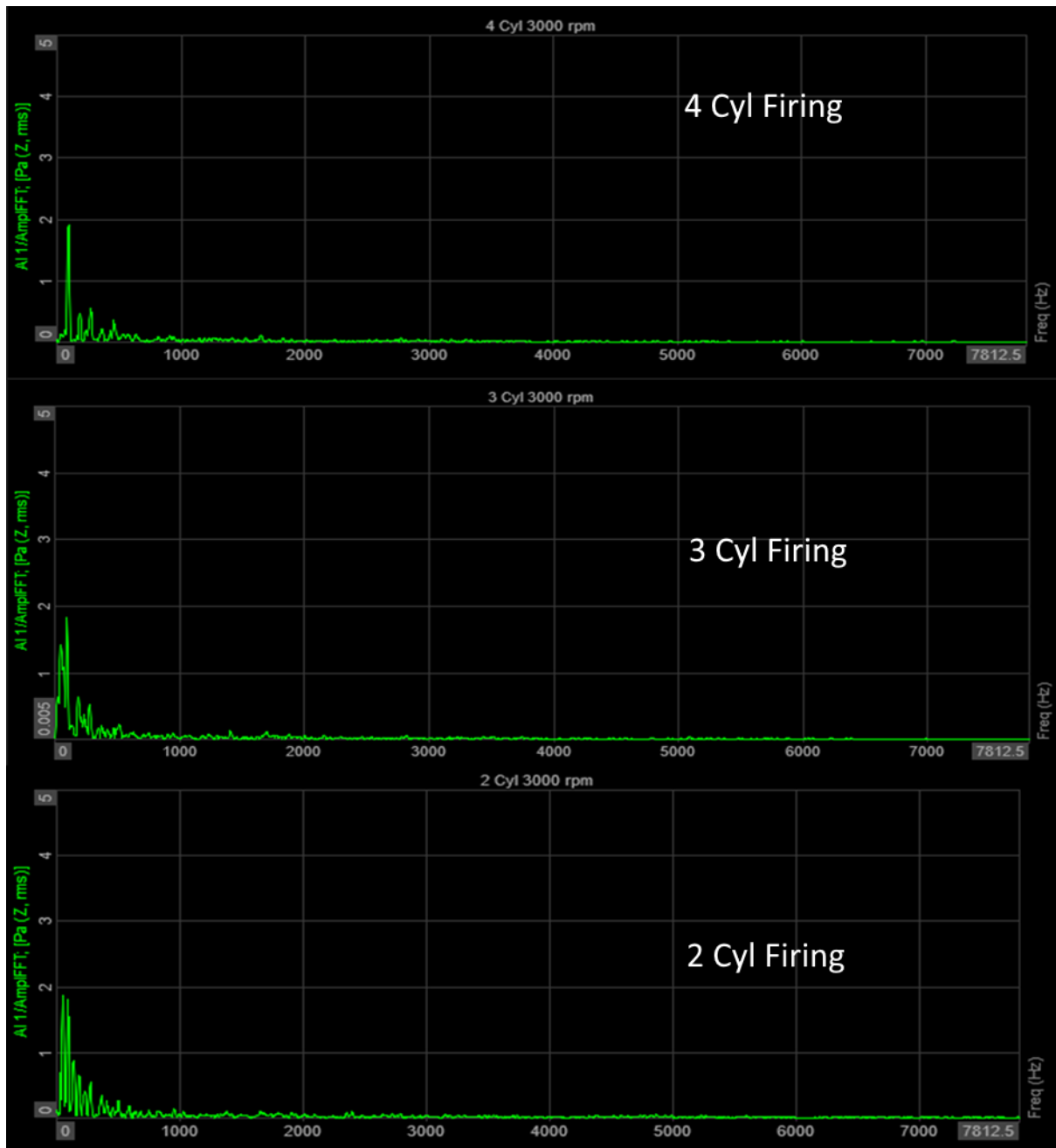


Figure 16 - AI1 FFT at 3000 rpm.

At 6000 rpm the differences between the 1st and 2nd order are exacerbated. The 1st order sound has twice the pressure of the 2nd order when running on 3 and 2 cylinders whereas under 4-cylinder operation the 1st order pressure is only 12% of the 2nd order. In all 3 cases, the 36th order is dominant with regards to human hearing (Figure 18); however, this may differ if it was being heard through a surface due to high frequencies being dampened more than lower.

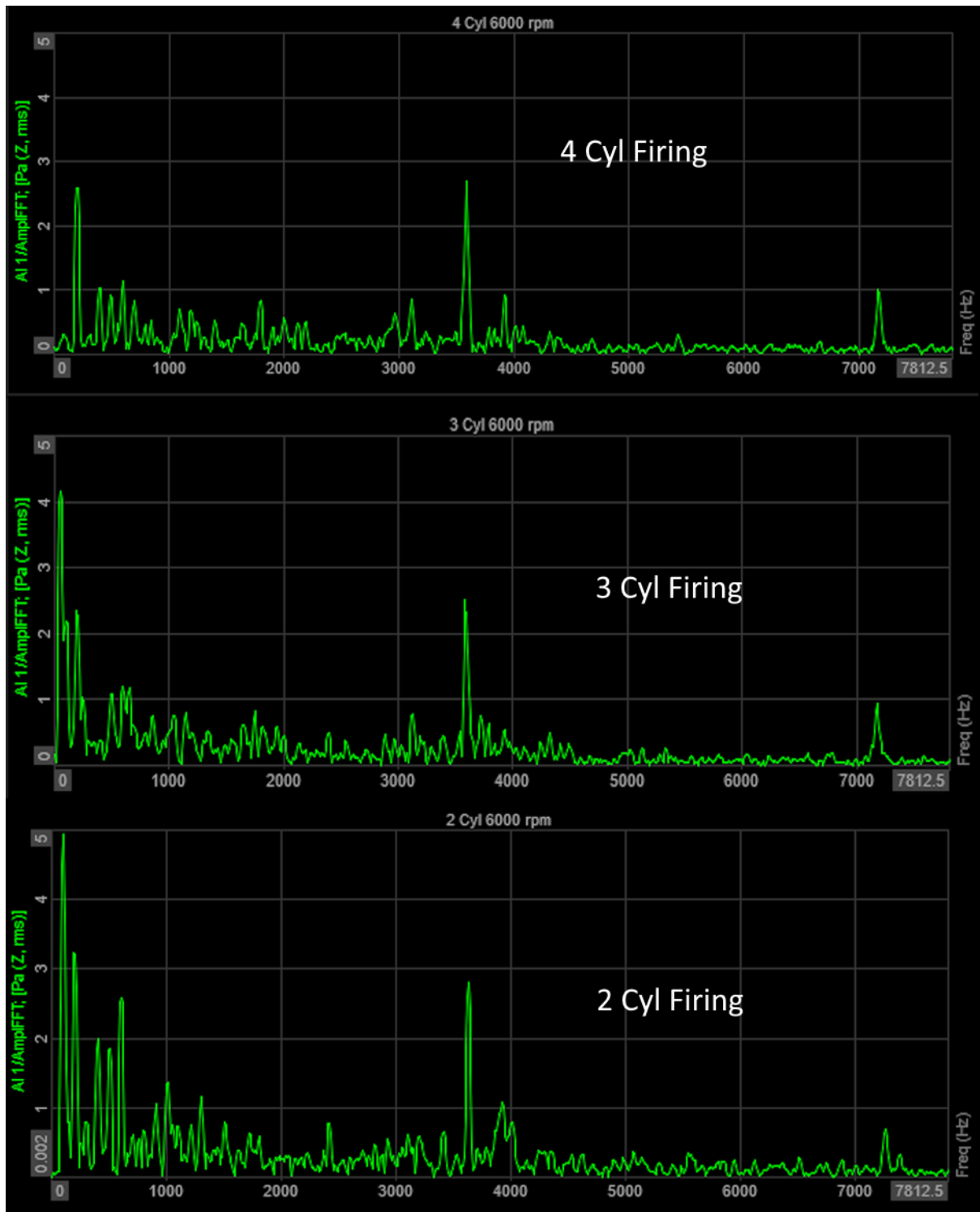


Figure 17 - AI1 FFT at 6000 rpm.

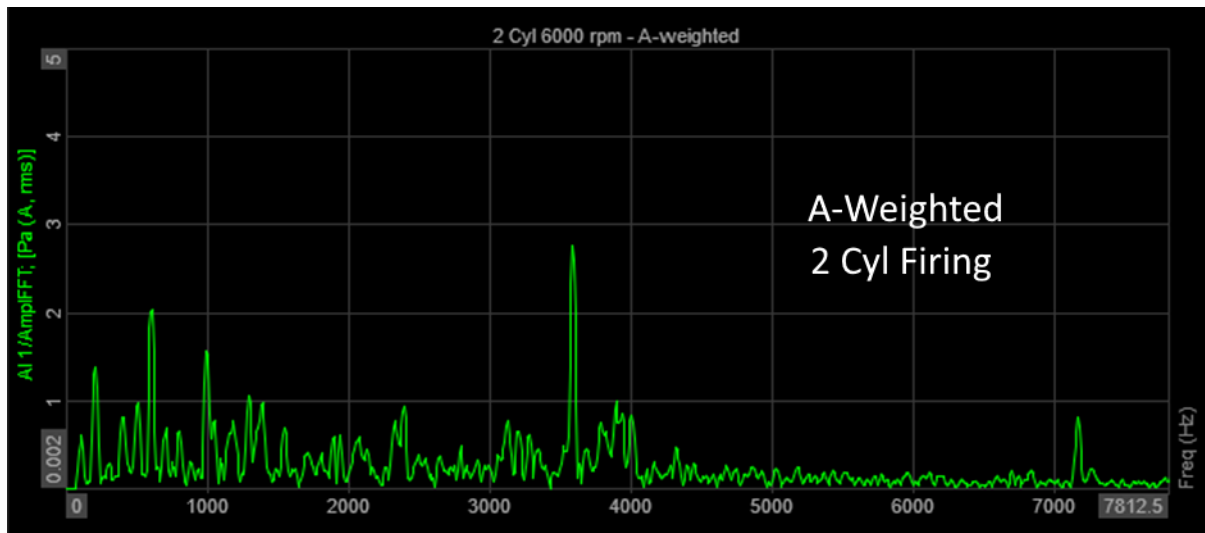


Figure 18 - AI1 FFT at 6000 rpm using an A weighted frequency curve.

4.3.2 Operational Cylinders FFT Waterfall comparison

Figure 19 shows the difference in vertical vibrations depending on the number of firing cylinders. When firing on 3 cylinders there seems to be an imbalance causing additional excitement throughout the frequency range, possibly due to the compression of a cylinder not being counterbalanced by the combustion of another. The vibration at 6000 rpm in the 3-Cyl is 313 m/s^2 compared to 83.3 m/s^2 for the 4-Cyl, and 150 m/s^2 for the 2-Cyl. The affected cylinders would depend on the firing order and the affected spark plug.

The same trend in imbalance is seen in the results from AI3 (Figure 20) with 3-Cyl having the largest excitement, and 2-Cyl having more excitement than 4-Cyl. This is likely due to the same reason as previously mentioned for the imbalance in AI2 but related to the inclination of the connecting rod, resulting in a lateral force.

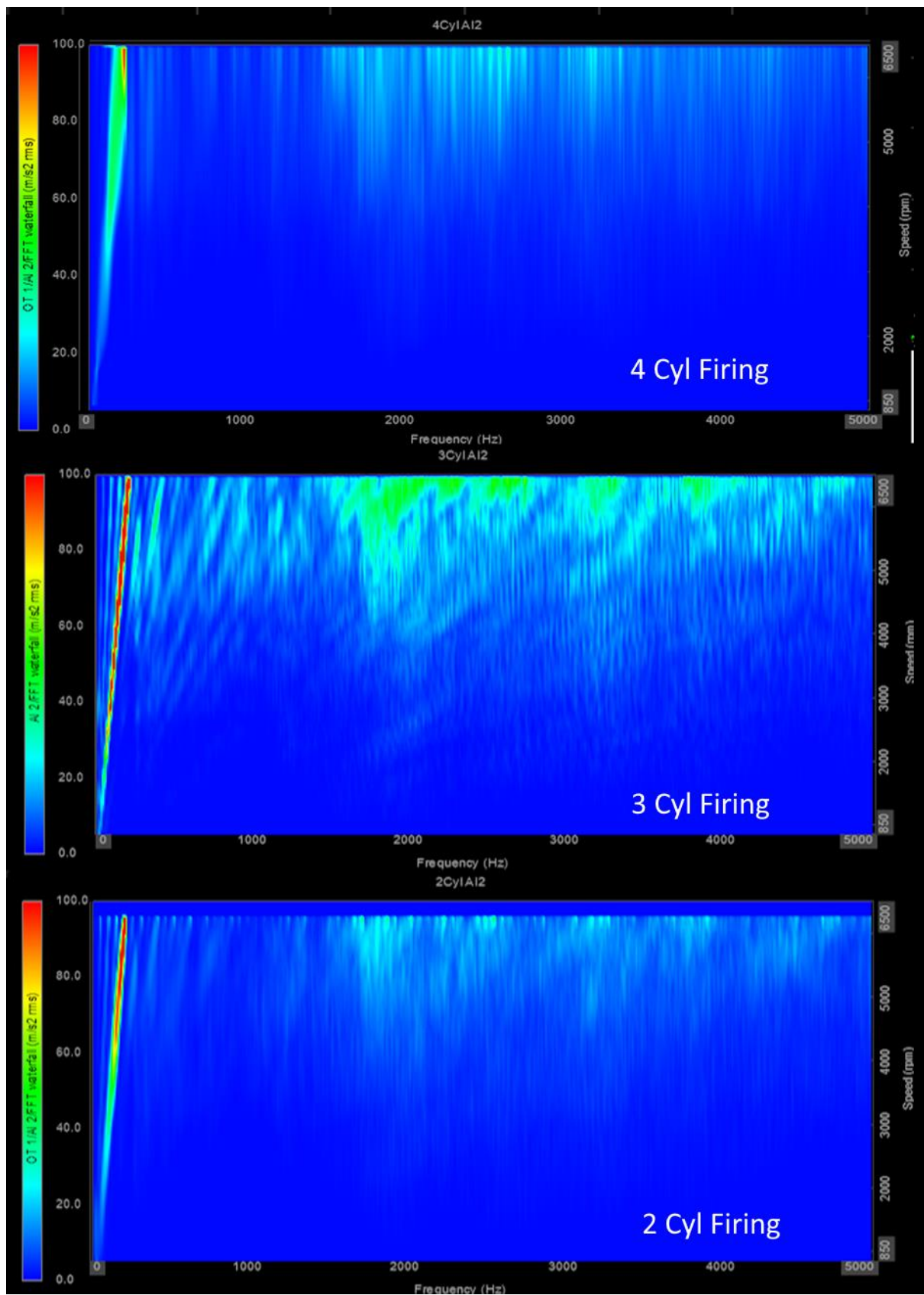


Figure 19 - Firing Cylinders Comparison of AI2

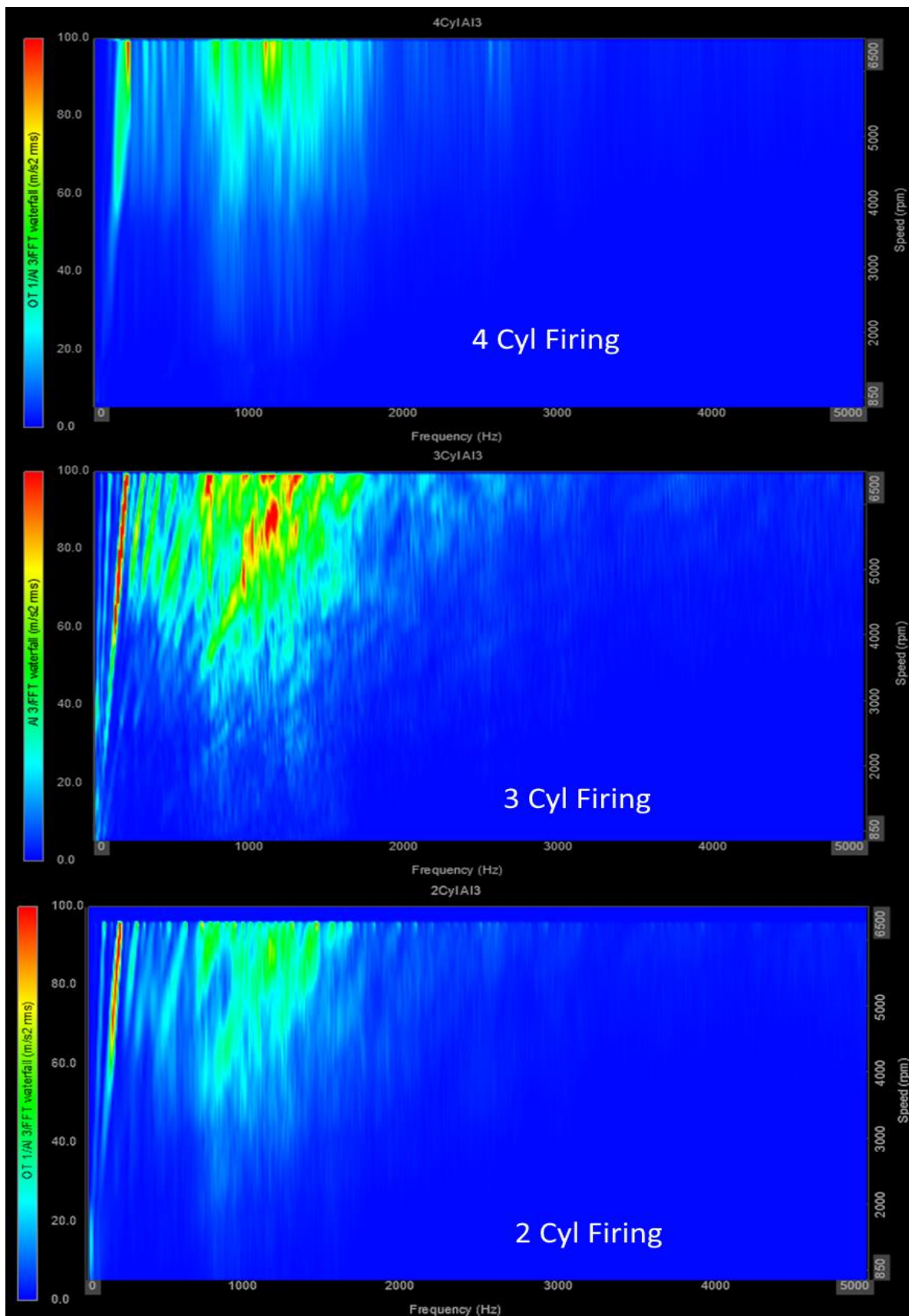


Figure 20 - Firing Cylinders Comparison of AI3

AI4 results also show vibrations with a larger amplitude being produced when there is only 3-Cyl and 2-Cyl firing. In both cases there is also excitement occurring at the 17 Hz natural frequency, when this is occurring it may be possible to see the component vibrating.

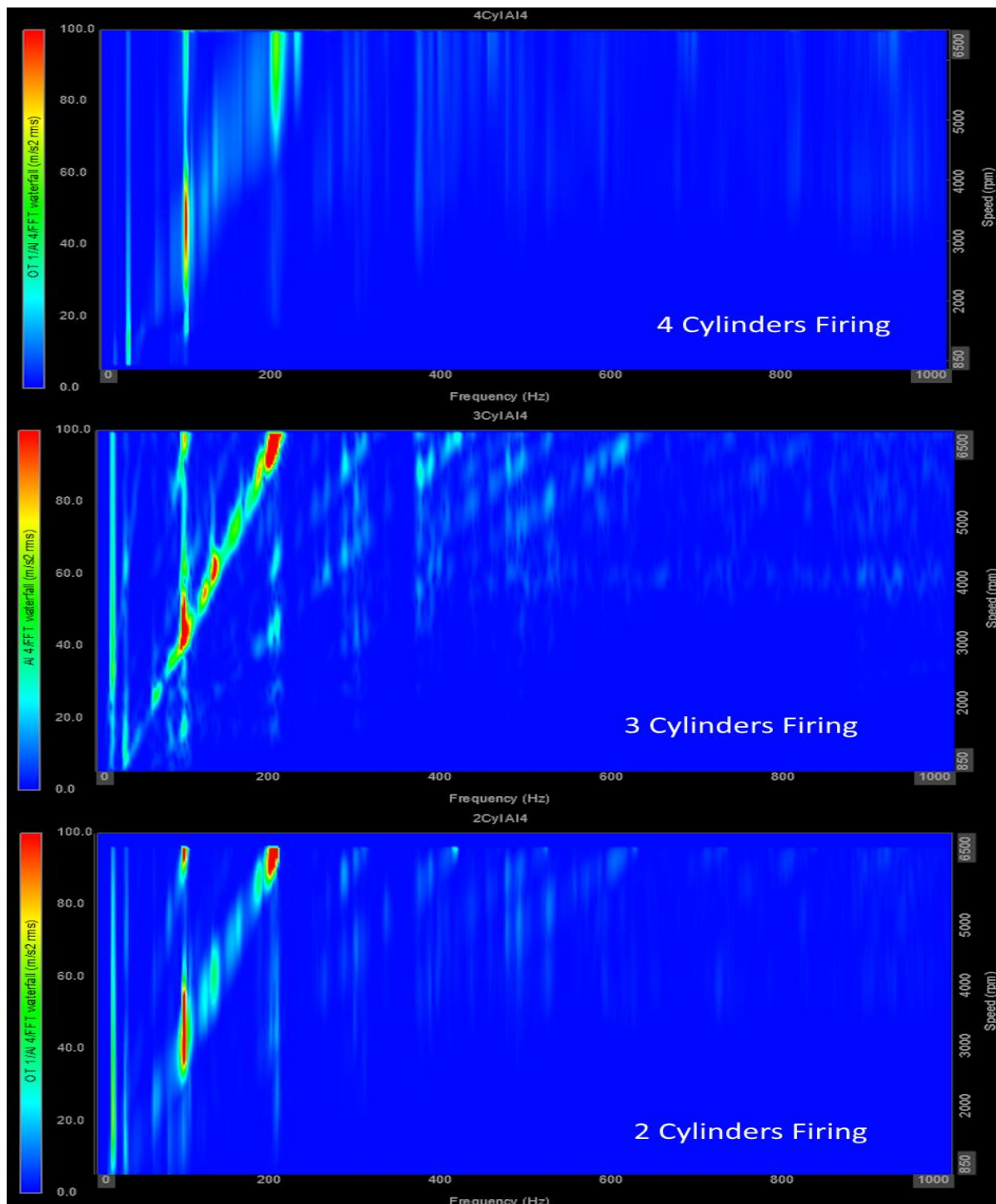


Figure 21 Firing Cylinders Comparison of AI4

5 References

Brandt, Anders. (2011) *Noise and vibration analysis signal analysis and experimental procedures*. Chichester, West Sussex, U.K. ; Wiley.

Continental Engineering Services (no date) *Noise-Vibration-Harshness (NVH)*. Available at: <https://conti-engineering.com/services/development/noise-vibration-harshness-nvh/> (Accessed: 8 December 2023).

Dewesoft (2021) *Modal test and Modal analysis Webinar*. Available at: <https://www.youtube.com/watch?v=zA1Y3cHJ2PU> (Accessed: 10 December 2023).

Dewesoft (2023) 'DewesoftX'.

Dewesoft (no date) *Data Acquisition (DAQ) - The Ultimate Guide*. Available at: <https://dewesoft.com/blog/what-is-data-acquisition> (Accessed: 7 December 2023).

Herres, D. (2015) *Basics of aliasing in sampled waveforms, Test&MeasurementTips*. Available at: <https://www.testandmeasurementtips.com/basics-of-aliasing-in-sampled-waveforms/> (Accessed: 10 December 2023).

Levinzon, F. (2015) *Piezoelectric Accelerometers with Integral Electronics*. 1st ed. 2015. Cham: Springer International Publishing : Imprint: Springer.

Martyr, A.J. and Plint, M.A. (2007) *Engine testing*. 3rd edn. Oxford, England: Butterworth-Heinemann. Available at: <https://doi.org/10.1016/b978-0-7506-8439-2.x5000-2>.

ni.com (2023) *Measuring Vibration with Accelerometers*. Available at: <https://www.ni.com/en/shop/data-acquisition/sensor-fundamentals/measuring-vibration-with-accelerometers.html> (Accessed: 5 December 2023).

Polytec (2023) *End-of-line test for noise and vibration on engines*. Available at: <https://www.polytec.com/eu/vibrometry/areas-of-application/industrial-quality-assurance/engine-cold-test> (Accessed: 10 December 2023).

Rennie, R. and Law, J. (2019a) 'Crystal Microphone'. Oxford University Press. Available at: <https://doi.org/10.1093/acref/9780198821472.013.0658>.

Rennie, R. and Law, J. (2019b) 'Microphone'. Oxford University Press. Available at: <https://doi.org/10.1093/acref/9780198821472.013.1921>.

Sontacchi, A. *et al.* (2016) 'Sound optimization for downsized engines', in *SpringerBriefs in Applied Sciences and Technology*. Cham: Springer International Publishing, pp. 13–27. Available at: https://doi.org/10.1007/978-3-319-24055-8_2.

soundref.com (2023) *The 4 Different Types of Microphones | 2023 Edition*. Available at: <https://soundref.com/different-types-of-microphones/> (Accessed: 10 December 2023).

Wang, X. (2010) *Vehicle noise and vibration refinement, Woodhead Publishing in mechanical engineering*. Boca Raton (Fla.): CRC press.

World Health Organisation (2022) *Deafness and hearing loss: Safe listening*. Available at: <https://www.who.int/news-room/questions-and-answers/item/deafness-and-hearing-loss-safe-listening> (Accessed: 10 December 2023).