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NVH Analysis

Ride, Handling and NVH (ACHA6003)

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1 Introduction

This assignment focuses on exploring the core principles of Noise, Vibration and Harshness (NVH) within automotive applications, as well as identifying measurement techniques, equipment and the implications NVH has on human comfort and perception(Liu, 2020). The tasks emphasize a structured approach to understanding how various subsystems of a vehicle generate and transmit vibrations and acoustic pressure waves through different excitation orders(Bayat and Sørensen, 2021).

A representative mechanical system alongside practical testing results were selected for analysis and dominant excitation sources were identified. The principles and applications of vibration and acoustic sensors, focusing on appropriate selection criteria for accurate data acquisition using specialised NVH software such as Dewesoft to interpret measured data from practical testing where key observations will be discussed. Using both theoretical and analytical approaches this assignment aims to deepen comprehension of NVH fundamentals, improve measurement methodology and highlight the significance of NVH considerations in engineering design and product development.

2 Research

2.1 NVH Basics

NVH Engineers in the Automotive sector focuses on understanding, measuring and analysing the effects of sound (noise), oscillations (vibrations) and roughness (harshness) that is produced from the components used and how they alter the experience of the occupants and are perceived outside of the vehicle. Components have unique mechanical characteristics that can produce NVH, by analysing key components that produce these phenomena, steps can be taken to refine the sensory experience to make the vehicle more comfortable, reduce component wear and align with the intended characteristics (Bayat and Sørensen, 2021).

2.2 System Orders

System orders are the harmonic components or multiples of the rotational speed of a component, they are critical in diagnosing and analysing vibrations and resonance within a system such as machinery (Li, Xie and Wang, 2019). Each system will have a Fundamental Order (1st Order) which is the base frequency of the systems rotation. 2nd Order refers to the rotational frequency that is double the 1st Order. Higher orders (3rd, 4th etc) can result from phenomena within the system such as imbalances or periodic forces in the system, higher orders may also indicate other issues (Zhang *et al.*, 2019).

Tools such as the Campbell diagram can be used to analyse the relationship between system orders and the rotational speed in rotating machinery to identify the natural frequencies and the interaction with other excitation sources. Figure 1 shows an example of a Campbell Diagram which shows the RPM on the X axis and the Natural frequency on the Y axis, the plot shows us how the system's behaviour changes as the engine speed varies.

Hmmm. A Campbell diagram usually utilities different diameter circles to represent the amplitude of the vibration at each measurement point

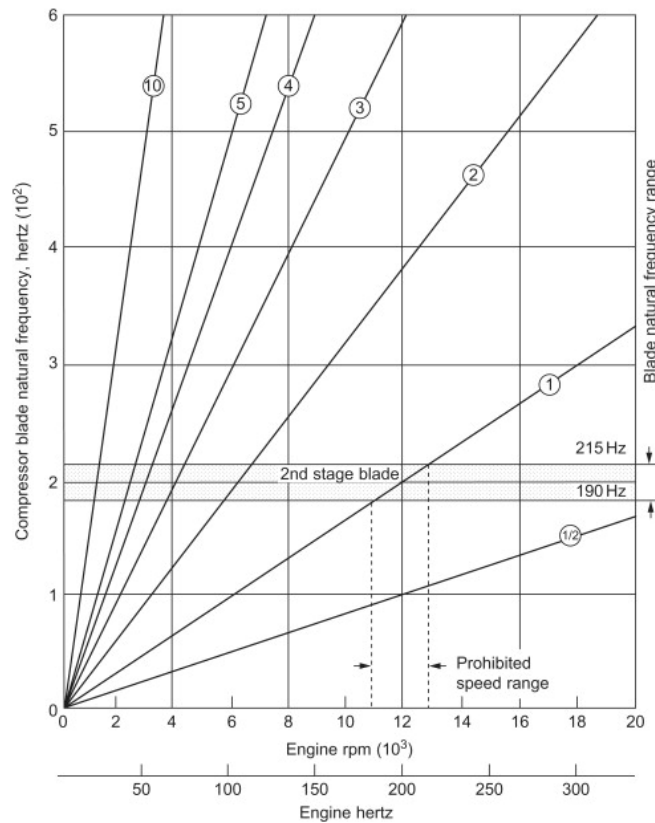


Figure 1 - Example Campbell Diagram (Boyce, 2012)

2.3 Harmonic Resonance

Harmonic Resonance occurs when excitation frequencies align with the natural frequency of a system or components, this can lead to amplification of vibration and noise levels produced which can lead to poor reduced comfort, cause mechanical fatigue leading to failure and a reduction in performance (Daruis *et al.*, 2013). It is vital that the natural frequency of these components do not produce excitation which would result in an increased amplitude of certain frequency ranges that could increase the resonance of the overall system (Kondaveeti, Ganesan and Panchada, 2022). Adjusting the stiffness, design or mass of a component can help move their natural frequency away from any excitations, components such as engine mounts also have a dampening quality to reduce the amplitude of resonant vibrations created by the engine.

2.4 Natural Vibrations

In the context of NVH, Natural Vibrations are the behaviour of a mechanical systems or the components that make up the system. A system will have a natural frequency which is determined from physical properties such as the mass and the overall stiffness (Chen and Dai, 2010). It is critical that these natural vibrations are managed to reduce noise, increase comfort and maintain reliability of the system. Each component will have a natural vibration, and the resultant frequency of these vibrations determines how the overall system will perform.

2.5 Sensor Selection and Operation

When measuring and analysing vibrations in a system it is crucial to select the appropriate sensor to ensure that the data acquired is accurate. Below several sensors have been explored including their working principles and applications. NVH testing involves complex interactions between various components, choosing the correct sensor ensures that accurate diagnostics are readily available, and the product will perform as expected. Using an incorrect sensor the required data acquisition can result in inaccurate data, increased costs due to the requirement to run more tests as well as product failures or a reduced life cycle of a system if unaddressed.

The selection of the correct sensor is critical for accurate and meaningful data. Two parameters that heavily influence sensor choice are the Frequency Range, which refers to the range of frequencies the sensor can accurately measure, typically given as a lower and upper limit in Hz or kHz. NVH phenomena span a wide frequency spectrum, lower frequencies including engine combustion and structural vibrations. Higher frequencies of 2000Hz and above will typically capture gear whine, brake squealing and rattles.

A dynamic range amplitude refers to the smallest and largest signal levels a sensor can accurately detect, gravity for accelerometers and Pascals (Pa) for microphone equipment. Minimum amplitude ensures the sensor can detect small vibrations which are important for identifying subtle issues or quiet phenomena. Maximum amplitude ensures the sensor does not saturate results under high load. The correct dynamic range selection of recording equipment is essential for picking up the subtle vibration/harmonics as well as expected operating conditions of the components/vehicle.

2.5.1 Accelerometers

Accelerometers are the most used type of sensor for measuring vibration as they can directly measure the vibration, come in various sizes and are easily integrated into a system. There are several types of accelerometers such as:

Piezoelectric which uses a specific material such as quartz or ceramics that generate electrical charges that are proportional to the force applied (Kim *et al.*, 2024), this makes them ideal for dynamic applications such as for engine monitoring as they have a high sensitivity and can be used in harsh environments, however, are better applied to higher frequency applications.

Microelectromechanical Systems (MEMS) use capacitive sensor to measure a displacement that is caused by vibration which can measure low and high frequencies whilst being compact and lightweight and integrated directly into a system.

2.5.2 Laser Vibrometers

Laser vibrometers are sensors that can measure the velocity or displacement of a surface that is vibrating using the Doppler effect (Li, Dieussaert and Baets, 2022). A laser beam is directed onto a target surface and the frequency shift of the reflected light is then analysed to determine the amount of vibration. They are suitable when components may be lightweight or fragile where physical contact may affect the dynamics of the component or cause damage. These sensors are highly accurate in measuring vibration and may be used to test body panels, exhaust systems or even engine components and will not affect the natural vibration of the component or system due to not having a physical contact.

2.5.3 Strain Gauges

Strain Gauges are another viable type of sensor that is used to measure the deformation of an object when it has been subjected to an external force. They are primarily used in NVH studies to measure the dynamic stress and deformations of components by measuring the strain induced by vibration and help identify regions where potential fatigue may occur as they provide localised data which may be useful if problem areas are identified. The strain on the gauge is determined by the resistance to change of the material which then alters its electrical resistance which is then converted to an electrical signal.

2.6 Acoustic Pressure measurement

When measuring acoustic pressure in an NVH application, the choice of microphone also plays an important role and the most common types are the free-field and pressure-field microphones, each are designed for different environments (Mohamed Moubark *et al.*, 2021).

2.6.1 Free-Field Microphone

Free field microphones are used to measure sound pressure in open environments where sound waves can propagate freely without interference from reflections such as buildings or components in a closed system where the sound source is not influenced by nearby surfaces (Estis *et al.*, 2011). They allow for accurate measurement of direct sound and for capturing sound propagation in larger areas as if the microphone was not introduced to the sound field which would affect the result.

2.6.2 Pressure-Field Microphone

Pressure field microphones are used for measuring the actual pressure on the surface on the diaphragm of the microphone, applications include reflective environments or where the sound field may be complex resulting in reflected sound waves. They may be useful when measuring the NVH inside the cabin of a vehicle as they perform appropriately within confined environments.

2.7 Equipment Considerations

2.7.1 Frequency Range

The frequency range of the measuring equipment is a vital aspect as it determines how much of the spectrum of sound or noise it can capture. Depending on the application and operating parameters having a wider frequency range will allow for an increase in data measurement, as components vibrate or produce more sound the frequency will shift.

2.7.2 Sensitivity

The ability for sensors to detect small changes in a short period of time is crucial for determining where different signals may be originating from as well as the level of amplitude of that detection,

equipment that is not sensitive to specific frequencies or vibrations may not give accurate data or introduce anomalies.

2.7.3 Mounting Methods

The importance of mounting the measuring device impacts both the accuracy and repeatability of measurements as well as the ease of installation. Improper mounting can skew results by introducing noise to the present characteristics of the system which could lead to inconsistent or inaccurate data.

3 Results

3.1 Ford Engine

The Ford engine data was analysed on DewesoftX where various tests were performed where engine parameters were changed to see how the NVH profile of the system changed. These changes included doing an RPM run from Idle (900RPM) and to a maximum RPM (5500RPM) then each test thereafter the fuel injector was removed so that the engine a cylinder down at a time until it only ran on one cylinder. Accelerometers were used to capture vibrations of the engine during these tests as well as ancillary components such as the exhaust guard. A laser was used to capture the rotation of the main crankshaft pulley to calculate the engine speed, as well as a microphone for overall audio signature.

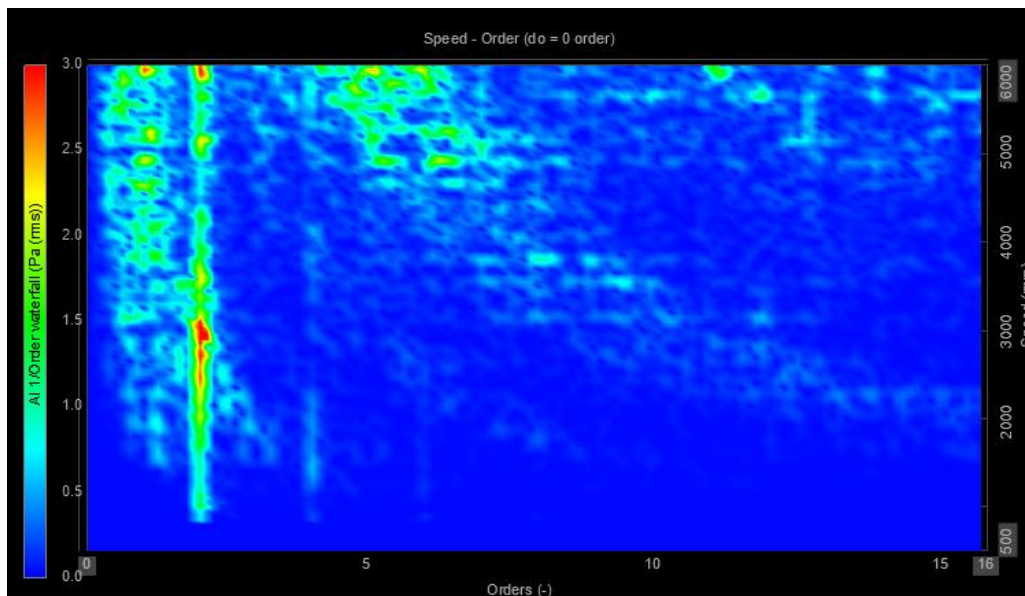


Figure 2 - Four Cylinder Order Plot

Figure 2 displays a waterfall plot of the four-cylinder test, the RPM channel was transformed into an order domain instead of time, using the RPM channel as a reference. The results show that the second order is the most active across the RPM range, with a peak at 3000RPM. This is due to the combustion events occurring per revolution, natural vibrations occur at twice the crankshaft speed (2x order). This is the primary combustion-related vibration component of the engine.

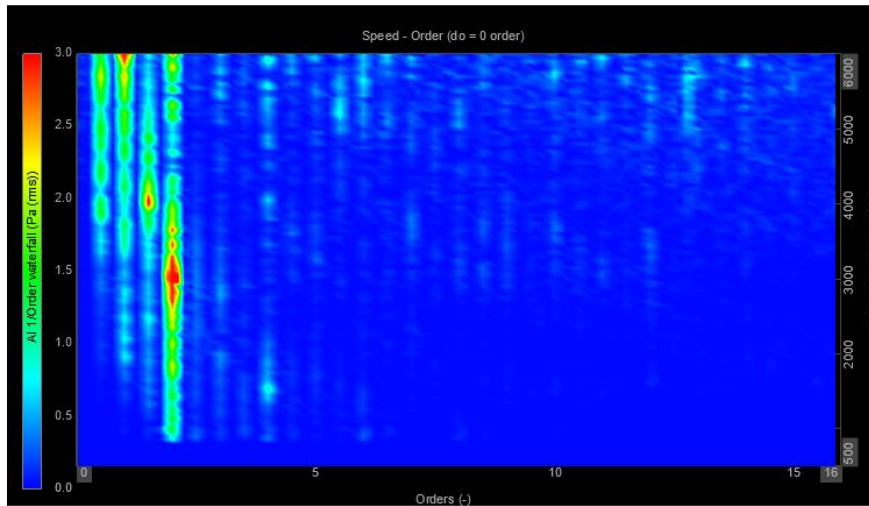


Figure 3 - Three Cylinder Order Plot

Figure 3 shows the vibration response across the engine when it has three active cylinders. Pronounced peaks appear at the 1.5th engine order suggests that the imbalance introduced by disabling one cylinder leads to excitation patterns. The dominant activity alongside low-order harmonic content indicates the presence of combustion imbalance and potential resonance effects associated with partial engine operation.

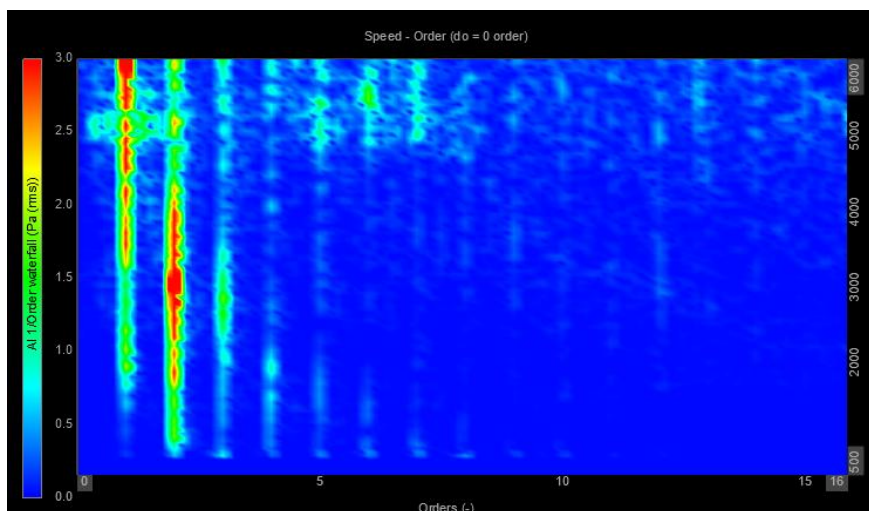


Figure 4 - Two Cylinder Order Plot

Figure 4 displays the order waterfall for the engine whilst running on two cylinders. The data shows strong components at the first and second orders, reflecting the effective shift in firing pattern and excitation forces. The prominent peak at the 2nd order corresponds to the two combustion cycles per engine revolution, the amplitude peak around the mid-RPM suggests resonance occurring near the 1X order. This may be due to firing imbalances produced by the engine.

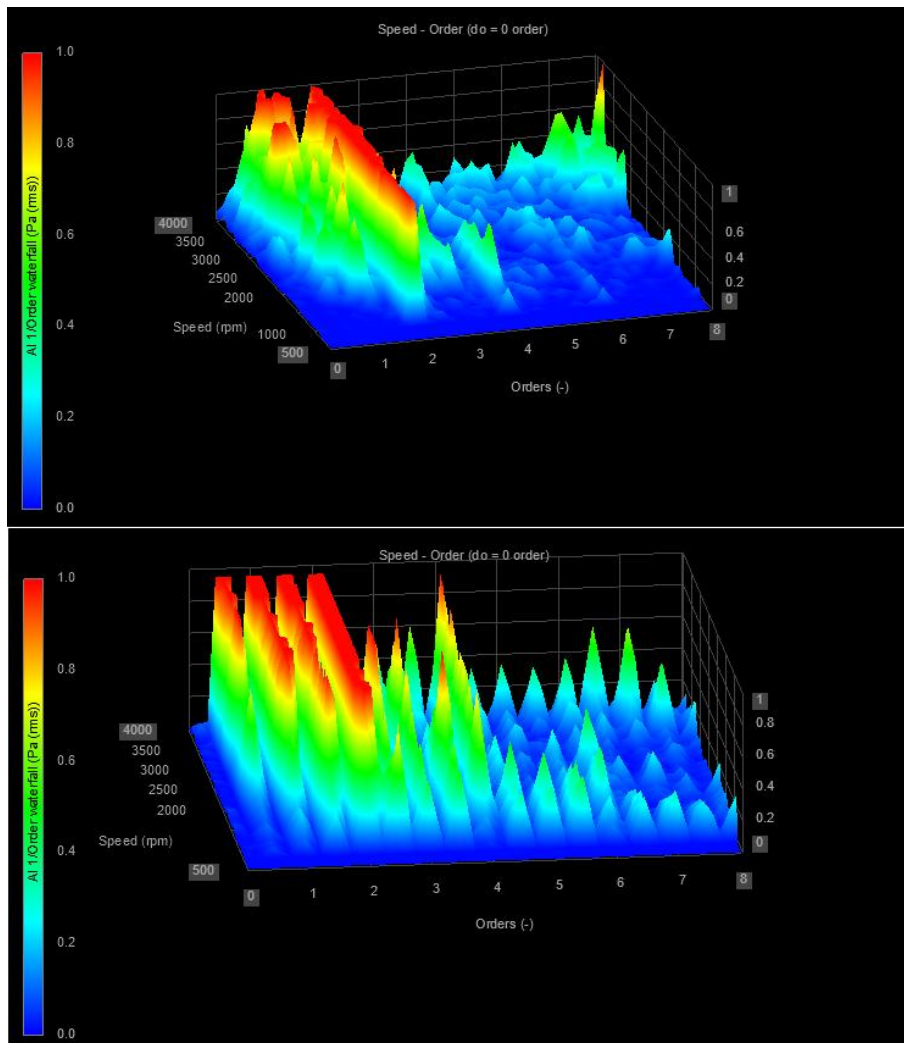


Figure 5 – Cylinder waterfall Comparison

These 3D order waterfall plots compare the results between the four cylinder (top) and the one-cylinder (bottom) tests. Due to the one cylinder being unable to rev above 4000 RPM, both waterfalls were capped at 4000RPM. The four cylinder shows dominant excitation at the 2nd engine order, with clear harmonic content up to 4th order, characterising the balanced engine. The one cylinder reveals intense activity across the order range. This shift highlights the effects of severe firing imbalance and torque effects of the engine where vibrations have been generated, resulting in disrupted harmonics.

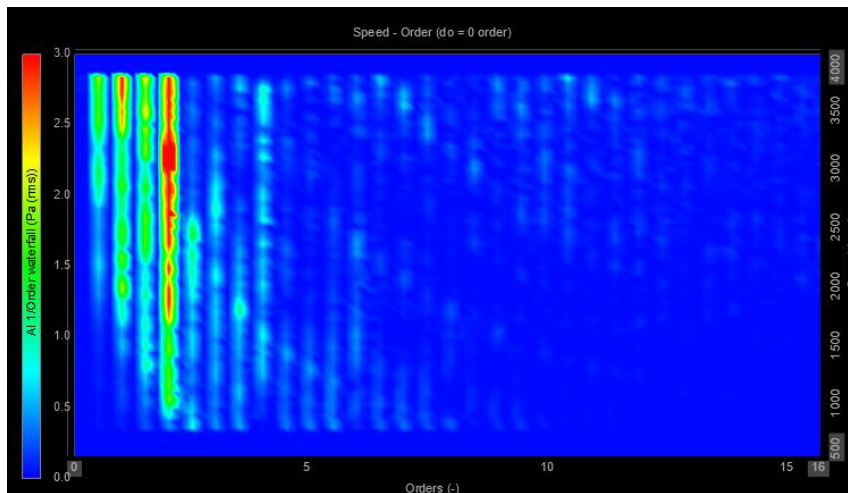


Figure 6 - One Cylinder Order Plot

Figure 5 shows the waterfall plot for the engine operating with only one active cylinder. The plot reveals dominant excitation remain in the second order however they are more apparent. Due to the single-cylinder operation, the engine exhibits limited ability to rev and produced significantly lower-order vibration, this reflects on the torque irregularity of the system with three cylinders inactive, creating an imbalance. The reduced and uneven firing frequency results in a disrupted harmonic structure.

3.2 Selected System



Figure 7 - Sunon DP203A Assembly

3.2.1 Tonal Contributions

The Sunon DPA203A is a direct current (DC) cooling fan used in electronic equipment for thermal management. The fan generates both broadband and tonal noise components with tonal noise being a particular interest in NVH analysis due to its distinct and often intrusive nature. Broadband or wideband noise refers to the sound energy that is spread over a wide range of frequencies rather than concentrated at a specific frequency. Broadband noise lacks sharp peaks and typically presents as a more uniform distribution across the frequency spectrum (Glegg and Devenport, 2017).

The DP203A like other axial fans, displays distinct tonal noise signatures which are primarily governed by its blade pass frequency and rotational harmonics. Contributions from both

aerodynamic and mechanical components means that understanding and isolating these components is essential for NVH mitigation, especially when integrated into a larger system where fan noise and structural resonance may amplify the results.

5 Analysis

The analysis of this system reveals that the primary contributions emerge from the blade passing frequency which is determined by the number of blades and the fans rotational speed. Vibrations and noise levels at this key frequency show that as the RPM of the motor increases so does the potential peak in the audible range. Analysis also suggests that certain components with specific structural properties may naturally resonate near to the critical harmonic orders, this would result in an amplification of vibration levels and increased noise.

Identifying where these resonant frequencies occur is valuable as it highlights a potential issue of the system during certain RPM speeds which may need modification to increase performance and the lifespan.

5.1 Ford Engine

As engine cylinders are disabled, the results show that the engine transitions from being a balanced platform to one having a highly unbalanced and irregular pattern. The 2nd order dominates in the 4-cylinder engine due to the evenly spaced combustion events. During the 3-cylinder test, strong components in the 1.5X order emerged, displaying an imbalance of the system as firing orders were no longer harmonious. Reducing the engine to 2 cylinders introduced stronger 1st and 2nd order components, although the engine was further from its original balanced configuration, the balanced firing order allowed the engine to retain some harmony as the signal was repetitive, avoiding fractional order excitations. The 1 cylinder test showed extreme imbalance with dominant 1st order excitation and very limited harmonic content due to the irregular firing events.

5.2 Selected System

The selected system was a SUNON DP203A AC axial fan that has a supply frequency range of 50hz and 60hz, rotating at a maximum of 2000 RPM at 50hz and a maximum of 2400RPM at 60Hz according to manufacturing specifications. The system consists of 5 blades. Figures 2 through 4 show the system and the components that make up the system. The fan body is made of a die-cast aluminium whereas the fan blades are made of plastic to reduce weight whilst allowing the blades to work more efficiently.



Figure 8 - Sunon DP203A Back



Figure 9 - Sunon DP203A Front

Using the fans specifications a spreadsheet was produced; the rotational frequency of the fan was dedicated as the Primary Order. The fans AC motor is energised at a line frequency of 50Hz or 60hz, this can induce vibrations, the frequencies represent potential excitation orders originating from the electrical supply, fans rotation and the blades passing.

To calculate the Fan Rotational Frequency (FRF) the following formula was used to replace RPM with Hertz which is cycles per second.

$$\frac{RPM}{60} = FRF(Hz)$$

5.2.1 Table 1 – Selected System Harmonics

Subsystem	Frequency Source	Frequency @ 50hz input	Frequency @ 60hz input
Electrical (Motor)	Fundamental Frequency	50hz	60Hz
	2x Fundamental Frequency	100Hz	120Hz
	3X Fundamental Frequency	150Hz	180Hz
Mechanical (Fan)	Fan Rotational 1st	33.3Hz	40Hz
	2x Fan Rotational	66.6Hz	80Hz
	3x Fan Rotational	99.9Hz	120Hz
	4x Fan Rotational	133.2Hz	160Hz
Aerodynamic	Blade Pass Frequency	166.5Hz	200Hz
	2X Blade Pass Frequency	333Hz	400Hz

Table 1 above shows each subsystem and the two operating conditions; it illustrates how the same parameter would change depending on which frequency is used.

The electrical motor is driven by AC supply and this subsystem includes vibrations which would be caused by the electromagnetic forces, each multiple of the fundamental frequency can influence the vibration generated by the motor and in turn affect the system. The mechanical system is determined by the fans rotating shaft and bearings which generate vibrations at 1x the fundamental frequency and further harmonics at multiples of that frequency. These can arise due to imbalances and misalignments.

The aerodynamic subsystem results from the interaction between the blades and the surrounding air, this would introduce vibrations and noise at the Blade Flutter Boundary (BFB) which is how the blades respond dynamically to airflow, self-excited vibrations may occur, potentially leading to fatigue failure.

By separating the excitations into subsystems, it is more easily identifiable which component may be responsible for creating certain vibrations within the system, this will help in diagnosing and developing potential issues.

6 Discussion

The theoretical examination of NVH principles applied to the selected system highlights how rotating machinery produce vibration and noise through excitations which can vary with load and RPM. The fundamental rotating speed of the fan's blades served as the primary reference which then allowed the implementation of frequencies as harmonic orders. These periodic excitations can produce tonal components which can contribute significantly to the perceived noise and vibration levels.

Crucially through research the presence of resonance must be considered as the material properties and mass of the component structures can display natural frequencies that may affect the lifespan and performance of the system. When natural frequencies align with specific harmonic orders, the amplitude of vibrations can increase dramatically, which would not only intensify the fans radiated noise through sound pressure waves but lead to structural fatigue or instability over prolonged operation of the system.

Predicting these behaviours can guide the design phase to select appropriate materials, incorporate dampening components or blade geometry to reduce resonances that may appear within the dominant excitation frequencies.

Sensor selection and measurement strategies were also discussed and researched evaluating the role they play in measuring NVH and how that data can be used to improve a system and reduce any problematic effects induced by resonance or vibration. Accelerometers with suitable frequency ranges and sensitivities must be used to accurately record subtle vibrations for accurate data as well as using Microphones that are positioned correctly with the correct device whether free-field or pressure-field so that external influences are not recorded in the data which may reduce accuracy in evaluation.

The order analysis demonstrates how deactivating cylinders in a balanced engine can lead to significant effects on NVH characteristics. During normal four-cylinder operation, the engine exhibits a balanced firing pattern and dominant excitation in the 2nd order, alongside well distributed harmonics. As cylinders are disabled, the firing balance became disrupted creating an increasingly irregular harmonic structure. Interestingly, the 2-cylinder test presents cleaner but unbalanced patterns, with dominant 1st and 2nd order content due to the evenly spaced firing orders. The changes not only increased the amplitude of vibration but also shifted the excitation frequencies.

7 Conclusion

This conceptual analysis of NVH principles and application to a simple system such as the cooling fan illustrates the relationship between the rotational speed, harmonic order and structural dynamics as each factor may have an overall effect on the systems performance and lifespan. Performing analysis using recording devices and explicit software to analyse the data collected allows engineers to improve systems and anticipate where the main causes for vibration and tonal noise may originate from. Effective NVH strategies emerge from the research conducted such as the geometry of components and mounting conditions of recording equipment which may shift resonant frequencies from the dominant orders therefore reducing unwanted vibration and noise. This analysis emphasises that even systems of a smaller scale have key similarities and fundamental principles to those of a larger scale such as the cooling fan which will be present on heavier machinery.

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Hello Tim,

I hope that you found the experience of 'analysing a NVH signature an interesting, entertaining and useful one.

Please read the assignment brief and in particular the rubric/scoring system to get an idea of the effort expected for each section. You see that some arrays require more effort..

You have selected a system of a PC cooling fan. You have concentrated on the motor, it is a pity that you did not look inside the motor, I assume that would have been destructive!.

You have mentioned some sensors but could have gone into more depth about options and limitations. You could have used annotated diagrams to support your discussion.

You have not performed any analysis on the engine test data and generated suitable plots. You have added some annotations to support your observations and discussions. You should have generated plots and shown graphs beside each other to demonstrate some of the differences between a 4cyl and 2 cylinder engine NVH output.

Some of the paragraphs and a little wordy and awkward to read. Please re-read what you have written, following the punctuation and preferably out loud. (or find a friend to do so).

Please have a look at the feedback bubbles embedded within the text. When you have some questions and are ready to discuss the resubmission of the assignment, please send me an email to arrange a meeting. Best regards. Mk (Mark Sandford)