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Challenges in Optimising System NVH Performance of Electrified Powertrains through Developing Correlated Component Models

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Summary

Complex interactions between electric powertrain components provide challenges in accurately predicting NVH performance through system-level models. Confidence in component-level simulation is required to ensure accurate system models, which reduce development time and cost in NVH performance optimisation. This paper studies the importance of motor modelling inputs through component modal testing, including stator orthotropic material properties, the influence of windings, and damping factors. These findings are used in an assembled motor test model and correlated with housing accelerometer response test data. Discussion into whether component and motor sub-assembly behaviour is seen in an assembled EDU and vehicle installation is presented.

Keywords: EV (electric vehicle), powertrain, noise, simulation, motor

1 Introduction

Despite significant improvements in the NVH performance of electrified powertrains and an improved understanding of behaviour in certain areas of NVH, costly and late emerging NVH issues are still commonplace within the industry. Targets and requirements are constantly evolving, with expectations from vehicle manufacturers, consumers and regulators becoming increasingly challenging. This is expected to continue into the future, particularly as there appears to be no industry consensus on the targets required to achieve good sound quality in electric vehicles.

The noise issues that are commonly seen in electric vehicles arise most often due to the complex interactions between components. Increased effort early in the design process is required to avoid these costly issues. However, as hardware is typically not available at this stage and is costly to test, simulation must be used instead. Simulation models and methods must represent real world components and be able to accurately predict NVH issues.

Due to the highly integrated nature of Electric Drive Units (EDU), with shared structures between the motor, transmission and inverter, each generating excitation sources, a system level approach is required. Including these key components within a single model, usually up to the isolation mounts, enables their interactions to be captured. This behaviour would otherwise be missed if individual component models were analyzed.

Achieving an accurate system simulation first time is extremely challenging. An understanding of how components within an EDU behave, and how they interact, can be applied to the sub-system and system simulation models to overcome these challenges. This can allow virtual verification against NVH requirements and, crucially, allow simulation-led design iteration loops to be made pre-hardware. This is much quicker and cheaper in the virtual world compared to hardware in future prototype samples or retrospective production fixes.

This paper describes a methodology to understand the behaviour of common EDU components, using a stator and its windings as the main example. The interactions and influence of the stator on sub-system and system level models is provided, with the process verified through physical testing.

2 System NVH Modelling Methodology

2.1 System Level NVH Simulation

A system level modelling approach is required in order to accurately capture the NVH behaviour of an EDU. This must include both the mass/stiffness representation of all components and sub-systems including motor, transmission, and integrated power electronics. The excitations originating from these components must also be included.

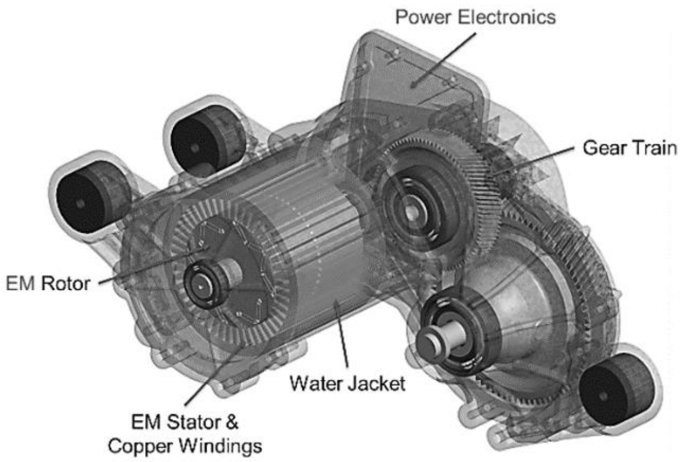

Figure 1: Typical System Level EDU NVH Model [1]

As explained by Furness [1], a typical system NVH model includes finite element (FE) models of complex geometries such as the housing, differential, stator, and complex gear blanks. Non-linear stiffness models should be included to represent bearings and mount locations. The effect of the excitations and the transfer path through to outer casing is simulated using a combination of FE and 1D representations where appropriate. This results in a response at the casing, usually in the form of virtual accelerometers or radiated noise.

2.2 Key Components within System NVH Models

Key risks and complexities at a component level must be understood. This allows for NVH issues at system level to be more easily traceable, allowing identification of components and joints which could be modified to mitigate the issue.

Electric motors are made up of multiple complex geometries and materials. Stator lamination stacks, manufactured through many bonded laminations, can be challenging to model. Unlike many solid mechanical components which can be modelled as an isotropic structure, stator lamination stacks behave orthotropically and must be modelled as so. It is generally understood that the shear stiffness between the laminations is reduced. How much it is reduced is not fully understood and can be dependent upon geometry and manufacturing methods. This can have significant effect on the response of the motor and, in turn, the EDU. The complex damping characteristics of the stator, in part due to the bonding process and materials, are important to capture in order to correctly determine the magnitude of response. Motor windings add significant mass to the stator sub-assembly, which must be captured. However, the effect on the stiffness of the stator teeth, and the influence on damping, are also important characteristics in determining the overall response. The rotor has similar challenges, and this can influence the stiffness of the transfer path from the excitations on the rotor into the transmission structures.

The methods and processes for gears within the system are relatively well known, with the effect of transmission error excitation and the transfer path through the structure somewhat similar to internal combustion engine vehicles. 3D representation of the gears is required for detailed NVH, to enable the simulation to correctly capture mode shapes and corresponding responses. Traditional design processes and design rules alone are unlikely to be satisfactory in reliably meeting the stringent targets within EDUs. This, along with advances in manufacturing materials and methods, leads to the need for improving component level understanding of gears within EDUs.

There are multiple excitation sources within an EDU, including inverter, motor and gear meshing excitations. Each of these have multiple harmonics and considerations to capture such as motor torque ripple and stator tooth forces in the radial, tangential and axial direction for the motor. The influence from the inverter, such as pulse width modulation (PWM) on the motor current ripple, should be captured to ensure accurate motor excitations. There are also excitations due to manufacturing deviations, such as rotor imbalance excitations, which is becoming even more important as the trend to higher speed motors continues. All of these excitations must be considered together against the full system structural model, and compared between each other to avoid coinciding orders leading to an increased response.

Component level correlation aids the development of system simulation models, and also improves general processes and understanding. This can allow correlation from one design to increase confidence for future analysis prior to hardware.

3 Component Correlation

Correlation of components, sub-systems and their interactions is required to build confidence within the system model. This section outlines the methodology and key correlation results, with an example focused on the stator and windings.

3.1 Simulation Methodology

Simplifications in the modelling of complex components and the joints between them, such as isotropic materials, are not sufficient to accurately capture certain NVH issues. An improved understanding of how these components behave and interact is required. Component correlation is used in order to achieve this, by optimising FE modal simulation models against physical modal tests of the components. FE models are generally well understood, particularly for individual components where the solid geometry is represented as a single meshed body. However, where components interact or are joined together, such as winding/lamination joints, pressed joints, or bolted joints, there are often limitations in the methods which are still to be overcome in software development. Linearised contacts in system NVH models allow some degree of accuracy, however for systems with transient contact conditions, these are often overlooked. Better understanding and representation of these interations will enable full system NVH simulation models to more accurately predict NVH issues. Using the stator example, it is unfeasible to model each lamination and bonding material separately, however it is possible to model the stator lamination assembly using complex material properties to capture the same behaviour.

The methodology will be validated in stages by correlating at component level (modal) and at system level (accelerometer response).

3.2 Test Methodology

There are multiple excitation methods for modal testing, with both a “hammer” test and a “shaker” test completed to compare the difference. Two different “shaker” angles were also completed to assess the sensitivity of the outputs to the method. Hammer testing was found to be consistent with the shaker for the first four stator mode shapes investigated.

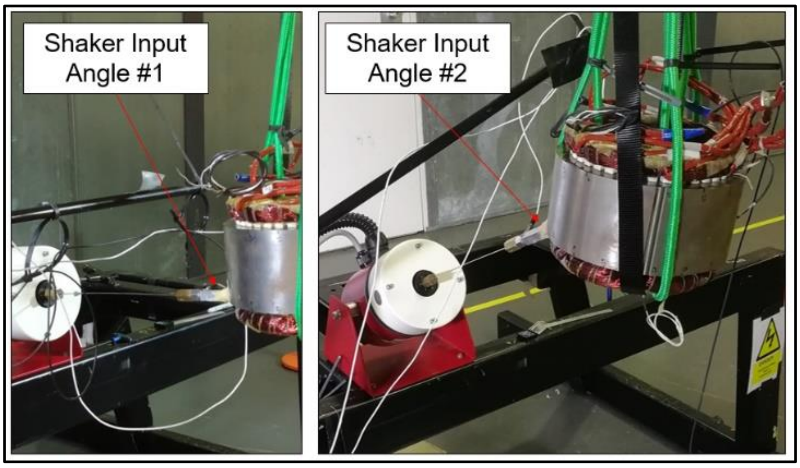

Figure 2: Shaker Input Angles

The frequencies are in general agreement with the shaker tester, however the quality of the mode shapes and frequency response function (FRF) curves are clearer with the hammer testing. Therefore, hammer test results are used for the component and simulation correlation.

Table 1: Comparison of Modal Frequencies Under Different Excitation Methods

Mode #	Shaker Angle 1 Frequency (Hz)	Shaker Angle 2 Frequency (Hz)	Modal Hammer Frequency (Hz)
1 (Ring 2,0 Mode)	772	773	771
2 (Bending 2,1 Mode)	809	801	797
3 (Tri-lobe 3,0 Mode)	2076	2078	2065
4 (Quad-lobe 4,0 Mode)	2168	2169	2160

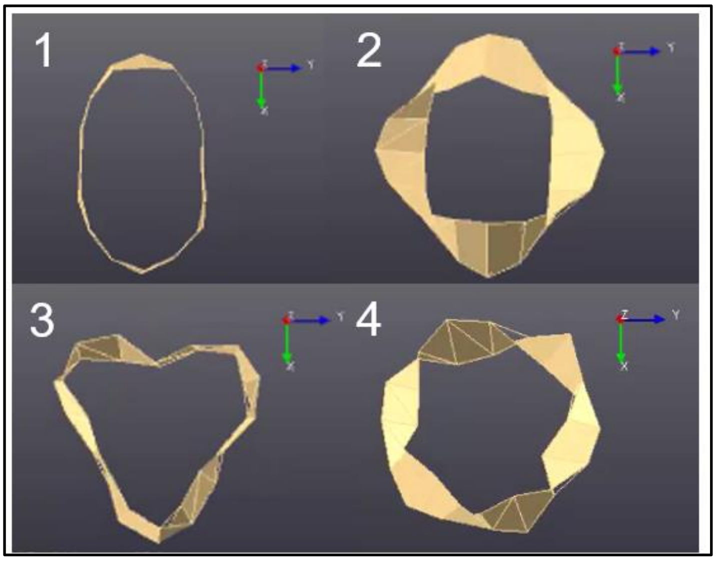

Figure 3: Stator Mode Shapes

3.3 Stator Lamination Stack

In order to accurately model the orthotropic nature of a stator lamination stack, the first three modes were extracted from the modal testing. These consisted of a (2,0) ring mode, (2,1) bending mode and a (3,0) Tri-lobe mode shape.

Figure 4: Stator Lamination Stack

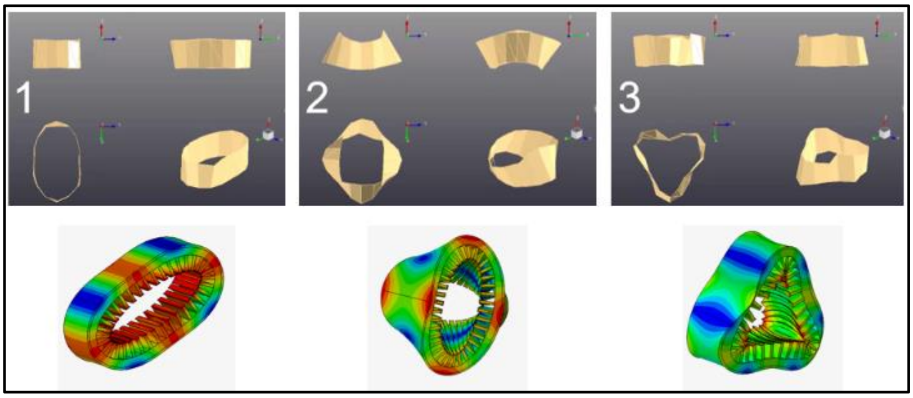

Figure 5: Stator Mode Shapes Test vs Simulation

The first two modes are close in frequency, so modal animations were required to identify the shape for each identified mode in the FRF. This is especially important as the second mode is particularly sensitive to the reduced shear modulus of the lamination stack.

Table 2: Stator Lamination Stack Modal Frequency Correlation

Mode #	Test Frequency (Hz)	Simulated Frequency (Hz)
#1 (Ring 2,0 Mode)	771	770
#2 (Bending 2,1 Mode)	797	796
#3 (Tri-lobe 3,0 Mode)	2065	2018

FE modal simulation correctly predicted the mode shapes as seen in the physical testing, however the frequency that these modes occur at must be accurately correlated too. Optimisation of the stator lamination stack material properties found best correlation occurred when the shear modulus between the laminations was around 13% of the shear modulus in the radial direction. As a comparison to a stator modelled as isotropic, the #2 Bending mode was found to be up to 90% higher frequency, showing the significance of capturing the orthotropic nature of stator lamination stacks.

3.4 Stator Windings

How the windings interact with the lamination stack, and their influence on stiffness and damping is crucial to the system NVH model. A wound stator, using the same lamination stack as in the previous section, was also tested and simulated in order to understand the effect of the windings.

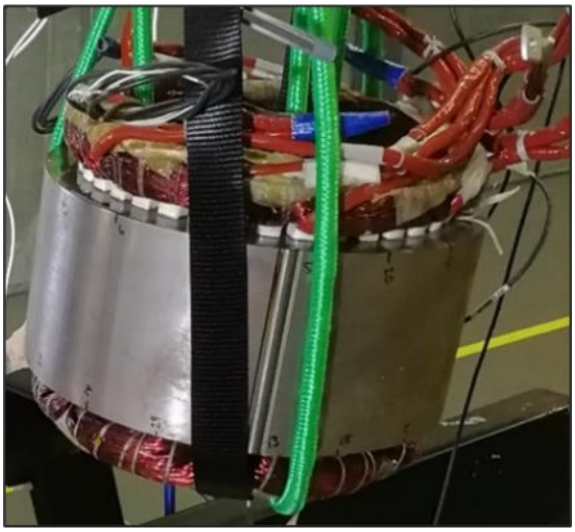

Figure 6: Wound Stator

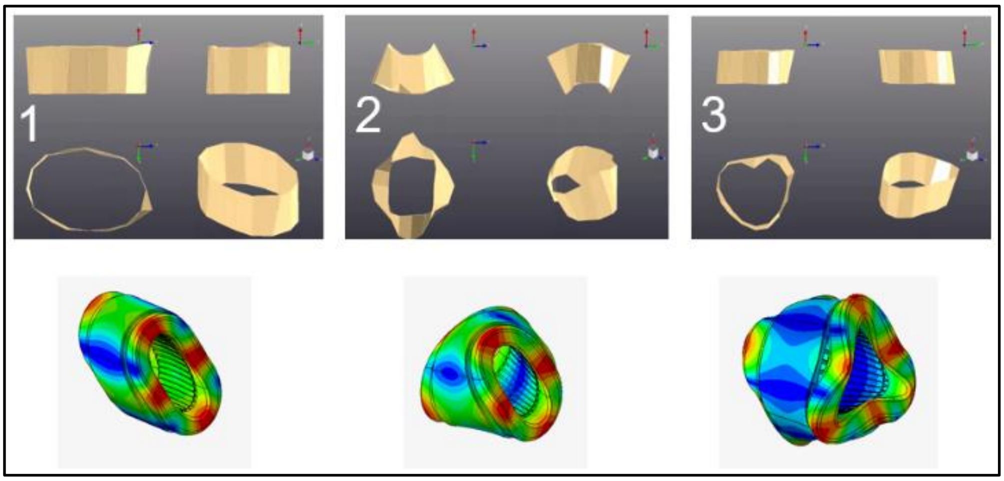

Figure 7: Wound Stator Mode Shapes Test vs Simulation

Similar to the stator laminations, windings are also orthotropic. This is due to the direction of wire within the wound stator providing differing stiffness contributions in various directions. Isotropic properties often do not correlate, and can lead to a compromise between modes #1 and #2, one resulting in too high a frequency and one too low a frequency. Both of these cannot be solved by only changing a single isotropic Young's Modulus value. Due to their orthotropic nature, windings provide a higher stiffness in shear than in the radial direction. This is to be expected as shearing the bundle of wires is more stiff than separating the individual wires within the slot radially.

In order to simplify the system model and improve solution times, it is possible to add the additional winding mass into the stator geometry. Crucially, the stiffness of the stator lamination stack must also be modified to match test frequencies including windings. This results in a stiffness increase of the stator lamination stack.

Table 3: Wound Stator Modal Frequency Correlation

Mode #	Test Frequency (Hz)	Simulated Frequency - Stator Update (Hz)
#1 (Ring 2,0 Mode)	675	678
#2 (Bending 2,1 Mode)	780	777
#3 (Tri-lobe 3,0 Mode)	1808	1775

Compared to 13% shear stiffness for a standalone stator, by including the winding effect within the stator lamination stack, this increases to 20%. These learnings can be adapted for future analysis without hardware available, depending on the geometry and manufacturing methods.

Table 4: Damping Factor Comparison of Stator with/without Windings

Mode #	Stator Lamination Stack Damping	Wound Stator Damping
#1 (Ring 2,0 Mode)	0.52%	2.14%
#2 (Bending 2,1 Mode)	0.62%	3.40%
#3 (Tri-lobe 3,0 Mode)	1.25%	3.09%

Damping is also significantly affected, with damping increased on average by around 3-5x with windings compared to a standalone stator lamination stack. Changes to damping are expected due to the change in mass and the slight stiffness contribution from the windings. This will impact the magnitude of the response when included in the system simulation model.

3.5 Other EDU Components

The process described can also be followed for other components within an EDU. This allows further understanding of the behaviour of other critical components and their interactions.

In particular, rotors have similar challenges to those discussed for stators, due to the laminations and magnets. This is especially important when dealing with modes with movement between the two motor end covers, where the stiffness of the rotor shaft between both ends of the casing through the bearing mounts can have significant impact.

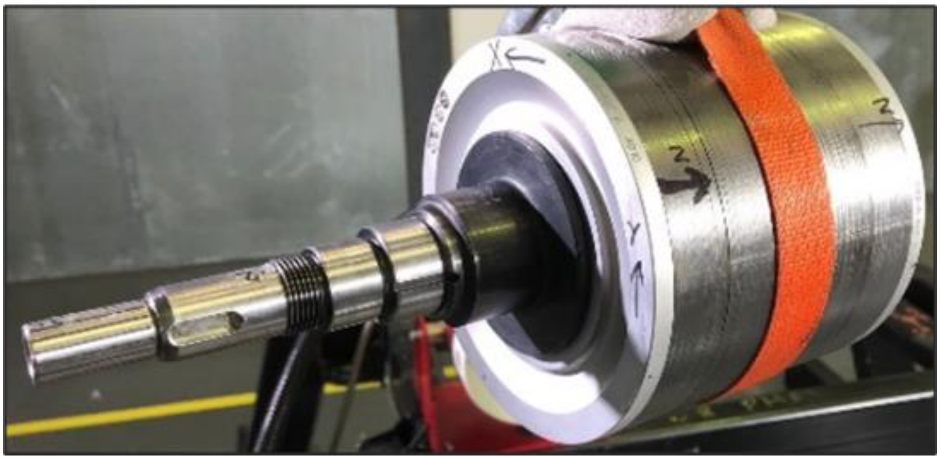

Figure 8: Rotor Modal Testing

As gears are a source of excitation in the EDU, including an accurate stiffness representation of the gear, such as correctly capturing any modes due to non-axisymmetric geometry, is crucial in confirming the transfer path from gear mesh through the structure.

Figure 9: Gear Modal Testing

4 Sub-System and System Effects

4.1 Motor Testing and Correlation

In order to verify the component level findings, sub-systems and systems must be tested to further understand the NVH response. To achieve this, an assembled motor was tested on a high-speed motor test rig at a range of operating conditions.

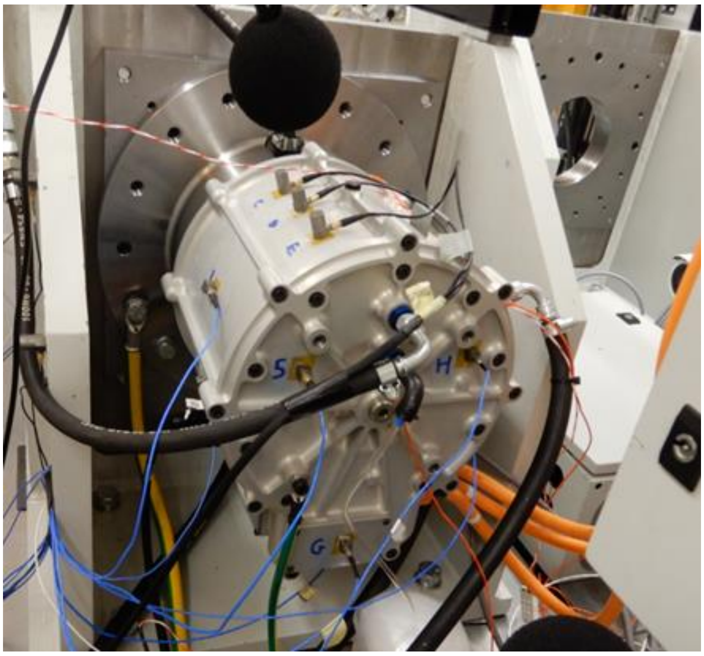

Figure 10: Motor Response Test Setup

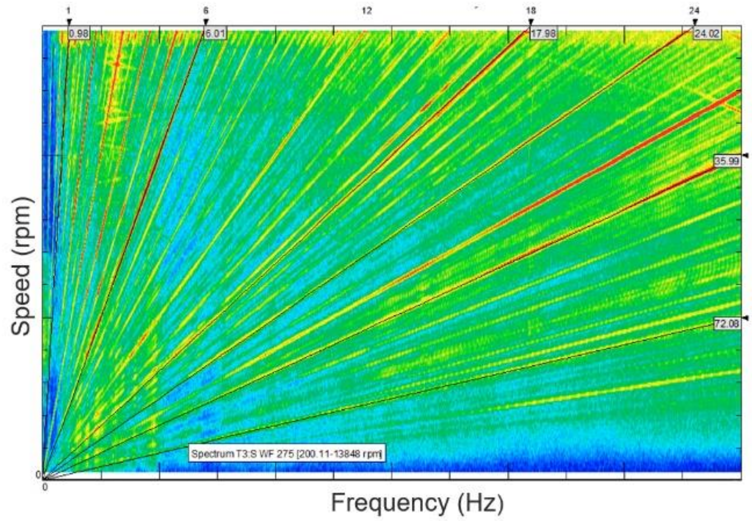

Figure 11: Motor Test Waterfall Plot

Accelerometer and microphone measurements were taken and correlated against a representative motor system simulation model.

System simulation models should be built by utilising a mixture of FE components for rig and motor structures, and 1D beam elements for downstream rig torsional shafts. The level of simplification must be determined through experience. Generally, being further away from the point of interest allows components to have reduced fidelity. This allows models to be used during iterative design processes by improving solution times and speeding up design activities.

A distinct 6th order peak was identified in the test data at 50Nm (20% of peak). This level of torque is particularly important during vehicle usage due to significant periods of vehicle cruising, and often reduced road and wind noise which can mask powertrain noise in other operating conditions.

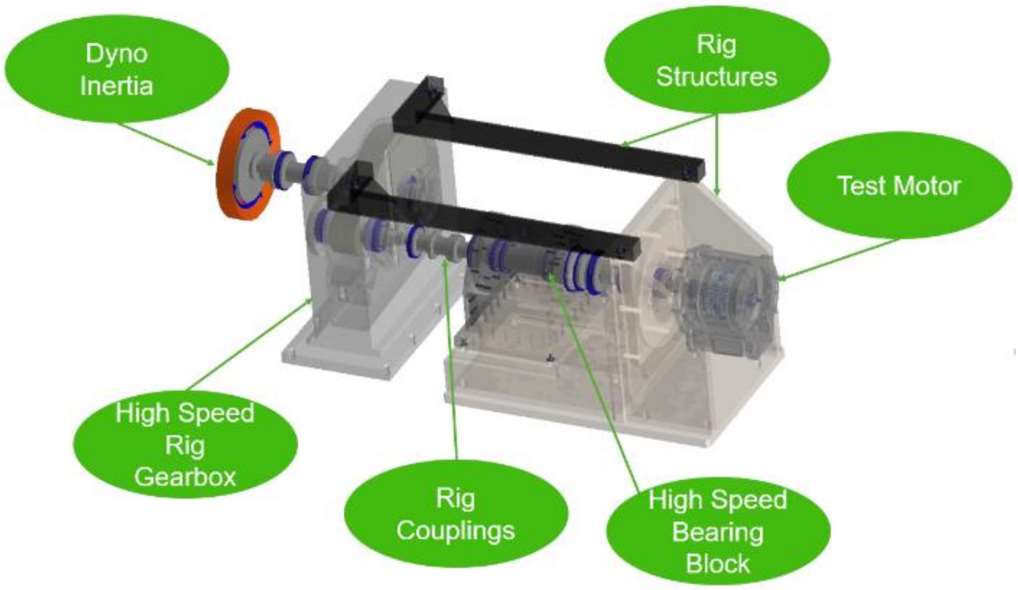

Figure 12: Motor Test Simulation Model

A motor simulation model using isotropic stator materials is unable to identify the 6th order peak as seen during test data. Modelling using isotropic stator materials is therefore likely to miss NVH issues in the design process, which would result in any issues only being discovered during hardware testing phases.

Using the method described in this paper, orthotropic material properties enable the system simulation model to identify the peak. Once identified during the early design stages, mitigation can be implemented to reduce or eliminate the peak.

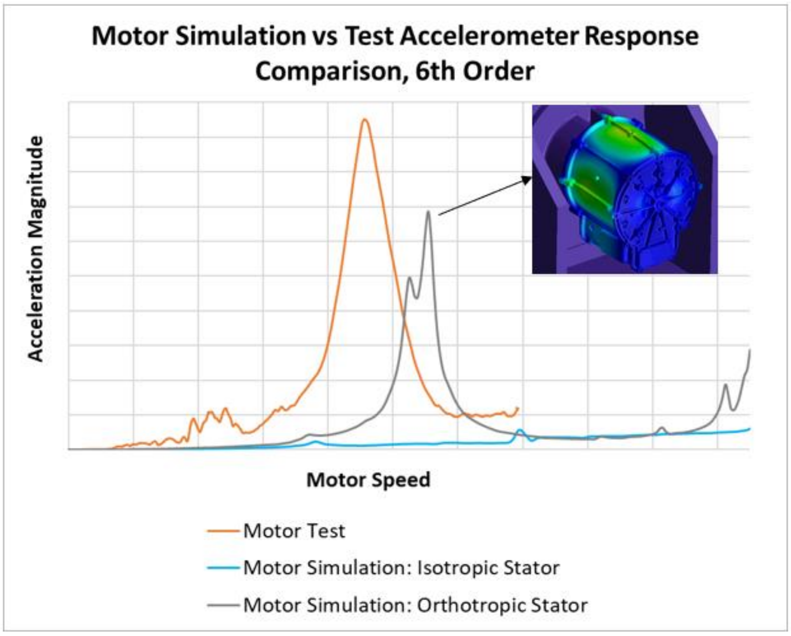

Figure 13: Comparison of Motor Test vs Simulation Response, with Operating Deflected Shape

The operating deflected shape of the simulated peak in response shows the behaviour to be the same as the identified stator modes, showing how component behaviour can propagate into sub-assembly and system models.

4.2 Effect on EDU and Vehicle

When integrating the various components within an EDU, the NVH characteristics can change due to the interactions between components and sub-assemblies. However, certain traits are likely to remain, and thus issues can propagate from component to sub-assembly to complete assembly. Identifying and solving any component level issues is therefore likely to reduce NVH risk throughout the design process, reducing late emerging issues.

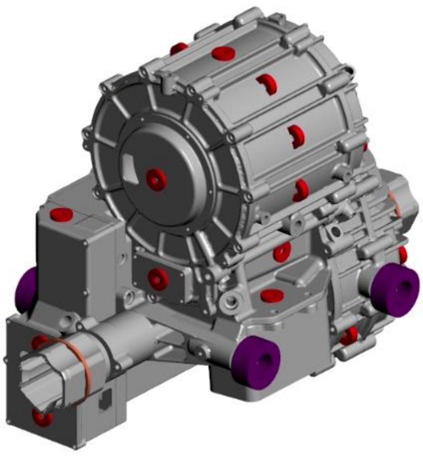

Figure 14: EDU Simulation Model

NVH response testing of the assembled EDU shows a decrease in the main 6th order response seen during standalone motor testing, however a peak in response still occurs. In contrast, the smaller peak captured around 4000-5000rpm is exaggerated and worsened during the assembled EDU. This comparison shows both the importance of system modelling and testing, whilst simultaneously demonstrating how component behaviour is propagated through assembled systems.

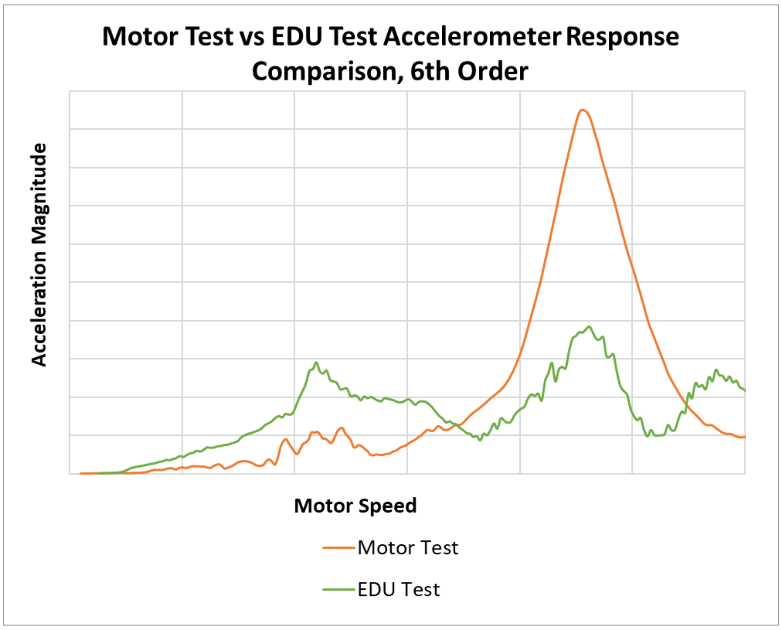

Figure 15: Comparison of Motor Test vs EDU Test Response

Improving NVH performance at vehicle level is of utmost importance as this is the environment in which the system will actually operate. Depending on the characteristics of the response, this could cause either airborne noise or structure-borne noise. In the example shown within this paper, the excited panels are on the outer surface of the motor, with minimal vibration occurring at the mounts. Under these circumstances, radiated acoustic noise should be the area of focus. However, in situations where the majority of the vibration occurs in close proximity to, or at, the mounts, structural vibration propagation in the chassis using a vehicle model should be investigated. An improved understanding of the characteristics of the response and the likely NVH issues which could occur and propagate through into the complete system allows for mitigation to be included early in the design process during pre-hardware simulation. This understanding could be used to alter the psychoacoustic signature of an EDU by tuning modes to alter the radiated noise, without impacting structure borne noise targets.

5 Conclusion

This paper has demonstrated that using isotropic materials and joint simplifications is not adequate for system NVH modelling of EDUs. Significant NVH issues may be missed, leading to costly rectifications required after hardware testing. Determining how to model anisotropic components and complex joints is key to capturing these NVH issues during pre-hardware simulation. The methods demonstrated in the paper show the importance of accurate component and sub-system level modelling to understand and correlate NVH behaviour. This subsequently contributes to improved system level correlation, and through substantial experience, allows potential issues to be identified and rectified prior to the costly procurement and testing of hardware. The example used in this paper shows that stator behaviour and mode shapes propagate throughout the various assembly stages, as shown during system response tests, and that modelling the stator with accurate orthotropic material properties is crucial in order to identify responses through motor and EDU assemblies.

Although this understanding has yielded significant benefits, there are still many challenges in the optimisation of NVH performance in electric vehicles. Advances in FE techniques, particularly joining methods such as representing transient contact conditions and integrating these within system NVH models, will enable the next phase of complex development within electrified vehicles. Sound quality targets and psychoacoustic metrics are quickly advancing, and using simulation to aid sound quality target definition, and sound quality verification is of great importance to the industry and consumers alike. This allows the industry to not only improve perceived quality of vehicles, but also reduce time to market.

Acknowledgments

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Jordan Craven is a Senior Engineer for Drive System Design's Mechanical Engineering team. Following his MEng studies in Mechanical Engineering at The University of Nottingham, Jordan has worked in electro-mechanical drivetrain consultancy, moving to Drive System Design in 2021. Jordan's most recent focus has been on system NVH research and development and thermal analysis methods for electric powertrains.

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