HEXAGON

White paper

Improving noise performance in electric and hybrid vehicles

How innovative thinking and applying a powerful methodology earlier can help to design quieter and more efficient environmentally friendly cars for a mass market

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Introduction: innovation in design to improve NVH performance

Continuing calls to reduce CO_2 emissions have provided automotive companies with a significant incentive to develop, manufacture and bring to market electric vehicles (EVs) and hybrid electric vehicles (HEVs, or hybrids), rather than producing niche vehicles in small volumes. This can only be achieved if the vehicles have a wide appeal to consumers and satisfy all the quality criteria that consumers expect in existing products: with EVs far quieter than internal combustion (IC) engine-driven vehicles, noise performance and wider NVH (noise, vibration, harshness) issues have come to the fore. This paper describes recent experiences in simulating and reducing noise in an EV powertrain using a switched reluctance machine (SRM).

It covers the process and results for noise simulation of the complete powertrain: dynamic properties are modelled as a whole-system and subjected to motor excitation (torque ripple, electromagnetic forces and rotor imbalance). Innovation comes from the speed of modelling and analysis: analysis and data interpretation takes place early enough in a project to enable effective steps to be taken in reducing noise. This contrasts with the more typical approach of simulating problems that have already occurred in testing.

Background and challenges

In recent years, passenger cars have seen improved noise, vibration and harshness (NVH) performance thanks to new methods used in design, analysis, development and manufacture. With the price of vehicles in real terms falling while quality and performance increase, this winning combination of quality and price sets a high benchmark for EVs and hybrids to achieve. Improving the noise performance of EVs is essential, not least to help them gain wider acceptance with consumers, but addressing this raises a number of important issues.

Noise performance: challenges to overcome

While everyone agrees that EVs have a bright future, the price volatility and uncertainty of supply of rare earth material is making an approach based on Permanent Magnet Synchronous Machines (PMSMs) increasingly less attractive as a solution for mass production. This is why companies are seeking alternative and potentially more cost-efficient motor technologies such as Switched Reluctance Motors (SRMs) as the way to mass-produce motors cheaply. Further, running a motor at higher speeds allows greater power density, giving lower weight, smaller motor and lower overall cost.

In terms of NVH, electric vehicles do not benefit from the "masking" effect normally provided by an internal combustion (IC) engine. What is more, SRMs have worse vibro-acoustic behaviour than their PMSM counterparts. SRM waveforms are non-sinusoidal, meaning SRMs have extremely high harmonic content compared with standard rotating field machines. Moreover, the radial forces that largely cause stator vibration are strong, as torque is produced by reluctance force and not Lorentz force. The harmonic frequencies are proportional to speed, with high rotational speed making low order harmonics hit the structural resonances earlier.

Vehicle OEMs tend to rely on component suppliers to design, test and manufacture sub-systems which are then assembled into the vehicle. As a result, suppliers may design and develop "quiet" sub-systems to what are considered "state-of-the-art" levels, for the vehicle OEM to find that the assembled electric-powertrain is unacceptably noisy. How can these various issues be resolved in the most effective manner? Computer-aided engineering (CAE) tools for simulation and modelling should be the answer. Problems arise, however, in the way such tools are applied, the underlying functionality they offer, and the point in the development cycle at which they are deployed.

Keep the noise down: rethinking simulation and modelling

The methods used by designers and engineers to develop quieter products have progressed substantially in the last two decades, using, for example, CAE tools such as Multi-Body Dynamics (MBD), Finite Element Analysis (FEA) and Multi-Domain Simulation tools. The overall objective is to simulate the dynamics of systems to identify and solve problems without having to manufacture – although for most companies, this remains an aspiration rather than business-as-usual.

Typical approaches: "too complex, too late"

In motors, electromagnetic forces are largely responsible for the excitation that causes NVH, with such forces typically calculated analytically or numerically. The numerical approach is usually performed using a software tool to discretely solve differential equations that describe the electrical machine, and which accounts for the geometry and the electromagnetic nonlinearities. The vibration response is provided by a 3-D structural FEA or MBD. The current "state-of-the-art" approach for vibro-acoustic simulation of an electrical machine is a coupled co-simulation between the tool that calculates the electromagnetism and the FE tool that determines structural behaviour. As a result, the structural FEA has to be solved in each time step.

This makes the entire approach time consuming and so largely impractical for a complete powertrain. Indeed, full run-ups or even whole driving profiles are all but impossible. Such models cannot realistically be used to guide the design process in a way that eliminates problems before they occur: Right First Time is the ideal. While MBD packages and Multi-Domain Simulation tools are also frequently used for time domain simulations, once again, modelling and analysis is too slow for results to be useful in guiding design at a time when such interventions could have the greatest impact.

"Division of responsibility" in a fragmented design process

Using FEA, a system's natural frequencies and dynamic response to an excitation can be calculated. It is accepted that to simulate phenomena whose excitation is inherently periodic such as gear whine, torque ripple and imbalance, it is more efficient to simulate in the frequency domain. The system is linearised, with the loss of non-linear behaviour more than compensated for by the speed of analysis gained and improvements in the "interpretability" of your results, with transfer functions giving an instantly interpretable indication of system behaviour across a wide range of speed conditions.

However, when simulating for natural frequencies and dynamic response, the definition of the "system" actually often follows the standard "division of responsibility" that exists in industry's supply chain. A motor manufacturer will focus on the motor system and simulate the rotor shaft, bearings, housing, and so on; motor excitation of the torque ripple, radial forces and rotor imbalance will be included. Similarly, a gearbox manufacturer will focus on gearbox shafts, bearings, gears and housing, with excitation coming from the gear transmission error. This division can lead to problems. For example, torque ripple is not usually in itself an NVH issue so long as the "system" consists of the single shaft of a motor. However, once this is passed through the gear pairs, this torsional excitation is converted into radial excitation - leading to housing vibration and radiated noise. Some observers have described how modelling the motor alone can imply no problem at all with motor noise, whereas including the full driveline indicates a noise propagation mechanism for the torque ripple through the gearbox housing. The risk, once again, is that such issues are revealed only once a prototype is already assembled.

Dealing with complexity

Problems tend to emerge if "generalist" tools such as FEA and MBD are applied to simulate noise in complex systems. Modelling the system becomes extremely time-consuming, with automeshing of little use in modelling non-linear components such as splines, gear meshes and rolling element bearings. Such modelling requires high levels of expertise, which is often in short supply and therefore has a high cost associated. Analysis times are long and the data difficult to interpret, meaning an extremely slow and elongated process. At best, such analysis of NVH issues tends to only be applied to problems that are identified later in the process, during hardware testing, and need resolving – rather than being used to avoid problems and optimise the choices available to designers and engineers far earlier in the design process. These may be CAE tools, but the main purpose of using such tools and techniques is not being realised.

A different approach

As an alternative to the previous approaches, Romax has developed a different methodology that aims to overcome the limitations of the conventional approach. The methodology is founded on two core principles:

- The speed of the process means results are available to designers, engineers and other decision makers within a time frame that enables more focused, informed effective design decisions far earlier in the process
- The results provided can be more easily interpreted and so guide smarter Right First Time engineering design decisions

The methodology works in the frequency domain and calculates the eigenvectors and eigenvalues of the complete structural system of a powertrain. From here, a number of analyses are now possible, from which a range of more informed engineering assessments can be made. This methodology makes use of the principle of modal superposition in calculating system response. From this, the resulting vibration due to a number of excitations and their harmonics can be calculated, and the operating deflected shape can be viewed, to give the resulting vibration at any frequency. The speed of the process means that such data is available early enough to inform the design team to make design improvements.

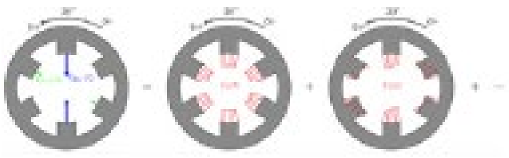

Figure 1 - The force shapes derived from the electro-magnetic simulation, expressed as a Fourier series

Increasing speed, gaining more easily interpreted results

With the electric motor, excitation is in the form of force shapes (see Figure 1). A simulation of the electromagnetic behaviour of the motor is used to provide force-shape amplitudes for the modal superposition. These shapes are the modal excitation of the structure's eigenmodes. The forces that influence the acoustic behaviour of the machine are usually radial force. The method we suggest also works for tangential and axial forces, to model a Switched Reluctance Motor (SRM), integrating a phase-voltage equation using a multi-domain simulation tool, and in a step that incorporates the geometry of the SRM and material properties of the steel used. A temporal Fourier analysis is also performed to further determine excitation. The force shapes are applied as excitations to the drivetrain structure, and the dynamic response found using the principle of modal superposition. From there the surface vibration and radiated noise can be calculated.

Understanding "the full system response"

With the importance of modelling the whole system established, in this case that meant not only the motor but also gearbox components and housing, mounts, driveshafts and power electronics housing. This would provide a far deeper understanding of the full system response and avoid the problems arising from simulation of separate sub-systems alone. For system modelling, a proprietary design and simulation package for drivelines was used to model the shafts and bearings of gearbox and motor, gears, mounts, driveshafts, stator and the housing of the gearbox, motor and power electronics. Like many FEA based approaches, the method involves multiple coupled shaft systems, with a linear model used to derive mode shapes forced in the frequency domain. The housing is included by taking an FEA model of it, and performing a dynamic condensation using Craig-Bampton modal reduction. Component Mode Synthesis is used to link the reduced dynamic model of the housing to the dynamic model of the internal components.

The most importance difference between this approach and methods based solely on generalist FEA packages is the use of specific algorithms to calculate the stiffness of non-linear components (rolling element bearings, gear meshes, splines) – resulting in solution times many times faster. At the same time, tailor-made post-processing routines enable analysis results to be interrogated effectively. This method's accuracy has been proven in many projects, including EV applications, with implementation by some manufacturers reducing the time spent on NVH modelling and simulation by 80% when compared to generalist FEA tools. This improved speed in analysis and interpretation is critically important for NVH simulation to help in the design process.

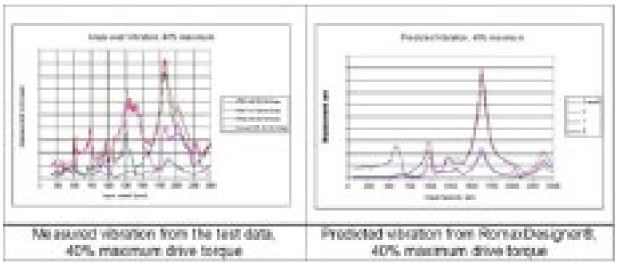

Figure 2 - Comparison of test and simulation results for vibration for an EV powertrain

"Failure Mode Avoidance" rather than "the perfect simulation"

The method described thus far is suitable for the rapid simulation of a complete EV powertrain, with all components included. However, if the design is complete then most of the design decisions which affect whether the system will be noisy or not have already been made. Too often, "design for low noise" means "design for low excitation" (excitation meaning torque ripple, transmission error etc.). What is needed is insight into the noise performance at the concept design stage, when the outcome can be more easily influenced.

At this stage the housing design is not complete and may not even exist, so the aim is not to produce "the perfect simulation", rather to indicate the major problems, identify the best performing layout and provide guidance to the design team on vibration reduction. Other industry experts, who espouse "Failure Mode Avoidance" rather than perfect simulation, increasingly embrace this approach. Our goal here is to better understand the principal noise generation mechanisms and reduce them, rather than to proceed to prototyping in ignorance of what the vibration peaks may be.

Romax developed groundbreaking approaches that allow the noise performance of the system to be assessed during the earliest stages of concept design, so the design team can select the quietest concept and take steps within the design process to further minimise the system's dynamic response. As a result, peaks in dynamic response were specifically targeted for reduction through intentional design modifications. This proved to be successful, meaning that "design for low noise" now means "design for low excitation AND response".

Practical application:
The ODIN project to create a highly integrated driveline

The innovation covered by this paper is not only that powertrain noise can be simulated more accurately - but also that it can be done in a way that enables performance improvements within the time line and constraints of an active design and development project. ODIN (Optimised electric Driveline by INtegration) is a European collaborative project co-funded by the European Union that aims to design an innovative integrated EV driveline to be installed into the Renault Zoe. Led by Bosch, consortium partners include Romax, GKN Driveline, Renault, Fuchs, CIE Automotive and ISEA (RWTH Aachen University). Romax is delivering CAE tools and expertise to the ODIN team to analyse the complete system and influence the end-to-end design process to arrive at more effective designs faster. With the project setting out to explore unknown territory regarding motor speed and other issues – to create a design that challenged "standard practice" – it places a large emphasis on designing for low noise. Innovation targets at the project outset included: use of a high speed Switched Reluctance Motor - up to 23,000 RPM; a high degree of integration between motor and gearbox; a single lubrication/cooling system for the entire drivetrain; and a high efficiency gearbox optimised for NVH. Romax set about applying NVH simulation as early as possible in the design process with a view to properly achieving design for low noise. Whilst this was applied to an SRM, it has subsequently been applied to PMSM and Induction Motors.

Initial simulation: concept design

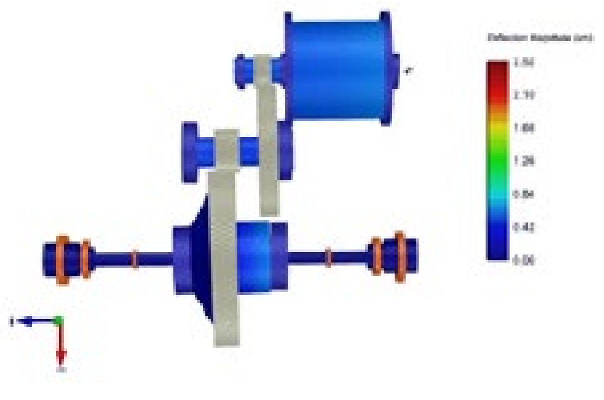

Figure 3 - An example of the initial dynamic simulation to illustrate the level of model complexity used in selecting the concept for dynamic performance

For the first design loop, the first stage was to identify the most promising of a large number of proposed basic concepts based on key targets such as cost and dynamic performance. Romax Concept software was used to rapidly iterate through all of the proposed layouts to narrow down the field, benchmarking concept layouts to identify those with the best chance of good noise performance. At this stage unit excitations were used, to enable understanding of the system's dynamic response. This included torque ripple, radial forces and imbalance from the motor and transmission error from the gears. Representative values for each were collected from specialists amongst the project consortium, based on their past experience. The complexity of this process should be highlighted. At this stage of the design process there is no housing, so no value of surface vibration or radiated noise can be calculated. The approach used was to calculate the total sound power transmitted through the bearings and use this as a metric in guiding concept selection.

The analysis team needed to check its approach was valid, so an existing EV driveline (in production, complete with housing) was subjected to the same analysis method. A model of the internal components, equivalent in detail to the concept model in ODIN, was created and the same analysis applied. The results for the total vibratory power through the bearings for the simple model was compared to that for the original model, complete with fully detailed housing design. After careful development it was confirmed that this simplified method provided results that were satisfactorily similar to those from the analysis of the fully detailed design.

Initial simulation: concept design

Once the concept layout for rotating components was selected, the decision remained as to how the driveline and power electronics should be assembled into the vehicle. Two driveline layout options were identified, referred to as T and L layouts. Of course, it was not possible to fully design a housing for both layouts: project timing required that the choice had to be made without either design being fully modelled. As a result, a simple representative housing was modelled for both structures and the system simulation carried out.

This time the simulation was more involved. Driveline mount stiffnesses were included and the assessment was made based on total structure-borne vibration, measured at the mounts, and by summing the housing kinetic energy, indicative of the total radiated noise. The same excitations were used as in the initial simulation. It was possible to identify which concept had the best fundamental dynamic behaviour. For the selected concept, it was possible to compare which noise mechanism (torque ripple, radial forces etc.) was most significant at each speed and also identify the problematic modes of vibration, associated with the peaks. Figure 4 shows the response for the different excitation sources, each of which has different frequencies. The frequency excitation at maximum motor speed varies from 400 Hz for imbalance to 19.2 kHz for Mode 6 Force Shape, 48 cycles. Informed feedback was therefore provided to the design team to change the housing design and so minimise these modes of vibration.

Detailed simulation: housing design

The housing design was detailed for the chosen concept, with the structure modified and ribs applied to reflect feedback from the intermediate simulation. The updated housing design was included in the system model and the reduction in vibration compared to the original design observed. Analysis showed that the levels of predicted vibration significantly reduced – meaning the specific intention of the design-analysis-redesign iteration was achieved.

The final stage is refinement of the design, where the vibration from all major sources including harmonics can be inspected and compared across the speed range. By using simulation of noise and vibration to lead design right from the outset, a more innovative concept with the best chance of success was selected, with potential problems identified and remedial action taken as early as possible: long before the detailed design was finalised.

Predicted noise from the motor and gearbox was reduced by up to 24 dB, with detailed simula-tion of the final design predicting that targets would be met before any metal was cut.

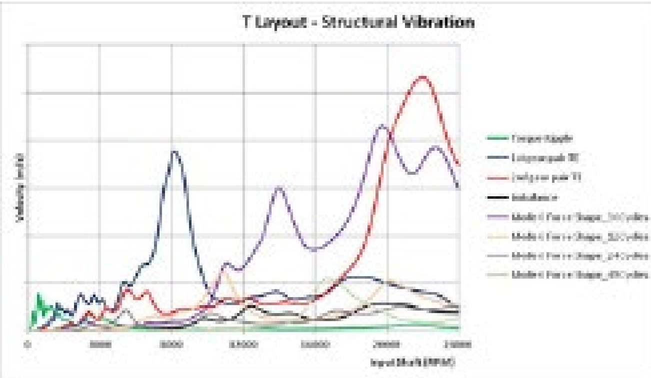

Figure 4 - Vibration response to representative unit vibrations across the full speed range, for all vibration sources

Conclusion

While it has been accepted that the most effective use of CAE is in the prediction and prevention of problems, until now the process of NVH simulation has been too slow to achieve this, and has been limited to correlation and elimination of problems once they have already occurred. CAE tools have often focused far too much on achieving greater capability of simulation (in isolation). The belief is that by modelling and analysing the world with greater levels of precision, then greater insight will be achieved and CAE will achieve its goal of engineering better products. However, the risk is that by targeting greater precision, the modelling and analysis process becomes far too slow and the results too difficult to interpret. Engineering insight is lost and results are not available in time to genuinely inform and shape the design process in the optimum ways.

Romax has shown that by using the correct analysis tools and by creating the right model at the right time, it is possible to simulate the noise from motors and to systematically target noise reduction during the design process. This represents a significant change from approaches used to date and directly targets the aim of CAE: engineering better products.

Through projects such as ODIN and in our own R&D and workshops, Romax has shown that at successive stages of the design process, the predicted peak levels of vibration can be systematically targeted and reduced. This represents a significant development that goes beyond what has been previously achieved – and we believe can significantly assist EV powertrains in achieving the design refinements required to make them acceptable for a mass market. The process can be illustrated using the V-model for system design and development. We are targeting insight at all points in the design process (the left hand side of the V) when it is cheaper and easier to fix, rather than waiting until the bottom of the V or, worse, until the end of the development phase when the full powertrain is finally assembled.

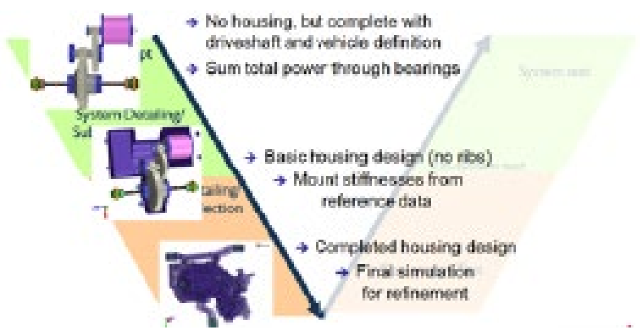

Figure 5 - Development and maturation of the simulation model - with reference to the V-model systems approach for design and development

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