Quietly Efficient Vehicles:
Reducing EV Powertrain Noise Without Compromising Efficiency

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Abstract. Late-emerging Noise, Vibration and Harshness (NVH) problems in an Electric Vehicle (EV) powertrain often occur due to unexpected interactions between excitation sources at a system-level. These are a high risk to businesses, as they are costly and generally lead to over-constrained NVH tolerances, at the expense of efficiency. This paper explores opportunities for quiet and efficient EVs. It focusses on a system-level approach to optimise powertrains for both NVH and efficiency. An Electrified Powertrain Optimisation Process (ePOP) developed in-house at Drive System Design allows the assessment of architectural decisions which impact both NVH and efficiency as early as the concept design phase. A system-level approach to NVH analysis then enables the study of interactions between the excitation sources, to reduce the risk of late-emerging NVH problems and identify the minimum trade-offs between noise and efficiency.

Keywords: NVH, efficiency, EV powertrains, system engineering

1 Introduction

Today, the market associates Electric Vehicles (EV) with technological innovation and refinement. Customers expect EVs to drive further than the market currently offers and are more sensitive to the level of acceptable noise produced.

Despite developments in design, analysis and testing capabilities, unexpected Noise, Vibration and Harshness (NVH) problems still occur late in the development process. These are often caused when the sub-systems, like the motor, the transmission and the power inverter, are brought together as a complete system and interact with one another, which typically occurs late in the conventional system V cycle.

These late-emerging NVH problems are a high-risk to businesses, especially when they occur after having invested in tooling and hardware. They can lead to retroactive design modifications, which are extremely expensive and generate delays, in a time when speed to market is critical.

Late emerging NVH problems can also lead to over-constrained NVH tolerances at the expense of efficiency. A loss of efficiency is likely to result in a decrease in range for the vehicle, as there are few opportunities to increase battery size or recover efficiencies from other systems at this stage in the vehicle development. Finally, over-constraining NVH tolerances increases manufacturing costs, as tight tolerances are required to avoid deviation.

If there was a way to study the effects of interactions between different excitation sources, evaluate NVH, and study performance criteria before key architectural decisions were made, manufacturers could increase the likelihood of offering attractive electrified powertrain solutions to the market in terms of noise, cost and range.

Therefore, Drive System Design (DSD) has developed an innovative approach to study the NVH performance of EV powertrains at a system-level.

First, to find the most efficient powertrain configuration and start assessing architectural decisions which impact efficiency as early as the very beginning of the system V cycle, DSD created an Electrified Powertrain Optimisation Process (ePOP).

Then, as the main challenge is to analyse the complex interactions between the different noise-generating sources, DSD developed a system-level approach to NVH management. While the conventional approach is to find a compromise between efficiency and NVH at a component-level, this novel process ensures that the system NVH can be delivered. It accounts for all the major excitation sources and expands the range of design parameters which can be optimised to both mitigate the risk of elevated noise produced by the powertrain and achieve high efficiency.

Finally, a case study illustrates how the system-level study of electrified powertrains can reduce the occurrence and severity of late-emerging NVH issues.

2 The need for a system-level approach to NVH analysis

Nowadays, with the advances in technology, EV powertrains are becoming more highly integrated. The electric motor, the power inverter and the transmission are included in the same structure. These elements generate excitations which interact within the same design space.

As a result of this high level of integration, the system could fail to meet global NVH targets due to compounding interactions between the excitation sources, even if each sub-system is optimised individually to meet its own NVH target. Therefore, it is essential to analyse and understand these excitations sources at a system level as this will avoid expensive, unexpected late-emerging NVH problems.

2.1 The main contributors to NVH

The three main elements contributing to NVH in an EV powertrain are the electric motor, the power inverter and the transmission [1].

As a Permanent Magnet Synchronous Motor (PMSM) is a popular solution for EV powertrains for its high efficiency, high power density and its compact structure [2], this paper will focus on this type of motor.

Transmission

In a transmission, excitations can be generated by the gears. This phenomenon is known as gear whine and originates from vibrations excited by Transmission Error (TE). TE is defined by Welbourn [3] as “the difference between the actual position of the output gear and the position it would occupy if the gear drive were perfectly conjugate”.

TE is influenced by several factors, including gear macro- and micro-geometry, a change in stiffness of the gears or the surrounding systems, assembly misalignments and manufacturing errors, for example.

The vibrations excited by TE are transmitted through the shafts and bearings and into the casing, which excite the structural resonances and generate gear whine.

Electric motor [4]

In a PMSM, excitations can be generated by electromagnetic forces. This phenomenon is known as whistling.

The electromagnetic forces are generated by the airgap radial flux density. These forces can be decomposed into axial, tangential and radial force components at any point in the air gap. Radial force harmonics generate radial vibrations of the stator, while tangential force harmonics create a bending moment of the stator teeth, generating radial vibrations of the stator. Tangential forces also generate torsional vibrations of both the rotor and the stator, which presents a high NVH risk.

The vibrations excited by the electromagnetic forces are transmitted through the stator and into the casing, which excite the structural resonances and generate whistling.

Power inverter

A power inverter converts a DC power source into an artificial AC power source to supply the electric motor, often in three phases. It uses Pulse Width Modulation (PWM), a control strategy using series of switching operations. The frequency of the AC source can be controlled by the switching strategy of the PWM.

The resulting current waveform supplied by the PWM is not a perfect sine wave, and therefore contains a lot of higher order harmonics. These harmonics influence the electromagnetic forces mentioned earlier, which presents an NVH risk.

There are several different ways to reduce the harmonic content of the excitation sources. However, many design parameters to optimise NVH result in reduced efficiency. The following section will analyse the trade-offs between the two attributes.

2.2 Trade-offs between NVH and efficiency

Transmission

Gear TE can be reduced by changing the macro- and micro-geometry of the gears, in order to optimise the contact ratio and minimise the variation of stiffness caused by the gear teeth moving in and out of mesh.

An example to reduce the NVH risk caused by gear whine is to increase the helix angle of the gear set. The downside is that it increases the axial loads in the bearings and reduces efficiency. Another way to increase the contact ratio, and therefore reduce NVH, is to increase the tooth height (increasing the addendum and dedendum of the teeth). But, increasing the tooth height increases tip sliding speeds, generating higher frictional losses, and therefore reducing the efficiency of a gear mesh.

Electric motor

The electromagnetic forces generated by the electric motor can be reduced by modifying some of the design parameters, such as the pole combination, the magnet shapes or adding skew angle.

Skewing a rotor can cancel torque ripple or radial force harmonics. However, adding skew angle to a rotor reduces the back electromotive force of the motor, reducing its overall performance.

Power inverter

The amplitude and frequency of the harmonics generated by the PWM are directly related to its switching frequency.

Increasing the switching frequency of the PWM reduces the amplitude of the current ripple harmonics due to the inductive reactance of the system. However, increasing the switching frequency of the PWM increases the associated switching losses, reducing the overall efficiency of the power inverter.

2.3 The need for a system-level approach

In a highly integrated powertrain, several design choices impact both NVH and efficiency. It is therefore important to consider the two attributes early in the design process to avoid late-emerging NVH issues which lead to over-constrained NVH design parameters, at the expense of efficiency and cost.

The next section will present DSD's novel system-level approach to powertrain analysis to ensure the NVH performance is achieved while minimising the effect on efficiency.

3 System level approach of DSD

To help manufacturers evaluate NVH against other performance criteria before key architectural decisions are made, DSD has employed its extensive design knowledge of all the major EV powertrain elements, coupled with its analysis led design methods, to develop an innovative approach to powertrain design and NVH management. Right from the start of the development process, it is possible to find a trade-off between NVH and efficiency.

The first step is to use an electrified Powertrain Optimisation Process (ePOP) which enables the most efficient powertrain variant to be found. It also allows the selection of architectures considering fundamental aspects of NVH, like the choice of skew angle, rotor poles or gear ratios for example.

This most efficient configuration can then be taken to a more detailed phase to analyse its NVH performance at a system-level by studying the interactions between different excitation sources. A trade-off between NVH and efficiency can then be found.

Combining ePOP and a system-level approach to NVH analysis allows the design of a powertrain which is both quiet and efficient. It allows for the impact of the numerous design parameters to be assessed at the earliest stages in the design before any significant investments of resources, time and money have been made. This ensures that the detailed design phase has significantly reduced risk of system NVH problems and minimises the need for design iterations, which are lengthy in this later phase.

3.1 Finding the most efficient powertrain solution using ePOP

ePOP is a powertrain optimisation tool which models each element of the powertrain, as well as the vehicle, as part of one simulation process. It is based on vehicle specifications and requirements. Vehicle specifications can include kerb mass and payloads, wheelbase geometry, aerodynamic coefficients and tyre friction coefficients. Requirements can include maximum speed, required torque at wheels, acceleration times or minimum gradient. These targets are inputs to the vehicle model, and ensure that only the powertrains that meet vehicle requirements are analysed. Figure 1 illustrates the overall process map of ePOP.

The specifications and requirements are fed into a vast library of power inverter, motor and transmission designs. The designs are then combined to generate thousands of powertrain variants, unaffected by human bias, subjective views, or opinions. These powertrain variants are then simulated against different drive cycles and performance targets specified as inputs. ePOP then allows the comparison of the powertrain configurations against efficiency, cost and mass and to determine trends based on the choice of subsystem.

The cost is based on the current market pricing of materials and manufacturing, and can be tailored by the customer.

The energy consumption is calculated from component losses. For the transmission, bearing, mesh, churning and seal losses are considered. For the electric motor, copper, iron and magnet losses are taken into account. For the power inverter, gate switching, gate conduction, diode switching, and diode conduction losses are considered.

The mass is calculated from the material density and component sizing based on torque, gear ratios, input peak and continuous power required.

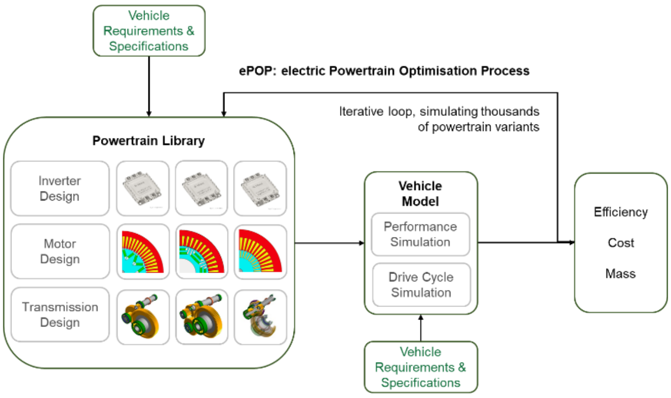

Fig. 1. Process map of ePOP

ePOP allows the identification of the most efficient powertrain variant depending on the customer's requirements and the vehicle specifications. This output can be taken to a more detailed design phase to analyse its global NVH performance.

3.2 Analysing the NVH performance of the powertrain using a system-level approach

Following the ePOP study, the chosen powertrain can be designed using SMT's MASTA software package, a Computer-Aided Engineering software suite for "the design, simulation and analysis of driveline systems" [5]. The excitation sources of the main contributors to NVH can then be imported to MASTA, and the system-level NVH can be analysed.

Harmonic calculations

Once the powertrain is designed, the different excitation sources from each powertrain element can be calculated so that all inputs can be assessed as a system.

Gear TE can be directly calculated in MASTA, depending on the macro- and micro- geometry of the gears.

Detailed models of electric motors can be created through different motor design software packages, like Motor-CAD or Altair's Flux. The electromagnetic forces and associated harmonics can then be calculated. The efficiency maps of the motors can also be generated and used in ePOP to evaluate its performance.

Finally, DSD has designed a validated power inverter modelling tool to simulate the effect of the power inverter on the motor harmonics. Based on the direct axis inductance (Ld) and quadrature axis inductance (Lq) values for a given operating condition calculated in the motor design package, the power inverter modelling tool simulates the effect of the switching frequency on the motor current. The generated harmonic current spectrum can be injected into the motor design tool to simulate the effect of the PWM on the NVH performance of the motor.

System-level NVH analysis

The motor excitations, including the effect of the power inverter's switching frequency, can be imported into MASTA. Gear whine excitations are calculated in MASTA based on the macro and micro-geometry of the gears. The excitations are then transformed into harmonic content (amplitude and phase depending on the harmonic order) using the Fourier Transform.

To evaluate the forced response of the system to these excitations, and therefore the global NVH performance of the powertrain, sound power can be calculated at the surface of the entire housing. Sound power is the energy of sound emitted by the casing, per unit of time. Sound power can be chosen as an NVH parameter to study, as it can be related to sound power level, measured in decibels (dB), and therefore to the level of acceptable noise for a human.

The sound power in response to each harmonic content can be determined. To evaluate the worst-case scenario, the sound power level in response to each excitation source is superimposed. This method allows the study of interactions between excitation sources and predicts potential NVH risks.

The following section will present a case study to illustrate the system level approach DSD has developed.

4 Case study

4.1 Case study presentation

For this case study, an electrified powertrain was optimised using ePOP. As previously mentioned, ePOP is based on vehicle specifications and requirements.

The intended powertrain application was a supermini electric vehicle which needed to reach at least 130 km/h. It had a fixed battery capacity of 50 kWh. It needed to be rated against the Worldwide harmonised Light vehicle Test Procedure (WLTP) drive cycle, a standard used to measure fuel consumption and CO2 emissions of passenger cars. [6]

Four different single-speed arrangements were considered: a two-stage parallel axis, a three-stage parallel axis, a single-stage into a planetary arrangement and a planetary arrangement into a single stage. They were analysed for cost and energy consumption, depending on the gear ratios.

An Insulated-Gate Bipolar Transistor (IGBT) power inverter and a Silicon Carbide (SiC) power inverter were compared for cost and efficiency.

A 48-slot, 8-pole interior PMSM was used. The rotor skew angle was analysed for NVH and efficiency.

4.2 Finding the most efficient powertrain solution using ePOP

Hundreds of powertrain variants were generated to meet specifications and requirements. ePOP allowed to compare the powertrain variants for cost and energy consumption, depending on the choice of sub-system.

Cost and energy consumption trade-off

The following graph shows the cost and energy consumption comparison of several powertrain variants depending on the design choice of the sub-systems.

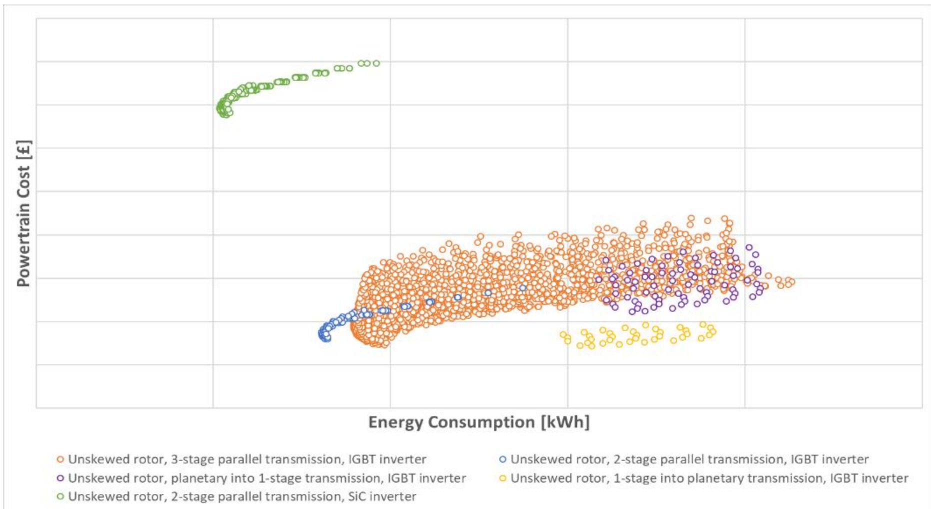

Fig. 2. ePOP results depending on the choice of power inverter and transmission

Each dot represents a powertrain variant with a combination of power inverter, motor and transmission arrangement.

Two distinct clusters can be identified in Figure 2, depending on the choice of power inverter. For the same motor and transmission, a SiC power inverter (top, green cluster) is more expensive and more efficient than an IGBT power inverter (lower cluster).

The lower cluster shows, for the same IGBT power inverter and the same motor configuration, the effect of different transmission arrangements on cost and energy consumption. As a two-stage parallel transmission has fewer bearings and gear meshes than the other configurations, the powertrain losses are reduced, making it a more efficient solution.

ePOP allowed the study of trends based on design choices for the power inverter, motor and transmission arrangement. Based on this preliminary analysis, the most efficient solutions which met the requirements of the customer were developed into a more detailed design.

ePOP also enabled the preliminary assessment of NVH and efficiency trade-offs between fundamental design choices, such as the design of the rotor, the number of poles, or the gear ratios for example. The following section presents an example of a high-level trade-off between NVH and efficiency depending on the rotor skew angle.

Early assessment of NVH and efficiency trade-off

The study was continued with the two-stage parallel axis configuration with an IGBT power inverter, as the ePOP study showed it was a cost-effective and efficient solution.

The effect of rotor skew on cost and efficiency was studied, as seen in Figure 3.

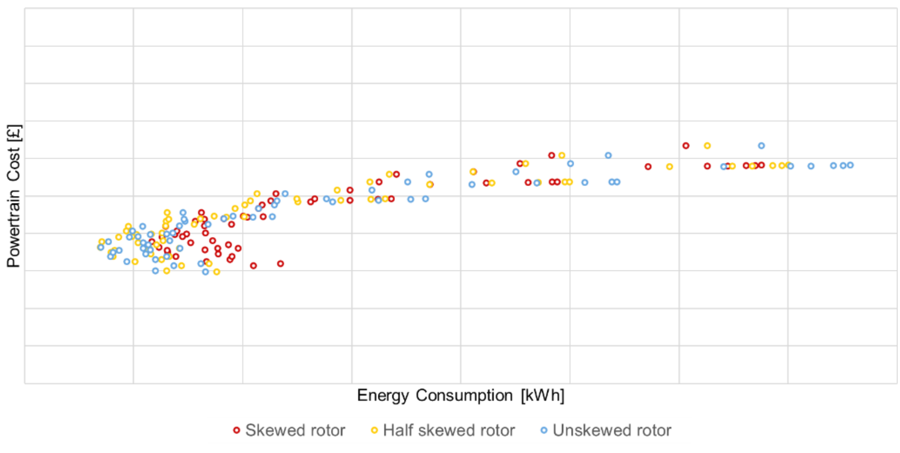

Fig. 3. ePOP results depending on the choice of rotor design

For the optimal designs for cost and energy consumption, tending towards the left of the graph, the most efficient solutions are with the unskewed and half-skewed rotors. As mentioned previously, adding skew angle reduces the back electromotive force of the motor, reducing its overall performance. This explains why the powertrains with a skewed rotor have a higher consumption for the same given drive cycle simulation.

However, the ePOP study shows that the powertrain variants with an unskewed or half-skewed rotor have similar energy consumptions, which mean they are as efficient over the drive cycle. As adding skew angle to a rotor reduces the harmonic content of the electromagnetic forces, choosing a half-skewed rotor would be the solution to both minimise the risk of NVH problems and maximise efficiency.

4.3 From ePOP to a system-level NVH analysis

Therefore, ePOP can be used to assess, as early as the concept design phase, architectural decisions that impact both NVH and efficiency.

Based on the results from ePOP, a full non-linear system model of a single-speed, two stage parallel axis transmission was designed, as seen in Figure 4. The casing and the mounting points to the vehicle were included.

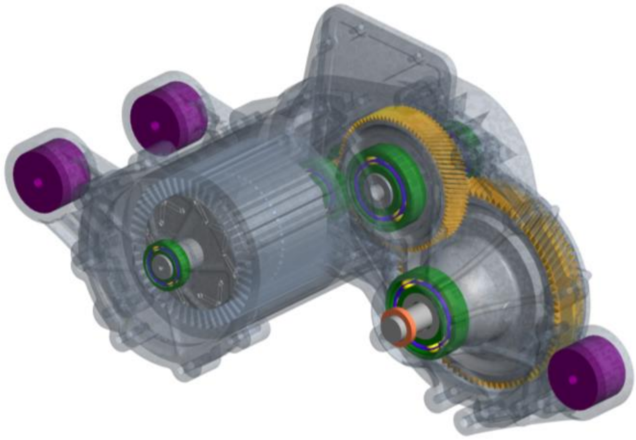

Fig. 4. 3D MASTA model of the designed powertrain

The torque ripple and stator radial forces of the three motor configurations previously mentioned (unskewed, half-skewed and skewed rotors) were imported into MASTA. Different gear sets with varying TE were designed to study the effect of gear whine on the system NVH performance.

To simplify the NVH case study, the effect of the power inverter's PWM switching frequency on the motor harmonics were not included.

The sound power level can be calculated at the surface of the casing.

4.4 System-level approach to NVH analysis

The following graphs shows the superimposed sound power response to the different harmonics interacting in the system, depending on the electric motor input speed. The sound power is evaluated against a threshold based on the level of acceptable noise for a customer.

A base design, represented in red in Figures 5 and 6, was created. The rotor is not skewed and the gears are not optimised for TE. The base design was used as our reference, as it is very efficient but has a high NVH risk. The sound power level of this base design goes above the threshold at both low and high speeds.

The graphs in Figure 5 illustrate the impact of optimising components for NVH in isolation.

A second powertrain, represented in dark blue, has gears with a very low TE. Nevertheless, the study shows that the sound power level still goes above the threshold. This powertrain is also less efficient, as optimising gears for TE has reduced their efficiency. It is also costly, as the optimisation loops to reduce TE are time-consuming, and manufacturing tolerances need to be tight as the gear response is sensitive to manufacturing deviation.

A third powertrain, as represented in grey, has a rotor with the maximum allowable skew angle, which reduces the harmonic content of the electromagnetic forces of the motor. But the study shows that optimising the motor in isolation does not improve the overall NVH performance of the powertrain. This means that the different excitations interact at a system level, which generates unexpected NVH problems. This is also at the expense of efficiency, as increasing the skew angle of a rotor reduces its performance, or requires it to be larger for the same torque/power requirements.

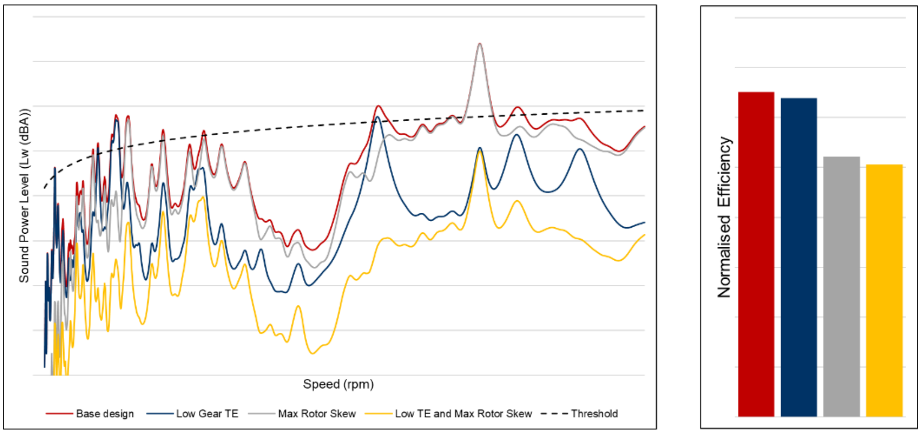

Fig. 5. Sound power analysis of the system when components are optimised in isolation

This study shows that even when components are optimised individually, NVH problems can still occur at a system level due to the interactions between excitation sources. These interactions are often the origin of late-emerging NVH problems, which are a high risk to businesses.

A fourth powertrain option, in yellow, has all its NVH tolerances over-constrained. The gear TE is very low and the rotor skew angle is maximal. The sound power level evaluation in Figure 5 shows that the NVH performance is over-achieved, at the great expense of efficiency and cost.

A system-level approach incorporating all of the powertrain element excitations is required to avoid unexpected late-emerging NVH issues, which lead to over-constrained NVH tolerance at the expense of efficiency and cost.

A final powertrain was designed, as seen in light blue in the Figure 6. The overall sound power level was reduced below the threshold, while the impact on efficiency was minimised compared to the base design.

Achieving both NVH and efficiency targets was possible as the NVH analysis was conducted early in the powertrain development process, which allowed flexibility to make architectural decisions which impact both NVH and efficiency.

For this powertrain, the number of teeth of the input pinion was modified to avoid gear whine harmonics and motor harmonics interacting at the same order. Therefore, the gear tooth number can be chosen to have the least impact on the system-level NVH performance of the powertrain.

Adapting the tooth number also enabled the reduction of tolerances on TE, which reduces manufacturing costs and increases efficiency. It also presents the opportunity to choose the motor with only half of the maximum skew angle possible. As mentioned in section 4.2, the half-skewed rotor is almost as efficient as the unskewed rotor but has the advantage of reducing NVH.

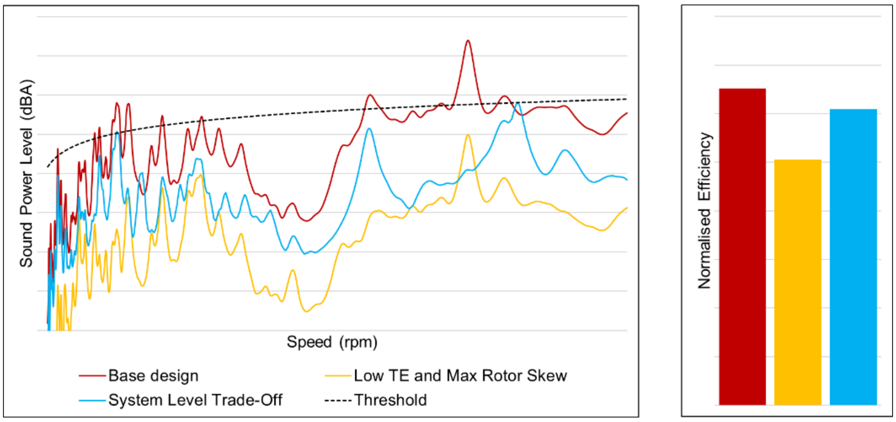

Fig. 6. Sound power level analysis of a powertrain optimised for NVH at a system-level

As a result of the system-level approach to NVH analysis, a powertrain was designed with fewer constraints. It met NVH requirements while achieving high efficiency compared to the base design, and with a reduced cost.

5 Conclusion

The electrification of powertrains is increasing. This creates opportunities to optimise the systems to have highly-integrated and efficient powertrains. However, integrating the components in the same design space generates new NVH challenges, as the risk of the sub-system excitations interacting is increased, which means that analysis on the individual elements of the powertrain in isolation has only limited value.

DSD's innovative system-level approach to NVH analysis presented in this paper allows the interactions between different excitation sources to be analysed and managed in a highly integrated powertrain. This is enabled by DSD's deep understanding of the design of each of the powertrain elements (transmission, motor and inverter) and its advanced analysis-led-design approach. While this process can add a small amount of extra time to the concept design phase, the system-level NVH analysis reduces the time spent iterating the detailed design of each powertrain element and more significantly reduces the occurrence of late-emerging NVH problems, which can take months to resolve, potentially holding up the vehicle validation phase. It also allows the design of powertrains with an extended range, as the system-level approach enables the delivery of a powertrain with maximised efficiency, and for this efficiency attribute to be protected through the design.

The electrified Powertrain Optimisation Process (ePOP) allows the identification of the powertrain configuration which has the maximum efficiency potential. It can also enable key architectural decisions considering both NVH and efficiency, as early as the concept design phase. Drive System Design has found that a system level approach to NVH is a powerful mechanism to meet customer noise requirements, while minimising the impact of the design choices on efficiency. Combining ePOP and a system-level approach to NVH allows the design of quietly efficient vehicles.

6 References

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