SOLVING NVH ISSUES IN HYBRID AND EV POWERTRAINS

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ABSTRACT

This paper discusses the potential conflict that can occur between vehicle and transmission teams regarding NVH issues when developing future electric and hybrid technologies. With over twenty successful projects across a period of four years, Drive System Design have developed valuable experience in solving such conflict in real world applications.

The automotive industry is facing increasing pressure, both from legislation and consumers, to provide “greener” vehicles; reducing emissions and fuel consumption. As a result, development of vehicles utilising electric drive systems in combination with, or instead of, traditional combustion engines, are becoming increasingly common. With the noise produced by traditional combustion engines either intermittent or eliminated entirely, noise from the vehicle transmission and driveline is an area of greater interest as a larger proportion of the overall vehicle noise. Design limits have become more stringent as the level of acceptable transmission noise has fallen.

This paper aims to discuss the range of obstacles encountered and the processes developed that allow Drive System Design to resolve such NVH issues. Significant challenges exist in the optimisation of both micro and macro gear geometry in order to reduce the magnitude of excitation. This must be combined with modal separation analysis to define the NVH issues at both a system and component level. Concurrent design and analysis using these methods has proven to be the only way to ensure that all aspects are effectively considered and addressed.

INTRODUCTION

Due to both consumer and legislative pressures, there is currently a strong industry focus on hybrid and electrically powered vehicles. As the volume of production of these kinds of vehicles has increased year on year [1], the demands related to NVH have also increased both in quantity and variety. Solving these problems can be very complex. In a vehicle solely powered by an internal combustion engine, acceptable noise limits are determined primarily by what can be heard over the internal combustion engine. In hybrid or purely electrically powered vehicles, this engine noise may be intermittent or even completely removed, making any drive train noise much more prominent. These developments in technology have resulted in previously established targets being outgrown. With the new limits imposed by the challenges of electric and hybrid vehicles, problems that arise in pre-production may ultimately be unnecessarily costly to resolve. Those who have anticipated these trends have developed tools and verified targets that allow a thorough system assessment and creation of effective solutions.

A theme that commonly arises has been the conflict between component and system design teams as to where the root causes of NVH issues lie. Should these issues be resolved through redesign of the components which cause excitation or through changes to structures that respond to it?

A common misconception is that NVH issues can be fully resolved through effective gear micro geometry design. If sufficient emphasis is not allocated to NVH in the design process, issues can come to light when volume production is imminent or even underway. In these situations, a solution that results in minimal impact to manufacturing is paramount and further drives the search for a gear micro geometry solution. However, experience shows that the root cause in NVH issues can originate from a range of sources, and as such it is no surprise that difficulties can be encountered by limiting the search for a solution in gear micro geometry alone. This paper will discuss the way in which NVH issues can be caused, as well as the way in which they can be analysed and solved. A full system approach is the only way in which interactions between components can be evaluated, and any conflict between design teams can be resolved. It is shown that while gear micro geometry design is undoubtedly a source of NVH improvement, the most effective solutions may actually be achieved through the design of gear macro geometry, transmission housing, supporting structures (mounts, brackets, sub-frames), as well as prop shaft and drive shaft design.

WHY USE A SYSTEM APPROACH?

As outlined above, NVH issues have to be approached on a case by case basis at a system level, and this can only be achieved by using a range of analysis tools and software. By using full system analysis tools, the interaction of components within the system can be assessed. As most NVH issues are typically load dependent, it is critical for the deflection of the system and resulting misalignments of shafts, bearings and gears to be accounted for. Finite element analysis (FEA) must be used in order to determine the stiffness of more complex components, such as gear wheels with high aspect ratios, or complex weight saving modifications and differentials, as well as the transmission housing and supporting structures. The results from the FEA must then be integrated within the analysis model.

Experienced judgement must be used in order to determine the extent of the drive train system that is considered within the analysis model. Once the model is complete, an assessment of the full system behaviour across a specified torque range can be made, and potential contributors to NVH identified. As with all simulation, the model becomes most useful once correlated with physical testing. In such drive train systems, transmission error is considered to be the source of excitation, but there are challenges associated with measurement. Transmission error alone is not always the cause and therefore often the best correlation is to measure the response of system in critical areas.

Once this correlation has been established, this analysis model can be used as the baseline from which performance criteria can be specified. Subsequent effects on the system NVH of proposed design changes can be compared directly to the baseline, as the sources and effects of NVH contributors are identified and reduced. These changes can influence the excitation of the system, typically through gear design, or the way the system responds to excitation. This may result in design changes to housings or support structures. A range of design solutions can then be investigated and compared with the defined performance criteria. After evaluation of the proposed designs has occurred, prototype components can be manufactured and physical testing repeated to verify design decisions.

CONTRIBUTORS TO NVH

There is no singular primary contributor to NVH issues encountered in transmission and drive train systems, and as such there is no singular solution either. Each system design is unique and as such should be investigated thoroughly to determine the unique way in which it responds to applied loading. Depending on the system, the issue may originate as a result of the gear micro or macro geometry, the transmission housing or supporting structures, or as far as the mounting bushings or surrounding sub-frame. It would therefore be a mistake to suggest that NVH issues can be solved solely through effective application of gear micro geometry, or any other singular method.

At component level, the potential effect on NVH of the gear design is judged predominantly by the peak-to-peak transmission error (TE); the departure from uniform relative angular motion of a pair of meshing gears. TE is influenced by all deviations from an ideal tooth form, due to design or manufacture, as well as the conditions under which the gears operate [2]. However, the most common factor is how the gear mesh operates under load.

At a system level, the vibration caused by the TE acts as the key source of excitation for the dynamic response of the drive train. Acting crudely as an amplifier or speaker, the design of the transmission housing and supporting structures dictate the way in which the TE is translated into a vibrational response and subsequently noise. A transmission housing designed with only structural requirements in mind may act to amplify TE that is within targets into unacceptable audible noise. This effect can be further magnified if the meshing frequency of the gears aligns with a natural frequency of the housing or supporting structures, resulting in resonance and increased audible noise [3]. In contrast, it is also possible for TE exceeding defined targets to be successfully by damped by an effective support structure. It therefore becomes vital to consider every element of the drive train as potential contributor to NVH, and to realise that consideration of each throughout the design process will provide the most efficient solution.

THE GEAR DESIGN APPROACH TO NVH REDUCTION

With this in mind, it is still good practice to start at the source of the system excitement. Alterations in gear micro geometry typically have relatively small impact on manufacturing processes and tooling, and are therefore the main area of focus for NVH issues after the design is frozen. To optimise gear design for NVH, it is necessary to have a thorough understanding of the detailed design of gear tooth geometry and how it can influence the meshing of gears. Optimisers used in software packages are not currently able to replicate this.

Experience must also be used in the generation of application specific TE targets. For example, while some profile corrections may be able to reduce TE at high load, or improve the distributions of contact pressures across the tooth, deviations from the true involute form typically result in an increase in TE at low torques [4].

Gear macro geometry can potentially be more important to a low NVH system than micro geometry. Typically, the primary concern in gear macro geometry design is the durability of the gears. With cars powered by an internal combustion engine, NVH targets could be typically be met by effective use of gear micro geometry. Relatively little focus on NVH was required in the gear macro design process. Due to more stringent targets, this is not necessarily possible in hybrid and EV drive trains.

In aiming to reduce TE using micro geometry alone, it is sometimes necessary to compromise between targets; compromising the durability of gears in order to reduce TE. This can be seen in Figure 1 and Figure 2 which show the effects of altered gear micro and macro geometry on the TE and durability respectively. Both the TE and safety factors have been normalised by the values obtained from the original design. The effect of the proposed design changes is quantified as a percentage of the original design.

It can be seen that TE is reduced across the torque range in Figure 1 by making changes to the gear micro geometry design. However, this improvement has resulted in compromised durability, with the bending and contact safety factors [5, 6] reduced slightly in Figure 2. In contrast, when the gear micro and macro geometry have been designed concurrently, the TE has been reduced further still over the entire torque range. Bending and contact durability safety factors have increased relative to the original design for both the pinion and wheel. As with the gear micro geometry design, there is no one rule to apply to gear macro geometry design in order to reduce TE. As with all complex processes, experience is critical to determining the most appropriate solutions to the application.

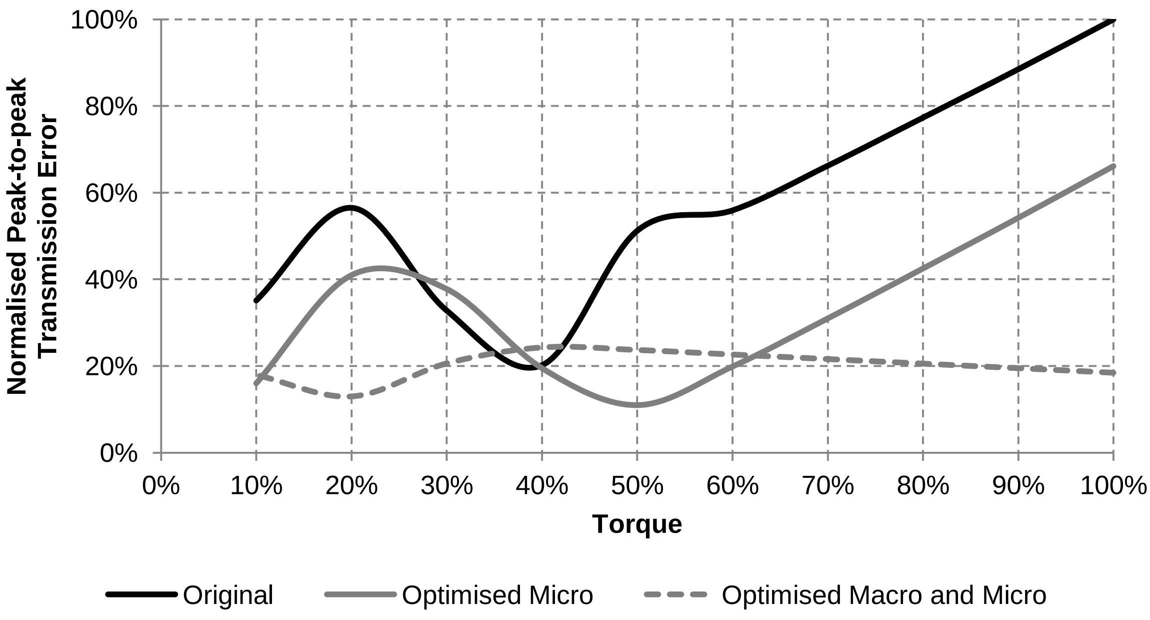

Figure 1 - Example of the effect of gear micro and macro geometry design changes on peak-to-peak transmission error.

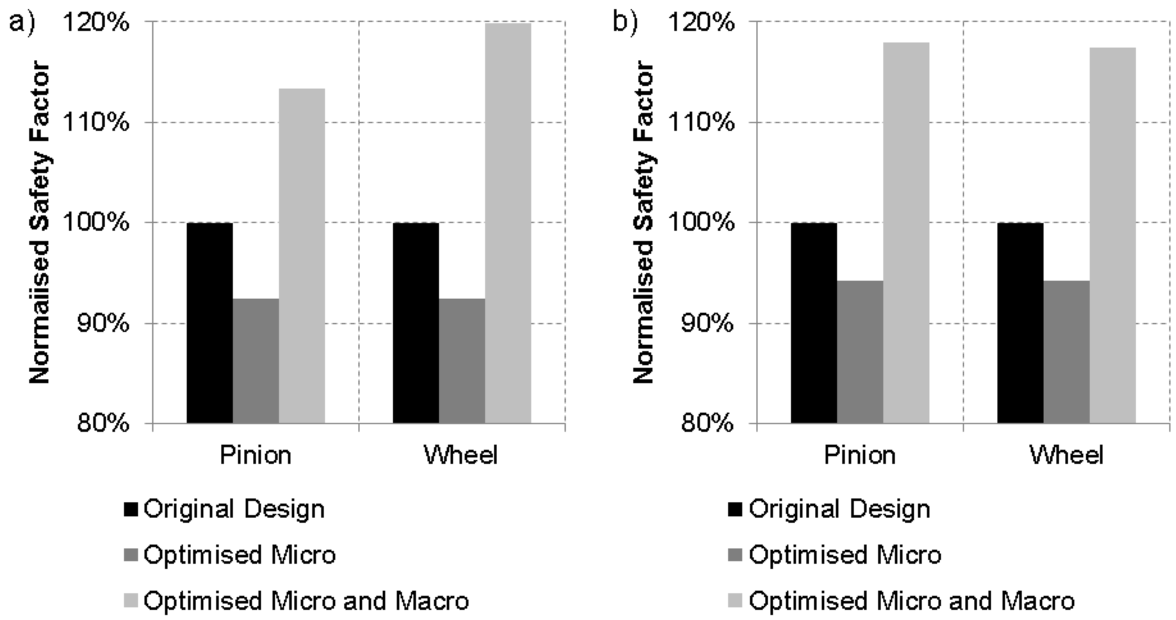

Figure 2 - Example of the effect of micro and macro geometry design changes on gear safety factors according to BS ISO 6336; a) bending safety factors [5], b) contact safety factors [6].

NVH OF BEVEL AND HYPOID GEARS

Bevel and hypoid gears can present NVH challenges over and above those presented by spur and helical gears. The underlying design principal is similar to that of spur or helical gears, in that a full system approach is necessary to evaluate and reduce NVH issues. Again, TE in bevel and hypoid gears is usually considered to be the source of the excitation for dynamic response. Difficulties arise in the manufacturing processes that limit the geometry and tolerances that can be achieved.

As NVH concerns in axle design become more prevalent, the integration of the manufacturing limitations into the design process is essential to the further development of low noise axle design. As yet, there is no integrated software that enables the design of bevel and hypoid gears for low NVH. Therefore, a wide range of analytical processes and software is required. A full understanding of manufacturing techniques and complex gear geometry is needed to reduce the number of iterations in the process from initial design to final product. Formalising specification and inspection processes that allow bevel and hypoid gear geometry to be more effectively controlled will in turn provide a more consistent low NVH solution.

DRIVE TRAIN SYSTEM RESPONSE

Outside of the gear design, further design choices can affect the NVH performance. The dynamic interaction between the gear mesh and supporting structures play a significant role in determining how much noise is created as a result of the TE [7]. Statically, the deflection of the transmission housing under operational loads can result in misalignment of bearings, shafts and gears and affect the transmission error. Dynamically, other components such as prop and drive shafts, as well as housings and supporting structures may respond to the vibration generated by gear mesh transmission error to create audible noise. Relatively large, unsupported panels in particular may crudely be described as “speakers”, amplifying the vibration. The design of the components may also result in the gear mesh frequencies and the natural frequency modes of the system aligning, resulting in responses of significant magnitude. NVH should be a consideration in the housing design process but changes in response can be made with surprising small modifications to existing designs, while or structural requirements are still met.

To analyse these effects, finite element analysis of complex components is necessary to determine the way the system responds in six degrees of freedom. Stiffness and mass are crucial to this response. Fully meshed component analysis is a resource intensive exercise that can be effectively replaced by stiffness and mass matrices created used component mode syntheses (CMS). Using CMS provides a quick and effective way of including complex components in the analysis, in comparison with using a full stiffness model. Virtual accelerometers are used to provide simulated response measurements that can be compared against real life test data. This is the most effective way to correlate simulated and test measurements due to the relative difficulty in measuring transmission error.

Modifications can be made to housings and supporting structures to stiffen flexible regions, aiming to reduce the magnitude of measured response and either separate natural frequency modes, or move them completely from the audible range.

Figure 3 shows the effect of proposed design changes on the forced response of a system. This shows the response in terms of acceleration, measured at a specific virtual accelerometer position, allowing direct comparison of the incremental improvements made by changes to the gear design and the transmission housing. The housing design modifications were driven by the analysis performed on the baseline model, identifying regions in which high strain energy occurs. The changes proposed were relatively small; adding and altering existing features to increase the stiffness in these regions. In each case, the responses have been normalised by the largest magnitude response from the original design. This can be seen at approximately 1.25 kHz.

It can be seen that the magnitude of the response can be greatly affected by each of the proposed design modifications. Gear micro geometry changes have resulted in a reduction of almost 50% of the response found to occur at approximately 1.25 kHz. Further reduction in response can be achieved through gear macro geometry. The same peak has reduced to less than 20% of the original design, and less than 40% of the improved response achieved using only gear micro geometry. A subsequent improvement to less than 10% of the original response could be achieved by making changes to the transmission housing. This corresponds to less than 20% of the response using optimised gear micro geometry. Even with optimised gear geometry, small changes in the housing design have reduced the response by an additional 50%.

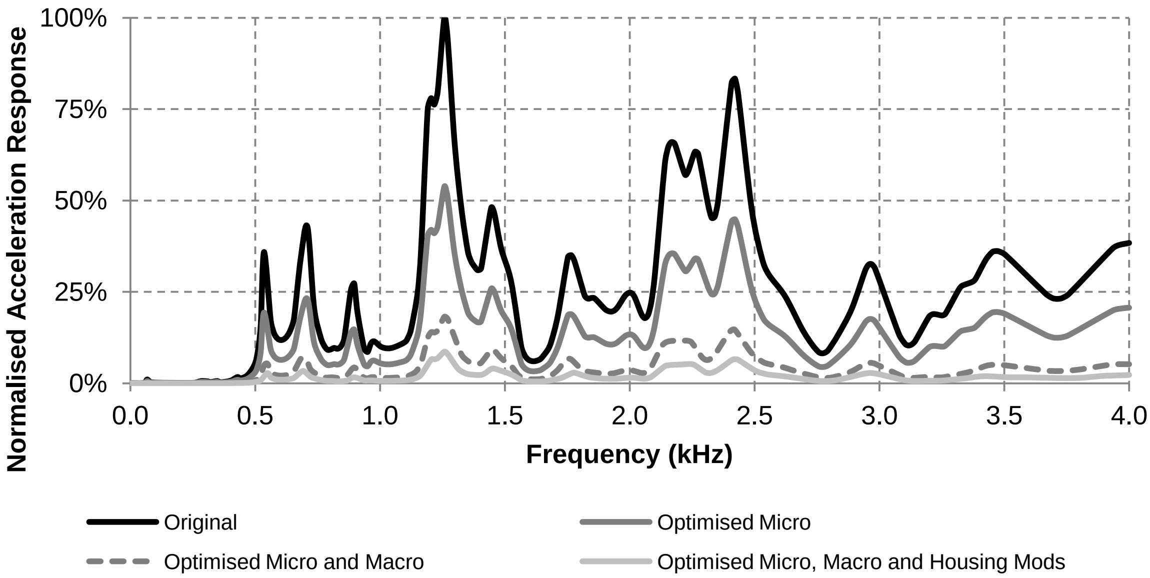

Figure 3 - Example of the effect of design changes on the acceleration response at a virtual accelerometer position on the transmission housing.

While the improvement in NVH is clear, each of these design changes has implications in terms of cost and timing. The greater the improvement of the solution, it is likely that the cost increases accordingly also. If production is already imminent when the problem arises, changes to housing tooling are likely to cause significant costs. It is therefore crucial to understand the requirements of the system, allowing relevant targets to be defined, based on experience in similar applications. This ensures that the most cost effective solution can be determined. The most cost effective manner of produced a low NVH drive train, is to consider NVH from the start, ensuring that NVH is considered throughout the design of each component.

CORRELATION OF SYSTEM ANALYSIS

As with all simulation work, correlation with physical testing is crucial in order to confirm that the results are meaningful. At the gear mesh, TE is typically used a measure of the potential effect of the gear design on NVH. TE is often measured using single flank test measurements utilising optical encoders [3], but by using such test rig measurements, influences from the rest of the system are ignored. A simpler method of seeking correlation is through employing accelerometers, comparing the responses measured in testing with those from simulation at critical locations. This has the advantage of considering the system as a whole, with less specialist measuring equipment required, but also requires more of the system components to be available.

Figure 4 shows an example of correlation between accelerometer test and simulation data. It can be seen that the analysis model has managed to capture the key features in the response of the system across the range of frequencies in question. However, some differences still exist. The response at 3.0 kHz for example is not as large in the analysis model as was found to occur in testing, while noise exists in the test data that would not be expected to be recreated in the model. In circumstances where time is restricted, a full correlation study is impractical. However, it is possible to develop application specific targets for both TE and magnitude of response that are proven to transfer from analysis to production.

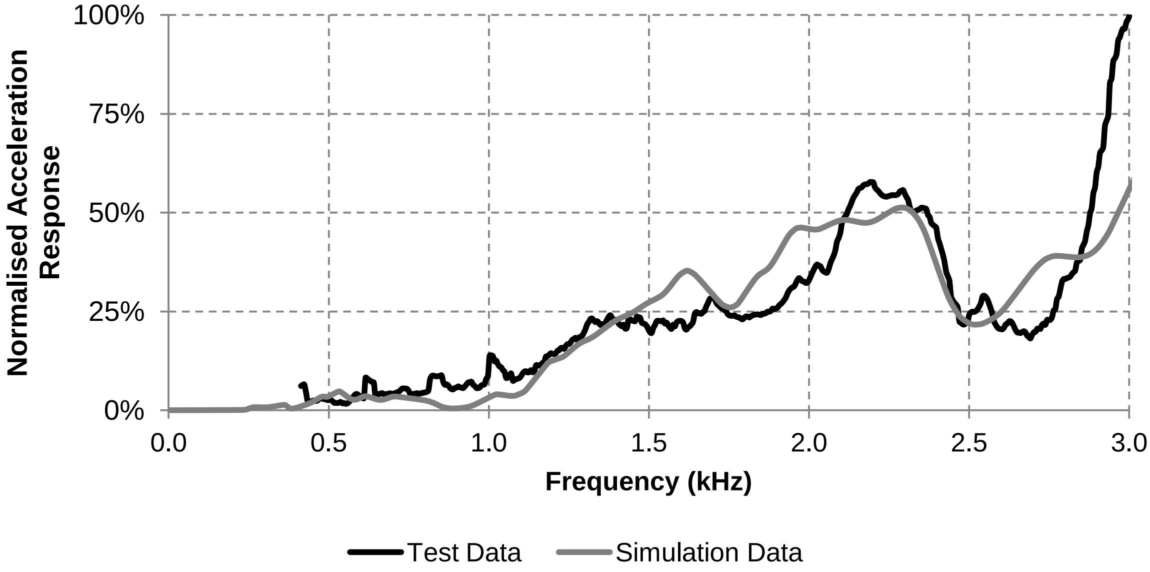

Figure 4 - Example of a correlation of test and simulation response data at a specific accelerometer location.

THE EFFECT OF MANUFACTURING ON NVH

However, even if all of these areas have been thoroughly considered throughout the design process, NVH issues can still arise if due consideration is not given to the manufacturing tolerances to which the designed components are made. For example, a nominal gear micro geometry design may show that TE targets are met across the torque range of the gear set. However, when the manufacturing tolerances are considered, gear geometry parameters will vary between a maximum and minimum value. These differences may result in sufficient variation for some production components to fall outside of the targets specified. Similar analysis can be performed away from the direct contact of the gear teeth, such as considering the effect of variation in the bearing positions, altering the alignment of the shafts and gears. Small changes in the angle of the shafts can have significant effect on the TE of meshing gear pairs.

Figure 5 shows an example of a gear micro geometry study, and the effect on transmission error that can occur as a result of typical variations that are within typical manufacturing tolerances. The parameters commonly used in such studies may be profile and lead crowning, linear relief and tip relief but can be further extended if necessary. The tolerances used in this study can be determined through discussions with suppliers in order to evaluate the results that are achievable with existing manufacturing processes, or with proposed improvements. A fully factorial design of experiments (DOE) study can be a very time consuming process, and in these instances a Taguchi style DOE method can be utilised to determine the sensitivity of the design to specific parameters, or combinations of parameters. This analysis should then be fed back into the design process, in terms of modifying the design with these sensitivities in mind, or provoke discussions with suppliers on how to effectively control the most crucial parameters.

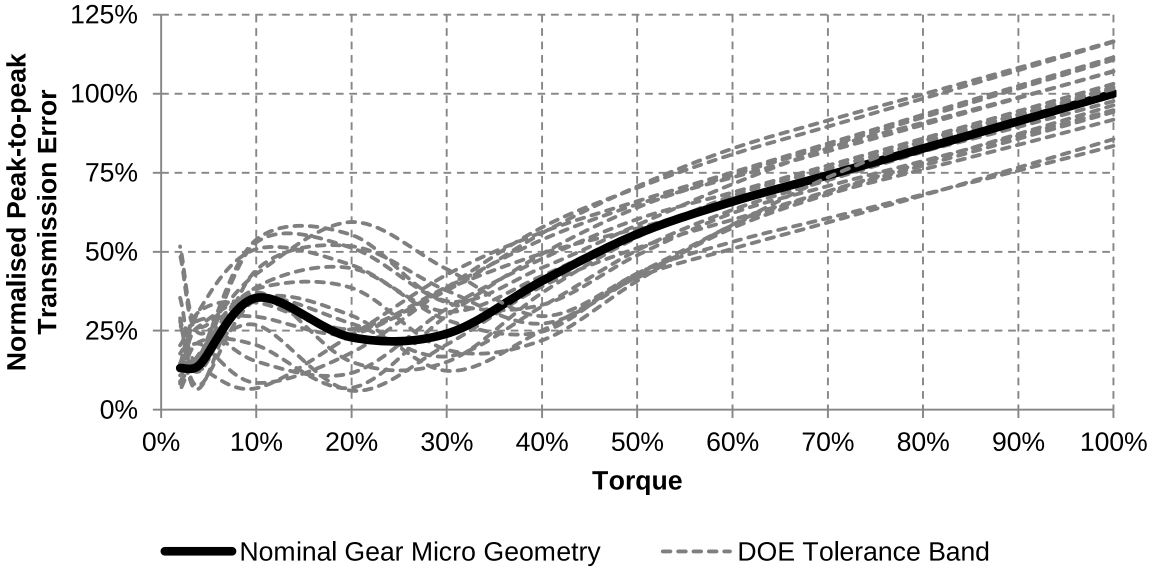

Figure 5 - Example of gear micro geometry tolerance DOE study.

SUMMARY

With hybrid and electric vehicles gaining prominence in the market, new challenges have generated in the field of NVH. While previously, internal combustion engines could mask much of the noise of the drive train, in hybrid and electric vehicles this is no longer true. Targets and design processes that had previously been established have proved to no longer achieve the desired results. Those who have anticipated these industrial trends have developed tools and processes to meet these more stringent requirements.

This paper has shown the benefit of a full system analysis approach to NVH. By understanding the interactions between components of the system, the root cause and effects can be identified. This allows the transmission and vehicle teams to work together more effectively to solve the issue. The ways in which the issue may be tackled have also been discussed. No one aspect should be focussed upon as the primary method in reducing NVH. The most effective way to ensure a low NVH drive train is consideration of NVH from the beginning and throughout the design process of each of the components.

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