ABSTRACT

NVH refinement is an important aspect of the powertrain development and vehicle integration process. The depletion of fossil-based fuels and increase in price of gasoline have prompted most vehicle manufacturers to embrace propulsion technologies with varying degrees and types of hybridization. Many different hybrid vehicle systems are either on the market, or under development, even up to all-electric vehicles. Each hybrid vehicle configuration brings unique NVH challenges that result from a variety of sources. This paper begins with an introductory discussion of hybrid propulsion technologies and associated unique vehicle NVH challenges inherent in the operation of such hybrid vehicles.

Following this, the paper outlines a two-dimensional landscape of typical customer vehicle maneuvers mapped against hybrid electric vehicle (HEV) operational modes. Overlaid on this map are NVH issues such as those associated with global powertrain vibration, driveline vibration, HEV component-specific noise, motor/generator whine, accessory noise, gear rattle, and noise pattern changes. The remainder of the paper focuses on specific examples from case studies illustrating key HEV NVH issues such as engine start/stop behavior, motor/generator whine, and influence of electric machines on powerplant integration issues. The use of advanced time-domain methods such as vehicle interior noise simulation (VINS) to understand and optimize HEV vehicle NVH behavior is shown. Finally, the findings from the discussed studies are summarized and appropriate conclusions are drawn with respect to understanding, characterizing, and solving unique hybrid vehicle NVH issues.

INTRODUCTION

The depleting supplies of fossil based fuels and associated increase in the price of fuel has prompted the automotive industry to focus efforts on development of fuel efficient vehicle technologies. While the development of fuel efficient propulsion technologies such as downsized/boosted internal combustion engines (ICE) and use of direct injection technology is expected to continue, there is increasing focus on the development of varying degrees of hybrid technology. Figure 1 provides a view of the tradeoffs between fuel consumption and cost of complexity for varying degrees of hybridization (shown for port fuel gasoline and directed injected Diesel engine based HEV’s). As the costs related to added complexity from the hybrid system go down, the degree of hybridization can be expected to go up to fully realize the potential to reduce overall vehicle fuel consumption.
For a given degree of hybridization, HEV’s can also be classified based on power flow as series, parallel and split hybrid vehicles, as shown in Figure 2. In series hybrid vehicles, the ICE power is converted completely into electric power that is used to propel the vehicle so that there is no direct connection between the ICE and the vehicle driveline. In parallel hybrid vehicles, the ICE and electric motor are both connected to the vehicle driveline, with many variants possible in both front wheel drive and rear wheel drive combinations. Split hybrids typically involve the use of power-split devices that direct the power either in a series or parallel fashion from the ICE and/or electric motor to the vehicle driveline.

Based on currently available battery technology, EV’s are expected to be limited to approximately 40 miles of driving on a fully charged battery. In order to provide customers with the flexibility of driving longer distances, developments are ongoing to add an ICE to the EV concept that would extend the driving range of the vehicle. Such vehicles are hence called range-extended electric vehicles (ReEV), electric range-extended vehicles (E-REV) or plug-in hybrid vehicles (PHEV) and can be developed in both series and parallel hybrid configurations. Figure 3 shows a schematic of a series ReEV vehicle.

While all the concepts discussed in this paper are designed to reduce fuel consumption and overall cost of vehicle ownership, they come with significant NVH challenges. Typically, customers’ perception of vehicle quality closely parallels the NVH characteristics of the vehicle. Drivers of conventional ICE powered vehicles have come to expect a high level of refinement in vehicles and will continue to demand similar levels of refinement in all HEV variants. NVH refinement is an important aspect of the powertrain development and vehicle integration process. In particular, HEV’s and ReEV’s present unique NVH challenges during the vehicle integration process.
Figure 4 shows a two-dimensional landscape of typical customer vehicle maneuvers mapped against range extender electric vehicle operational modes. Overlaid on this map are NVH issues such as those associated with global powertrain vibration, driveline vibration, HEV component-specific noise, motor/generator whine, accessory noise, gear rattle, and noise pattern changeover. From the point of view of customer acceptance of the end product, the plot shown in Figure 4 should be customized to a given vehicle program, so that a focused plan can be developed to address each NVH item systematically.

Figure 4: Unique HEV and ReEV NVH Challenges

Clearly, ReEV’s combine the NVH integration challenges of conventional hybrid electric vehicles and all electric vehicles. The remainder of this paper includes specific case studies from various ReEV and HEV development programs.

ICE START/STOP VIBRATIONS

It is important for the engine start/stop behavior to be transparent to the driver from both a tactile (vibrations) and acoustic (noise) standpoint. Figure 5 shows an example of seat track vibrations measured during ICE start-up conditions on a ReEV vehicle. As discussed in previous publications [e.g., 1], the start-up event can be split into the engine cranking phase and initial start of combustion.

Figure 5: Vibrations during ICE Start-up

Although the vibration behavior might seem generally similar to the starting phase of a conventional ICE powered vehicle, the ICE start-up vibration for HEV and ReEV can be more important. In a conventional ICE powered vehicle, the ICE start-up occurs only at the beginning of vehicle operation and the resulting vibration feedback (in response to cranking the engine to start the vehicle) is expected from the driver of the vehicle. For HEV and ReEV, the start-up of the ICE is linked to factors such as the state of charge of the battery and driver torque demand, which can result in “unexpected” vehicle vibration. Depending on the layout of the driveline, the start-up vibrations for HEV can be further complicated by the fact that the start-up of the ICE does not occur in neutral [1], causing excitation of driveline torsional modes (in addition to powertrain rigid body modes).

A proven metric to describe vibration during transient events such as ICE start-up is the VDV (Vibration Dose Value). The VDV is defined as [2]:

\[
VDV = \sqrt[4]{\frac{1}{t_s} \int_{t_c}^{t_s} \alpha^4(t) dt}
\]

The VDV is typically based on the low-frequency content of the vehicle’s fore-aft acceleration signal during the transient event of interest [3]. The VDV results in a single number metric, which can be used for vehicle benchmarking, target setting, and to track the ICE start/stop performance of a vehicle during the HEV and/or ReEV development phase.
Figure 6 shows VDV numbers for the seat track vibration (longitudinal direction) during ICE start-up calculated for five different hybrid electric vehicles. Three of the HEV’s tested (called Vehicle 1, Vehicle 2, and Vehicle 3, in Figure 6) were evaluated under two loads, i.e., ICE start from all electric drive under moderate pedal input and aggressive pedal input. As shown, the VDV metric captures the expected trends relative to driver input, i.e., the aggressive pedal ICE start-up vibrations are higher than those for the moderate pedal inputs. However, the difference in VDV’s (Figure 6) among the five vehicles tested also shows that there can be a wide range of ICE start-up behavior among HEV’s and it is important to develop production vehicles towards a not-to-exceed target line as shown on Figure 6.

![Figure 6: VDV for ICE Start-up](image)

While the VDV is useful for benchmarking, target setting, and assessment of the ICE start/stop behavior of a given HEV or ReEV, it does not provide additional insights that might be needed to focus development efforts. Another useful metric that can help with ICE start/stop refinement is the ESD (Energy Spectral Density) of vehicle seat track fore-aft (or steering wheel) vibration. The ESD is defined as [2]:

$$ESD = \frac{G_s(\omega)}{\Delta f} \Delta T$$

where $G_s(\omega)$ is the autopower spectrum of seat track or steering wheel vibration, while $\Delta f$ and $\Delta T$ are the frequency resolution and time period for the ESD calculation respectively.

The ESD metric allows for development of scatterbands based on benchmarking the state-of-the-art HEV for their ICE start/stop behavior. In addition, the ESD based analysis can provide insights into the ICE start/stop measurements on a development vehicle and assist with focusing refinement efforts.

Figure 7 compares the vehicle seat track fore-aft vibration ESD spectra for two HEV during the ICE start-up conditions. In addition, the data from the two vehicles are presented in the context of a scatterband based on testing many production HEV’s. While both tested vehicles show similar behavior in the frequency range up to 20 Hz, Vehicle B exhibits significantly higher levels than Vehicle A in the frequency range from 25 Hz to 45 Hz. In addition, the ESD levels for Vehicle B clip the top of the scatterband, indicating a need for refining the vehicle with respect to its ICE start-up behavior to avoid potential customer satisfaction issues.

The ESD analysis in this example is conducted on a time window which includes the ICE cranking phase and the initial combustion phase. As describe in previously published literature [1], these phases can contribute to excitation of different frequencies, such as those corresponding to ICE rigid body modes, torsional modes of the driveline, and vehicle body modes (vehicle sensitivity). Therefore, for further investigation and optimization of the ICE start-up vibration, it is beneficial to have a good understanding of all relevant modes in the frequency range of interest (< 50 Hz).
A significant contributor to the vehicle vibrations during an ICE start-up (or shut down) event is the excitation of the engine rigid body modes. Specifically, the roll mode of the ICE (motion about the crankshaft axis) is excited under ICE start-up and shut down events. In order to minimize the transmission of vibration to the passenger compartment during these transient events, it is essential to optimize the mounting layout of the engine. This is accomplished by using a multi-body systems based analysis of the ICE installed in a simplified vehicle model. Specifically, the model includes a rigid body representation of the ICE (and transmission or motor/generator, as appropriate) and vehicle body with appropriate values for the location of the center of gravity, masses, and mass moments of inertia. A simplified wheel and suspension assembly is often used with appropriate mass, geometry, stiffness, and damping information. The powerplant mounts are represented using specific mount models that capture the static nonlinearities and frequency-dependent dynamic (stiffness and damping) behavior.

The multi-body systems based model is utilized to decouple the ICE rigid body modes. Specifically, it is important to decouple the ICE roll mode from the other rigid body modes as far as possible. Figure 8 shows an example of optimization study conducted on a hybrid ICE application with the goal of decoupling the ICE rigid body modes, within other program constraints (maximum allowable motion of ICE under road excitation, packaging, etc.). The motion of the ICE at each rigid body modal frequency is analyzed to ensure that optimal decoupling of key modes has been achieved.

Figure 8: Decoupling of ICE Rigid Body Modes

Having achieved a desired degree of separation from the ICE rigid body modes, the engine calibration and engine start procedure should be optimized for reducing the vibration excitation. This can affect both the cranking phase and the initial combustion phase of the engine start procedure. Typical engine control related parameters which have an influence on the ICE start/stop vibration are:

- Injection time
- Amount of initial injection
Compression rate at cranking, which can be influenced by valve opening time and throttle position

Crank speed rise rate

Engine speed at which the combustion process starts.

Defined crank angle positions for engine stop. The position of the crank shaft when starting influences the vibration levels.

The influence of various ICE calibration parameters can be evaluated by combining simulations from 1-D CFD combustion process simulations with the optimized mounting multi-body systems model by conducting transient ICE start/stop events with the model. Figure 9 shows an example of one such model being exercised for a parallel HEV application.

For conventional powertrains the engine start/stop is usually performed with the transmission in neutral. Hence, torsional vibrations during the start/stop events are decoupled from the vehicle driveline. However, HEV drivetrains do not necessarily have this decoupling, as a result of which the torsional vibrations from the ICE cranking and combustion phase can excite low-frequency driveline torsional modes such as driveline shuffle. As part of the start/stop calibration, it is important to ensure that these torsional modes are not excited by engine torsionals during these transient events. As indicated previously, seat track acceleration ESD analysis can be used to diagnose the presence of resonances excited and focus development effort to refine the ICE start/stop behavior.

Finally, the use of the electric motor to actively damp the engine torsional vibrations should be explored. In such a scenario, the electric motor applies a torque fluctuation with a 180° phase offset relative to the torque fluctuation caused by the ICE cranking, so that the torsional excitation of the driveline can be minimized. For the implementation of active damping, the crank shaft position must be known and a good understanding of the cranking torque is mandatory.

ICE START/STOP NOISE

It is equally important to minimize the increase of powertrain noise in a hybrid electric vehicle when the ICE starts up. Figure 10 shows an example of interior noise measured on a ReEV before, during, and after engine start-up during a vehicle speed sweep. During initial operation the vehicle (up to a vehicle speed of ~17 kph) was running in an all electric mode, with all interior noise resulting from road noise, wind noise, and electric motor noise shares. As soon as the ICE starts up, the interior noise is dominated by noise from the ICE, causing a sudden change in the sound quality (frequency content) and absolute noise level.

Figure 11 illustrates the increase of overall noise level caused by the start-up of the ICE. The ICE start-up event is clearly noticeable in the overall noise levels, as indicated by the encircled area in Figure 11. The interior noise level increased by ~8 dB(A) when the ICE started up. In addition to the measurement data, trend lines are shown in this figure for the vehicle speed dependency of the overall interior noise level while operating in AER (all electric range) mode and with the fired combustion engine (ICE mode). These lines show that the interior noise level difference between the AER mode and ICE mode can be up to 12 dB(A). Therefore, it is extremely important to manage the transitions between the ICE mode and the AER mode on HEV and ReEV carefully.
In order to reduce customer annoyance with ICE start/stop noise issues, it is important to reduce the overall powertrain noise share in the interior noise signature of the vehicle. This becomes especially important, as ICE in HEV and ReEV applications are typically downsized and can have significantly increased torsional fluctuations, noise and vibration levels in comparisons to ICE in conventional vehicles.

Optimization of the ICE related noise and vibration is necessary to minimize significant level differences between AER and ICE modes of operation as well as to smooth out the interior noise pattern changes during transitions. For successful NVH optimization, this process needs to start early in the development process of the combustion engine. Specifically, the following NVH related issues should be addressed during development.

- **ICE Engine Level**
  - Reduction of combustion noise (direct and indirect shares) by integrating NVH metrics as part of the engine calibration process
  - Reduction of radiated noise levels by optimizing the noise shares from engine block, cylinder head, valvecovers, oilpan, etc. and use of acoustic covers
  - Reduction of structureborne excitation, i.e., mount vibration by optimizing mount brackets and location of engine mounts

- **Vehicle Level**
  - Reduction of airborne interior noise shares using treatments to reduce the body acoustic noise transfer functions
  - Reduction of structureborne interior noise shares by optimizing the vehicle side mount brackets, body stiffness at mount attachment points, and mount dynamic stiffness
  - Calibration of the engine start/stop process (engine speed rise rate, vehicle speed at which the engine starts/stops, steady state engine operating speeds, etc.) to minimize the transition related noise

In order to ensure successful integration of the ICE in a HEV or a ReEV, it is important to consider all items listed above.

**ELECTRIC MACHINE SPECIFIC NOISE**

As previously mentioned, the vehicle interior noise of HEV is composed of road noise, wind noise, ICE noise, battery fan noise, and electric machine noise. The noise from electric machines such as motors and generators manifests in the form of whine noise, i.e., tonal noise (typically in the 400 Hz – 2000 Hz range). The tonal nature of the whine noise from the electric machines can be annoying to the customer. The tonal noise issues can play a larger

![Figure 10: Interior Noise during ICE Start-up](image1)

![Figure 11: Interior Noise during ICE Start-up](image2)
role on HEV, ReEV and electric vehicles (EV) due to
the lack of sufficient “normal” masking noise from
the ICE under the AER and regeneration modes of
operation.

Figure 12 shows an example of interior noise
measurements made on a ReEV operating in AER
mode. Specifically, the vehicle was tested by first
ramping up the vehicle speed, holding a constant
vehicle cruise speed, and then conducting a braking
operation. Clearly, there is significant whine noise
present under both the vehicle speed ramp-up
phase and the braking phase. The absence of
masking background noise from the lack of ICE
operation underscores the need to minimize the
levels of whine noise shares in the interior noise of
ReEV in AER mode.

Figure 12: Interior Noise of a ReEV in AER Mode

As shown in Figure 12 the electric machine whine
order is prominent during vehicle acceleration and
braking (due to regenerative braking). In addition,
the whine noise order amplitudes change during
vehicle acceleration and braking due to differences
in the loading of the electric machines.

Figure 13 shows an example of the electric whine
order in the interior noise signature of an EV
measured under light, medium, and full load
conditions. The traction motor load is dependent on
the acceleration level requested by driver’s pedal
input. As seen from Figure 13, the load
dependence in the interior noise for the whine
orders on this vehicle was as high as 10 dB.

Figure 13: Electric Whine Order Load Dependence

During braking conditions, the maximum power
which the electric motor/generators absorb is
normally restricted due to vehicle safety concerns.
Therefore, unlike the load dependence of electric
motor whine during vehicle acceleration, the electric
motor/generator whine during braking is not as load
dependent during vehicle braking (deceleration).

As discussed previously, the lack of ICE noise can
render the presence of electric whine noise in EV
and ReEV in AER mode very audible and hence,
objectionable.

In order to understand potential vehicle NVH issues
related to electrical whine noise, it necessary to
understand the influence of masking levels (from
other noise sources) that might make the whine
noise more or less objectionable to the driver.
Specifically, listening studies have shown that it is
important to evaluate the whine orders relative to
masking noise bands composed of noise from other
sources (e.g., ICE noise, road noise, wind noise) in
a given frequency band.

Figure 14 shows the electric whine order for
medium acceleration (from Figure 13) plotted
against masking noise bands as the electric whine
order goes through various vehicle speeds. As
seen in Figure 14, the whine order drops below the
masking bands only for vehicle speeds above 45
mph. For vehicle speeds above 45 mph, relatively
higher levels of road and wind noise shares
effectively masks the electric whine noise under the
tested conditions. However, the whine noise on the
tested vehicle was clearly objectionable for vehicle speeds lower than 45 mph.

The tonal character of the electric whine and its rather wide frequency range (corresponding to the vehicle speed range) makes the NVH development of ReEV and EV challenging. It is important to use advanced transfer path techniques such as vehicle interior noise simulation (VINS) to understand the relative contributions from various structureborne and airborne transfer paths, so that appropriate NVH countermeasures can be developed to meet the refinement needs of the vehicle. The following section provides some information on the VINS process and provides examples from application of this methodology on a ReEV.

VEHICLE INTERIOR NOISE SIMULATION (VINS)

VINS is a time-domain transfer path synthesis technique that allows for a detailed breakdown of the powertrain induced interior sound at a target location in a vehicle. While the details of this technique can be found in previous publications [5, 6], a brief overview of the VINS process is provided here.

As show schematically in Figure 15, the VINS process begins with measurements of the airborne and structureborne noise sources. Radiated powertrain noise, intake orifice noise, and exhaust tailpipe noise measurements are considered for characterization of vehicle interior airborne noise contributions. Similarly, mount vibration measurements (engine side) are used to quantify the source levels of structureborne inputs into the vehicle. The source measurements are used in conjunction with corresponding vehicle level transfer functions (airborne and structureborne) to simulate the powertrain-induced interior noise shares from the various airborne and structureborne paths.

The primary advantage of the time-domain simulation over comparable frequency-domain techniques is that the resulting path contributions can be evaluated both objectively and subjectively via listening studies. In addition to the typical quasi-steady-state results, the VINS process can be applied to transient test conditions. Therefore, events such as ICE start/stop noise can be understood using the VINS process.

An additional advantage of the VINS analysis which is relevant for NVH optimization is the prediction of the engine mounts’ dynamic stiffness properties. This component is critical for all structureborne noise shares. The structural paths are treated as shown in Figure 16, with the dynamic stiffness properties of the mount calculated based on the operating transmissibility of the mount and on the point mobility of the body attachment location. This treatment of the dynamic stiffness of the mount allows for a true in-situ evaluation of the dynamic stiffness characteristics of the mount and hence provides accurate estimation of mount stiffness properties beyond the practical frequency range limitations of typical mount test bench measurements. In addition, the VINS process captures the dynamic stiffness of the mount under the right preload, deflection amplitude, and temperature boundary conditions, based on the test condition being investigated.
Figure 16 shows an example of the VINS process, as applied on a HEV tested under a coastdown condition with braking. To conduct the VINS process, source measurements (radiated noise as well as vibration) were conducted on the ICE as well as the electric machines in the HEV. Similarly, transfer function measurements were conducted from all relevant airborne and structureborne paths from the ICE and electrical machines into the interior of the vehicle. Specifically, Figure 17 shows the VINS noise synthesis of the interior noise field, along with the airborne and structureborne component noise shares that make up the interior noise under the tested conditions. In this example, the electric whine present in the interior noise under regenerative braking has noticeable airborne and structureborne components. Since the VINS process allows for a breakdown of the noise shares to each individual component, the interior noise field can be not only defined as a general split between airborne and structureborne noise, but it is also possible to determine the sub-components of each critical path (e.g., bracket resonances, mount isolation, attachment stiffness weakness, etc.) to help understand such NVH issues and focus engineering development effort to obtain refined solutions.

OTHER HEV NVH INTEGRATION ISSUES

In addition to the examples discussed in the previous sections, the integration of the electric machines in the driveline can pose challenges in the NVH integration of otherwise conventional powerplants (i.e., engine and transmission) and driveline system that would need consideration.

Due to the inertia of the electric machines in the driveline system, driveline torsional modes need to be re-evaluated and tuned appropriately so that they do not cause any NVH issues. Torsional dampers and dual mass flywheel are typically used for reducing torsional vibration inputs into the driveline and moving torsional vibration modes outside the excitation range. In addition to NVH considerations, electric motors are sensitive to torsional excitation. Therefore, the torsional system needs to be designed that the torsional vibration of the ICE must not exceed the vibrational excitation limit of the electric motor. The use of multi-body systems (MBS) based torsional analysis of the entire driveline is often necessary to ensure that the HEV powerplant and driveline are torsionally acceptable.

Another item worthy of consideration is computation of fundamental bending and torsion modes of the powerplant (i.e., engine and transmission). The additional mass and inertia of electric machines in a HEV transmission will reduce the frequencies of fundamental bending and torsion modes in comparison to conventional powerplants. As an example, Figure 18 shows one example of a HEV powerplant bending frequency in relation to a
powerplant bending frequency scatterband for conventional powerplants. It is important to first optimize the powerplant bending characteristics of the HEV powerplant within program design constraints. Following this, the use of advanced transfer path techniques such as VINS would be necessary to assist with integration of the HEV powerplant in the vehicle.

![HEV Powerplant FEV-Scatterband Conventional Powerplants](image)

**Figure 18: Fundamental Powerplant Bending**

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