Analysis of Impulsive Powertrain Noise

ABSTRACT

Refining vehicle NVH is a key aspect of the powertrain development process. Powertrain NVH refinement is impacted not only by overall sound levels, but also sound quality. Powertrain sound quality and therefore the level of NVH refinement can be adversely impacted by excessive impulsive noise. A process is outlined in this study to comprehend the occurrence of impulsive powertrain noise. Additionally, a process has been developed that identifies the source of the impulsive powertrain noise and is illustrated in this study through examples from case studies. Special emphasis has been placed on primary sources of impulsive powertrain noise such as diesel knocking noise, injector ticking, impulsive cranktrain noise, and gear rattle. A portion of the analysis involved the development of key objective metrics, optimization measures, and the examination of the potential for improvement. The metric development process, where possible, considers the correlation with subjective studies. The optimization process that was created highlights the various engineering alternatives that have been developed to control the specific impulsive powertrain noise issues.

INTRODUCTION

The perception of vehicle quality by a customer is closely aligned with the NVH characteristics of the vehicle. Competition in the automotive marketplace requires that vehicle NVH characteristics are well optimized in order to compete in the global arena [1]. The customer's primary interaction with vehicle NVH comes from interior sound, which is primarily composed of shares from road noise, wind noise, and powertrain noise. Increased market demand for lighter and more powerful vehicles, dictates that powertrain-induced noise will continue to be a primary factor for creating interior noise.

Powertrain noise levels and sound quality have one distinct advantage over wind noise and rod noise. The NVH refinement of powertrain noise levels and sound quality can used to assist in defining the vehicle's character. However, if the presence of impulsive engine noise is not addressed it can cause the vehicle to be perceived as rough and unrefined.

A vehicle's brand character (sometimes referred to as corporate sound or brand DNA) is essential in terms of developing a desired image and creating customer loyalty for a particular brand. Once the target powertrain sound (e.g., pleasant, sporty, etc.) has been decided, the development of the vehicle is directed to achieve the target sound in a two-step process [2] (Figure 1).

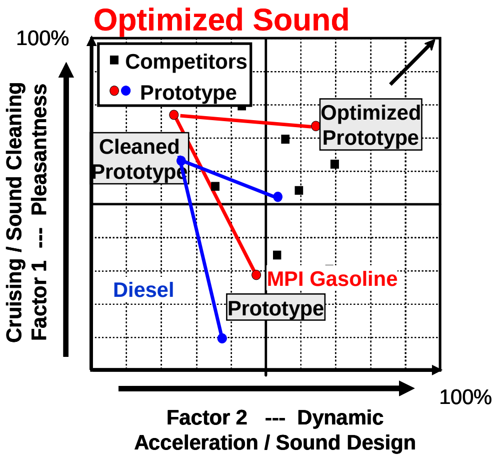

Figure 1: Brand Character Development Process

The initial stage in the development process takes a prototype vehicle's sound and cleans it so that the interior vehicle sound signature is refined. This initial refined sound is usually marked by low sound levels that do not contain any strong resonant character or impulsive powertrain noise. When the desired levels of noise cleaning are reached, a certain degree of roughness is designed into the interior sound to provide the required vehicle brand character. This first step is usually the most crucial to reaching the desired sound character and is best achieve through the use of a time domain transfer path technique. This technique allows offending noise shares to be identified, such as impulsive powertrain noise, and then directs the development process towards the use of appropriate countermeasures to optimize the design.

This study includes an introduction to impulsive noise that provides examples of representative phenomena that lead to impulsive engine noise. Initially, an introduction is provided for the Vehicle Interior Noise Simulation (VINS) process, which is a time-domain based transfer path technique [3, 4]. Specific case studies of impulsive noise are analyzed, such as diesel knocking noise, cranktrain noise, and injector ticking noise.

IMPULSIVE NOISE

Figure 2 shows an example of the time signature of impulsive radiated engine noise. The sharp “impacts” (shown by the blue arrows in Figure 2) are responsible for the impulsive nature, and hence the broadband frequency content of the radiated noise. Figure 3 shows plots of impulsiveness, a standard sound quality metric used to describe the character of the impulsive signal.

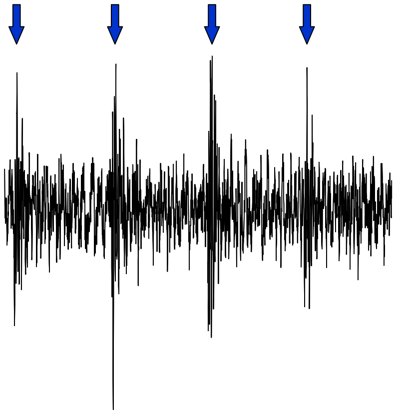

Figure 2: Impulsive Engine Noise Signature

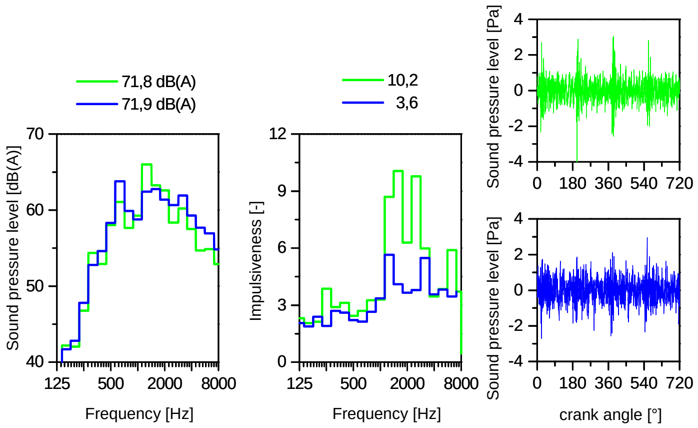

Figure 3: Impulsiveness Sound Quality Metric

As seen in Figure 3, the overall sound level metric (shown on top of spectral plot) is not capable of discriminating between impulsive noise and non-impulsive noise. However, the impulsiveness metric (shown on top of impulsiveness plot, Figure 3) does well to objectively quantify the impulsive nature of the noise. In addition, modulation spectral analysis can be used to gain further insights into the time-structure of the impulsive noise as well as offending frequencies that could be modulated with various engine orders (Figure 4).

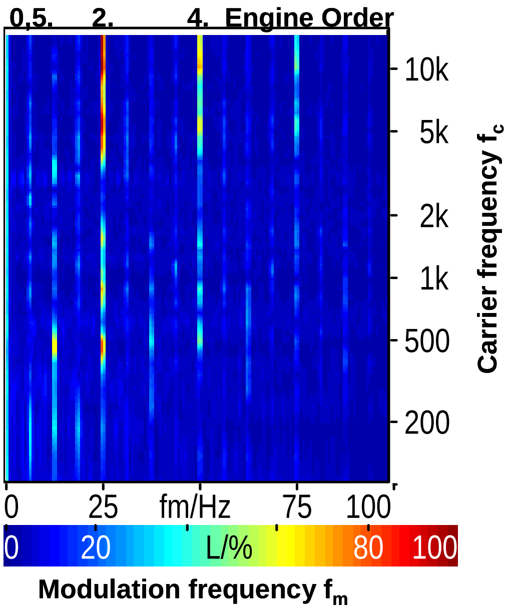

Figure 4: Modulation Analysis

In the example above (Figure 4), the objectionable impulsive noise results from modulation of various carrier frequencies by modulation frequencies corresponding to the 0.5th, 2nd, and 4th engine orders. For a range of impulsive noise issues, Figure 5 shows a schematic of the carrier frequencies and modulation frequencies [5].

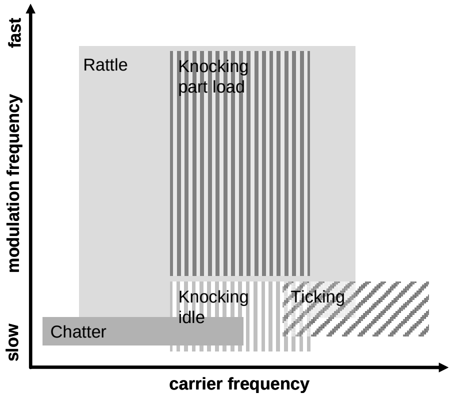

Figure 5: Impulsive Noise Modulation Spectra [5]

To fully understand the source of various offending resonances (carrier frequencies) that might contribute to the objectionable impulsive noise, a time domain transfer path analysis such as VINS (described in the next section) is used.

VEHICLE INTERIOR NOISE SIMULATION (VINS)

VINS is a time-domain transfer path synthesis technique that allows for an accurate breakdown of the powertrain induced interior sound field in a vehicle. While the details of this technique can be found in previous publications [3,4], a brief overview of the VINS process is provided here.

As shown schematically in Figure 6, the VINS process begins by measurements of the airborne and structureborne sources. Accordingly, radiated powertrain noise, intake orifice noise, and exhaust tailpipe noise measurements are used to characterize the sources 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 steady-state or quasi-steady-state results, the VINS analysis can be applied to transient test conditions and impulsive noise problems. Hence, items such as diesel clatter under transient pedal tip-in conditions, as well as modulation noise can be readily understood using the VINS process.

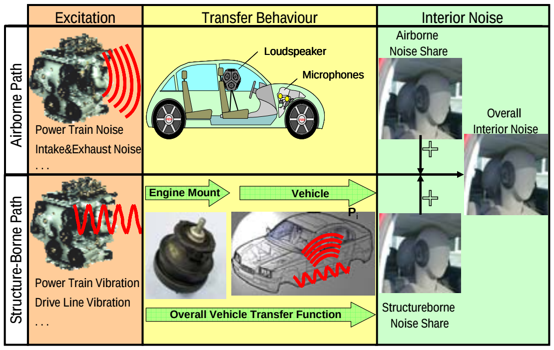

Figure 6: VINS Methodology

One additional advantage of the VINS analysis is the prediction of the engine mounts' dynamic stiffness properties. The structural paths are treated as shown in Figure 7, 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 a mount test bench measurement.

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.

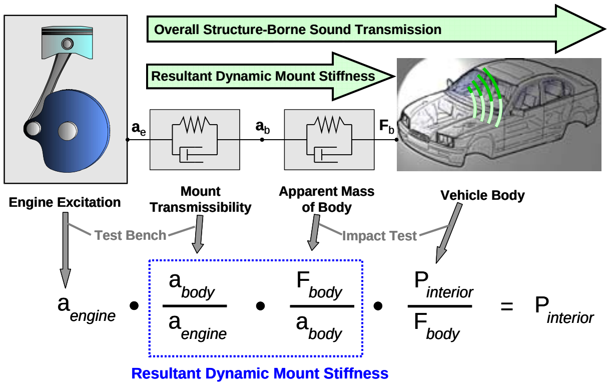

Figure 7: VINS Mount Stiffness Prediction

The application of such processes to the understanding and resolution of impulsive noise problems is examined using examples from case studies in the following section.

IMPULSIVE NOISE ANALYSIS: CASE STUDIES

Impulsive noise issues related to the powertrain can manifest themselves in a variety of situations such as diesel knocking (clatter), cranktrain noise (piston slap, piston pin ticking, connecting rod ticking, etc.), valvetrain noise (valve seating impacts, tappet impacts, etc.), and gear rattle (timing drive, accessory gear drive, transmissions, etc.). The following sections describe case studies for understanding and resolution of various impulsive noise issues.

DIESEL KNOCK

Diesel knocking or clatter noise is an impulsive noise phenomenon that can contribute significantly to the perceived quality of the diesel powertrain or vehicle. Diesel clatter is most significantly observed under low engine speeds and loads. Satisfactory resolution of diesel knocking noise requires a structured approach. Engine level refinement for diesel knocking noise typically involves structural changes to reduce the engine's combustion noise transfer function as well as calibration refinement aimed at reducing the direct and indirect combustion noise shares [6]. Having achieved engine level refinement, significant vehicle level refinement potential can be obtained by using techniques like modulation analysis and VINS.

Figures 8a and 8b shows plots of modulation analysis for a selection of frequency bands, conducted on interior vehicle (4-cylinder diesel engine) sound measurements taken under transient tip-in conditions.

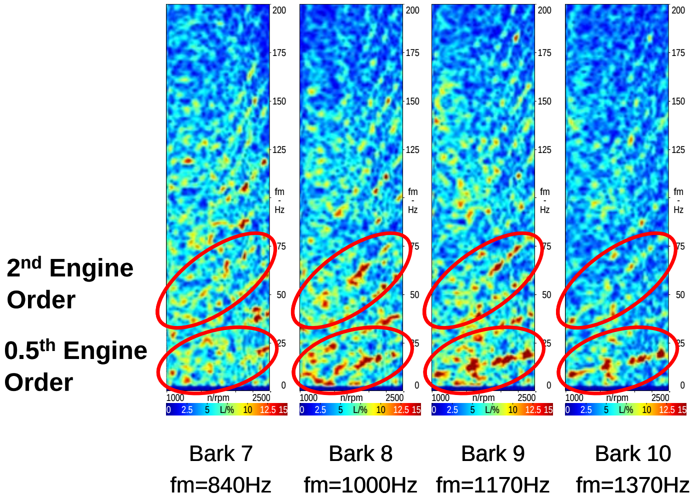

Figure 8a: Modulation Analysis for Selected Frequencies

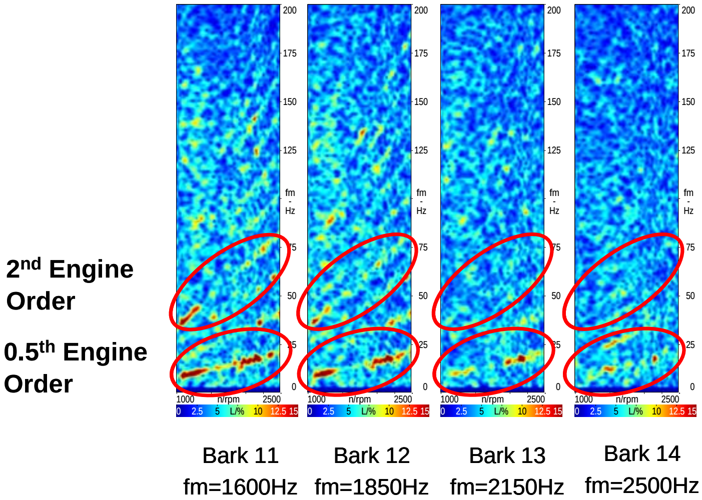

Figure 8b: Modulation Analysis for Selected Frequencies

The Bark scale (Figures 8a, 8b) ranges from 1 to 24 and corresponds to the 24 critical bands of hearing of the human ear. Jury evaluation studies of the measured sound showed a clear correlation between the subjective clatter noise impression and high degrees of modulation related to the engine orders. For the vehicle evaluated in this case study, modulation corresponding to the 0.5th and 2nd engine orders were deemed as being most critical. Specifically, the subjective impression of the 0.5th order modulated noise share corresponded to the typical annoying diesel combustion noise, commonly associated with tractors or trucks.

Having understood the subjective character of the diesel clatter noise, detailed noise breakdown analysis was conducted under transient conditions, using the VINS (Vehicle Interior Noise Simulation) process. Accordingly, the vehicle was tested in a semi-anechoic chassis roll dynamometer test cell and data were acquired during a transient sweep from 1000 rpm to 2000 rpm under light load conditions. “Source” data consisted of airborne as well as structureborne measurements. Radiated engine noise measurements as well as intake and exhaust orifice noise measurements were used to characterize the airborne sources. Similarly, acceleration measurements across the powertrain mounts (engine mounts and roll-restrictors) were used to measure forces through the mounts at the body attachment points. Finally, the source measurements were combined with airborne and structureborne noise transfer functions to generate a VINS analysis.

Upon obtaining good correlation between measured transient diesel noise and the VINS analysis, the VINS model was used to obtain a detailed breakdown of various structureborne and airborne noise shares.

Listening studies showed that three resonances (1050 Hz, 1600 Hz, and 2000 Hz) contributed to the negative impression of the transient diesel clatter sound. Airborne noise radiation from top, right and rear sides of the powertrain contributed to significant noise shares at 1600 Hz and 2000 Hz, while the resonance at 1050 Hz was predominantly structureborne (mainly roll restrictor A). With this level of understanding, additional vehicle level countermeasures can be developed to complement engine calibration oriented improvements to refine the transient diesel knocking noise behavior of the vehicle.

INJECTOR TICKING NOISE

Injector ticking is another source of impulsive powertrain noise. Injector ticking noise can be divided into the following categories

- Direct injector noise
- Indirect injector noise

Direct injector noise is defined as the noise share that is directly emitted by the injector. Indirect injector noise is defined as the injector noise share that is related to the vibration excitation (stemming from the injector) of the cylinder head, valve cover, manifolds, and fuel rails.

Injector noise/vibration generation is caused by mechanisms such as needle seat impacts, fuel pressure pulsations, and deformation of the piezoelectric stack under electrical loading. Increases in fuel rail pressure and needle velocities with advanced engine technologies (common rail piezoelectric injection, direct injected gasoline, etc.) lead to higher levels of injector noise that necessitate appropriate countermeasures.

Injector Ticking Noise Countermeasure Development

Countermeasures for injector ticking noise can be classified into primary approaches aimed at reducing the source excitation and secondary approaches targeted towards reducing the effective sensitivity of the engine to injector excitation. Figure 9 shows an example of the influence of injector switching time on cylinder head vibrations. Figure 10 shows the influence of injector switching times on radiated engine noise under idle conditions.

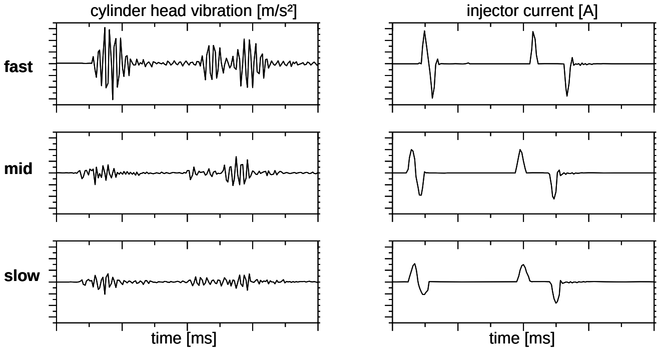

Figure 9: Influence of Switching Times on Head Vibration

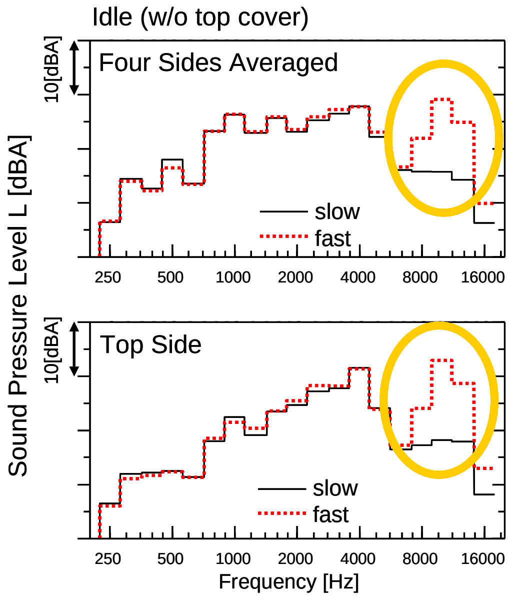

Figure 10: Influence of Switching Times on Idle Noise

Clearly, the injector switching time has an influence on the high frequency ticking noise behavior. Reducing the number of injection events per stroke also has a similar influence on reducing injector ticking noise. However, the trade-off with combustion noise must be evaluated before reducing the number of pilot injections on diesel applications, as shown schematically in Figure 11.

After optimizing the source excitation levels, secondary approaches can be used to reduce the sensitivity of the engine to injection system inputs. For example, the mounting of the injectors and modification of structural dynamics of the cylinder head offer optimization potential as secondary measures for reducing injector ticking noise. Similarly, isolated valve covers and acoustically treated engine top covers can offer potential to suppress the injector ticking noise radiating off the engine.

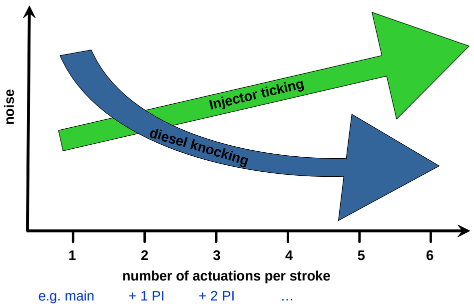

Figure 11: Influence of Multiple Injections on Noise

CRANKTRAIN IMPULSIVE NOISE

Frequently, impulsive engine noise issues are associated with impacts occurring in the cranktrain and valvetrain of the engine. Valvetrain impacts are normally connected to valve seating events while cranktrain impacts are associated with specific clearances being taken up during load reversals. In all such cases, the problem resolution process involves collecting acceleration and sound pressure measurements that can be adaptively re-sampled in the crank-angle domain. The locations of the impacts in the crank-angle domain (timing) typically provide insights into the mechanism of the impulsive noise. The strengths of the impacts determine the severity of the issue. A few examples of impulsive cranktrain noise are provided in the following.

Piston slap occurs as a result of secondary piston motion and is associated with impacts between the piston and the cylinder liner that can occur when the piston side forces go through a reversal. Figure 12 shows typical block acceleration measurement locations to quantify piston slap.

Figure 12: Block Acceleration Measurements

Figure 13 shows an example of block acceleration measurements resolved in the crank-angle domain and reported as squared (and averaged) traces to accentuate the location of the piston slap related impacts.

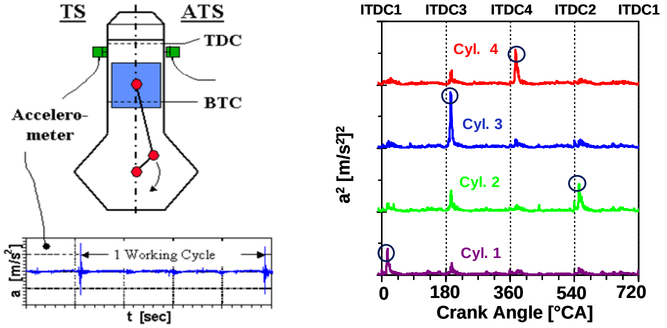

Figure 13: Piston Slap Measurements

An example of piston tertiary motion was reported [7], where the impacts occurred between the piston and the cylinder liner in the fore-aft direction. The impacts in this case resulted from instability in the cranktrain corresponding to a load reversal in the piston normal force. Figure 14 shows an example of block acceleration measurements (V8 engine) corresponding to piston tertiary motion [7].

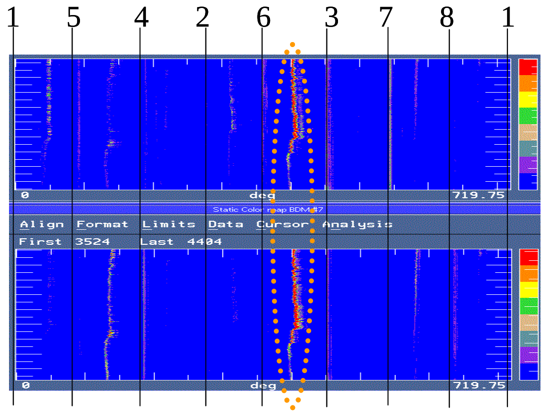

Figure 14: Cranktrain Impacts Relative to Ignition TDC

Figure 15 shows an example of piston pin ticking noise corresponding to the clearances between piston-pin and the connecting rod being taken up during normal piston load reversal.

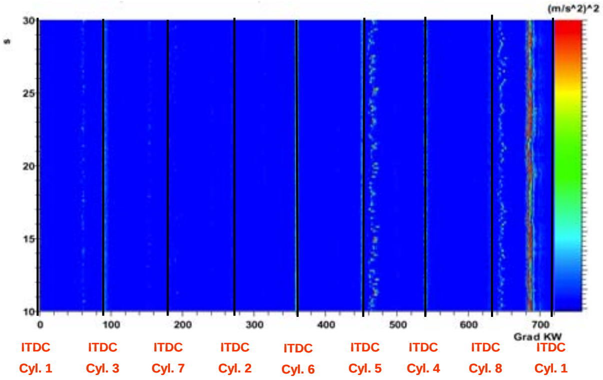

Figure 15: Piston Pin Ticking Impacts

Optimization of parameters such as profiles of piston skirt and top-land, piston skirt stiffness, piston pin offset, and piston pin clearances (to piston and connecting rod) is typically conducted to arrive at the refined solution.

GEAR RATTLE

Gear rattle is another phenomenon that can cause objectionable impulsive noise. Gear rattle can be prevalent in manual transmissions as well as in geared engine systems (accessory drive, timing drive, balance shaft drive, etc.). Figure 16 shows an example of interior vehicle sound (x-axis: engine speed, y-axis: frequency) with high levels of gear rattle noted.

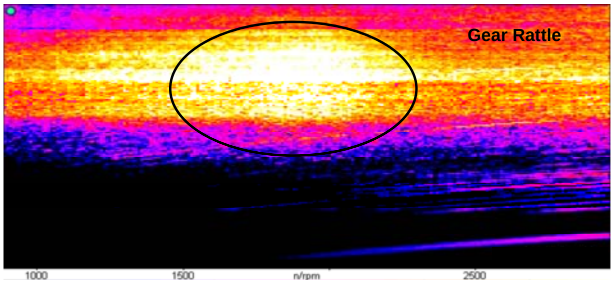

Figure 16: Vehicle Interior Sound with Gear Rattle

Figure 17 shows a plot of modulation analysis conducted on the interior noise, while Figure 18 illustrates the process of developing an objective metric for gear rattle.

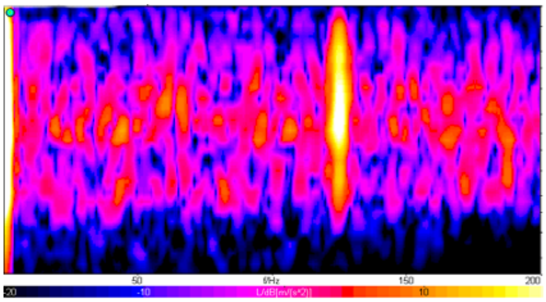

Figure 17: Modulation Analysis of Gear Rattle Noise

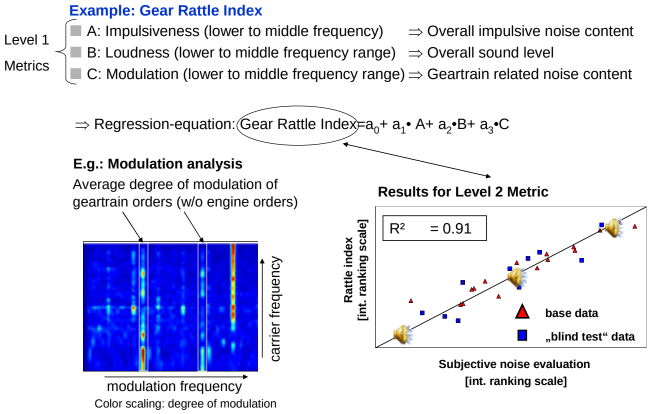

Figure 18: Gear Rattle Metric Development Process

As shown in Figure 18, “Level 1” metrics are initially chosen from standardized psychoacoustic metrics such as impulsiveness, loudness, and modulation. In a second step, the Level 1 metrics are combined together to obtain a “Level 2” metric called the “Gear Rattle Index”. Figure 18 also shows that the developed metric functions well in correlations done with “blind” data.

Figure 19 shows results from normal modes analysis obtained from a finite element (FE) calculation conducted using a RWD driveline model. Fundamental driveline modes like “driveline shuffle” affect the low-frequency response of the vehicle, while higher frequency flexible modes such as “manual transmission torsion” are responsible for manual transmission gear rattle.

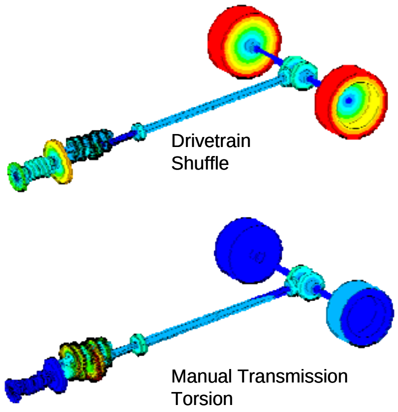

Figure 19: RWD Driveline Torsional Modes

Manual transmission gear rattle results when the transmission torsion mode is excited by the engine firing order. Under the resonant conditions, impacts occur in the unloaded gear pairs, resulting in impulsive noise generation (gear rattle) that is transferred via the shaft bearings to the housing of the transmission from where it is radiated. Figure 20 shows the influence of various technologies that can be applied to either damp the angular accelerations of the input shaft of a manual transmission or provide sufficient torsional isolation between the engine and the transmission. A dual mass flywheel (DMF) is commonly employed with manual transmissions, especially for 4-cylinder engine applications.

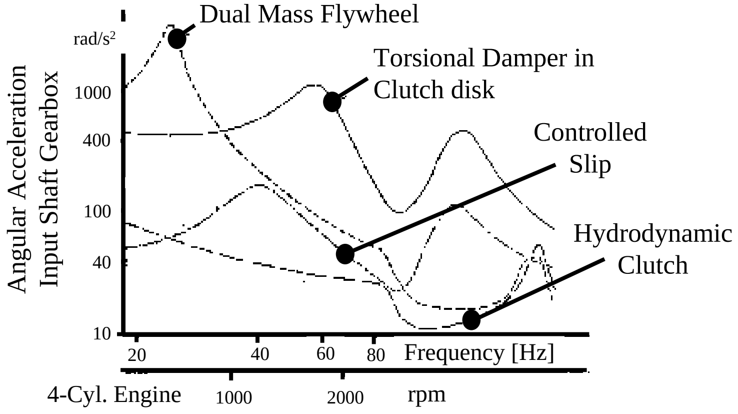

Figure 20: Technologies for Gear Rattle Reduction

Figure 21 shows results from Multi-Body Simulation (MBS) on optimization of the primary and secondary masses in an application of a dual mass flywheel. Figure 21 also shows a plot of measured radiated sound data with and without a dual mass flywheel. In this example, the engine speed range from 1000 rpm – 3000 rpm was the most sensitive range for transmission gear rattle and up to 7 dB(A) of improvement was obtained by using an optimized dual mass flywheel.

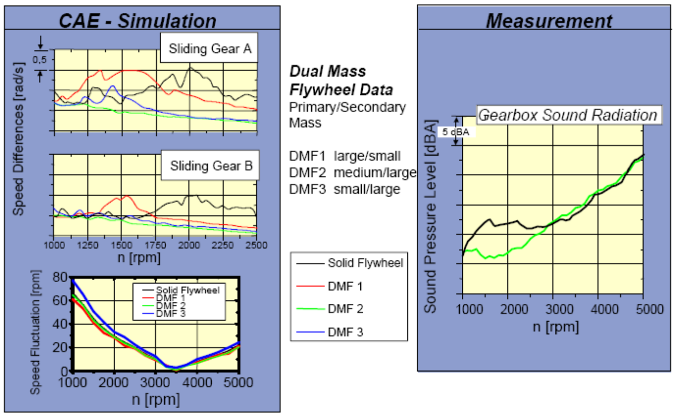

Figure 21: Dual Mass Flywheel Optimization

SUMMARY AND CONCLUSIONS

A customer's perceived product quality can be negatively impacted by impulsive powertrain noise. Therefore, it is imperative to determine the source of the impulsive powertrain noise and address it with proper solutions. Common characteristics are shared by all impulsive powertrain noise phenomena. However, the vehicle refinement process requires complete knowledge of the underlying mechanisms that contribute to the creation and spread of impulsive noise.

Metrics and methods, such as impulsiveness and modulation analysis, were used in this study to objectively quantify the impulsive behavior of the measured noise. Additionally, applying advanced time-domain based transfer path techniques such as Vehicle Interior Noise Simulation (VINS) help in acquiring the knowledge needed to solve challenging impulsive noise problems. Individual case studies provided a sampling of a variety of impulsive powertrain noise issues, such as diesel knocking noise, injector ticking noise, cranktrain impulsive noise, and gear rattle were provided. The case studies provide a starting point for discussing the source of the specific impulsive noise mechanisms, objective quantification methods, and creation of the appropriate refinement-oriented solutions.

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