Driveline boom interior noise prediction based on multi body simulation

T. Wellmann, K. Govindswamy, G. Eisele

ABSTRACT

It is important to develop powertrain NVH characteristics with the goal of ultimately influencing/improving the in-vehicle NVH behavior since this is what matters to the end customer. One development tool called dB(VINS) based on a process called Vehicle Interior Noise Simulation (VINS) is used for determining interior vehicle noise based on powertrain level measurements (mount vibration and radiated noise) in combination with standardized vehicle transfer functions. Although this method is not intended to replace a complete transfer path analysis and does not take any vehicle specific sensitivity into account, it allows for powertrain-induced interior vehicle noise assessments without having an actual test vehicle available. Such a technique allows for vehicle centric powertrain NVH development right from an early vehicle development stage. While this is a proven tool for powertrain level sound quality evaluations and correlates well for front wheel drive (FWD) vehicles, the interior noise for rear wheel drive (RWD) vehicles is often under-predicted on account of missing contributions from the driveline. RWD vehicles can have significant contributions through the rear axle mounting paths, especially for powertrains with manual transmissions or during lock up of the torque converter clutch with conventional automatic transmissions. Torsional vibrations are transmitted through the driveline, causing reaction forces at the rear axle, resulting in driveline boom. Resonances in the driveline system typically amplify the driveline boom excitation.

This publication extends the dB(VINS) approach for interior noise simulation by determining the driveline-induced noise of a RWD vehicle. The influence of the structureborne path and firing order related torsional vibration through the rear axle is demonstrated with a time domain transfer path process. Generic transfer functions for extension of the dB(VINS) process are developed in order to capture driveline noise share of RWD vehicles. In addition to vehicle measurements, a multi body simulation (MBS) model is generated and rear axle vibrations are calculated via MBS simulation of the vehicle driveline. The results are discussed in the context of driveline NVH integration and appropriate conclusions provided.

INTRODUCTION

The demand for more fuel efficient powertrains and reduction of CO_2 emissions leads to a general engine downsizing trend. Technologies like charged direct injection technology (Diesel and gasoline) lead to a high torque, which allow reducing the number of cylinders without compromising vehicle performance. Cylinder deactivation technology allows the fired cylinders to operate at points of lower specific fuel consumption. All these technologies result in significantly increased engine torsional excitations from the firing order, making the driveline NVH integration more challenging. The tendency towards increased “low-end” torque combined with “down-speeding” of the engine as well as the need to have good drivability at low engine speeds amplify the challenge of controlling driveline boom [1, 2]. Fuel economy needs are driving lower torque converter lock-up speeds on planetary automatic transmissions while dual clutch transmissions (DCT) and automated manual transmissions (AMT) are also being operated at reduced engine speeds.

Front engine, rear wheel drive vehicle configuration is the standard vehicle architecture for larger (and often more powerful) vehicles. Engine torsional vibrations are transmitted through the transmission and excite the vehicle driveline. Driveline torsional vibration at the rear axle result in reaction forces of the axle housing mounts, which can cause noticeable driveline-induced boom [3, 4]. Due to the high reaction forces at the rear axle, efforts to further increase isolation via softer bushings are often limited. Since the engine torsional excitation tends to increase for improved fuel efficiency, the key factor for controlling driveline boom is torsional isolation. Understanding the driveline’s torsional characteristics and resonances allows for tuning the isolation via countermeasures such as clutch dampers, dual mass flywheels or turbine dampers on torque converter equipped vehicles [2, 4].

Efficient driveline NVH optimization must begin in the concept phase of a vehicle via simulation tools. Numerous studies have been published which describe the driveline torsional modes and driveline torsional models [e.g., 5, 6, 7, 8] used for such up-front optimization. Most commonly, lumped mass torsional models are used for describing low frequency driveline phenomena (e.g., driveline shuffle), which are felt as vehicle vibration rather than audible disturbance. Torsional driveline models are also typically utilized for optimizing countermeasures like the dual mass flywheel or turbine damper for vehicles with torque converter equipped automatic transmissions.

It is desirable for both target setting and driveline torsional optimization if the simulation does not end at the torsional vibration output, but if the expected vehicle interior noise response is predicted. This can be achieved if the axle mounts are included in the simulation model and the vibration at these locations is calculated in the driveline simulation. A one-dimensional torsional vibration model is not sufficient to perform calculation of the reaction at the axle mounts. Parameters like mount location and stiffness, center of gravity of the axle and its gear ratio are necessary input data for this simulation. The noise share of the rear axle for a vehicle can be computed by combining the simulated results of the vibration at the axle mounts in conjunction with noise transfer functions from the rear axle to the interior noise. Since typically the actual transfer paths of a given vehicle are not known in an early development phase, standardized transfer functions that are based on the predecessor vehicle or from a database of competitive vehicles can be utilized to aid with the interior noise simulations.

EXAMPLE OF REAR AXLE INDUCED DRIVELINE BOOM

The interior noise signatures on RWD vehicles can include significant noise shares as structure borne noise through the rear axle mount paths. To give an example, a complete time domain based transfer path analysis via vehicle interior noise simulation (VINS) [11, 12] was performed for a four-cylinder Diesel engine powered RWD passenger vehicle. In the VINS process, the interior noise is synthesized based on structureborne and airborne noise related excitations and corresponding measured transfer functions.

The breakdown of the individual noise shares of the four-cylinder Diesel propelled RWD vehicle is shown in Figure 1. In this example, the overall interior noise level below 1750 rpm is only driven by the noise share of the rear axle. Order analysis reveals that the firing order is the key contributor to the rear axle induced interior noise in the low speed range. This speed range is critical in particular for Diesel engines since it is in the vicinity of typical cruising conditions.

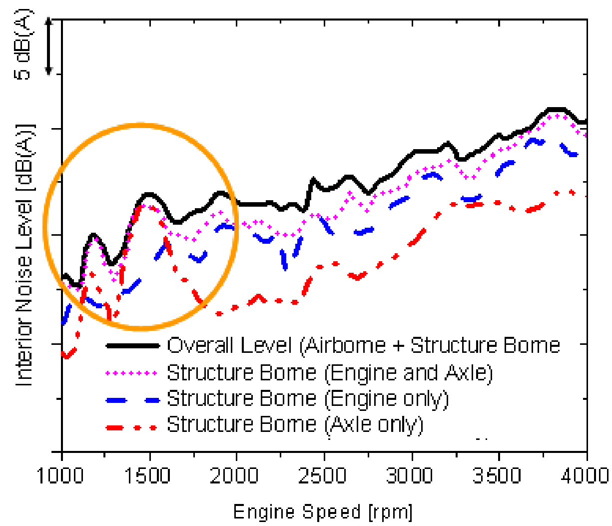

Figure 1: Noise share breakdown of a four cylinder Diesel engine propelled RWD vehicle via VINS transfer path analysis

This example shows that the rear axle noise path can be very critical for boom related interior noise issues. The general excitation mechanism is via engine torsional vibrations, which are transmitted to the driveline. CAE simulations and vehicle measurements shown in this paper discuss this path in more detail.

DB(VINS)

Powertrain NVH tests are conducted to measure radiated engine noise (e.g., according to SAE J1074) and mount vibration, but no assessment is typically made about the expected vehicle interior noise based on these results. Furthermore, no assessment is made of which noise shares will be most dominant or noticeable in the interior noise of the vehicle. For example, while two different engines can have similar noise radiation characteristics, the corresponding interior noise of a vehicle equipped with these engines can be significantly different, e.g., due to the engine mounting strategy or use of balance shafts. The dB(VINS) process was developed precisely to bridge the gap between powertrain level NVH tests and vehicle level NVH needs. The dB(VINS) process is a powertrain level tool that allows for determination of the interior noise level of a vehicle based on powertrain (source) measurements combined with corresponding structureborne and airborne noise transfer functions. Since the process is meant to be used for powertrain development, "standardized" vehicle transfer functions are utilized. The standardized transfer functions are developed from years of benchmarking and represent a virtual vehicle in the class of interest. The use of such functions becomes especially important in the early development stages, when the program vehicles are not yet available.

The general process of dB(VINS) is illustrated in Figure 2. The radiated noise and mount vibrations are measured on a powertrain in a semi-anechoic powertrain dynamometer test cell and combined with standardized vehicle transfer functions to estimate the powertrain-induced interior noise. As an example, Figure 3 shows the measured noise radiation of two engines, where Engine B shows a slightly lower overall level than Engine A. Since Engine B is not equipped with balance shafts (2^{nd} order, for an inline 4 cylinder engine), it will result in significant higher interior noise level (structureborne content), shown in Figure 3 on the right as the dB(VINS) result. Such analysis allows for identification of excitations that are relevant to vehicle interior noise levels and sound quality. Significant findings can then be traced back to individual engine sides and/or engine mount brackets [13].

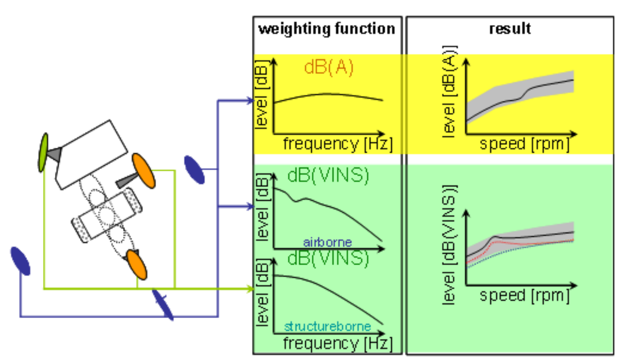

Figure 2: dB(VINS) process for powertrains

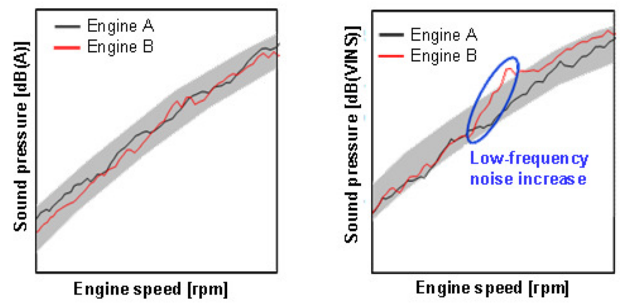

Figure 3: Radiated engine noise level and estimation of interior noise of two different I4 engines with dB(VINS) [3]

Since dB(VINS) is a time domain tool it allows for listening to the synthesized interior noise signatures and hence, objective and subjective sound quality assessments. As stated previously, the dB(VINS) process is not intended to include any vehicle-specific NVH sensitivity. For full vehicle transfer path assessments, specific noise path analysis tools such as the VINS process [11, 12] can be employed. The use of the standardized transfer functions in dB(VINS) allows for determination of the interior noise without having actual vehicle hardware available. Additionally, utilizing standardized transfer functions enables one to focus on powertrain level NVH development without taking any vehicle specific weaknesses into account. Should structureborne and airborne transfer functions be available for a specific vehicle (e.g., from a vehicle level VINS analysis), the standardized transfer functions can easily be replaced with the specific functions in the dB(VINS) process.

INTERIOR NOISE SIMULATION BASED ON DB(VINS)

As previously shown, the transfer path through the driveline and rear axle of a RWD vehicle can be a dominant contributor of booming noise and must be considered throughout the driveline integration. In order to include this path in the dB(VINS) process, the standardized transfer functions for RWD vehicles with independent rear suspension (IRS) are determined, based on vehicle level measurements of various vehicles. The interior noise share of the driveline path can be estimated by combining the structureborne noise transfer functions from the axle mounts with the actual measured vibration at the axle mounts during operation.

Figure 4 compares the measured interior noise level with the prediction of dB(VINS) for the rear axle mounts of a V8 engine propelled RWD test vehicle operated with fully locked torque converter. Measurements are performed under full load in 2nd gear. The dB(VINS) calculation contains the engine mount and rear axle mount structure borne noise paths. When comparing the levels between measured noise level and dB(VINS) prediction, an under-prediction of up to 10 dB(A) is noticed. This separation is caused by the following two factors:

- The peak at 1900 rpm is caused by two factors: torsional vibration peak in this vicinity (see peak at 2100 rpm in Figure 8 and for driveline torsional vibration for this vehicle), combined with a noticeable sensitivity in the transfer path of the given vehicle. While specific transfer functions of a vehicle typically show significant peaks due to resonances, the standardized transfer functions used with dB(VINS) do not include any vehicle-specific peaks since these are based on an average of transfer function measurements of many vehicles. In the given example, a vehicle specific sensitivity at 120 Hz is not captured with the standardized transfer functions. Apart from the peak at 120 Hz, the driveline boom(1500-2500 rpm) shows good correlation in the range of interest.

- The following noise paths were not considered in this example due to missing excitation measurements of: engine airborne noise, induction and exhaust noise, structureborne noise components of the exhaust system as well as road-induced noise.

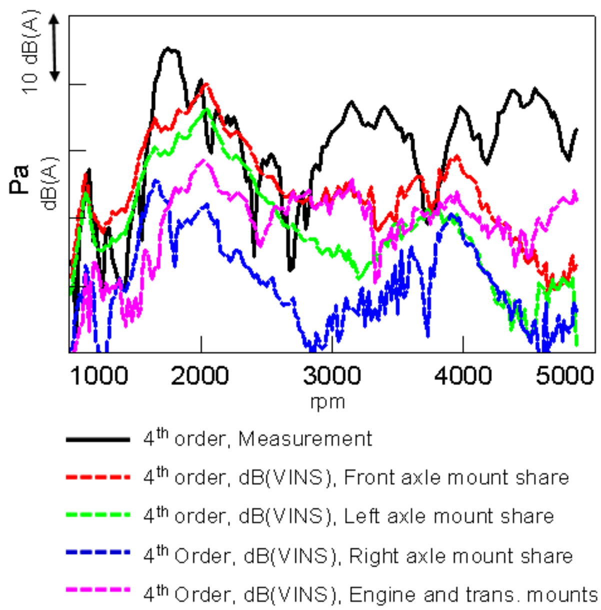

Figure 4: Comparison between measured interior noise levels and dB(VINS) prediction of the structure borne noise paths

Although these factors influence the correlation, the dominating engine firing order causing a vehicle boom is predicted well with the given approach. The comparison of the rear axle related noise share to the powertrain related noise share shows that the boom noise is clearly transferred through the driveline path. The predicted interior noise of the axle is broken down into its individual paths. It becomes obvious that the front mount of the axle shows the highest noise share of the driveline related boom, followed by the rear left mount of the 3 mount IRS axle. The differences between the noise shares of the individual rear axle mounts are caused by variations of the axle mount vibration, related to the pitching of the rear axle. It is a common characteristic to see the highest amplitudes for firing order at the pinion nose of the axle. The firing order excitation is related to engine torsional vibrations, which are transmitted through the transmission and vehicle driveline to the rear axle, causing reaction forces at the axle bushings. For a detailed investigation on driveline torsional vibration, a MBS model of the driveline was generated and is described in the next section.

DRIVELINE MBS MODEL DESCRIPTION AND CORRELATION WITH MEASUREMENT DATA

The driveline model used for this study is based on a kinematics multi body simulation, which has been successfully utilized for driveline shudder investigations [14]. Compliances of the driveline components are added to the kinematic model.

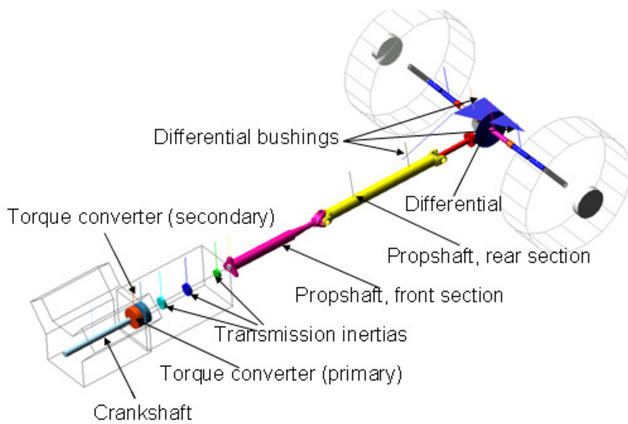

Figure 5: Multi body simulation model for driveline torsional vibration (boom)

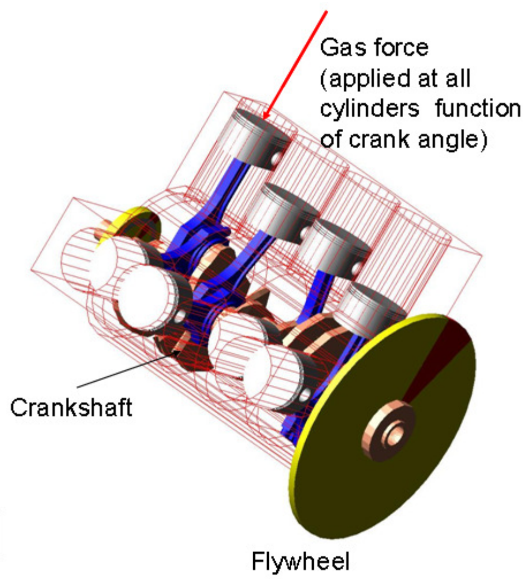

Figure 6: Virtual engine model of the V8 engine used for flywheel dynamic torque calculation

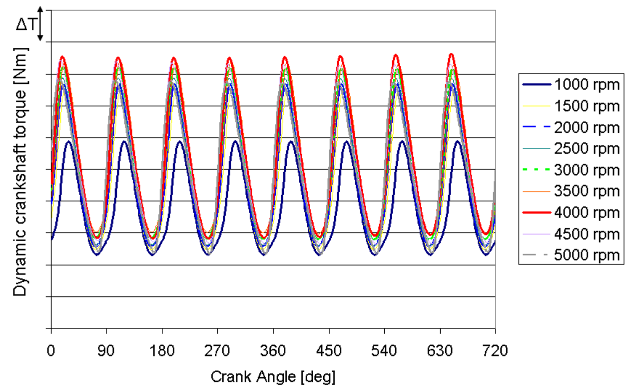

Figure 7: Dynamic crankshaft torque for a V8 naturally aspirated gasoline engine at WOT for different engine speeds

In order to correlate the driveline model with test data, measurements were conducted on a test vehicle running on a semi-anechoic chassis dynamometer test cell. The vehicle was operated under full load conditions during quasi-steady-state speed sweeps. Under these conditions collected data included speed signals (engine and propshaft), vibration at mounting points (accelerometers at the powertrain and axle mounts), and driveline vibration (torsional and bending vibrations measured using a laser vibrometer at multiple points in the propshaft).

The simulation results for torsional vibration at the end of the propshaft (axle input) for 4^{th} order is shown in Figure 8. This figure shows excellent correlation between measurement and simulation results for firing order torsional vibration. The spectral map for propshaft torsional vibration of measurement and simulation is shown in Figure 9.

The simulation shows good correlation in both frequency content as well as amplitude, in particular for the dominant 4^{th} engine order. The spectral maps reveal two torsional driveline resonances in the frequency range of excitation, which are captured in both the tests and simulated data.

The corresponding acceleration at the axle bushings can be simulated since the driveline model is generated as a three-dimensional model including the IRS axle, housing, and axle mounts. A comparison between measurement and simulation of the axle mount vibration is shown in Figure 9 for the WOT run-up in 2^{nd} gear. Specifically, this figure shows vibration comparisons for the vertical direction of the front mount of the axle, which is often the most critical measurement point with respect to driveline boom (see also Figure 4). The correlation between tests and simulations is shown to be reasonably good. For completeness, Figure 11 shows the front axle mount vibration in vertical direction for a WOT simulation in 3rd gear. Upon calculation of the axle mount vibration, the dB(VINS) process is used to simulate the rear axle induced structureborne noise into the vehicle.

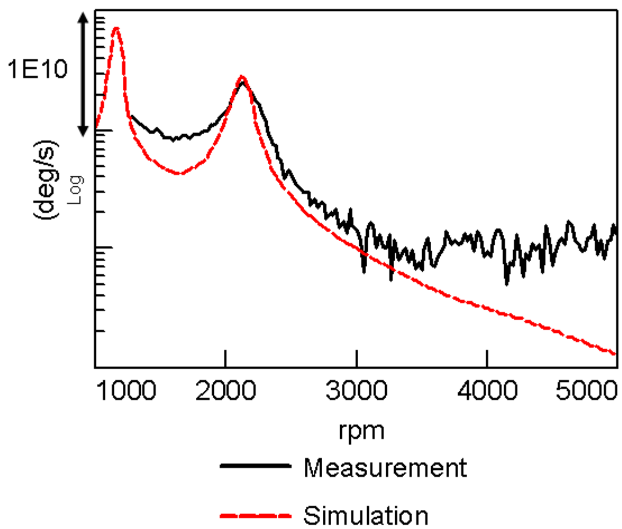

Figure 8: 4th engine order correlation of propshaft torsional vibration (close to axle input) between measurement and simulation for WOT run-up in 2nd gear

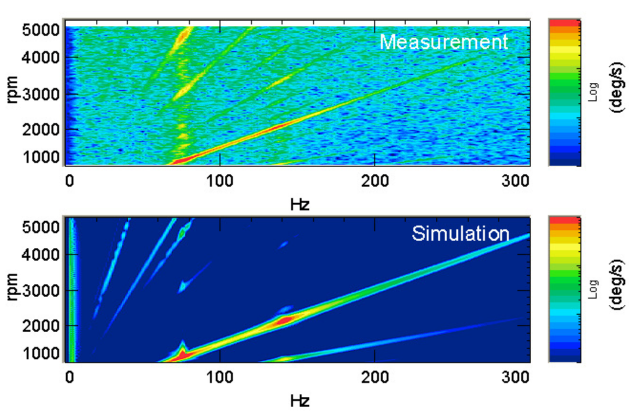

Figure 9: Spectral map information of measurement and simulation for propshaft torsional vibration (close to axle input) for WOT run-up in 2nd gear

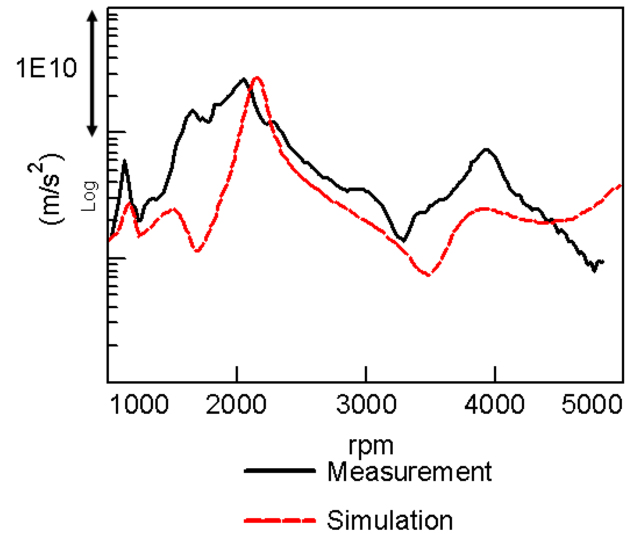

Figure 10: Axle mount vibration, active side, 4th engine order for WOT run-up in 2nd gear

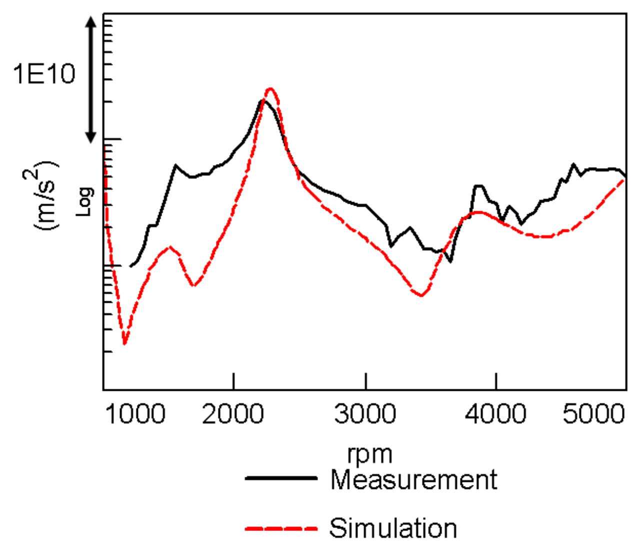

Figure 11: Axle mount vibration, active side, 4th engine order for WOT run-up in 3rd gear

DB(VINS) PREDICTION BASED ON MULTI BODY SIMULATION RESULTS

With the correlated driveline model, the interior noise share of the rear axle can now be predicted by combining time domain simulation results with the existing dB(VINS) weighting functions for the rear axle. Instead of utilizing the measured axle mount vibration, the driveline model simulation results of the axle mounting point acceleration can be used as input to the dB(VINS) process. Figure 12 and Figure 13 compare the rear axle (front mount) noise share determined via dB(VINS) for measurement results and MBS results for 2nd and 3rd gear, respectively. While at higher speeds the correlation quality is reduced, the correlation of dB(VINS) measurement and dB(VINS) simulation is good up to 3500 rpm, and it predicts the main area of driveline boom well. Also here, the amplitude of dB(VINS) prediction is below the measurement levels due to the differences in transfer path sensitivities of the specific test vehicle compared to the dB(VINS) weighting functions.

With the given correlation it is now possible to predict the vehicle interior noise share of the driveline boom based on a hybrid approach of combining MBS simulation and vibroacoustic transfer paths using the dB(VINS) process. Simulation iterations can be easily assessed with respect to their expected influence on the NVH characteristics on the vehicle. In addition to evaluating driveline modification and the influence of torsional isolation components like turbine dampers, it is also possible to determine the driveline related interior noise when integrating a new engine into an existing vehicle. Specifically, this can be important with downsized engine variants, which tend to have higher torsional vibration content in comparison to the base engine being replaced. For example, the excitation of the port fuel injected (PFI) V8 engine (used in prior simulations) was replaced with corresponding excitation of a turbocharged, direct injected (DI) V6 engine. The excitation was determined via MBS simulation of a V6 engine with associated cylinder pressure data measured on a state-of-the-art, direct injected turbocharged V6 engine.

Figure 14 shows the dB(VINS) comparison of the rear axle noise share for the same driveline, excited by a downsized V6 turbocharged DI gasoline engine and the original V8 PFI engine. The amplitude of the interior noise peak increases by approximately 5 dB(A), only due to the driveline torsional vibration increase and the path through the rear axle. Due to the different firing orders, the boom resonance is excited at a different engine speed, which can be important when developing transmission shift strategies or torque converter clutch lock up schedules. In the given examples, both of these measures would not be effective since the boom peak is between 2000 rpm and 3000 rpm, which is the “high occupancy” operating speed range of the combustion engine. Generally, ‘out-calibrating’ torsional vibration excitation via shift map and torque converter lock up schedules contradicts the desire for lower fuel consumption and higher efficiency.

The expected interior noise increase in the given V6 example Figure 14 demonstrates the need for controlling torsional driveline vibration in order to achieve acceptable vehicle NVH behavior. With the trend towards downsized engines with high “low-end” torque, desire to lock the torque converter as much as possible, and use of fuel efficient transmissions such as DCTs and AMTs, driveline torsional vibration excitation tends to further increase in significance. Hence, understanding the driveline torsional vibration and its impact on interior noise is a critical task during the driveline integration process. The driveline simulation tool and interior noise simulation methodology described in this paper allow for optimizing driveline torsional vibration and tuning torsional isolators in a relatively early design phase of the vehicle.

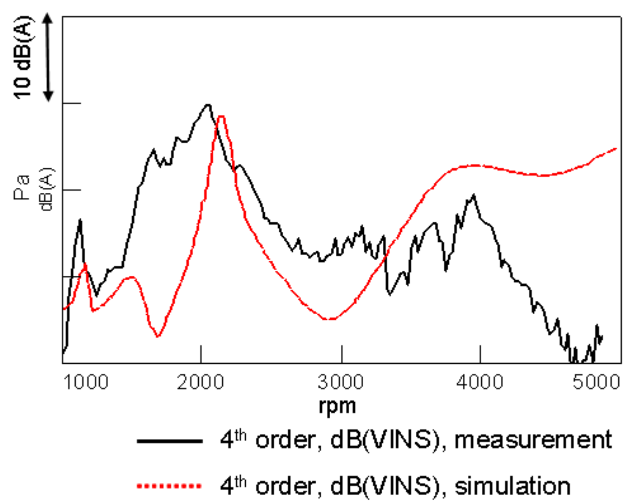

Figure 12: Comparison of interior noise share for rear axle boom between measured and simulated rear axle vibration for 3rd gear

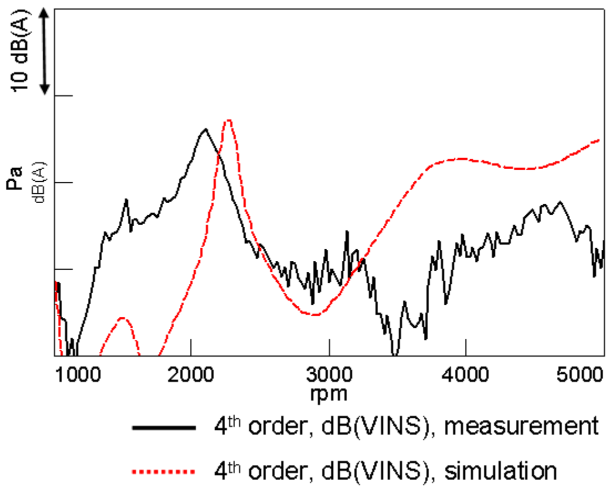

Figure 13: Comparison of dB(VINS) rear axle noise share for a V8 PFI and a V6 charged direct injected engine

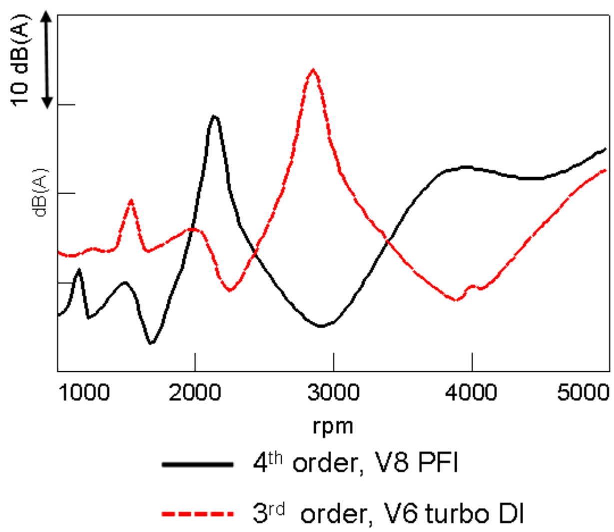

Figure 14: Comparison of dB(VINS) rear axle noise share for a V8 PFI and a V6 charged direct injected engine

SUMMARY/CONCLUSIONS

With the demand for more fuel efficient vehicles, torsional vibration excitations will inevitably increase. Charged gasoline or Diesel engines, demand for "low-end" torque and low converter lock-up speed (or manual/DCT transmission) all have the tendency to increase driveline torsional vibration. In order not to compromise NVH with these fuel efficient technologies, an understanding of driveline torsional vibration, its effect on interior noise, and ways to efficiently reduce the engine induced vibration to the driveline are key for successful driveline integration. This paper discussed the phenomenon of driveline boom and the influence of torsional vibration transmitted via the rear axle as structureborne interior noise. Specifically, the use of dB(VINS), a time-domain transfer path analysis process to evaluate the rear axle induced noise share was developed. An MBS based driveline simulation model was created to predict the vibration at the axle mounting points and the results were shown to correlate reasonably well with measured data. The predicted axle vibrations were combined with standardized transfer functions using the dB(VINS) process to estimate the rear axle induced interior noise share in the vehicle. Although this process does not replace a full vehicle transfer path analysis, the dB(VINS) approach allows the engineer to do the following, even before a test vehicle is available:

- Simulate the interior noise shares from engine mounts, axle mounts and airborne noise (if engine noise radiation is measured)
- Conduct driveline tuning evaluations (e.g., torsional isolation), based on the relative importance of various noise shares
- Generate audible interior noise shares for subjective listening studies (sound quality)

The results from the dB(VINS) analyses are used to optimize the layout and design of the powertrain and driveline components. Upon availability of a first test vehicle, a full TPA would need to be conducted to fully understand the interactions between the powertrain/driveline components and specific noise sensitivity of the vehicle.

REFERENCES

1. Juergen Knoll, Ad Kooy, Roland Seebacher: Land in sight? Torsional vibration damping for future engines; 9th Schaeffler Symposium 2010
2. Winfried Keller, Werner Wastl: Neue Methoden und Konzepte zur Drehungleichförmigkeits-reduzierung; Getriebe in Fahrzeugen, VDI Berichte 2008
3. Thomas Wellmann, Kiran Govindswamy, Eugen Braun, Klaus Wolff: Aspects of driveline integration for optimized vehicle NVH characteristics; SAE 2007-01-2246
4. U. Wolz, F. Moser: Antriebstrangschwingungen im KFZ - Aggregate- oder Systemoptimierungsaufgabe; VDI Berichte Nr. 1416, 1998
5. Norbert Alt, Klaus Wolff, Eugen Braun, Kiran Govindswamy: CAE driveline optimization; Fisita F2004F292
6. H. Stoffels: Untersuchungen zur Verminderung von Torsionsschwingungen in PKW-Antriebsträngen; VDI-Berichte 1630, 2001
7. Thomas Lückmann: Simulation von Antriebsstranggeräuschen; Dissertation University Braunschweig, 2003
8. Arthur Hülsmann: Methodenentwicklung zur virtuellen Auslegung von Lastwechselphänomenen in Pkw; Dissertation University Munich, 2007
9. Alexander Fidlin, Roland Seebacher: DMF simulation techniques – finding the needle in the haystack; 8th Luk Symposium, 2006
10. Dmitry Balashov, Lidia Burkovski, Frank Ferderer, Alexander Fidlin, Maria Kremer, Bertrand Pennec Roland Seebacher: Simulation of Torsional Vibration Dampers; ATZ 12/2006
11. Georg Eisele, Klaus Wolff, Norbert Alt, Michael Hüser: Application of Vehicle Interior Noise Simulation (VINS) for NVH Analysis of a Passenger Car; SAE 2005-01-2514
12. Marcus Pollack, Kiran Govindswamy, Thomas Wellmann, Georg Eisele, Fabienne Pichot, Phil Thomas: NVH Refinement of Diesel Powered Sedans with Special Emphasis on Diesel Clatter Noise and Powertrain Harshness; SAE 2007-01-2378
13. Christoph Steffens, Klaus Wolff, Stefan Heuer, Georg Eisele: NVH Target Value Definition from Cylinder Pressure right through to the Driver's Ear; MTZ 11/2008
14. Thomas Wellmann, Kiran Govindswamy: Development of a multi-body systems approach for analysis of launch shudder in rear wheel diven vehicles; SAE 2009-01-2073

Andreas Laschet: Simulation von Antriebssystemen, Springer Verlag 1988