

Model Based Approach by Combination of Test and Simulation Methodologies for NVH Investigation and Improvement of a Rear Wheel Drive Vehicle

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ABSTRACT

The increasing pressure on fuel economy has brought car manufacturers to implement solutions that improve vehicle efficiency, such as downsized engines, cylinder deactivation and advanced torque lock-up strategies. However, these solutions have a major drawback in terms of noise and vibration comfort. Downsized engines and lock-up strategies lead to the use of the engine at lower RPMs, and the reduced number of cylinders generates higher torque irregularities. Since the torque generated by the engine is transferred through flexible elements (clutch, torsional damper, gearbox, transmission, tire), these also impact the energy that is transferred to the vehicle body and perceived by the driver. This phenomenon leads to low frequency behavior, for instance booming noise and vibration.

This paper presents a combined test and CAE modelling approach (1D/3D) to reverse engineer a vehicle equipped with a CPVA (centrifugal pendulum vibration absorber). The objectives were to fully understand and predict vehicle behavior with respect to the drivetrain torsional oscillations and low frequency booming noise and vibration. For this purpose, the procedure was divided in two phases: testing and modelling. The testing phase was used to get insight into the vehicle behavior, noise sources and noise transfer paths, using operational measurements. Moreover, dedicated component tests were carried out to obtain parameters to be used in the modelling phase, with the CPVA being the most complex and important component. The modelling phase used the test results as input to build a full vehicle model and to validate the booming noise results. The final model was fit for sensitivity studies and was also used to evaluate the performance of the CPVA, which is dedicated to the reduction of lock-up booming noise. Such an approach is a first step which can accelerate the SDPD (system driven product development) into a consolidated MBSE (model based system engineering) framework.

CITATION: Marques dos Santos, F., Enault, T., Deleener, J., and Van Houcke, T., "Model Based Approach by Combination of Test and Simulation Methodologies for NVH Investigation and Improvement of a Rear Wheel Drive Vehicle," *SAE Int. J. Veh. Dyn., Stab., and NVH* 1(2):2017, doi:10.4271/2017-01-1774.

INTRODUCTION

The growing demand for lower automotive vehicle emissions and higher fuel efficiency has led to the design of lightweight and other technology solutions to automotive vehicles [1]. These new proposed solutions can also negatively affect the drivetrain. New technologies, such as start-stop systems [2], downsized engines [3], cylinder deactivation [4] and advanced torque lock-up strategies [5] are all examples of solutions that can be effective in reducing emissions, but that at the same time can generate undesired vibration issues, mostly propagated through the vehicle driveline. In this scenario, the advance of those technologies raises the importance of an in-depth understanding of torsional vibrations as they negatively impact comfort and are directly related to engine and drivetrain efficiency. The main consequences of these new technologies are:

- High torque oscillations: the torque generated by internal combustion engines is irregular, containing ripples due to combustion cycles. Reducing the number of cylinders has the consequence of increasing this torque irregularity.

- Lower engine speed: engine efficiency can be higher at lower rotational speeds, making it the tendency to operate engines at lower RPMs. However, these lower speed conditions can excite driveline torsional modes and suspension modes, leading to higher vibration levels.
- Lower torsional damping: in automatic transmissions, locking the clutch at lower RPMs can increase the transmission efficiency, with the drawback of having less torsional damping in lower rotational speeds.

Figure 1 summarizes these changes in the powertrain and how they affect the overall vibration levels. The first graph indicates how the lock-up condition happens before employing the more efficient methodologies, with the dashed vertical line representing the RPM state in which the clutch is locked, and the peak is related to the drivetrain resonance. By using turbo charged engines with a lower number of cylinders, the direct consequence is higher vibration levels, as shown in step number two of the first graph. Then, the use of a reduced number of cylinders leads to a shift in the position

frequency, represented in the second graph. And finally, the clutch lock-up is carried out at lower rotational speeds, as shown in the fourth step in the second graph. The consequences of these measures is the increased vibration level which is not damped by the torque converter, leading to undesired booming noise.

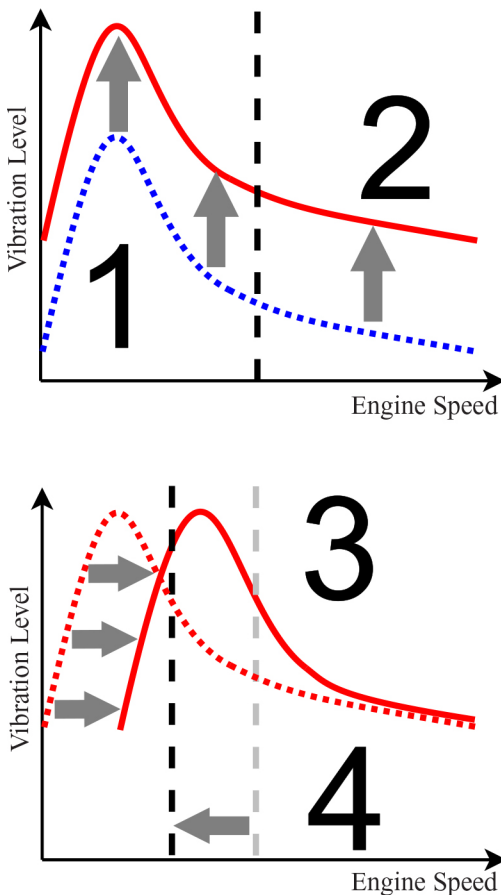


Figure 1. Vehicle automatic transmission lock-up evolution: (1) Clutch lock-up without efficient technologies; (2) Increase of vibration levels due to turbocharged engines; (3) Shift of excitation peak due to reduced number of cylinders; (4) Use of lock-up at lower RPMs.

Vibration can propagate from the powertrain to the driver and passengers mainly in two ways: via the powertrain mounts and into the car body, or through the transmission and driveline into the suspension and then into the car body [6]. Figure 2 shows a scheme with the two vibration paths. In this context, vehicle boom can be defined as an undesirable low-frequency noise (below 100 Hz), which is induced by torsional vibrations propagated through the vehicle driveline (mainly transmission, propshaft and drive shaft) to the suspension [7]. The low frequency torsional vibrations can excite the differential and suspension natural frequencies, leading to amplified vibration.

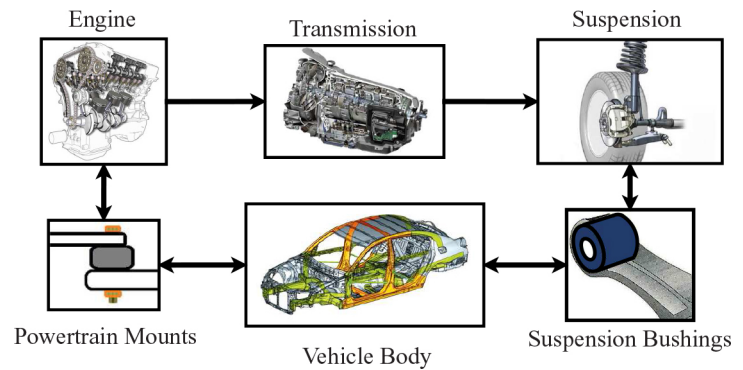


Figure 2. Vibration generated by the powertrain and the two transmission paths.

Model Based System Engineering and Testing

The growing need of more efficient methodologies for product development, combined with the increased use of mechatronic systems in automotive vehicles [8] has led to an evolution on the way testing, simulation and correlation is carried out. Experimental methodologies have gone beyond the boundaries of purely mechanical systems, with their applications expanded to other fields, such as electrical motor testing [9], electromechanical systems [10] and mechatronic applications [11]. Testing is also no longer solely related to troubleshooting analysis, and the identified parameters can be used to estimate forces and loads [12,13] acting on a system. These factors lead to a much closer relationship between testing and simulation, with both being used synergistically to ensure the right design and validation procedures.

The challenges that arise with respect to physical testing are related to the growing complexity and multiphysical nature of these new systems and applications. In turn, this leads not only to new ways of carrying out the tests (and a more diverse type of measurement quantities), but also to new types of numerical models to be validated, such as multibody and 1-D multiphysical simulation models. In this way, test data can be used on one hand to validate these models, and on the other hand for more complex and realistic interactions, combining these multiphysical models with experimental data into hybrid approaches, where a system can be tested in a system-in-the-loop (SyIL) configuration, where part of the system is physical, and part of it is simulated.

Integrated Test and Simulation Approach

One of the traditional ways of carrying out NVH analysis in automotive vehicles is transfer path analysis (TPA). This technique is widely employed in the automotive industry, and is used to determine the overall contribution of different transmission paths towards defined targets, such as seat vibration or driver's ears. TPA is very efficient in determining the vibration paths and their contributions in higher frequencies, but can have limited accuracy in the lower frequency range (below 100 Hz), due to bad condition numbers which can lead to matrix inversion problems. More importantly, due to the fact that booming noise arises from the interaction between rotational components and the vehicle

suspension, it is hard to obtain realistic measurement scenarios when the vehicle is not in operational condition, which is one of the requirements of classical TPA approaches.

To overcome this limitation, an integrated approach is proposed, using 1D simulation tools combined with testing. In this way, test data is used to validate and improve 1D simulation models, which in turn can be used to analyze important system attributes. Figure 3 shows a diagram of the procedure and how it is carried out. Initially, static and component specific measurements are carried out for different components, to obtain their parameters used in simulation. This includes the geometry of parts and components, when necessary for the simulation, but also static stiffness and mass and inertia measurements. Modal analysis can be used to obtain the vibration modes of the suspension and related components. Then, operational measurements are also carried out, with the goal of understanding the interaction between the drivetrain and other components (engine, clutch, driveline, suspension, car body). These test parameters are used to model some components, and are also used to validate and correlate simulation with test results. There are two sets of results from the test and simulation parts. The testing can be used not only to obtain component parameters and validation data, but can also be used for troubleshooting, to verify root cause of possible problems. The analysis based on the simulation model can be used to predict changes in components, and how these will affect the overall behavior of the vehicle, with respect to the low-frequency NVH parameters.

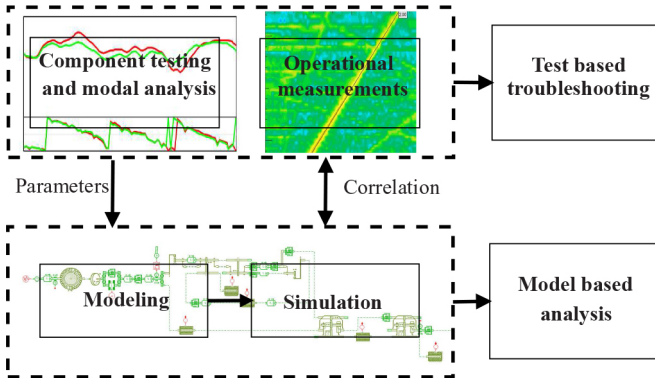


Figure 3. Diagram of test-simulation integration

An advantage of combining simulation with tests is that much more information can be extracted and obtained, leading to a better understanding of the underlying principles that lead to the different phenomena. For example, when measuring torsional vibrations on a vehicle, the excitation frequency is limited to the idle speed of the engine, meaning that any dynamics below that frequency cannot be directly measured. However, by using a validated simulation model to analyze the system, one can extrapolate the limited and sometimes fixed boundaries or loads, to be able to view the full system behavior and therefore carry out a better troubleshooting analysis. Figure 4 shows such a case, where the resonances that can lead to booming noise cannot be properly measured due to the excitation frequency limit

(and how different gears affect the system), but can be predicted by using a proper model. The model can moreover be used to verify how different components interact, and optimize operational characteristics.

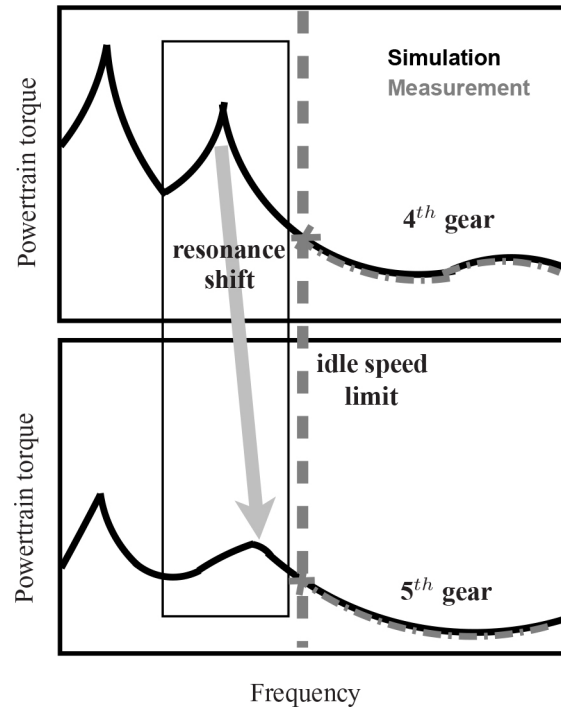


Figure 4. Example of extrapolation of data obtained using simulation, when compared to test data: second-order torsional vibrations for 4th and 5th gear

This article will show a benchmark procedure carried out on a D-segment rear wheel drive car, with the objective of troubleshooting and modelling the booming characteristics of the vehicle, and to analyze how some components affect its performance. One important objective of these measurements was to characterize the dynamic behavior of the centrifugal pendulum vibration absorber (CPVA) [14, 15]. This component, which has a nonlinear complex behavior, can be used to absorb torsional vibrations in the driveline, and the goal was to determine its impact in the NVH behavior.

The next sections will explain the procedures in detail - the testing phase section will show in detail the different parts of the experimental procedure, model parameter characterization, operational measurements and test based diagnosis, while in the modeling and validation section the full vehicle modeling, validation and model based analysis will be presented.

TESTING PHASE

Testing has mainly three purposes - to identify physical and dynamic parameters to be used in the model, to obtain operational data that can be used to validate and correlate simulation results, and also provide test based diagnosis and troubleshooting, generating additional insight into the system and its behavior. In this way, the test phase can be divided in three parts: