

Investigation of NVH Characteristics of a Downsizing Vehicle

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ABSTRACT

The automotive industry permanently enhances Downsizing concepts due to environmental commitments and energy consumption concerns. Even in the category of city- and supermini-cars, great efforts are made for the development of highly charged engines with small displacement. So far the main focus of these developments is set on the reduction of CO₂ emissions and fuel consumption. However these are not the only aspects, which have to be fulfilled by the vehicle in order to meet the demands of the customers and to be successful in competition. The NVH characteristics of such Downsizing vehicles have to match a class-specific level, which can only be achieved by additional measures. Regarding this, a view of the dynamic behavior of the entire vehicle is required.

At the Institut für Kraftfahrwesen Aachen (ika) the potential for reducing fuel consumption and CO₂ emissions of a Downsizing concept is investigated using a city-car as reference. For this purpose, among other things, the three-cylinder-engine of the reference car is replaced by a highly charged two-cylinder-engine with same power output but smaller displacement. Apart from the environmental aspects the NVH behavior of the Downsizing concept is investigated and optimized in a holistic approach including measurements and simulations. Focus of this paper is the analysis and the improvement of the NVH-phenomenon "shuffle", which is excited by load change procedures of the two-cylinder-engine. With the help of a simulation model several measures for reducing "shuffle" are evaluated with respect to the acceleration of the vehicle. The measurements, the developed simulation model and the corresponding results are represented in this paper.

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INTRODUCTION

In the scope of a research project the partners Institute for Automotive Engineering of the RWTH Aachen University (ika), Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka) and Meta Motoren- und Energie-Technik GmbH jointly developed a downsized drive train concept which is suitable for subcompact and small cars. Besides the reduction of CO₂ emissions a further object during development is the optimization of the vehicle NVH behavior, since the customer is simultaneously demanding low fuel consumption and driving pleasure. A high drive train efficiency in combination with sufficient engine torque especially at low engine speed is achieved by the implementation of a consequent downsizing and downspeeding concept with a highly charged two-cylinder-engine. Additional CO₂ saving potentials can be exploited if besides the new engine concept further measures on vehicle

side are taken. Hence the starter motor is replaced by a belt-starter generator in combination with an intelligent generator control which enables the recuperation of braking energy and reduces the total vehicle weight. The recuperation of thermal energy is realized with an integrated heat accumulator inside the cooling system. By storing the thermal losses this system helps to shorten the engine warm-up during a following cold start and leads to lower friction and thermal losses. Finally, reducing the vehicle mass as a benefit of the engine downsizing, as well as rolling and aerodynamic drag resistance has further positive influence on the fuel consumption and CO₂ emission. Due to the reduced number of cylinders, engine speed and engine torque characteristic, the vibration behavior and hence the corresponding vibration excitation are changed fundamentally. In order to guarantee class specific NVH behavior full heat investigation and

optimization utilizing a holistic approach, based on accurate measurement and multi disciplinary simulation methods, as well as subjective evaluation are conducted.

INVESTIGATION OF NVH CHARACTERISTICS

Customers do have increasingly high demands in terms of vehicle acoustics. This means that it is inevitable to design an attractive vehicle noise and vibration behavior in addition to low fuel consumption for the acceptance of the downsizing concept by the customer. Hereby the most important component is the entire drive train with its attachment points to the body. A balanced NVH performance is to be achieved by selective influencing the noise source and the corresponding noise transmission paths. At the beginning of the development process extensive airborne and structure borne noise measurements, as well as longitudinal vibrations measurements during load change reactions are carried out with a reference vehicle to define target values as basis for the evaluation of NVH measures. Furthermore the obtained measurement data is used for the buildup and validation of a transfer path model, which considers noise transfer from the engine and drive train to the interior of the vehicle. The eigenfrequencies and displacement of different engine and gearbox mount configuration are estimated with the help of a multibody simulation tool. In addition these mount variants are evaluated with the help of the transfer path model and test bench measurements of the new engine as the corresponding interior noise is predicted. Different number, position and volume of mufflers, as well as the principles of sound attenuation are considered for the adaption of the exhaust system to the changed engine behavior. An assessment is based on the orifice noises that are obtained from both test bench measurements and simulations. To support the simulation, a test bench for the experimental determination of the acoustic damping (transmission loss) is designed and built. Another challenge is the improvement of the longitudinal vibration behavior as a result of load change reactions. This point is discussed in detail in the following chapters.

NVH PHENOMENON SHUFFLE

The drive train of a vehicle is a complex system, consisting of rotating masses and torsion springs. During a load change with high torque gradient, the first natural mode of this system is mainly excited [1]. The resulting torsional vibration is transferred by the wheels to the vehicle body, where it is reflected in a low frequency longitudinal vibration, also known as shuffle. Shuffle is not excited by the torque fluctuations of the combustion process, only the effective torque change at the flywheel is relevant.

The frequency range of shuffle is normally located between 2 and 8 Hz [2], depending on the present gear engaged. As

humans are very sensitive to vibrations in this frequency range [3], the Shuffle phenomenon strongly degrades the driving comfort.

Figure 1 presents the time-dependent torque characteristics in consequence of a load change from low partial load to full load of the new two-cylinder Downsizing engine used in the prototype vehicle. The shown load step is conducted at an engine speed of 1250 rpm.

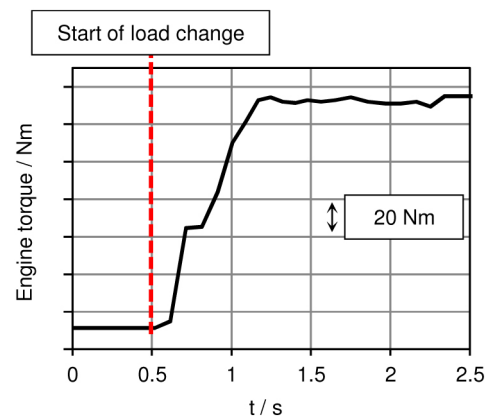


Figure 1. Time-dependent torque characteristics due to a load change

According to the figure, the maximum torque of the two-cylinder engine is reached within 0.65 seconds. In comparison to turbo charged engines with a comparable torque output, that require up to 2 seconds for reaching the maximum torque [4], the torque course of the two-cylinder engine shows an increased torque gradient. Moreover, this torque course contains a step, which is caused by the changeover from naturally aspirated to charged mode.

Since results of former studies demonstrate a negative influence of enlarged torque gradients and torque-steps on the vibrational behavior of the drive train [5], the torque characteristic of the two-cylinder engine may possibly degrade the shuffle behavior of the prototype vehicle in comparison to the reference vehicle.

Regarding this, a detailed investigation of the load change behavior of the prototype vehicle in terms of load steps from low partial load to full load is required. The main objective of this investigation is on the one hand an early prediction of the shuffle phenomenon and on the other hand the determination and evaluation of optionally needed countermeasures in order to guarantee a class-specific vibration level.

Methodology for Analyzing Shuffle Vibration

For the investigation of shuffle vibrations and the evaluation of different countermeasures, simulations and measurements have to be conducted. The general investigation process is shown in figure 2.

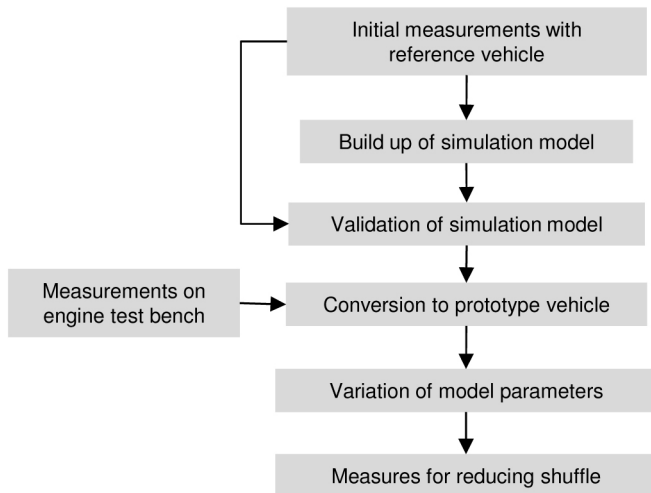


Figure 2. Process of investigation

At the beginning of the investigation, Tip-In-maneuvers are performed on the test track of ika in order to determine the load change behavior of the reference vehicle. During the Tip-In maneuvers, the accelerator pedal is actuated from low partial load to full load, starting from an engine speed near idle speed. In this, the first and second gear of the vehicle are considered, as in these gears shuffle is strongly perceptible due to large amplitudes. While the Tip-In-maneuvers are carried out, the longitudinal acceleration at the seat rail of the driver's seat, the engine speed, the engine torque and the vehicle speed are measured. This comprehensive dataset enables the determination of parameters for a simulation model and also provides an evaluation basis for the future prototype vehicle.

In the second step of the investigation, a simulation model of the reference vehicle is built up and validated with the help of the acquired dataset. The model enables the simulation of the longitudinal vehicle dynamics, especially with regard to shuffle. After the validation, the drive train and vehicle parameters of the model are adapted corresponding to the conversion from reference to prototype vehicle. In particular, the torque characteristic of the new two-cylinder Downsizing engine, derived from test bench measurements, is considered. Hence, the resulting model provides the possibility to simulate Tip-In-maneuvers of the prototype vehicle and to evaluate its shuffle behavior.

In the next step, a variation of the simulation model parameters can be conducted in order to define and evaluate measures for reducing the shuffle vibration of prototype vehicle, if required. However, since these measures influence not only the shuffle characteristic but also the performance of the vehicle in many cases, there is a conflict of aims between shuffle respectively driving comfort and agility. For this reason, the driving performance of the prototype vehicle is additionally evaluated for the different measures. It is intended, that the shuffle vibrations and the driving performance of the prototype vehicle are at least on the same level with the reference vehicle in

order to meet the customer demands concerning comfort and drivability. Based on the results of this parameter variation, an implementation of suitable measures can be derived.

The advantage of this procedure is the possibility to make assessments and improvements concerning the shuffle behavior in an early period of the development process without the presence of the final built-up prototype vehicle.

Buildup of Simulation Model

The simulation model of the reference and prototype vehicle is built up in Matlab Simulink. This software is chosen, because, in contrast to commonly used multi-body-simulation programs, Matlab Simulink allows the integration of control structures such as engine control units or transmission control units in an easy manner.

The investigation and evaluation of shuffle phenomena requires a model of the entire vehicle [6]. Therefore, the model does not only contain the drive train but also the vehicle body with its connections to the drive train. In general, the model can thus be divided in two parts. The first part is a comprehensive model of the drive train, which includes the clutch, the transmission with its variable gear ratios, the differential gear, the drive shafts and the tires. The different components of the drive train elements are modeled with torsion spring-damper-elements and rotating masses. Friction losses are also taken into account. Furthermore the tire slip is considered, as it has a big damping effect and consequently not negligible influence on the shuffle vibration [7].

The second part is a vehicle model containing the mass of the body and the characteristics of the chassis. In addition, the engine mounting and the engine block are taken into account due to the fact, that big deflections of the engine block in consequence of load changes from low partial load to high load have a significant influence on the torsional vibration behavior of the drive train and the resulting shuffle [8]. In order to consider this effect, the engine block, characterized by its inertia tensor, is connected on the one hand to the drive train and on the other hand to the vehicle body via three engine mounts, which are modeled by their characteristic stiffness curves.

The coupling of drive train and vehicle model enables the simulation of the longitudinal dynamic and shuffle behavior. A modeling of the transverse dynamic behavior of the vehicle is not necessary and therefore not considered.

As input parameter for the excitation of the vehicle, the engine torque is used. The implementation of the model allows using time-dependent torque characteristics from measurements as well as engine characteristic maps. After the simulation is done, a multitude of results such as the revolution speed of the different drive train components, the velocity of the vehicle, the engine speed or the acceleration of the engine can be derived.