NVH of Hybrid Vehicles

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Abstract: The technology used in hybrid vehicle concepts is significantly different from conventional vehicle technology with consequences also for the noise and vibration behavior. In conventional vehicles, certain noise phenomena are masked by the engine noise. In situations where the combustion engine is turned off in hybrid vehicle concepts, these noise components can become dominant and annoying.

In hybrid concepts, the driving condition is often decoupled from the operation state of the combustion engine, which leads to unusual and unexpected acoustical behavior. New acoustic phenomena such as magnetic noise due to recuperation occur, caused by new components and driving conditions. The analysis of this recuperation noise by means of interior noise simulation shows, that it is not only induced by the powertrain radiation but also by the noise path via the powertrain mounts. The additional degrees of freedom of the hybrid drive train can also be used to improve the vibrational behavior. As an example it is shown with a multi-body simulation of the drive train how its low frequency vibrations can be reduced with a targeted control of the electric motors.

Keywords: hybrid vehicle, NVH, simulation, drive train, vibration control, recuperation, masking

1. Introduction

Designing the noise and vibration behavior of hybrid vehicles is not only concerned with overcoming the challenges caused by this new technology. It is also about finding ways to utilize the new possibilities that it has to offer to the acoustic engineer. The noise and vibration behavior of hybrid vehicles is dramatically different from conventional vehicles. A hybrid powertrain features additional and different components as well as new operation modes compared to a conventional powertrain. This results in new interactions which are uncommon in this form for conventional vehicles. The noise and vibration mechanisms of the individual components (combustion engine, electric motor, transmission etc.) are known in principle. However, more research needs to be done into the interplay and the interactions of these components within the entire system, especially with regard to powertrain induced interior noise and vibration comfort.

The results presented in this paper are largely based on a research study funded by Forschungsvereinigung Antriebstechnik e.V. (FVA) and carried out at the Institute for Combustion Engines of RWTH Aachen University. The study specifically investigated the noise and vibration behavior of a power-split hybrid powertrain.

2. Hybrid-Specific Noise and Vibration Issues

The noise of hybrid vehicles currently available on the market is generally low during purely electric driving compared to conventional propulsion systems with internal combustion engines. However, if the combustion engine of a hybrid vehicle is turned off, the masking effects caused by the combustion engine noise are also absent. Thus, otherwise inconspicuous noise and vibration sources such as the ventilation noise of the air conditioning can become annoying. Hybrid-specific operation modes such as recuperation can also generate potentially annoying noise and vibration phenomena. Moreover, new operating states, especially the frequent start and stop of the combustion engine during driving, can cause additional noise and vibration problems. Figure 1 gives an overview of the NVH phenomena occurring in a power-split hybrid system in different operating modes.

The transitions between the different operating modes are generally critical, since transient phenomena are to be expected. For instance, during the transition from a purely electric mode to a mixed mode with the combustion engine turned on, the starting process should not produce unpleasant noise and vibration phenomena. In both operating ranges – with the combustion engine is active either in combination with an alternator or with an electrical motor – intelligent regulation procedures are necessary to avoid sudden torque changes and torque fluctuations. The relevant NVH aspects of hybrid vehicles fall into three categories:
- Dominant noises due to the absence of masking effects
- Unexpected acoustic behavior
- Specific acoustic phenomena

These phenomena will be examined in more detail in the following three chapters.

2.1 Dominant Noise Due to Missing Masking Effects

In driving conditions where the combustion engine is turned off, acoustic phenomena become prominent, which in conventional engines are masked by the combustion engine noise. Typical examples for this are the pump noise of the electric water pump and the vacuum pump, the ventilator and the rolling noise as well as ambient noise [1], [2].

Figure 2 depicts the interior noise spectrum of a ventilation system at different fan settings. The gray area indicates the interior noise of typical gasoline and diesel engines at idle. It is obvious that the fan noise up to ventilation level 3 is masked by the engine noise. At idle, the fan noise becomes more prominent due to the low engine noise. This has been a steady trend for several years. With hybrid vehicles, a low blower noise becomes even more important due to the fact that the combustion engine is often turned off.

2.2 Unexpected Acoustic Behavior

In conventional vehicles with pure combustion engine propulsion, vehicle speed is linked to engine speed. The resulting interior noise is perceived by the driver as a feedback on the driving condition.

By contrast, in hybrid vehicles vehicle speed is not entirely determined by the combustion engine but – depending on the configuration – additionally by the operating condition of the (or several) electric engine(s). Very often there will be no clear connection between vehicle speed and engine speed which is due to the fact that in hybrid concepts the speed of the combustion engine is also influenced by the load demand and the state of the battery. Figure 3 depicts engine speed and vehicle speed of a hybrid vehicle during full load acceleration. Whereas vehicle speed increases continuously, engine speed increases abruptly at the beginning of acceleration and remains nearly constant after approximately 15 s. This speed course generates an interior noise (also known as “the motorboat effect”) that is unusual compared to a conventional powertrain [2]. Here it is necessary to find a well-balanced compromise between the expected acoustic feedback and the power demand.
2.3 Hybrid-Specific Acoustic Phenomena

Compared to a conventional powertrain, a hybrid powertrain features additional components such as electric engines, electronic control units and a high-voltage battery. This results in different new interactions between these components which are not found in this form in conventional engines. Additional components as well as resulting interactions can lead to acoustic problems with a negative effect on comfort [3], [4], and [5]. In the following, NVH phenomena due to hybrid-specific components and their interactions are listed:

- Low-frequency vibrations of the powertrain during start/stop of the combustion engine at load change
- Modified moments of inertia and eigenfrequencies in the powertrain
- „Streetcar Noise“: magnetic noise of the engine/generator during electric driving and regenerative braking
- Aerodynamic noises of the battery cooling system
- Switching noise of the power control unit

One of the essential aspects which has to be taken into account in the development of hybrid powertrains is the frequent starting and stopping of the combustion engine. With a start/stop system the engine is shut down automatically at standstill for example at a traffic light or in a traffic congestion and it is started again when the driver wants to move on. This can reduce fuel consumption in urban traffic considerably. If the hybrid powertrain is built in such a way - which is the case for instance for the power-split hybrid - that combustion engine speed is decoupled from vehicle speed, the combustion engine can be turned off also in driving conditions with little load demand.

Since the start/stop event happens frequently, its influence on the noise and vibration behavior should be thoroughly investigated and analyzed. The main tasks regarding the improvement of hybrid vehicle NVH behavior are the optimization of the vibrations in the vehicle during start and shut off of the engine and the prevention of disturbing noises due to the start/stop system. Typical problems are the tooting noise due the use of a pinion starter and the gas forces of the piston engine, which lead to severe shaking of the engine by excitation of the roll eigenfrequency.

With a power-split hybrid, a frequent change between electric and combustion engine propulsion can occur also during constant-speed driving at low speeds. Figure 4 shows an example where the driver hardly notices the change between electric and combustion engine propulsion. It shows a time period from constant driving in which the combustion engine is operated during three short time intervals. Each time the 3rd engine order (6-cylinder engine) appears on the level diagram. However, the level of this order is 15 dB(A) below the total level and thus it is only perceived as a slight background noise. The reason for not providing an acoustic response to the driver in this situation is that the operation of the combustion engine depends on the charge state of the battery and not of the driver’s load demand. If during constant driving, suddenly and without any recognizable reason, the combustion engine started up and dominated the vehicle interior noise, it would only serve to confuse the driver.

Aside from the above-described acoustic effects due to the operation of the combustion engine, the starting process can also lead to disturbing vibrations. Control methods can be applied to reduce unwanted vibrations [6], [7]. This will be discussed for a power-split hybrid vehicle in more detail in Chapter 3.
3. Simulation of Powertrain Vibrations in Hybrid-Specific Driving Conditions

During start and stop of the combustion engine and load alterations, vibrations can occur that the driver may perceive as subjectively annoying. Particularly during the starting process, vibrations are caused by the excitation of eigenmodes of the powertrain due to the low engine speed and by an impulse-like excitation due to the sudden increase of torque. Hybrid vehicles are especially problematic in this regard, since the starting process of the engine occurs very often. On the other hand, the new components of the powertrain also offer possibilities to counteract these comfort-impairing effects. The following example illustrates this in more detail for a power-split hybrid vehicle. Subsequent to a description of the powertrain, its dynamic behavior will be analyzed by means of a multi-body simulation model. It will be shown how electric motor control can help to reduce vibrations.

3.1 Description of the Powertrain

As test vehicle a full hybrid vehicle was chosen with a power-split powertrain and an all-wheel-drive without mechanical coupling of the axles. A V6 cylinder 3.3 l gasoline engine as well as two electric motors propel the front axle. A third electric motor (mechanically decoupled) propels the rear axle.

Figure 6 shows the assembly of transmission and internal combustion engine (ICE) of the test vehicle. The crankshaft is connected to the planetary gear carrier of the first planetary gear (PG1). The motor/generator (MG1) drives the central gear and the annulus gear is fixed to the annulus gear of a second planetary gear (PG2). Motor/generator 2 (MG2) drives the central gear of the second planetary gear (PG2) and the planetary gear carrier of PG2 is fixed to the housing. This results in a fixed transmission ratio from MG2 to the annulus gear and thus also to the wheel.

MG2 works mainly as an engine – it propels the wheels directly and controls the powertrain torque. Only during recuperation, it is used as a generator. On the other hand, MG1 works mainly as a generator – it provides the electric power for MG2 and it charges the high-voltage battery. Moreover, MG1 has to propel the combustion engine at start. MG1 counters the torque if the combustion engine and controls the transmission ratio of the combustion engine and the annulus
gear. Through a variable adjustment of the transmission ratio, the combustion engine can be increasingly operated within the fuel-efficient range. PG2 has to reduce the speed of the electric motor, while PG1 serves as a power distributor.

3.2 Model Set-up

Figure 7 shows the model which was used for the torsional vibration simulation. The internal combustion engine (ICE) and the two electric motors (MG1 and MG2) act as excitation sources on the transmission. The very rigid hybrid planetary gear is depicted as a purely kinematic module without stiffness. Its inertias are reduced to the differential gear. Torsion spring damper elements model the drive shaft and the tires. The model has several rotational degrees of freedom and one longitudinal degree of freedom in driving direction. The vehicle is represented within the vibrational system as rotational inertia.

3.3 Modal Analysis

The modal analysis of the powertrain model shows that four characteristic eigenvalues in the investigated low frequency range are below 250 Hz (Figure 8):

1. Jerking mode (10 Hz),
2. Torsional-vibration damper mode (17 Hz)
3. Tire mode – asymmetrical (29 Hz)
4. Tire mode – symmetrical (35,6 Hz)

By means of impact tests and operational measurements, the jerking mode at 10 Hz and the torsional-vibration damper mode at 17 Hz can be verified which matches well with the simulation.

Figure 8 shows in a schematic diagram the eigenmodes of the power-split hybrid powertrain compared to a conventional powertrain with a single-mass flywheel (SMF) and alternatively with a dual-mass flywheel (DMF). The eigenmodes of the hybrid concept are similar to the eigenmodes of a conventional powertrain with a dual-mass flywheel. In case of a conventional vehicle with a single-mass flywheel, the second eigenmode lies between 40 Hz to 80 Hz. High vibrational amplitudes occur mainly in the proximity of the gearbox and can lead to transmission rattling. In case of a powertrain with a dual-mass flywheel, a
part of the flywheel mass is shifted behind the torsional-vibration damper. The jerking mode is thus nearly unchanged, but the second eigenmode is shifted below the idle range between 10 Hz and 15 Hz. This is also the case for the hybrid concept discussed in this paper. The rotor of MG2 is comparable to the secondary mass of a dual-mass flywheel and the flywheel corresponds to the primary mass. In the torsional-vibration damper mode of this hybrid powertrain, the MG2 mass vibrates against the combustion engine, and in the DMF mode of a conventional engine, the DMF secondary mass vibrates against the DMF primary mass.

In the jerking mode, the entire powertrain vibrates against the vehicle and is particularly excited during start/stop. In the torsional-vibration damper mode, the combustion engine vibrates against the powertrain which corresponds to major tensions in the torsional vibration damper. With a 6-cylinder engine, the 3rd engine order meets this 17 Hz resonance at the critical speed of approximately 340 1/min. The critical speed is only reached during the start and stop process of the combustion engine which however occurs much more often in hybrid vehicles than in conventional powertrains.

Both tire modes are highly damped and thus hardly noticeable.

3.4 Control Methods for Vibration Reduction

With hybrid vehicle concepts, start and stop occur very often. To reduce the vibrations caused by this, control methods of the electric components are used in addition to measures at the engine mounts as well as combustion engine control [10-14].

The starting of the combustion engine can be divided into two phases: 1) Starting phase: MG1 speeds up the combustion engine to about 1000 1/min, combustion has not yet started. The excitation occurs through the 3rd engine order at low frequencies. 2) Combustion start: the combustion starts at about 1000 1/min. The sudden torque increase acts as an excitation on the powertrain.

During start, the powertrain vibrations are caused by the excitation of the torsional-vibration damper mode when the ignition order of the combustion engine meets its eigenfrequency. For this purpose, starting torque control is applied to minimize the rotational angle in the torsional-vibration damper by controlling the additional torque of MG1, as the largest vibrational amplitudes are found at the torsional vibration damper.

The jerking mode is excited by a rapid torque increase or decrease of the combustion engine, especially during start/stop, sudden acceleration or deceleration. To take care of this problem, jerking control is applied. Its task is to minimize the difference between the current dynamic wheel speed and the (according to the transmission ratio converted) speed of MG2 by control of MG2 torque. This suppresses the jerking mode, as it features considerable angle and/or speed deviations between MG2 and the converted wheel speed.

Figure 9 shows a schematic overview of the simulation model consisting of the powertrain mode, the speed regulator, the model of the starting process, the jerking controller and the starting torque controller.
To achieve a stable transmission ratio, the electric counter torque of MG1 needs to be controlled. This is why a speed regulator is necessary for this type of hybrid concept, even for standard operation. The torque of MG1 is not an input value of the total system, but it is determined by the speed regulator. The starting process module yields the torque of the combustion engine while allowing for start of combustion. Starting torque control accesses MG1; jerking control accesses MG2. The controllers receive the speeds \( n \) as input values and the corresponding torques \( T \) are yielded as output values.

In Figure 10, the simulated starting process of the combustion engine during driving is shown with and without control. Without control (gray curves), MG2 yields the constant driving torque for vehicle acceleration. MG1 becomes active twice: at start, it revs up the combustion engine to approximately 1000 1/min. At the beginning of combustion, the torque of the combustion engine needs to be countered.

With control, the dynamic intervention of the starting torque control into MG1 can be noticed (black curve). The maximum amplitude of the drive shaft irregularity and vehicle acceleration are reduced to a third.

All in all, without control, the excitation during the starting process is more critical than at the beginning of combustion. With active control, both vibration phenomena are significantly reduced and on a similar level.

So far, the starting process was always simulated with a delayed beginning of combustion compared to the real behavior to facilitate the separate investigation of the phenomena in both areas. Figure 11 shows a simulation of the drive shaft irregularity without such a delay. Obviously, there is a good match between simulation and measurement. Also in terms of quantity, the occurring amplitudes correspond well.
Fig. 11: Speed Irregularity of the Drive Shaft for the Starting Process, including Control of the Electrical Engines for Vibration Reduction – Comparison between Simulation and Measurement

One important criterion for vibration reduction mechanisms is their robustness against disturbances that occur in reality, for instance through inaccuracies or production variance. As expected, the vibration reduction through MG2 jerking control at the beginning of combustion proves to be considerably more robust against the interferences that were built into the model than MG1 starting torque control during start (Figure 12).

Fig. 12: Robustness of Vibration Reduction Mechanisms (Control of MG1-Torque at Starting and Closed-loop Control of MG2-torque at Start of Combustion) Against Disturbances

All in all, it can be seen that through a specific use of electric motors in the form of pre-regulated or controlled dynamic torques, the powertrain vibrations can be reduced to a third. Regarding the regulation and control algorithms, it is necessary to ensure sufficient robustness against disturbances.

4. Interior Noise During Recuperation

The magnetic noise content of the interior noise during purely electric driving or during recuperation (Figure 5) is generally low compared to combustion engine noise. However, without the masking effect generated by the combustion engine, this noise is perceived by the driver as disturbing. In the following, the noise during recuperation is described in more detail. By means of an interior noise simulation, approaches for the reduction of unpleasant noise content will be pinpointed.

4.1 Powertrain Noise Components

The different noise components during recuperation were already depicted in Figure 5 for the interior noise and will be demonstrated here by means of the directly measured powertrain noise, since the engine orders can be seen more clearly here. The powertrain in this example is composed of a generator, an electric engine and a combustion engine. Figure 13 shows a Campbell diagram of an airborne noise recording in the engine compartment during recuperation.

Fig. 13: Powertrain Noise Radiation during Recuperation with Magnetic Noise and Gear Noise

Different orders occur which lead to considerable whining. The whining in this example is not only caused by the magnetic noise of the generator (white circles) but also by the transmission toothing noise (black circles). The area around the 22nd up to the 24th electric motor order is subjectively perceived as particularly disturbing. The whining of the vehicle could be clearly noticed in the vehicle interior. In addition to the magnetic
and tooting noise, severe road noise occurs in a broad range around the 8th electric engine order which, however, does not have a whining noise character and is thus not perceived as disturbing.

4.2 Interior Noise Simulation

The method for interior noise simulation (Vehicle Interior Noise Simulation – VINS) can be generally used for the analysis of vehicle interior noise and is applied here to a hybrid vehicle during recuperation. It decomposes the interior noise into the individual noise content of the different paths. These are – according to the functional chain – split up into noise source and transfer function (Figure 14). While the airborne noise content has mostly only a monadic airborne noise transfer function, the structure-borne noise transfer function results from the linking of mount transmission and body transfer function. This method has already been described in more detail in other literature [15], [16], [17].

Fig. 14: Principle of Vehicle Interior Noise Simulation – VINS

VINS always produces an audible interior noise as well as audible interior noise shares of the different sources. These can be systematically summarized and analyzed according to groups. Figure 15 shows the Campbell diagrams of these individual subtotals for the simulated interior noise at recuperation. The shares of the different powertrain mounts in each of the three spatial directions are summarized into one noise for a better overview. In the lower right corner of the figure, the Campbell diagram of the overall noise is shown.

The whining noise during recuperation is not only generated via the powertrain airborne noise, but significant shares are also caused by the powertrain mount paths. In addition to that, there are structure-borne noise shares from the electric engines which propulse the rear axel. The noise induced via the chassis extends over similar frequency ranges, but it lacks the subjectively unpleasant whining noise character.

Fig. 15: Campbell Diagrams of the in Groups Summarized Simulated Interior Noise Shares during Recuperation

By decomposing these groups into the individual shares and through an analysis of the excitation and the transfer function, the noise generation mechanisms can be examined more closely. It can be seen that the major share of the whining noise induced via the powertrain mounts is caused by a high excitation and an unfavorable transfer function of the right engine mount.

The powertrain airborne noise content can be also analyzed according to the number of microphones used. The left powertrain side produces significant noise shares due to high radiation and the rear powertrain side also contributes a considerable noise share due to its unfavorable transfer function.

Based on this analysis, the components whose modification promises a reduction of whining noise can be identified. In case of the investigated vehicle, those components are in particular the right powertrain mount and the fire wall insulation.

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