Reducing Combustion Noise

ABSTRACT

The design and development of modern internal combustion engines is marked by a reduction in exhaust gas emissions and increase in specific power and torque. Correspondingly, combustion noise excitation and fuel consumption also have to be reduced. These objectives can be achieved through the development of advanced combustion systems, the increased flexibility of fuel injection systems and ECUs. However, development of modern combustion systems and vehicle applications has become increasingly complex. Creating an exact, yet straightforward description of combustion noise is a very important task. The customer's subjective impression of the entire vehicle, regarding items such as diesel knock sensitivity, provides evidence to support its value.

FEV has developed a modern method to describe combustion noise excitation using the in-cylinder pressure-based FEV CSL (Combustion Sound Level) tool. This tool provides the potential to completely investigate the NVH calibration, while meeting the targets for emissions and fuel consumption. FEV CSL-CAL (Combustion Sound Level – Calibration) is a tool FEV specifically developed for NVH-related vehicle calibration. These tools enable all of the important ECU parameters to be optimized simultaneously under the customer-relevant driving conditions. The optimal calibration map for steady-state as well as for cold start and during acceleration is created from by FEV SQO (Sound Quality Objective) tool that develops the parameters used to subjectively judge combustion noise. These tools provide a complete description of the combustion noise, which allows it to be optimized towards the expectations of the customer.

INTRODUCTION

The key parameters of developing new or existing combustion systems are exhaust gas emissions, specific power and torque, combustion noise and fuel consumption. Key parameters for the vehicle application include drivability, cold start and transient behavior.

Countries around the world continue to legislate against the release of specific levels of exhaust gas emissions, such as nitrogen oxide, hydrocarbon, carbon monoxide and smoke. Europe typically introduces new emission legislation approximately every four years. Since the beginning of the year, new vehicles in Europe have been required to meet the Euro 4 exhaust emission levels. The Association des Constructeurs Européens d' Automobiles (ACEA) target values for fleet fuel consumption and carbon dioxide emissions are scheduled to be reduced again in the year 2008 and 2012 Currently, this target value appears to be difficult to achieve, due to the actual focus on exhaust gas emissions, vehicle power and torque, which has been increased on average more than 60% (specific values) within the last 10 years. Additionally, customer requirements for combustion noise need to be met, which can be accomplished through optimization of the combustion system.

These goals can be met through the development of advanced combustion systems and the increased flexibility of fuel injection systems and ECUs. However, the complexity of combustion system development has dramatically increased. A variety of parameters, such as EGR rate, boost pressure, injection pressure and charge motion, have to be used to create the optimum design. The engine's injected fuel mass and injection timing also has to be optimized, to include up to five single injections per stroke for diesel engines.

It is crucial that the descriptions for all of the resulting parameters be accurate and concise, due to the large array of variants that are available. The combustion noise component is not to be taken lightly, because this is the source of the customer's subjective impression of the vehicle. Ideally, an evaluation by a jury would provide the optimum design direction; however, this is typically is not feasible for all of the variants. Because of this limitation, FEV has developed several parameters and methods for judging combustion noise.

FEV describes modern combustion noise excitation using the in-cylinder pressure-based tool, FEV CSL. This tool allows for the exploration of the vehicle's full NVH calibration potential, while meeting the emission and fuel consumption targets. The specific tool FEV developed for NVH-related vehicle calibration is known as FEV CSL-CAL. The simultaneous optimizations of the key ECU parameters that are present under customer-relevant driving conditions are also described in this document. Parameters for independently judging the subjective combustion noise impression are accomplished using

FEV CNI. This tool is used to find the optimal calibration map for steady-state operation, cold start and under acceleration. Utilization of all of these tools enables FEV to provide a complete description and limitation of the combustion noise.

COMBUSTION SYSTEM NVH DEVELOPMENT

Charging is the most important measure to realize an increased specific power and increased specific torque. The most common method today of realizing charging is though the use of a turbocharger. The increase of peak pressure correspondingly increases the level of firing order and harmonics. However, combustion noise can be decreased because of the higher combustion chamber pressure and temperature. NVH development in this document focuses on the mechanical noise radiation of the charger (e.g. optimization of turbocharger tolerances / flow noise and application of sound damping measures at the charger). The turbocharger noise excitation mechanisms and countermeasures in general are to a large extent well known today. Beside turbochargers, electrical and mechanical chargers are also being produced. Continued development on electrical and mechanical chargers typically increases the engine noise level, but often without negative feedback from the customers. Chargers, which are used to increase low speed torque and are switched off at a certain engine speed, can cause a significant noise quality issue. In the future, more and more two-stage turbochargers and combined mechanical / electrical and turbocharged engines will be introduced into the market with increased specific power and torque. Excellent NVH can be realized for these engines, when taking into account NVH during the whole development process [1 and 2].

The optimization of combustion noise and exhaust gas emissions is performed mainly at part load and from low- up to mid-engine speeds. The necessary calibration to meet the desired exhaust gas emission level in general can cause an increase of combustion noise at part load. The reduction of hydrocarbon, carbon monoxide and smoke emissions sometimes lead to an increase in combustion noise. The reduction of nitrogen oxide emissions and combustion noise typically accompany one another. To fulfill the Euro 4 emission level and reduce combustion noise for diesel engines, the beginning of main injection (BOI) typically is retarded and EGR rate is increased. Increased flexibility of injection systems, such as through the application of double pilot injection, can also reduce combustion noise. Conversely, rail pressure at part load has been increased and pilot injection timing and quantity sometimes cannot be selected at the NVH optimum. A certain increase in part load combustion noise can be observed with Euro 4 compared to Euro 3 engines.

For simultaneous optimization of exhaust gas emissions, combustion noise and fuel consumption, all values have to be available simultaneously and directly at the combustion system development test cell. For this purpose, FEV developed a tool called FEV CSL that can predict the level and quality of engine noise. It uses cylinder pressure analysis combined with the appropriate structure weighting functions for the prediction of the different noise shares. Thus, the effects of calibrating parameter variations (e.g. injection timing, rail pressure and EGR) on the combustion noise as well as on the overall noise level and quality can be accurately predicted. A prediction of the combustion noise effects caused by the harsher combustion process during transient operation and at cold start can also be made [3].

The individual combustion noise shares are determined by combining the excitation parameters with the associated structure weighting functions for direct combustion noise, indirect combustion noise, flow noise and mechanical noise (Figure 1). The engine noise level is predicted by combining al of the combustion noise shares. FEV-CSL predicts all of the combustion noise shares. Changes in these noise shares, due to combustion parameter modifications, can be predicted and explained independently of each other.

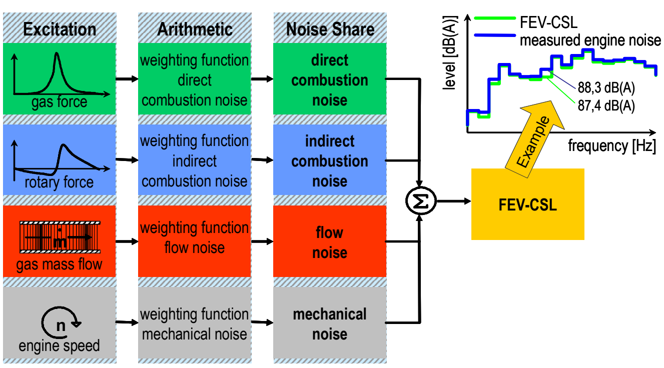

Figure 1: Combustion Sound Level Calculation

The FEV-CSL engine noise level provides important information when developing a combustion system. Additional important information is obtained through a subjective noise evaluation. For this purpose, noise radiation variants of an engine are measured in an acoustic test cell and subsequently compared in pairs by a jury of NVH specialists. The FEV-CSI (Combustion Sound Index) is determined, based on FEV-CSL, which includes additional information such as the direct combustion noise share, The FEV-CSI is the combination of parameters with the best correlation to the jury ranking. FEV-CSI allows the subjective noise impression of calibration variants obtained on the emission test bench to be calculated based on cylinder pressure data. FEV-CSI is typically calculated according to the international ranking scale of one to ten. FEV's highly-qualified NVH engineers explore the full NVH calibration potential, while meeting the emission and fuel consumption targets.

NVH-RELATED VEHICLE APPLICATION

NVH-related development of the vehicle application requires optimization of such parameters as exhaust gas emissions, fuel consumption, drivability, transient and cold start behavior. Changes in the combustion process, such as the shift from homogenous to stratified operation or DPF regeneration mode, have to be applied without degrading the vehicle's noise and vibration behavior.

FEV CSL-CAL is used in combination with DoE (Design of Experiments). The factors used to create the DoE model are the injection parameters of beginning of pilot- and main injection, pilot injection quantity, exhaust gas recirculation rate and rail pressure. The responses for the DoE model are the different exhaust gas emissions, fuel consumption, NVH and robustness. NVH is analyzed by subjective judgment as well as by objective analysis of the measured interior and exterior noise, and by a cylinder pressure-based CSL analysis (Figure 2). CSL allows clear judging of the effects of the combustion process variants in respect to combustion noise excitation. The exhaust gas emissions and fuel consumption values are recorded at an engine or vehicle emission test bench, while the NVH values are recorded at a vehicle NVH test bench. The DoE measurement program is performed at both test cells and the results are combined into one DoE model. Figure 2 (left side) shows typical examples of regression models obtained by DoE for two variation parameters (pre-injection quantity and BOI) and two responses (FEV-CSL and HC emissions).

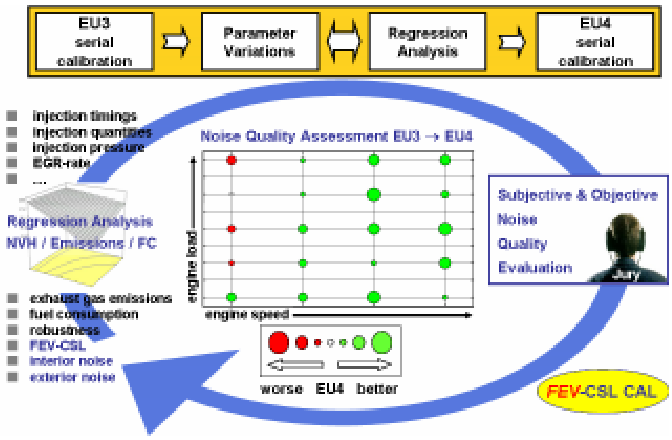

Figure 2: CSL-CAL Procedure

The modulation analysis of the interior noise shows that with optimized calibration, the predominant amplitudes (especially the 2nd engine order) has been lowered considerably in the characteristic frequency range for knocking sound (1 - 3 kHz) and sound quality has been improved significantly. The demonstrated optimization potential of course is also defined by the acoustic quality of the base calibration. The calibration of the cold start and warm-up run at low ambient temperatures is extremely complex and determined by many partially conflicting parameters [4].

Typically, disadvantages in NVH behavior can be seen at cold conditions, mainly due to the necessary changes of injection parameters. In the temperature range up to about minus 20°C, the ability to start is by far the most important requirement. All other demands and development goals must be subordinated. This is superimposed by the requirement for the prevention of ignition/combustion faults, which is critical up to approximately 0°C. Reasonable acoustic optimization starts at about minus 10°C, while black and white smoke must be avoided. From 20°C onwards, test cycle relevant exhaust emission regulations must be met. Noticeable changes of the sound impression during warm-up must also be avoided.

One other field of work for the NVH-related vehicle application is the shifts in engine operation mode, due to the exhaust gas aftertreatment systems. The combustion noise can decrease during the regeneration of a diesel particulate filter and be replaced by a humming noise that can occur resulting from throttling and/or adjustment of the turbocharger and a booming that can be caused by combustion in the exhaust system. For the nitrogen oxide reduction with an absorber catalyst the combustion noise can also decrease during the rich mode. Frequent changes in the operation mode occur here, compared to those of the particulate filter. The change-over processes can be especially critical. Future combustion systems (homogenous diesel, two-stage charged DI gasoline, controlled auto ignition) and exhaust aftertreatment systems will become more important. The effects to NVH have to be minimized and the change-over should be applied in the vehicle acceleration phase, to realize strong NVH performance.

OBJECTIVE COMBUSTION NOISE PARAMETERS

A disturbing vehicle sound, such as engine knocking, ticking or turbocharger whining, cannot be described easily by the noise level. Several sound quality objective parameters (FEV SQO) for subjectively judging disturbing noise sources have been developed by FEV.

The FEV SQO parameters are worked out by regression analysis between jury quotations and noise sources associated acoustic parameters. In the first step, a clear and common linguistic description of the disturbing noise source has to be established. A certain number of different sound samples are then judged by a jury according to the international ranking scale. Based on the FEV's expert knowledge of time and frequency characteristics, the available physical and psychoacoustic parameters are analyzed and modified in respect to the specific noise pattern. Lastly, a small number of those parameters are combined through the use of regression analysis to the specific, objective parameter. The SQO then describes the jury quotation concerning the specific noise pattern (Figure 3). The parameter judges the gasoline engine injector ticking noise during idling conditions. The parameter is build-up using a band pass level, modulation analysis and sharpness. The correlation to the jury quotation is 91% [5].

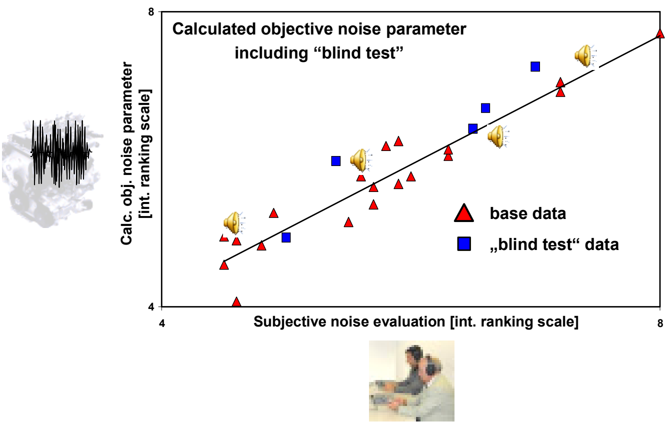

Figure 3: Parameter for Idle Ticking Noise

FEV CNI (Combustion Noise Index) judges the diesel knock intensity. CNI is calculated based on modulation analysis (Figure 4).

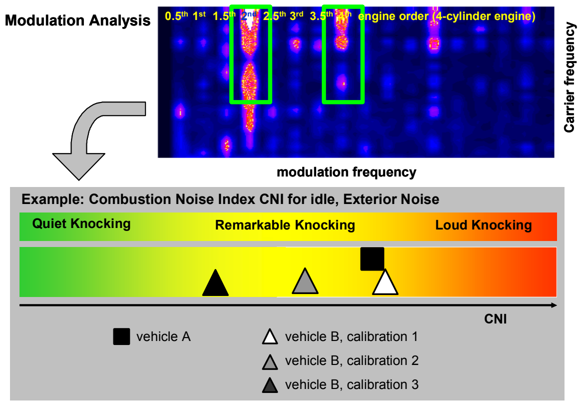

Figure 4: Parameter for Idle Diesel Knock

In addition to the knocking and ticking parameters, tonal noise components of such as those of the camshaft drive and the turbocharger are used. A roughness characteristic caused by crankshaft dynamics is judged by roughness parameters and gear rattle noise by a rattle parameter. Subjective disturbing noise components can be identified and countermeasures can be worked out, using those parameters.

FUTURE TRENDS AND COMBUSTION PROCESS NOISE

Today, a certain focus can be seen on the development of vehicles with increased specific power and torque and with decreased exhaust gas emissions. Both points will still be important in the next few years, even if the exhaust gas emissions are currently at a very low level. However, reducing noise and fuel consumption is expected to become more important in the future.

The development of vehicle fleet fuel consumption in Germany and Europe is reflected in the ACEA target value of the voluntarily agreement for the years 2008 and 2012 (Figure 5). These goals can only be really achieved in the European market with favorable boundary conditions. In recent years, the development of the German vehicle market has experienced a slowing down of the trend to reduce fuel consumption. One of the primary causes is the tendency towards higher performance and heavier vehicles. A second cause is that diesel engines have exhibited constant fleet fuel consumption since the year 2000, because of intensified emission legislation. There is a chance that nothing could change in the near future, because of the intensified introduction of diesel particle filters. However, beyond that is the realization that vehicles with reduced fuel consumption will become more important. In addition, further increasing fuel prices at the gas station will mean that fuel consumption will become more important for a greater number of consumers [6].

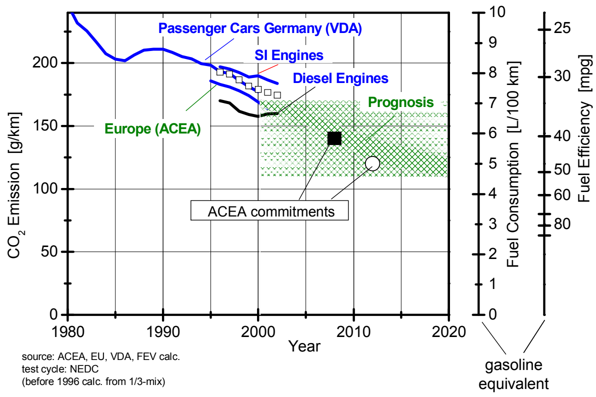

Figure 5: Fuel Consumption Development

Pass by noise legislative restrictions have not changed in the last 10 years. Therefore, there is no need for intensive development work at the moment. However, traffic noise in general, is being discussed with increasing frequency. In Figure 6, urban noise is illustrated for the city of Aachen, Germany. The value of 70 dB(A) is used as a starting point from which health endangerment could be expected, is crossed in many places (see red colored roads). This is a typical result for the noise of many cities and motorways. European vehicle research work is starting to focus on those themes. Engine noise is one important noise source in this context, for vehicles operating under urban driving conditions [7].

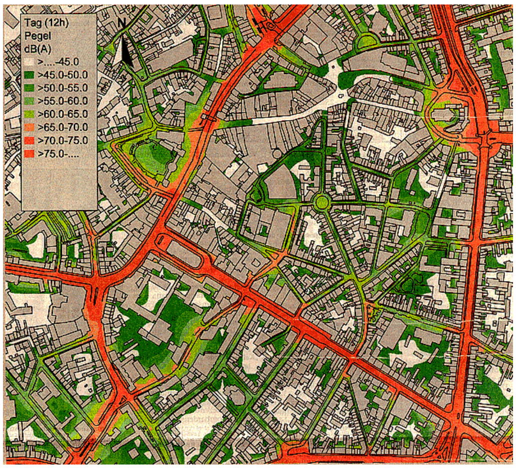

Figure 6: Traffic Noise in Aachen, Germany

Combustion systems that realize a low combustion noise level are becoming increasingly important in Europe and in other areas with large metropolitan cities. Exhaust gas emissions like smoke are important, but reducing levels of nitrogen oxide is becoming even more important. Calibration modifications for reducing nitrogen oxide emissions can often be used in conjunction with reducing combustion noise. For diesel engines, measures like intensified EGR cooling, reduced compression ratio or increased part load boost pressure, which will be realized in the future and can be calibrated with comparable NVH excitation like today's engines. Additionally, further increasing the maximum rail pressure and having a more precise and variable injection combined with combustion control systems will allow for a reduction in combustion noise excitation. These tools can help to realize the potential for all of these demands in parallel.

Shifts in the operation mode for gasoline and diesel engines, such as those due to the combustion process, will be one challenge for NVH engineers in the future. Hybrid vehicles with a variety of operating modes, two-stage charging concepts and variable valvetrain and intake systems will become a part of many production vehicles. All of these concepts will have to be applied while exhibiting excellent NVH behavior.

A low noise engine can be developed as shown in the example in Figure 7, which takes into account NVH demands for the entire engine development process. The noise level of the engine that is illustrated is far below that of its competitors, based on the comparison shown by the FEV scatter band [8]. The idling noise of the Jaguar XJ, equipped with this engine, is 72 dB(A), which is up to 10 dB(A) below the competitors [9].

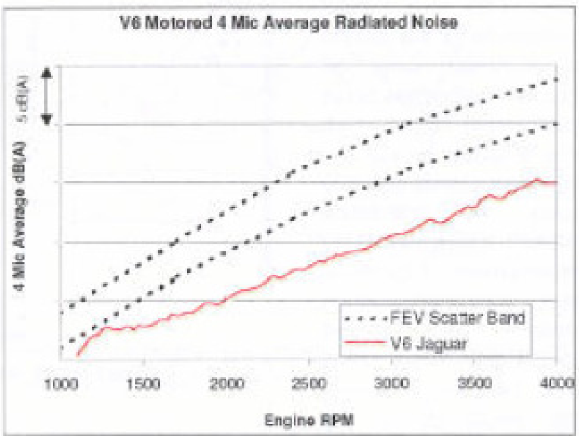

Figure 7: Low Noise Engine Development

SUMMARY

Modern internal combustion engine development is marked by a decrease in exhaust gas emissions with a corresponding increase in specific power and torque. Corresponding decreases in combustion noise excitation and fuel consumption must also occur. These goals can be achieved through the development of advanced combustion systems and the increased flexibility of fuel injection system and the ECU. However, the complexity of combustion system development and vehicle applications has increased rather dramatically in recent years.

Development of an accurate yet basic description of combustion noise is critical. The consumer's personal opinion of the interior and exterior of the vehicle, such as through diesel knock intensity, is a very important measurement to consider.

Currently, FEV illustrates combustion noise excitation using the in-cylinder pressure-based tool called FEV CSL. The complete calibration potential for NVH is examined, while simultaneously achieving the emission and fuel consumption goals that have been predetermined. FEV utilizes the tool we developed (FEV CSL-CAL) for the completion of NVH-related vehicle calibrations. All of the key parameters for the ECU are optimized concurrently under driving conditions that the consumer would experience. FEV utilizes sound quality objective (FEV SQO) parameters to subjectively evaluate the combustion noise. FEV SQO is used to determine the most favorable calibration map for steady state operation, cold start and during acceleration. Combustion noise can be accurately described using the tools that FEV has developed. The resultant design combustion noise can then be optimized toward customer expectations.

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