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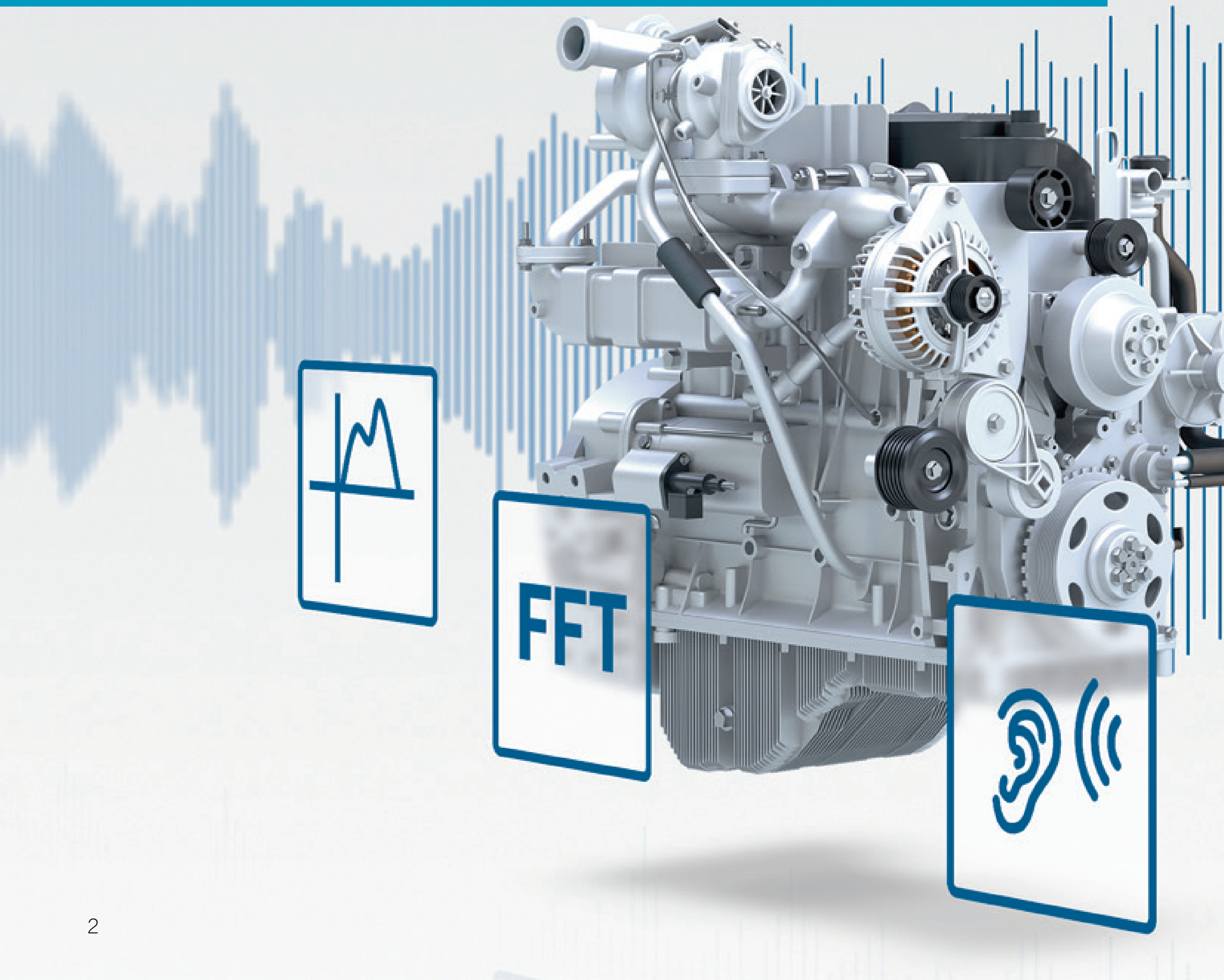
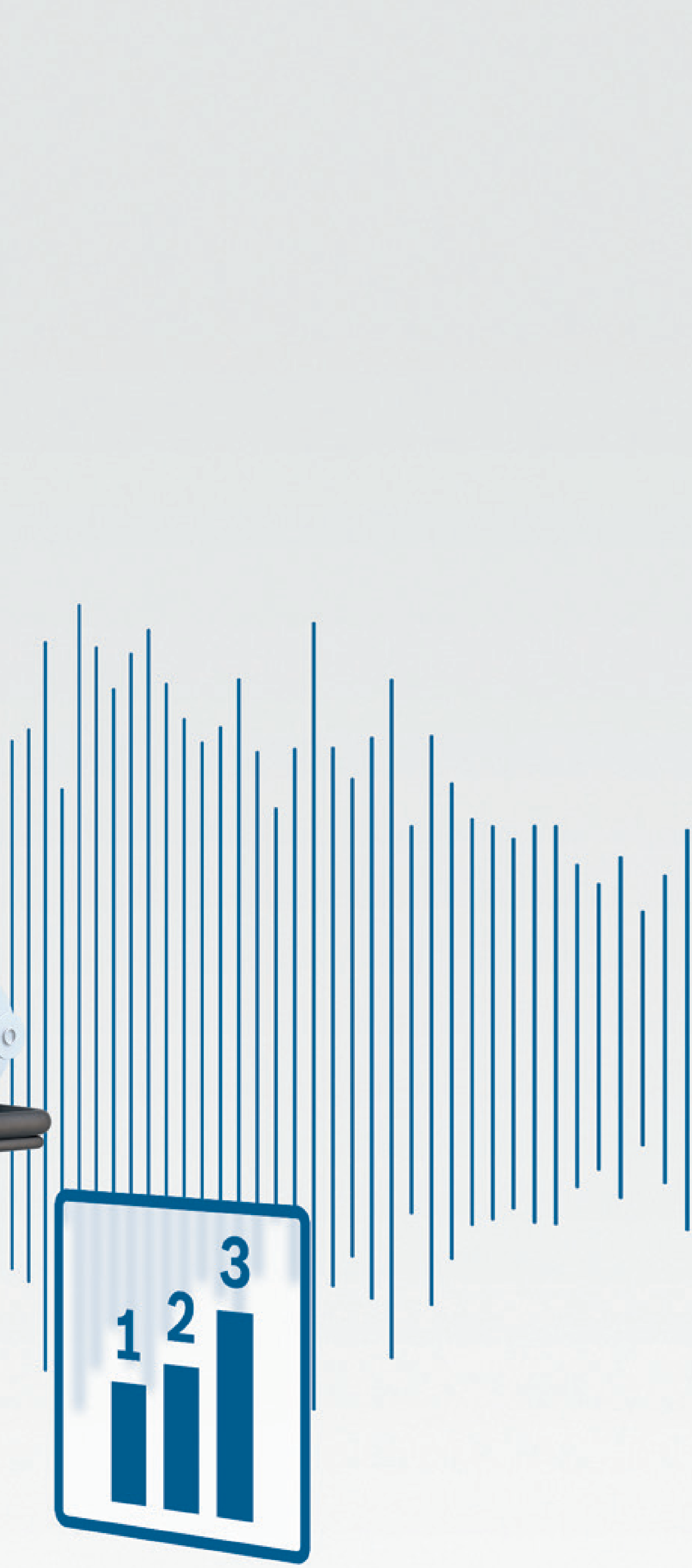
AKUSTIK | NVH
Evaluation of Impulsive Diesel Combustion Sound Components

INTERVIEW
with Dipl.-Ing. Jörg Vetter and ir. Rob Opdam, Bosch Engineering GmbH

Evaluation of Impulsive Diesel Combustion Sound Components

The ability to rate the impulsive components of combustion noise is a key issue when developing modern diesel engines. With this in mind, Bosch Engineering investigates a method to quantify these impulsive components without additionally using NVH measurement techniques. The resulting evaluation method is based exclusively on the data of the cylinder pressure curve.





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CYLINDER PRESSURE DATA ALONE AS THE BASIS

Steadily increasing demand for comfort and quality has created a situation whereby a road vehicle's sonic footprint is a growing concern in vehicle development. It is a differentiator for car manufacturers that sets brands apart from industry competitors. The impulsive noise components of combustion-engine powered vehicles are of particular interest. And certainly the impulsive noise of passenger cars with diesel engines in particular is hardly seen as an attractive feature.

The method presented by Bosch Engineering herein aims to rate the annoyance of impulsive sound components using a conventional engine test bench – that is, without an acoustical treatment. The method requires no measurement

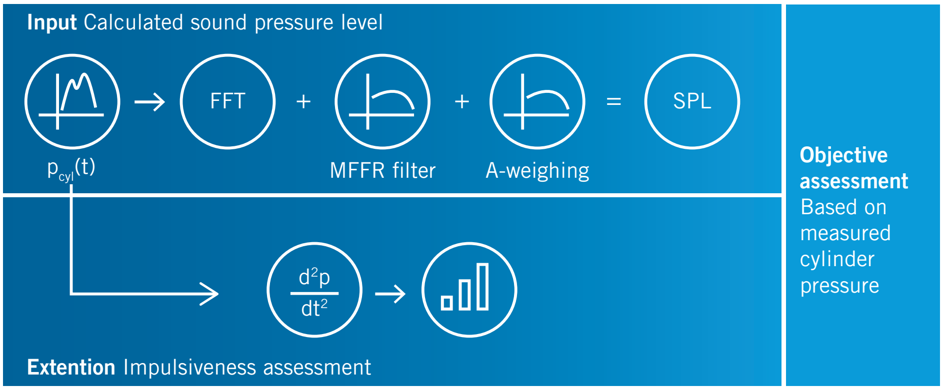

FIGURE 1 Diagrammed steps for determining the calculated Sound Pressure Level (SPL) and evaluating the annoyance of impulsive sound components (© Bosch Engineering)

equipment beyond conventional calibration tools such as cylinder pressure indication. Cylinder pressure data recorded by this measuring system provides the basis for further investigations. Note that this does not demand any additional measurement equipment nor requires an acoustics engineer to be present to record and assess the measurement data.

A comparison of results from the analysis of the cylinder pressure data with subjective perception confirmed this method's findings. Listening tests using a full pairwise comparison method were performed to rate the subjective perception.

EVALUATING ENGINE NOISE ON THE TEST BENCH

An engine noise evaluation on an engine test bench is usually carried out under stationary, steady-state operating conditions. The cylinder pressure data of a complete operating cycle is converted into the frequency domain by a Fast Fourier Transformation (FFT). The resulting cylinder pressure spectrum is then combined with a transfer function and merged into a single-number sound pressure level, **FIGURE 1**. The transfer function used is also known as the MFFR filter (Mean Free Field Response Function) [1, 2] and describes the relation between cylinder pressure and airborne sound [3]. The usage of this method is particularly well suited for conventional engine test benches, which are not suitable to perform accurate measurements of airborne sound.

Impulsive sound components cannot be quantified by measuring the sound pressure level alone. This requires an alternative or additional method. This is why several algorithms have been developed that can quantify "diesel knocking" in a single-value. These methods include, for instance, the Diesel Knocking Index (DKI) or the Combustion Knocking Index (CKI) [1, 4]. However, these methods require measurement data of structure-borne or airborne sound.

Another option for assessing the annoyance of impulsive sound components is to analyze the cylinder pressure data. The advantage of this option is now that the already installed measurement equipment on the engine test bench is sufficient. There is no need to use further NVH measurement equipment (for instance accelerometers and/or microphones) as well as their integration into the test bench environment.

METHOD FOR EVALUATING THE ANNOYANCE

The proposed method to quantify the annoyance of impulsive sound components – without using additional NVH measurement technology – is presented in detail in the following. This is an extension of the previously mentioned method for calculating sound pressure levels. Both methods are based exclusively on cylinder pressure data.

This evaluation of the annoyance of impulsive sound components is closely linked to the trajectory of the convex part of the curve describing the pressure increase caused by the combustion in the combustion chamber. An evaluation of the second derivative serves to charac-

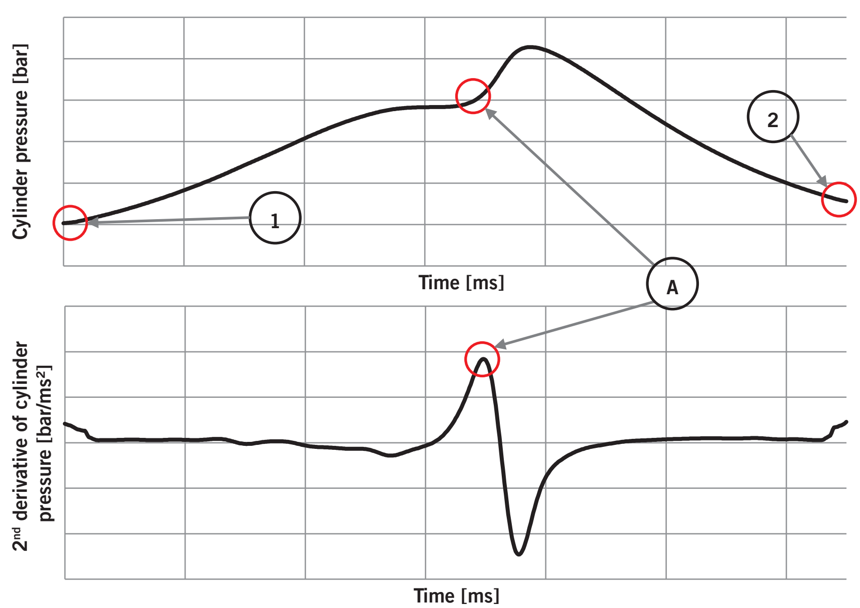

FIGURE 2 Example of a cylinder pressure in time domain (top) and its second derivative (bottom); separately indicated are the starting point of compression (1), the end of the expansion (2) and the maximum of the second derivative (A) (© Bosch Engineering)

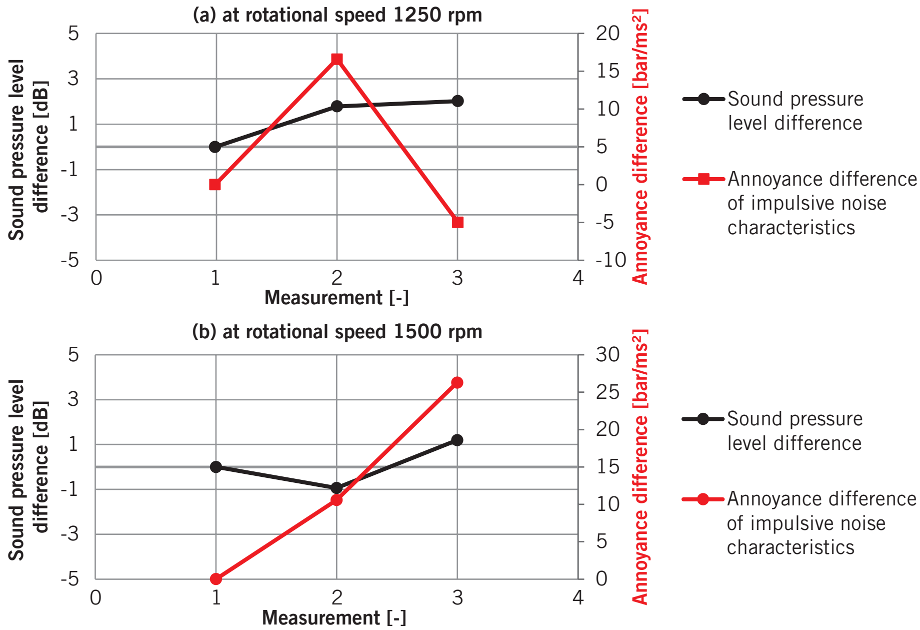

FIGURE 3 Representation of the difference in sound pressure levels and the difference in impulsive noise annoyance ratings ($\Delta(d^2p)/(dt^2)$) at engine rotational speeds of (a) 1250 rpm and (b) 1500 rpm (© Bosch Engineering)

terize this increase. This derivative is taken with respect to the time domain rather than to the customary domain of crank angle degrees, which is often used in calibration activities. The reason for this is that the human auditory system processes stimuli that change over time.

FIGURE 2 shows an example of both a cylinder pressure curve and its second derivative in the time domain. It describes the rising or falling trajectory of the cylinder pressure curve. The maxima of the second derivative (point A in **FIGURE 2**) describe the maximum curvatures induced by the combustion of the injected fuel mass into the combustion chamber. Maxima are only considered in the time domain from the beginning of the compression (in point 1) to the end of expansion (in point 2). The values of the second derivative are a measure for assessing the annoyance of impulsive sound components.

Combustion noise is also assessed on the basis of the pressure gradient in the domain of crank angle degrees. This value primarily describes the loudness of combustion noise and less so the annoyance of impulsive sound components as such [3, 5, 6]. Hence this value is not used in the evaluation method presented in this paper.

A few restrictions apply for using this method. Evaluating or comparing the annoyance of impulsive sound components is only possible when the same engine is operated at the same rotational speed. It is not possible to compare different engines because the number of cylinders and engine rotational speed dictate the combustion repetition rate. The repetition frequency is a variable that describes the sequence of impulsive noise events. The effects of this parameter on the individual's subjective perceptions vary, so the assessment of the measurement data for this method is only possible for the same engine and rotational speed. Furthermore, the repetition frequency has to be considered. This method describes the force excitation and therefore does not take into account the engine-specific transfer path. However, this does enable a direct assessment of the effect of the engine calibration on the combustion noise is possible. However, sound contributions from other engine components are not evaluated.

APPLYING THE METHOD

In the following it is described how the developed method is applied to a diesel engine in a comparison of various calibrations. This engine was measured under stationary operating conditions with the engine's rotational speed and injection pattern kept constant. The engine load and calibration varied within the scope of the constant injection pattern. The injection pattern corresponds to the timing of the injected fuel quantity per operating cycle.

FIGURE 3 (a) and **FIGURE 3** (b) depict the results of this test for two different engine rotational speeds (1250 and 1500 rpm) and present the impulsive noise annoyance ratings for various engine calibrations. Here, the data is ranked by relative rankings on a scale ranging from most annoying to least annoying. The comparison shows only those calibration variants that have an approximately constant calculated sound pressure level. The deviation was limited to less than 2 dB.

METHOD VALIDATION

Two listening tests based on the principle of dominant pairwise comparison were held to validate this ranking. In total, 14 test subjects rated three different stimuli in different paired combinations to subjectively compare the annoyance of impulsive sound components. The aim was to identify the more annoying of the pair. All test subjects had a technical background, but no experience with listening tests. This test used stimuli with a maximum deviation in the sound pressure level of less than 2 dB to rule out the influence of different sound pressure levels on the results.

The sound samples used for this listening test were recorded with a microphone while simultaneously measuring

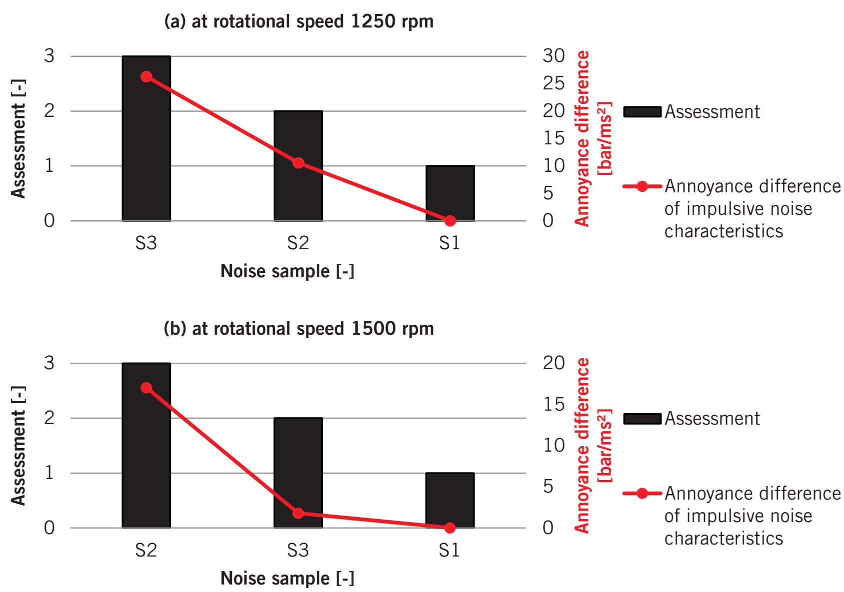

FIGURE 4 Impulsive annoyance of sound components compared to relative, subjective evaluations of noise at engine rotational speeds of (a) 1250 rpm and (b) 1500 rpm; the least annoying sound sample (S1 to S3) is ranked as number 1 (© Bosch Engineering)

the cylinder pressure. Airborne sound was recorded at the front or belt side of the engine and reproduced as a stereo signal. The distance between the microphone and the engine was 1 m.

FIGURE 4 (a) and **FIGURE 4** (b) show the rankings for the stimuli in this listening test. The results show that the annoyance level rated by the test subjects are in line with the results of the method based on the cylinder pressure data.

CONCLUSION AND OUTLOOK

Bosch Engineering developed a method to objectively quantify the annoyance of impulsive sound components of diesel engine combustion. The focus was on a cost-effective method that may be used on a conventional engine test bench – thus without optimized acoustics. This resulted in a ranking of the relative annoyance level based on the cylinder pressure curve.

A listening test confirmed that the annoyance ratings for the impulsive noise components correlate with the method based on cylinder pressure data. This enables calibration engineers to objectively assess the impulsive components of combustion noise and optimize them within the scope of the calibration. The advantage of this method is that it uses measurement equipment that is already available on the engine test bench and integrated in the automated tool chain. Therefore, this makes it an efficient and cost-effective method.

The influence of the repetition frequency is to be taken into account when further developing this method. The method could then be expanded to allow for the comparison of different engines and for the definition of target values.

REFERENCES

[1] Zeller, P. (Ed.): Handbuch Fahrzeugakustik. 3rd edition, Wiesbaden: Springer Vieweg, 2018

[2] Russell, M.; Haworth, R.: Combustion Noise from High Speed Direct Injection Diesel Engines. SAE Technical Paper 850973 (1985)

[3] Seifriedsberger, J.; Rumplmayr, P.: Evaluation of the Combustion Noise of Passenger Car Diesel Engines. In: Automotive and Engine Technology, Vol. 1, No. 1-4 (Dec. 2016), pp. 47-56

[4] Sellerbeck, P.; Nettelbeck C.; Heinrichs, R.; Abels, T.: Improving Diesel Sound Quality on Engine Level and Vehicle Level – A Holistic Approach. SAE Technical Paper 2007-01-2372 (2007)

[5] Flotho, A.; Spessert, B.: Geräuschminderung an direkteinspritzenden Dieselmotoren – 1. Teil. In: Automotive-Industrie 33 (1988), pp. 255-261

[6] Flotho, A.; Spessert, B.: Geräuschminderung an direkteinspritzenden Dieselmotoren – 2. Teil. In: Automotive-Industrie 33 (1988), pp. 561-565

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"Our strength are our highly customizable solutions"

The growth in vehicle powertrain electrification gives rise to special, new challenges for NVH engineering. In this interview, Jörg Vetter and Rob Opdam present and explain the benefits that Bosch's holistic systems engineering approach offers within this context.

What are currently the main challenges in terms of NVH engineering in automotive development?
One of the challenges arises from the interaction during calibration of the powertrain's NVH characteristics and calibration of the internal combustion engine's (ICE) emissions performance, particularly during cold starts. To ensure the strict RDE emission requirements can be reliably met at all times, quick heating of the catalytic converter components generally takes priority in new system designs over other functions that are more related to the aspect of comfort or the driving experience. This severely limits the amount of scope available to acoustic engineers for NVH-related calibration, particularly in light of the fact that the stringent requirements remain unchanged.

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Interview
with Dipl. Ing. Jörg Vetter (l.) and ir. Rob Opdam (r.), experts for NVH at Bosch Engineering GmbH in Abstatt.

The second aspect is electromobility. Electrification, be it in the form of hybridization or fully electric driving, will fundamentally change our acoustic perception of automobiles. Since there is no longer the masking background noise of the combustion engine, sounds will come to the fore in the vehicle interior that vehicle users have not been able to hear before – and that will also have an effect on the end customer's perception of quality. That is a challenge that applies to the ancillary units in the vehicle just as much as it does to the powertrain and its primary components, the inverter and electric machine. Engineers will have to optimize the powertrain system also in terms of NVH early on in the development process. If you already consider beforehand which electric machine and inverter configuration in the overall system is the best in terms of acoustic design, you can save a lot of time and effort in the development process.

With regard to designing the external sound of electric vehicles, the new statutory requirements for the pedestrian warning system AVAS (acoustic vehicle alerting system) are authoritative. The legislator has made provisions allowing a certain degree of freedom with regard to the acoustic design, though it has also defined various attributes that are not permissible, such as the imitation of animal noises. Furthermore, the vehicle must sound like a vehicle with an ICE, but it must not sound exactly like one. In this regard, vehicle manufacturers will therefore need to decide on and define what kind of sound impression is right for their brand.

NVH Dynamometer

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Are the requirements for full hybrids more stringent than for fully electric vehicles?

Generally, the NVH characteristics for a combined electric and ICE powertrain is more difficult to handle than for a single system on its own. Particularly the transition from one operating mode to another can lead to acoustic and vibration issues, such as when the combustion engine starts up. The phenomenon does not have to be particularly pronounced, but if it follows a period of absolute quietness then the vehicle occupants' perception of it will be much stronger compared with their perception of a continuously running motor or engine. This also applies to diagnostic functions where, for example, actuators or valves are activated. In electric driving mode, these kinds of activations should be avoided. That is a huge challenge in terms of software and calibration.

How are automobile manufacturers dealing with the changes brought about by electrification?

Currently, we see that many automobile manufacturers still really do not know in what direction they should be developing their electric vehicle acoustics. After all, mere noise minimization is not really what end customers are expecting from their vehicle. It is also about an acoustic design that underscores the value and quality of the product and that serves as a differentiating characteristic. Automakers are currently working on the standards for their new vehicle concepts, but they lack empirical data from customer feedback. When it comes to vehicles with combustion engines, the acoustic fingerprint of the vehicle make is something that has evolved over many years; but in the case of electric vehicles, carmakers are in uncharted territory. So, for them it is very difficult at the moment to design a sound for full hybrid vehicles driving on electric power that is characteristic of their brand and is easily recognizable as such.

Electromobility is bringing new vehicle manufacturers into play that have no previous automotive experience. What specific challenges arise from this for you?
For car buyers, the NVH characteristics are – alongside design – the second immediate, primary attribute of a brand and are, to some extent, the vehicle's mark of quality. To ensure success on the market, it is therefore essential that customers' perception of the NVH characteristics of a newly developed vehicle is in line with the carmaker's brand. This means that NVH system design must already be taken into consideration at the concept stage of development and that NVH-related validation must be performed continuously throughout the engineering process. In the case of vehicle manufacturers that are new players in the automotive sector, we often see, however, that NVH is not yet even a key topic in their engineering work; instead, they tend to focus on aspects like the powertrain and additional connectivity functions. Our job within the scope of our holistic systems engineering approach is therefore to increase awareness among our customers to this issue and to make it clear to them that NVH-related development costs only increase further the later they address the issue in their engineering project.

Are there regional differences when it comes to vehicle acoustics?
From the Chinese market, for example, we are hearing that end customers are very discerning and that expectations are correspondingly high. There, consumers expect to get the acoustics of a premium car already in the mid-sized car segment. But the aspect of NVH is also coming more to the forefront in Europe too. Since the quality of vehicle components in terms of durability and function is now at a very high level, consumers increasingly see the acoustics of a vehicle as being a characteristic that conveys high quality.

Sound measurement room

How does the ever-increasing system complexity in the vehicle influence NVH characteristics?
The increasing connectivity of the systems and the added new functions lead to operating phenomena that never existed before. Here are a few real-world examples to explain what I mean. Bosch Engineering is involved in many super sports car projects. For reasons to do with consumption and emissions, technologies like cylinder deactivation are often used here. So, the challenge for us is to ensure that the acoustics are not impaired. Another example is safety systems, like ESP and brake boosters. During emergency braking, the NVH characteristics of the system are of course absolutely irrelevant; what is important in that situation is a short stopping distance. But this functionality is also used nowadays for adaptive cruise control systems in stop-and-go traffic. The vehicle's noise level in that situation is relatively low, because you are driving slowly, so the switching of control valves can be heard very clearly. What is more, drivers are much more aware that this is taking place, because they are not applying the brakes themselves and therefore cannot immediately identify what is causing the sound. This observation also applies to vibrations, which when felt on the brake pedal, steering wheel, or seats, for example, are perceived as being more distracting and irritating.
And when it comes to autonomous driving, such aspects are even more prominent, because systems for longitudinal and lateral guidance are working continuously in the background without any intervention by the driver. The noise level alone, however, is not the only significant factor in acoustics. It is not just about reducing the noise level; rather, it also comes down to the interaction of all the sounds with one another. For example: the more optimal acoustic concept may be to ensure that the sound of the powertrain and wind noise are harmoniously balanced instead of trying to make everything as quiet as possible and then


Acoustic studio

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having a situation where you can hear an individual component very clearly.

What implications do the changed requirements have for the NVH-related development process?

In the light of the high complexity of systems in today's vehicles, new methodological approaches are required in order to be able to make assertions regarding NVH. So, for example, the transfer path analysis is very useful for identifying and evaluating the most dominant NVH effects. Using the measured or calculated transfer functions, it is possible, for example, to make a component audible for the vehicle manufacturer using the virtual transfer path already at the beginning of the development process without the need for a real vehicle. Parameter changes, such as stiffness or damping, can likewise be realized virtually, thus enabling engineers to generate and evaluate synthetic acoustic effects. In future engineering projects (e.g. the development of functions for automated driving), psychoacoustic feedback about the interaction of the individual components and subsystems must be available to engineers early on in the development process. Here, auralization makes it possible to synthesize sounds in order to help vehicle manufacturers to create their sound signature virtually. Overall, the trend is tending towards a greater use of simulation in development processes. Measurements, which are often very costly, are then only used to effectively validate the results of the calculations.

Can you provide an example of a simulation-based development?

In the near future, a component like the pump of an ESP unit will no longer be selected merely on the basis of its specific performance but also based on its NVH fingerprint and connection and integration capabilities. Engineers could, of course, install sample components in a vehicle and then test them; but that is much too time-consuming and costly. It is easier to just measure the acoustic and vibration path to the pump, then use this data to integrate the component virtually into the vehicle model, and subsequently synthetically generate the corresponding sound of the pump in the vehicle interior. In order to do this, we have set up a sound studio in our testing center that allows engineers to listen to the results in advance and gain an impression. Although this does not precisely correspond to what will be measured later, it does provide a very representative approximation. In a next step, it will then no longer even be necessary to measure the acoustic path in trials; instead, the pure CAE data will be sufficient.

What added value does Bosch Engineering offer vehicle manufacturers in terms of NVH engineering?

With Bosch Engineering, customers can get everything they need from a single source. After all, we always regard NVH as a constituent element of the systems engineering process. Our NVH engineers are located in the very same office building as their colleagues in the engine calibration department and work together with them very closely. This enables us to boost synergies between the individual engineering units, which also results in time and cost savings. Because of the nature of this concept, it works better for small customers that have less internal engineering capacities at their disposal than for big customers that generally only outsource small parts of their engineering work. Our strength is our highly customizable solutions that allow us to respond to the needs of our customers efficiently and with a high degree of flexibility.
A real-world example is the case of an acoustic phenomenon that a customer's engine development department and vehicle development department blamed on each other. We, as an external party, were very quickly able to locate the problem and remedy it with a relatively straightforward software solution.
Our acoustic engineers also have a wealth of experience in operating test rigs, as is demonstrated by the fast set-up and preparation times and their in-depth knowledge of the specialist measurement solutions for each particular test. Thanks to our broad portfolio of engineering services, our customers are also able to tap into the comprehensive acoustics expertise of the entire Bosch Group. This includes more than 200 acoustic engineers and other experts around the world whose advice and assistance we can always count on when needed.

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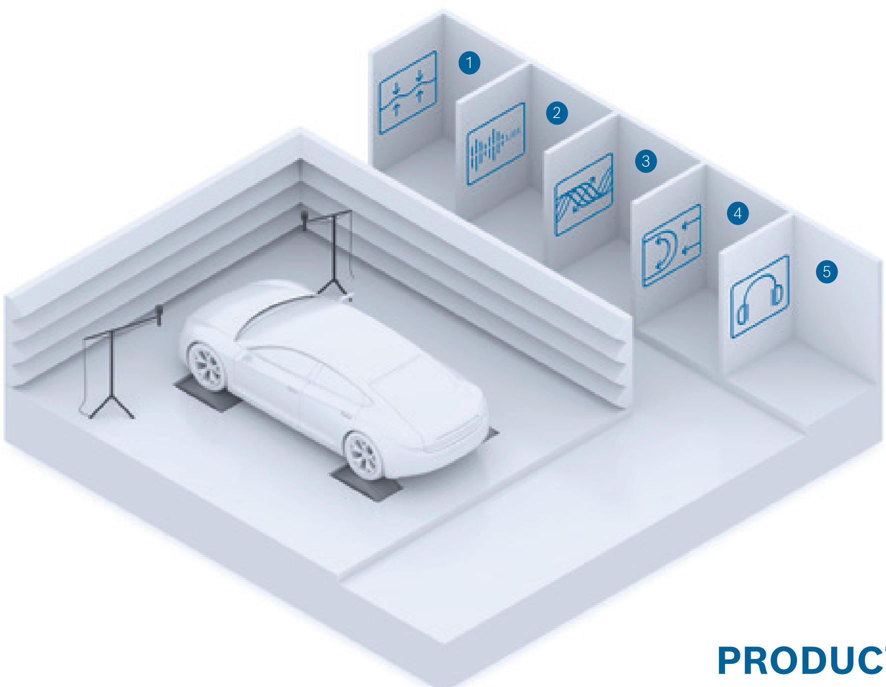
Bosch Engineering acoustics test center



1. Vibration measurement
2. Sound power test bench
3. Hemi-anechoic chamber
4. Modal analysis
5. Audio studio

PRODUCT BENEFITS

- Shorter development times
- Improved overall vehicle acoustics
- Better evaluation of acoustic phenomena

TECHNICAL CHARACTERISTICS

Output asynchronous motors	4 × 150 kW
Speed range	0 - 250 km/h
Roller	acoustically optimized 75“ roller
Axle load	up to 2,500 kg
Wheelbase	1,800 - 4,300 mm
Temperature range	15 - 35 °C
Lower limit frequency	80 Hz
Quiescent level	10 dB (A)

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