Compact Indicating Measurement Systems for Combustion Development

Optimization of exhaust-gas emission, noise and fuel consumption of the diesel engine in the vehicle is based on stationary tuning at the test bed. Only here all relevant measured variables can be acquired precisely and all parameters can be adjusted optimally, independent from the drive train and environmental impact. Not till then the development in the vehicle can be continued, especially focusing on the optimization of driveability, dynamics, acoustics and full load next to emission performance. As the measuring equipment in the vehicle in general is not as comprehensive as at the test bed the estimation of the measure effects on the emissions, like serving the driveability, can be more complicated. The article of AVL List GmbH will present how the development of the vehicle can be improved by means of compact measuring technology and the use of model based information of the engine.

1 Model Generating at the Engine Test Bed

Modern diesel engines stand out due to a high number of actuators and variable injection systems. More complex control strategies and different engine operating conditions (for example particle filter regeneration) lead to a very high number of degrees of freedom that have to be adjusted optimally. Therefore more often model based methods are used for mostly automated measurements of the dependency on the corresponding parameters. Based on the determined models the control unit base calibration is then carried out.

For evaluating such models at first variation parameters as well as their variation range are defined. Afterwards, based on the number of parameters and the desired model accuracy, a test plan is generated. In the example in **Figure 1**, a space filling design with approximately hundred measuring points has been selected. The design (systematical arrangement of the measuring points) is generated according to principles of statistic test planning (Design of Experiments or DoE). This arrangement of the measuring points in the space filling design is chosen in such a way that the measuring points are evenly distributed in the parameter range. Therewith a high quality of the model at any number of measuring points is achieved. The generation of this test design is effected with computer based algorithms. Afterwards the measurement of the individual parameter variations is carried out at the test bed.

Based on adjustments inside of the ridable engine operation boundaries each of these points is measured automated under continuous control of all limits at the test bed by means of optimization software (for example AVL Cameo). After the determination the data quality is checked regarding plausibility and reproducibility and if necessary post processed. The engine model is generated with AVL Cameo FNN (fast neural networks). Here the values of system responses, for example consumption, emission or noise, are transferred to a model. This model describes these system responses in relation to the adjusted parameters. Miscellaneous approaches exist; however, in practice the FNN model generation at stationary engine models has currently proven to be the most adequate. FNN is a model that is composed of various polynomials. In the different areas of the testing space diverse polynomials apply so that also distinctive nonlinearities can be represented clearly. A smooth and steady progress of the model is obtained by using transitional functions.

Figure 1 exemplifies in an operational point – here close to the 120 km/h point

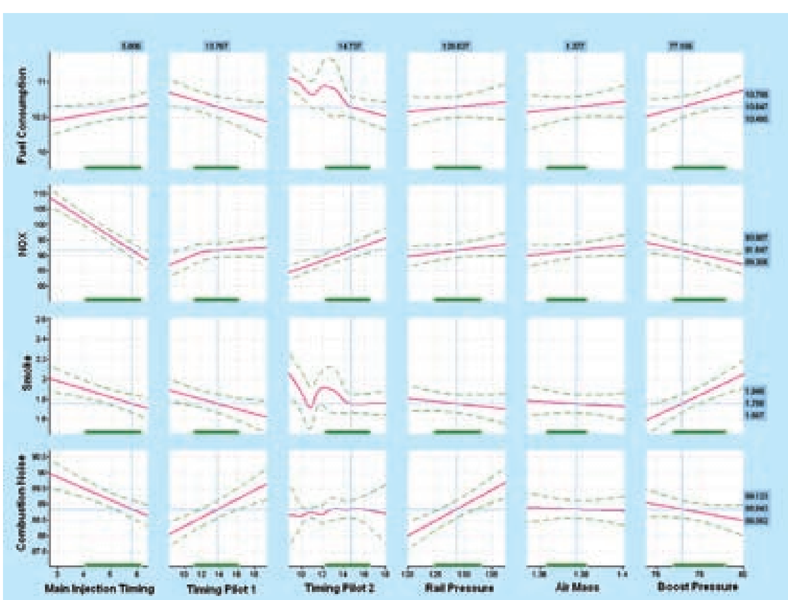

Figure 1: Evaluation 14 Mode Double Pilot at 2670 rpm and 148 Nm

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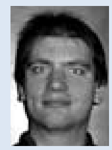

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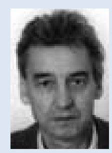

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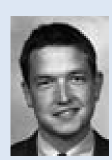

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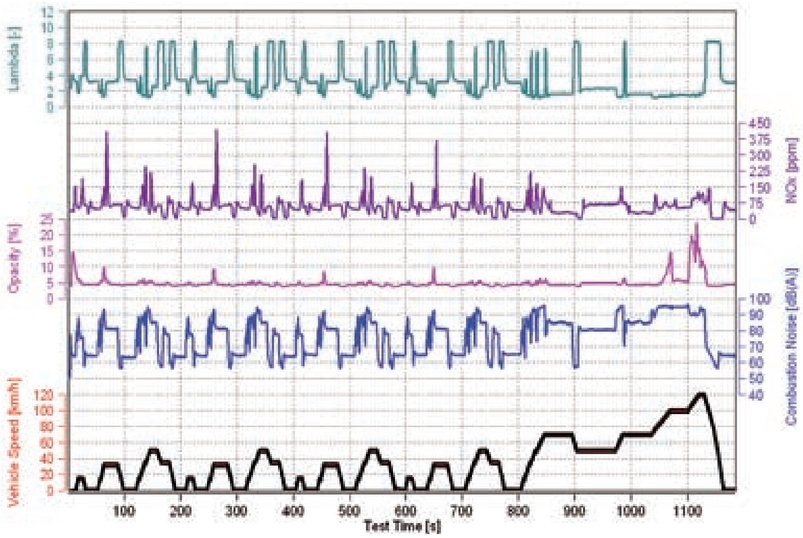

Figure 2: Transient noise measurement in the NEDC cycle

in the NEDC cycle – how consumption, NO_x emission, smoke and the combustion noise, depending on the start of main injection, distance of both pilot injections, rail pressure, air mass and VNT position behave. This behavior is displayed in a model, based on the measuring results. In the diagrams this is represented by the continuous red line. The green doted lines represent the 95-% confidence intervall, in which the model is situated with a probability of 95 %. By means of these diagrams the optimum adjustment can be selected. Based on practical experiences with similar engines, however, it must be considered to which extent these adjustments in the vehicle can actually be realized. Evaluating the cylinder pressure curve and the distance to the misfire limit are thereby very helpful.

This process has to be repeated in all operating points. Thus the first data set, representing the base calibration is achieved.

2 Calibration in the Vehicle

Based on this first calibration derived from steady state tests further optimizations are executed directly in the vehicle acquiring transient data. Apart from the adaptation of the emission relevant parameters on a chassis dyno, aspects such as driveability, transient transitions, comfort, control quality, subjective noise evaluation, etc. are observed on the road or test courses. Measuring equipment in the vehicle is not as extensive as at the test bed. Thus the combustion noise during vehicle calibration so far was not considered. With the use of a noise measuring device in the testing vehicle this parameter can be acquired in the calibration phase during chassis dyno tests or road drives next to other measured variables. This avoids additional chassis dyno tests caused by calibration loops in the past.

Additionally it must be mentioned that equipping the vehicle with the cylinder pressure sensor technology and evaluation unit has proven to be successful also in other applications, as for example in the following:

- Full load application: Under several climatic conditions (hot and cold temperature and high altitude) the full load of the engine in the vehicle is calibrated with correction functions. Thereby the engineer requires the cylinder peak pressure measurement for the achievement of an optimal result.
- Cold start behavior: An important influencing value for cold start optimization is rail pressure. Pressure variation, however, has an essential influence on the generation of combustion noise. In order to avoid changes in the acoustical behavior the combustion noise should be measured at such optimizations.

The example of stationary calibration, described in Chapter 1, only covers one defined operating point, **Figure 2**. With a special method of model generation, however, also several so called local operating points can be merged into a global model. This global model is generated in a defined speed and load range of the engine, in which the model subsequently shall be used for the calibration. After the chassis dyno test the noise track is examined for potential peaks. Each too high peak can be assigned to a definite operating point. Due to the evaluation of the model adhering to the same NO_x level and preferably little additional smoke and consumption a decrease of the noise level can be achieved.

3 In-Vehicle Measurement Chain

The typical measuring chain, **Figure 3**, for noise acquisition consists of a piezoelectric pressure transducer in the combustion engine, an AVL FlexIFEM Advanced amplifier and evaluation unit and an application system. The device thereby is the central link that determines the relevant results out of the pressure trace outputting them via several interfaces. It consists of a charge amplifier, an analog-digital converter as well as a high performance calculating unit for real time data evaluation.

The unit can be used as conventional charge amplifier as well as compact measuring unit for various parameters (for example peak pressure or combus-

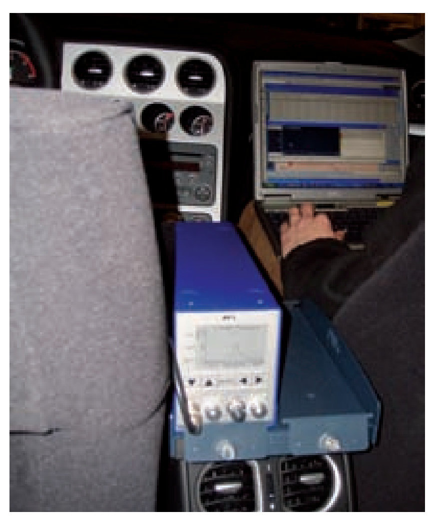

Figure 3: Measuring chain for noise acquisition

tion noise). The flexible concept allows downloading the modifications of the algorithms (for example customer specific filter curves) or additional new algorithms via a USB interface from a connected PC and to save them on the internal Flash-memory.

Parameterization of the device also is effected via the USB or RS232 interface. The most important parameters can also be edited directly at the device by means of the integrated LCD and the keys, mounted in the front cover.

Result values are shown on the display and provided in real time via the integrated CAN-bus interface as well as over analogue outputs to other systems, for example application systems. In addition digital I/Os (TTL and relay) are implemented that can be used for report incidents. Such incidents typically are the exceeding of limit values whereby either the individual working cycles or a continuous collective of working cycles can be evaluated statistically.

Due to the wide range of power supply from 9.5 to 36 V direct current and the flexible setting the device is applicable for the operation in the vehicle as well as for measurements at the test bed and the laboratory.

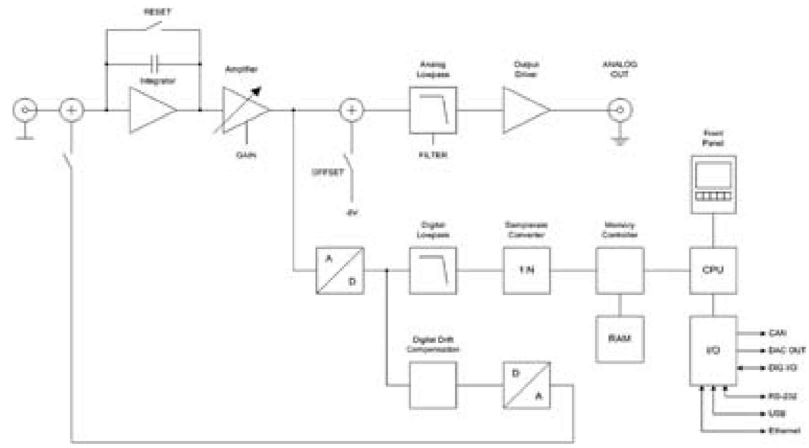

Figure 4: Function block diagram

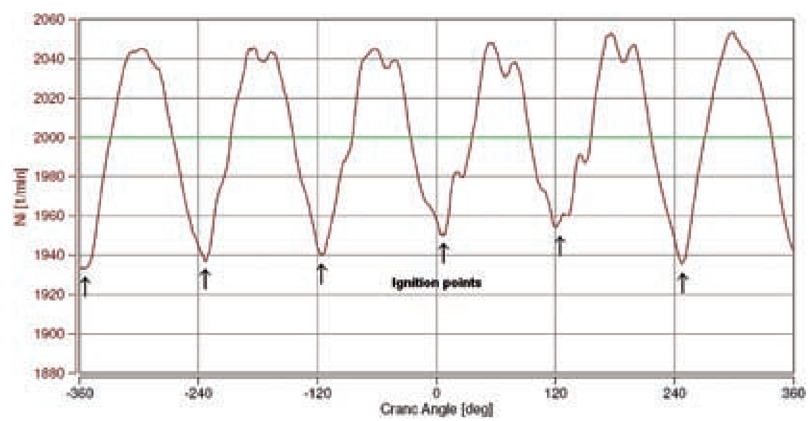

Figure 5: Uniformity of rotation at the example of a six-cylinder engine

3.1 Internal Structure

The internal setup consists of an analog part with two charge amplifiers as well as a secondary digital part for calculating the result values. In order to avoid the influencing of the measuring signal the analog part is decoupled electrically from the digital part, **Figure 4**.

3.1.1 Analog Part

The amplifier part consists of an integrator that transforms the charge, released from the pressure sensor, into voltage, proportional to the pressure. Possible drift, evoked by insulation flow and thermal effects, can be compensated by a digital calculated compensation current. This is followed by a variable amplifier stage for adapting the measuring signal to the subsequent circuit. The amplifying factor thereby is automatically determined from the adjusted sensor sensitivity and the selected measuring range.

A consecutive low pass enables the damping of high frequencies with adjustable filter cut off frequencies (−3 dB) between 2 and 100 kHz. The output stage decouples the single ended output socket from the measuring mass.

3.1.2 Digital Part

The analog-digital converter converts the analog signal of the charge amplifier outlet into a digital data flow. A digital low pass filters high interference frequencies from the signal whereby the signal-noise-relation is improved and anti-aliasing-effects of the secondary scanning rate converter are avoided. The converter provides the data rate required for the respective evaluation algorithm. By means of a memory controller the data are directly written into a random access memory.

Significant for the evaluation is that it is effected working cycle specific. Therefore an identification of the cycle limits is required before applying the actual parameter algorithm. This is carried out by a cut of the compression phase of the cylinder pressure with a constant threshold. Thus additional signals for detecting the position of crankshaft and camshaft can be avoided.

The actual evaluation algorithm – for calculating combustion noise and peak pressure – can therefore be applied exactly on a sector of the time based acquired data stream, corresponding to the last working cycle.

4 Noise Analysis

In physics noise is defined as fluctuations of pressure waves in air or other media that are recognized under specific preconditions regarding frequency and level by the human sense of hearing. Combustion noise is that noise that forms due to the combustion of gas mixture in the cylinder of an engine. This combustion results in a rapid pressure increase in the combustion chamber

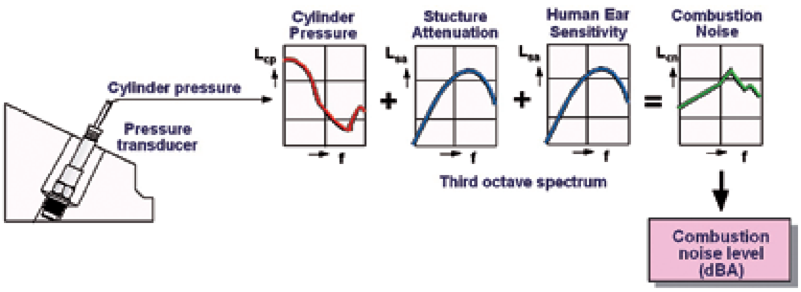

Figure 6: Process diagram

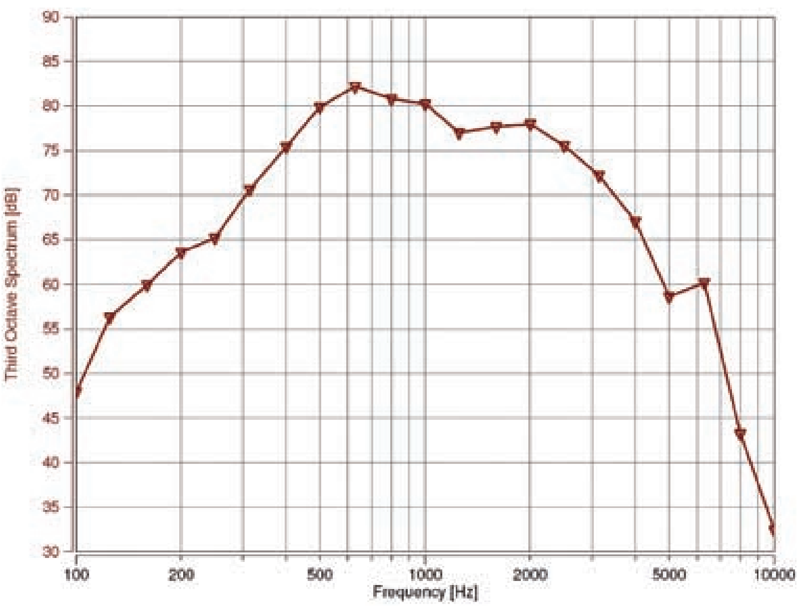

Figure 7: Third octave level spectrum with marked third octave mean frequencies

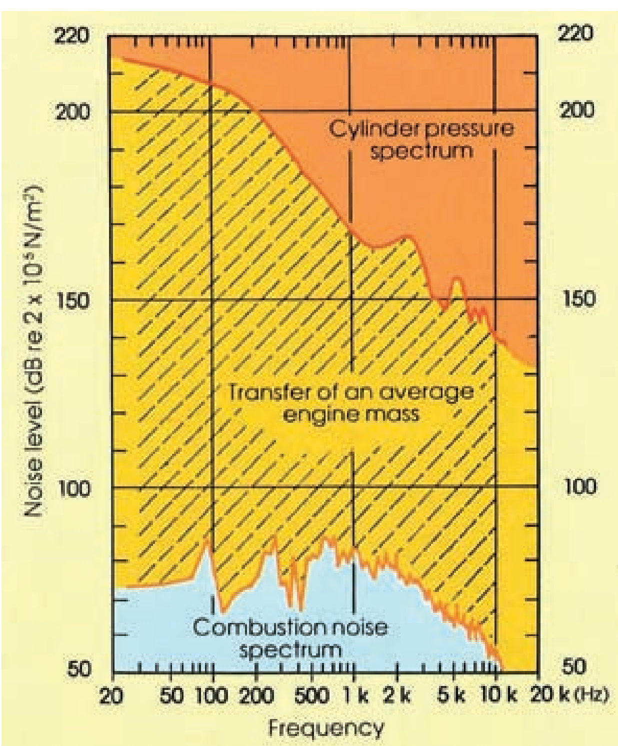

Figure 8: Structure transmission

that is transferred damped by the engine structure to the ambient air and there is recognized by humans as combustion noise.

4.1 Requirements to the Measuring Data

As the frequency spectrum orientates itself on the human sense of hearing and therefore is predetermined the data can be acquired with a constant scanning rate. According to the Shannon theorem this has to be at least twice as high as the maximal processed signal frequency. However, the evaluation has to take place working cycle based. This means that according to the actual speed also data sectors, varying in length, have to be processed. Therefore big data buffer result especially at low speed wherefore the minimal speed for the algorithm has to be set at 100 rpm.

Variable data buffer can only be avoided with an angle synchronous acquisition. This would require the supply of crank angle marks with a high resolution (0.1 °). A crank angle based acquisition has to take the instantaneous engine speed, **Figure 5**, into account when preparing the data for the consecutive FFT analysis.

4.2 Calculating Process Combustion Noise

Figure 6 presents the schematic process of the calculating operation during noise analysis. The cylinder pressure signal is converted into its harmonic vibration units by means of a Fourier transformation in order to determine their power ("power spectrum"). This spectrum subsequently is transformed into a third-octave spectrum, **Figure 7**, by combining the spectral lines. It consists of frequency bands that broaden exponentially to the higher frequencies according to the logarithmical perception of the sense of hearing. From 100 Hz up to 10 kHz these are 21 consecutive frequency bands. The width of a frequency band corresponds in music to one third octave. This is defined by its mean frequency and its upper and lower cut off frequency within which the power amplitude of the vibration parts are cumulated. Referring to a reference acoustic pressure a level progress is determined in dB.

Two filters, defined by the third octave mean frequencies, now are applied

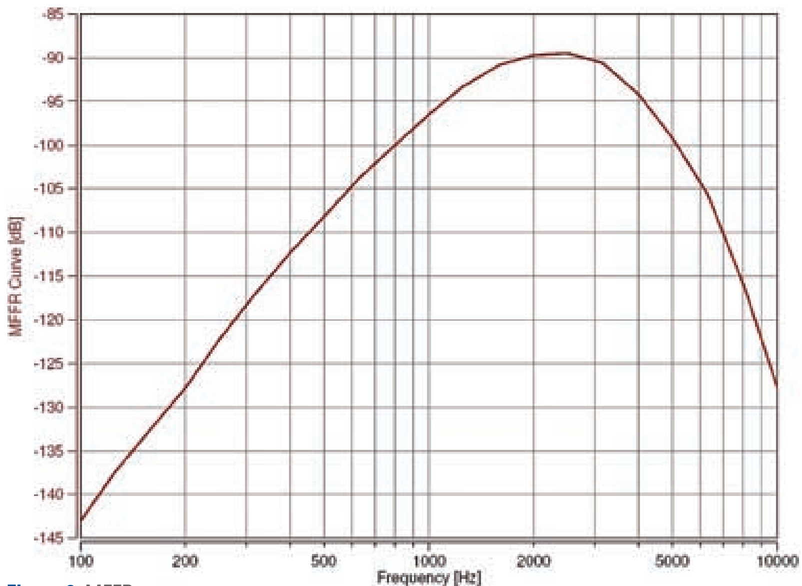

Figure 9: MFFR curve

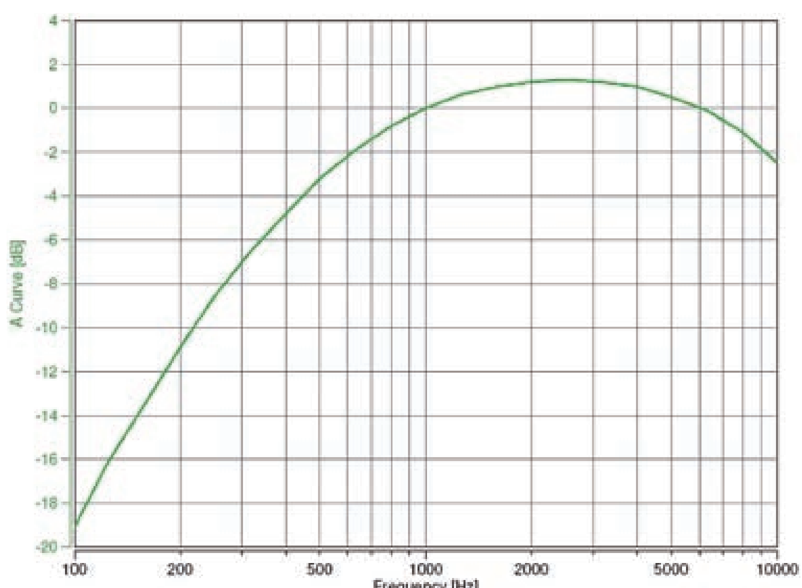

Figure 10: A-curve

to the third octave spectrum, determined in the above explained manner. One is the so called MFFR filter (Mean-Freefield-Response) that characterizes the sound transmission of the pressure in the combustion chamber via the engine mass to the ambient air, **Figure 8**. This transmission function was defined in the publication [1], and represents the illustration of several significant engine structures in a curve. This transmission function is very similar for several engines so that in general one is sufficient to characterize the combustion noise, **Figure 9**.

For better evaluation of new and typically stiffer engine structures in its transmission function the MMFR curve is revised at AVL whereby a stronger emphasis of higher frequencies is introduced. The AVL FlexIFEM Advanced allows unrestricted adaptation of the MFFR curve so that also apart from the standard MFFR curve customer specific transmission functions can be applied.

The second filter curve is the so called A-curve, **Figure 10**. It represents the subjective noise sensitivity of the human sense of hearing. Two sounds of the same amplitude but different frequency are perceived with different intensity. Thus frequencies between 1000 and 4000 Hz appear a lot louder than higher or lower frequencies.

To accommodate this behavior the third octave spectrum is also damped with the A-curve after being filtered with the MMFR curve. After these filtrations a logarithmic mean value is calculated out of the resulting third octave spectrum representing a parameter for the combustion noise (in dB or more precisely dB(A)).

This calculating operation is repeated for each working cycle. The parameter is put out in real time whereas alternatively to the individual cycle values also a floating mean value generation over a definable number of cycles is possible. This parameter can also be transferred to an application system for common recording with other measured values and thus is available as an additional application parameter.

5 Summary

In the development of current engine and power train concepts not only emission formation, fuel consumption and driveability are taken into account but also occurring noise generation is attached importance to. Thereby especially the evaluation of interactions between the changes in the calibration, which are required for target achievement of limit values, and their effects on noise generation are essential for the developer. For precise fulfillment of these requirements especially in transient modes of operation in the engine and vehicle development, that are gaining importance especially in emission testing, measuring devices are required that support such developing and calibration tasks. For this purpose this article from AVL presented a device that offers robust, real time determination and display of parameters, such as combustion noise, and is applicable for the test bed as well as for the vehicle.

Reference

[1] Russel M. F.; Young, C. D.: Measurement of Diesel Combustion Noise. In: Proc. I Mech E Autotech 85, seminar, 1985