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Optimization of Diesel engine noise

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ABSTRACT

In Europe compression ignition (or Diesel) engines are outselling spark ignition (Gasoline) engines by numbers. To promote sales even further there exists a strong interest in enhancing the sound quality of Diesel engines to match their performance in fuel economy and CO_2-emissions. The German Research Association for Combustion Engines, FVV, supports the project "Noise controlled Diesel engine". Within this project we investigate how the engine management can utilize of noise-related sensor signals to reduce and control acoustic emissions whilst maintaining the overall goals on fuel efficiency and regulations regarding harmful exhaust emissions. It is common understanding among experts that purely physical parameters such as the overall sound power level are insufficient to quantify the acoustic effect on the environment. Rather psycho-acoustic parameters such as loudness or impulsiveness of the signal are required for that purpose. This is even more important if development effort should be guided towards quantifiable and noticeable benefit. To support this point and to demonstrate the approach measurements on a Diesel engine were conducted on a test bench with variation of input parameters previously identified of having an influence on the engine noise. The tests were planned by Design of Experiments (DoE) with the following inputs: engine speed, engine load, injection timings, and injection durations. From the measured airborne engine sounds psychoacoustic parameters were calculated. From these the Diesel grade was derived which was developed to quantify the acoustic impact on humans. The Diesel grade was (indirectly) modeled in terms of the ECU parameters and optimized. This optimum shows the best possible sound that can be achieved within the valid ECU parameter combinations. The maximum potential can be shown by computing additionally the worst Diesel grade.

INTRODUCTION

For long time Diesel engines were and, up to this day, are bought for their fuel economy but are are at the same time much disliked for the noise they produce. In their common goal to change this German Diesel engine developers are supported by the German Research Association for Combustion Engines, FVV, who is supporting - among others - the project "Noise controlled Diesel engine". The goal is to show possible benefits of using noise-related sensors in the engine management system with respect to emissions, fuel consumption, and radiated noise and under the legal constraints.

Among calibration engineers it is known that traditional hard-fact acoustic parameters like the overall sound pressure level - the omnipresent dB(A)-value - are an insufficient description of the noise perception. In order to characterize Diesel engine noise closer to human perception, psychoacoustic parameters such as annoyance or impulsiveness provide a much better match.

For a first investigation, experiments were conducted on a Diesel engine at the Chair of Reciprocating Machines at the Otto-von-Guericke-University Magdeburg. ECU parameters like injection timings and injected fuel masses were changed and the resulting engine responses, such as noise and vibrations were recorded. From the microphone signals the psychoacoustic features were extracted. These features were then related to the ECU parameters.

The obtained models were used to optimize the Diesel grade of the investigated engine. The optimized Diesel grade shows the potential of the engine in terms of its sound.

Having motivated the use of psychoacoustic parameters in Diesel engine calibration, we continue with their detailed description and computation. Subsequently the test setup and the measurements will be presented, followed by the optimization and a discussion of the results. The conclusions summarize the work and give an outlook to an inexpensive way to obtain the psychoacoustic parameters.

METHODS

The combustion noise of an Diesel engines dominates all other noise sources by far at start and warm up phase as well as at low engine load and speed. In particular annoying is the Diesel noise because of its impulsive character stemming from the sudden explosions of the injected fuel, its Dieselness.

Diesel Grade Computation

Within the FVV project "Objective measures of subjective perceptions" combustion noise features were related to perception, (Hoppermanns (2006)). Among others, loudness, L, and modulation, M, as 1st level psychoacoustic parameters were combined to 2nd level Diesel grade, DK, an annoyance measure for part-load range:

$$DK = a - bL - cM. \qquad (1)$$

The standard scale ranges from 1 - inacceptable/deafening to 10 - perfect/unhearable. As these features are computed from engine responses it takes some time to record and calculate them - too slow to use this approach in closed loop control. In order to speed up the loop, they are computed from the ECU inputs by a regression model:

$$\widehat{L} = f_1(MI, PI_1, PI_2, N, T), \qquad (2)$$

$$\widehat{M} = f_2(MI, PI_1, PI_2, N, T), \tag{3}$$

with:

MI – *timing main injection*
PI_1 – *timing pilot injection* 1
PI_2 – *timing pilot injection* 2
N – *speed*
T – *torque*

The 1st pilot injection is the closest to the main injection, the second one is farther away, i.e., the second pilot occurs before the first injection. Hence, the estimate of Diesel grade is computed from the estimates of Loudness ($\widehat{L}$) and Modulation ($\widehat{M}$):

$$\widehat{DK} = a - b\widehat{L} - c\widehat{M}. \tag{4}$$

As mentioned before, during the previous FVV project "Objective measures of subjective perceptions" the Diesel grade has been correlated with subjective perception.

Loudness Computation

Psychoacoustic loudness (measured in sone) should not be confused with acoustic sound pressure level (measured in dB(A)). Loudness describes the relation of two sounds in terms of perceived loudness (Fastl and Zwicker (2007)). A signal of twice the loudness of another signal is perceived twice as loud. The frequency bands are defined in terms of bark groups following physiological investigations. The Diesel grade in partial load is based on a weighted specific loudness (N_s), (Figure 1):

$$L = \frac{1}{10}\sum_{k=10}^{19} N_s(k). \tag{5}$$

with: k – *Critical band rate*

An implementation of loudness models are given in Timoney et al. (2004). Zero sone are total quietness, 2 sone are already disturbing depending on the environment.

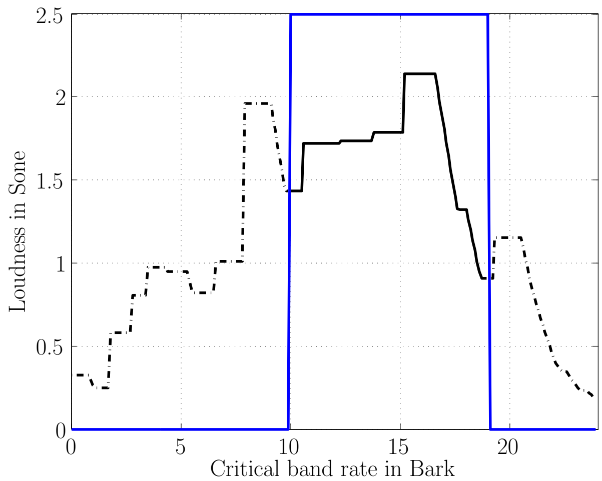

Figure 1: Only the part with the solid line is used to calculate the loudness in the relevant range for Diesel knocking in part-load

Modulation Computation

The modulation is a measure of the impulsiveness of the Diesel engine noise. The modulation spectrum (Bodden and Heinrichs (1999), Bodden and Heinrichs (2005)) is typically obtained by a twofold application of the short-time Fourier transform (STFT):

$$P(u,k) = \sum_{n=u-N/2}^{u+N/2-1} x(n)w(n-u)e^{-j2\pi\frac{kn}{N}}. \tag{6}$$

with each frequency index k representing the behavior of the envelope at the corresponding carrier frequency. In the next step the modulation spectrum is calculated by applying the Fourier transformation along the windowed time series of the absolute values of $P(u,k)$ at each frequency index:

$$P(m,k) = \sum_{u=0}^{M-1} |P(u,k)|\, w(u)e^{-j2\pi\frac{um}{M}}. \tag{7}$$

Finally the modulation spectrum is normalized:

$$P_N(m,k) = \frac{|P(m,k)|}{|P(0,k)|}. \tag{8}$$

From the modulation spectrum the aurally compensated pitch (critical band rate) is calculated using Zwicker (1961). In the last step the modulation M is calculated as a weighted sum over the critical band rate over a selected band of modulation frequencies or a selected modulation frequency. For inline 4 cylinder engines such as the investigated engine, the second engine order is the most prominent frequency and hence the dominant modulation frequency (m_{eo}):

$$M = \frac{1}{15}\sum_{k=10}^{24} P(m_{eo},k). \tag{9}$$

with: k – *Critical band rate*

Figure 2 shows the modulation spectrum of the Diesel noise and the applied windows in both directions. A modulation of 0% implies no variation of the envelope, at 100% the envelope varies between its maximum and zero.

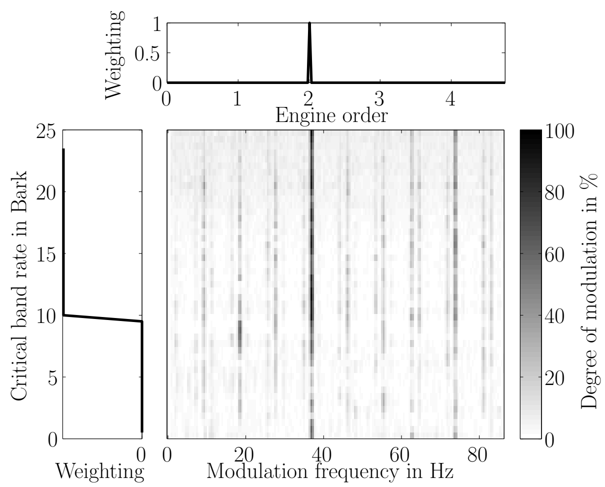

Figure 2: Modulation spectrum with weighting in carrier frequency and modulation range for the relevant range of the Diesel noise in part-load

TEST SETUP

The experiments were conducted at the Chair of Reciprocating Machines at the Otto-von-Guericke-University Magdeburg. There, a completely indicated series-4-cylinder Diesel engine was operated on a conditioned dynamometer with total access to the ECU. 86 stationary measurements were planned by design of experiment and conducted at operating points in the region speed N = 1000 ... 2000 rpm and torque T = 50 ... 160 Nm. At these points the injection timing parameters MI, PI_1, PI_2 were varied such that speed and load were kept constant as fas as possible. Hence, a more efficient combustion would be controlled to get less fuel to remain at the chosen speed and load.

The selected parameters were previously identified as the most relevant factors for Diesel noise. For test automation and measurement, the software ATI Vision from Accurate Technologies was used. The input parameters and the slow engine reactions/output parameters, such as temperatures and pressures of airborne path, fast parameters such as cylinder pressure and airborne noise, were measured at several positions and recorded with a PAK system from Müller BBM.

The three microphones were positioned in a distance of one meter to the engine block:
Microphone 1 - exhaust side (hot)
Microphone 2 - intake side (cold)
Microphone 3 - top.

The data was recorded at the steady-state operating point after stationary conditions were reached. Subsequently the data was imported into MATLAB for all analyses. Repeatability was checked with additional measurements indicating good stability of the test bench and the test setup.

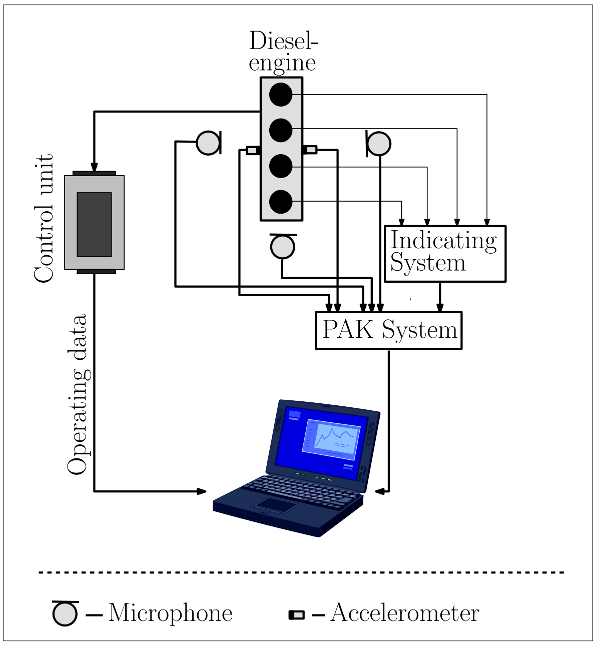

Figure 3: Test setup

RESULTS

From a scan of the recorded signals, it was decided to use signals from Microphone 1, located at the hot exhaust side. This garantees that the combustion noise is clearly audible and dominates the signal, while in the signals of Microphone 3, top side, the noise from brake and uncontrolled ventilation set a high noise floor, masking the combustion noise.

Loudness

Even though different from the sound power, the loudness correlates with the sound power. As expected the loudness rises with engine speed and load. From common observation one expects an engine to emit more noise at higher speeds than it does at lower speeds.

From the measured data, and using IAV's DoE Toolsuite a model of the loudness was devised according to Equation 2. The achieved correlation is quite high, sufficient for the task at hand, Figure 4.

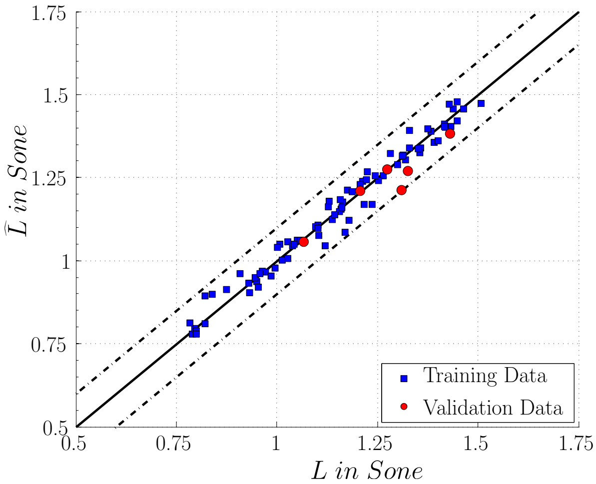

Figure 4: Correlation plot of the calculated loudness (L) and modeled loudness ($\hat{L}$)

Modulation

On the other hand, the modulation decreases with engine speed an load. This is due to the psychoacoustic perception of modulation, which takes into account the masking of the modulation frequency component by a high overall sound power level. The modulation frequencies are not any longer dominating the noise and hence their effect on the envelope reduces for higher speed and load. For the load dependency the modulation decreases, because the carrier frequency component increases and hence the modulation degree decreases, influencing the modulation itself proportionally.

As for the loudness, a model was fitted to the measurements. Again, correlation is quite high, Figure 5.

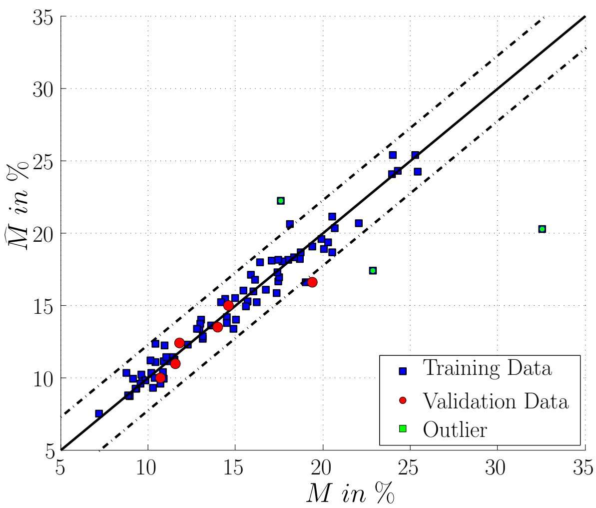

Figure 5: Correlation plot of the calculated modulation (M) and modeled modulation ($\hat{M}$)

Diesel grade

The two models of loudness and modulation were combined to obtain a model for the Diesel grade, Equation 4. The correlation is still quite good, with less than half a grade prediction accuracy, Figure 6. As expected from its two influences, the Diesel grade does not show that clear a dependency with speed or load, Figure 9. As described above, the influence factors loudness and modulation show contradictory behavior, resulting in a decrease of the Diesel grade between 1000 and 1400 rpm and a leveling off at higher engine speeds. The good values at low engine speeds are due to the low loudness and the level at higher speeds is due to the balance between the loudness and the modulation components of the Diesel grade, Equation 1.

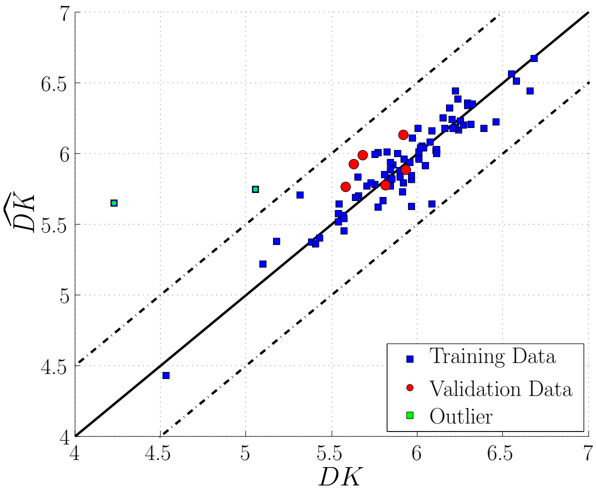

Figure 6: Correlation plot of the calculated Diesel grad (DK) and modeled Diesel grade ($\widehat{DK}$)

Optimization

The Diesel grade can now be used as target function of an optimization. In internal combustion engine calibration, the fuel consumption and the exhaust emissions are the most important targets of most optimizations. But with more injection parameters to adjust, such as the timing parameters in this study, more targets can be persued. The optimization was carried out in the DoE Toolsuite from IAV, with the target function defined by the Diesel grade estimate, Equation 4. The optimization was carried out over the same region as the measurements, with a speed step $\Delta N = 50\ rpm$ and a load step $\Delta T = 5\ Nm$.

For two points $N = 1250\ rpm$, $T = 75\ Nm$ and $N = 1750\ rpm$, $T = 75\ Nm$ the result shall be demonstrated in Figures 7 and 8. PI_1 and PI_2 were varied while MI was left fixed at $-3.5°CA$ for ease of visualization. For physical considerations, P2 must occur before P1 with some extra angle difference, required to inject fuel and to close the injector in between:

$$PI_2 > PI_1 + 2.5\,°CA. \tag{10}$$

This constraint limits the plots to the lower right hand side triangle. The shades of gray correspond to the Diesel grade. It can be observed that the extrema occur at the limits of the allowed parameter space.

The optimizer will find maximum and minimum and record the values of MI, PI_1, PI_2.

Using these recorded values for a grid of operating points (N,T), maps of maximum and minimum Diesel grades are computed, for the whole operating range Figures 9 and 10. The maximum Diesel grade is the best achievable sound with the allowed parameters, while the difference between maximum and minimum, Figure 11, can be interpreted as potential improvement assuming that the engine starts at the minimum value. An improvement of one grade is a noticeable and will spurn the interest of developers. Also, smooth changes over the operating range are of interest as booming and sudden changes are typically not well received by the customers.

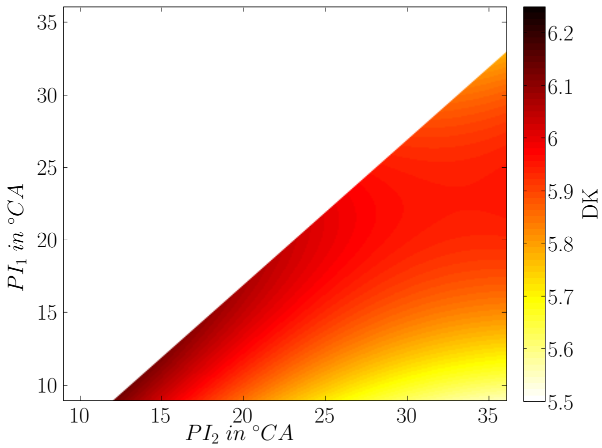

Figure 7: Diesel grade for varying PI_1, PI_2 at the operation point $N = 1250\ rpm$, $T = 75\ Nm$, $MI = -3.5\ °CA$

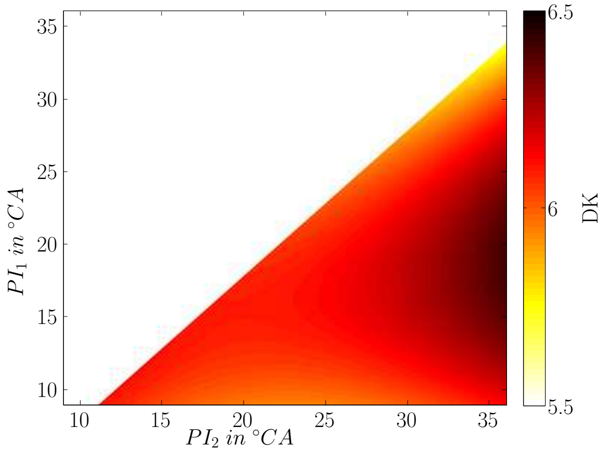

Figure 8: Diesel grade for varying PI_1, PI_2 at the operation point $N = 1750\ rpm$, $T = 75\ Nm$, $MI = -3.5\ °CA$

CONCLUSIONS

We have presented the use of psychoacoustic parameters for the characterization of Diesel engine noise. From a minimal set of stationary measurements models for loudness and modulation were derived and combined for the Diesel grade. The Diesel grade ranges between 4.2 and 6.7. The DK model was used for optimization, showing the best possible sound of the investigated engine. By looking at the difference between best and worst DK, we showed the maximum potential for each operating point (N, T). This was for the operating range of this analysis about one grade. For luxury car manufactures this is a valid aim to spend development effort on. The presented optimization does not consider fuel consumption and emissions. Hence the possible optimum will not be reached in general. Subsequent analyses will include these strict constraints.

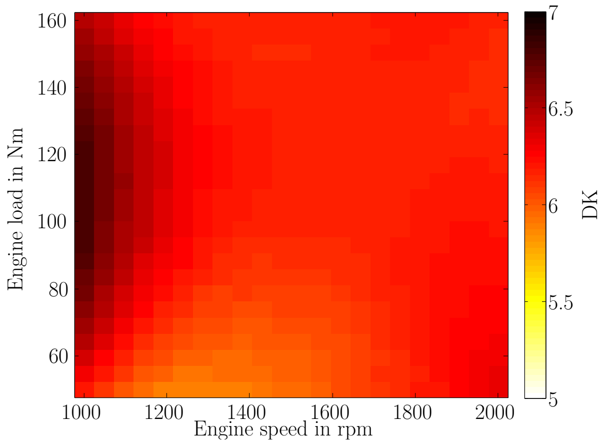

Figure 9: Best Diesel grade after optimization (DK_{max})

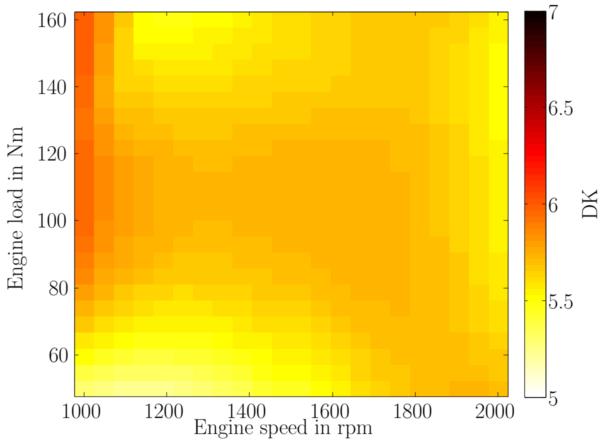

Figure 10: Worst Diesel grade after optimization (DK_{min})

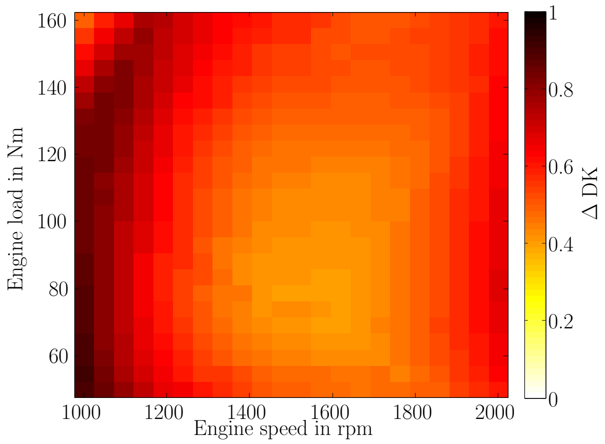

Figure 11: Potential improvement ($\Delta DK = DK_{max} - DK_{min}$)

In a recent analysis of the authors (Decker et al. (2010)), we demonstrated the use of structure-borne sound signals or accelerations. With slight changes to the algorithm and a subsequent correction computed from a regression analysis, almost identical values for the Diesel grade were obtained. This is a major benefit considering the expenses of carrying out acoustic measurements in standard engine test cells. This approach will be generalized and further validated.

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