Diesel Sound Quality analysis and evaluation

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Both, the quote of diesel powered engines and the expectations of customers on vehicle acoustics have been increasing in the past years. The characteristic diesel sound, the Diesel Knocking (or Diesel Impulsiveness) is an important issue of Vehicle Sound Quality which has to be adjusted to the customers expectations. In order to do so a new method to analyse and evaluate Diesel Sound Quality is proposed in this paper. The Diesel Impulsiveness is caused by the cylinder firing process which introduces a periodic time structure. This periodic impulsiveness can best be analysed with the Narrow Band Modulation Analysis (NBMA) which will be introduced as a sophisticad tool to render detailled information on perceptually relevant aspects and for root cause analysis of interior, exterior and structure borne signals. The basic relation between parameters of the firing process (the cylinder firing itself and of differences between cylinders and variations of cylinder firings) and the NBMA result are then discussed. Based on the NBMA two single value metrics have been developed to quantify Diesel Impulsiveness, extended by a prediction of the customers rating of interior Diesel Impulsiveness for the most critical condition, idle.

1 Introduction

Nowadays diesel powered vehicles are very popular in Europe, the Diesel market share did already exceed 43.5% in 2003. In Germany, the biggest European market, more than 44% of new vehicle registrations have been Diesel powered vehicles in 2004, and the trend is still going up.

Much effort has been spent in the past to reduce Diesel Impulsiveness of diesel engines, and some vehicles were yet able to approach the customer requirements. But, with new legal requirements such as EURO IV, modern engines are facing again tough challenges from the acoustical point of view. These legal requirements lead to the necessity to set the engine control parameters in such a way that a 'harder' cylinder firing is produced, which results in stronger Diesel Impulsiveness.

Besides a basic investigation on the perception and the customers requirements and expectations of Diesel Sound it is of crucial importance to have a suitable and powerful method to analyse and evaluate Diesel Sound available. Parts of these investigations and results are presented in the following chapters.

2 Perception of Diesel Sound

The sounds of vehicles which are equipped with a diesel engine can well be distinguished from vehicles with a gasoline engine. The typical characteristic is called "Diesel Impulsiveness" here, an impulsive signal component with a periodicity defined by the cylinder firing.

Customers usually associate this Diesel Impulsiveness with negative characteristics ("it sounds like a tractor"), so that the aim of car manufacturers is to reduce it as much as possible or to completely eliminate it's perceptability in the vehicle interior.

The perceived character of Diesel Impulsiveness is composed of three different features:

- the basic impulsiveness:
  This impulsiveness is defined by its repetition frequency which is the 2nd engine order for a four cylinder engine (30 Hz at an idle rpm of 900 rpm);
- cylinder-to-cylinder variations:
  Differences in the firing process between the cylinders result in additonal rythms. These ryhtms follow the 0.5th and 1st engine order (7.5 and 15 Hz for idle at 900 rpm);
- shot-to-shot differences:
  variations of the firing of a cylinder over time.

The perceptually most critical condition for Diesel Impulsiveness usually is idle. Most engines run into a strong and clear impulsiveness in this condition, and the other masking sounds are rather faible. There is no interaction with the driver so that the knocking can not be interpreted as a feedback, and furthermore the attention of the driver is not blocked by driving the vehilce.

The analysis method presented here will thus first concentrate on the evaluation of idle, although it's principles allows also to apply it to different conditions. All examples are shown for four cylinder engines where the main firing order is the second engine order.

3 Analysis of Diesel sound

The characteristic feature of diesel sound are impulsive signal components. The excitation of these components is driven by cylinder firing, so that they set up a periodic time structure.

The base frequency of this periodicity is the 2nd engine order (for a 4-cylinder engine which will be investiagted here), which is the repetition frequency of cylinder firing. Differences in the firing of the cylinders introduce different periodicities, so that in addition multiples of the half engine order can occur.

This combination of impulsiveness and periodicity can not be directly analysed with a single analysis method. Nevertheless, the best method to render information about the process is modulations analysis. In order to interpret the results of this analysis it first has to be reflected that the modulation analysis inherently describes sinusoidal amplitude modulations and not periodic impulsiveness as it is the case for Diesel Impulsiveness.

Diesel vehicle sound is thus considered as being an amplitude modulated signal with the modulator being the cylinder firing signal. Since the signal is not sine-modulated but more a kind of rectangular-modulated, the modulation analysis will show not only the base modulation frequency, but also multiples of it - the modulator can be described as a Fourier series with the base frequency and it's multiples.

The use a broadband modulation to describe Diesel Impulsiveness is limited since it does not reveal the frequency composition of the sound. To do so a frequency selective modulation analysis has to be performed, which can efficiently be implemented as the Narrow Band Modulation Analysis (NBMA).

3.1 Narrow Band Modulation Analysis NBMA

The Narrow Band Modulation Analysis was presented by Bodden and Heinrichs in [1] . It is an efficient implementation of a carrier frequency selective modulation analysis using a twofold series of FFTs:

- the first set of FFTs is applied to subsequent overlapping windowed segments of the time series of the sound and determines its spectrogram;
- for each carrier frequency of the spectrogram its time coarse represents the envelope of the signal;
- the second set of FFTs is thus applied to the time coarse at each carrier frequency.

The resulting Narrow Band Modulation Index (NBMI) is depicted in Fig. 1 for two different vehicles.

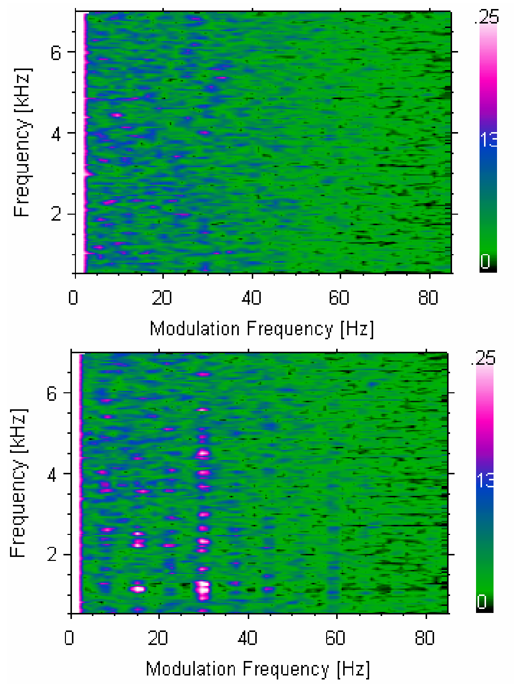

Fig. 1 NBMI result for two vehicles in Idle, interior recording.
Top: nearly no Diesel Impulsiveness
Bottom: strong Diesel Impulsiveness

For the vehicle with nearly no Diesel Impulsiveness (top) no significant modulations occurs, while for the vehicle with strong Diesel Impulsiveness clear modulations can be observed at modulation frequencies which correspond to multiples of the half engine order.

Besides the general information about the strength of Diesel Impulsiveness the NBMA offers a much more detailled insight into its character and composition. Although strong impulsiveness results in broad modulations it can be seen that the modulations are significantly different as a function of carrier frequency. This means that specific carrier frequencies are very strong modulated while others are less. Furthermore, the different contributions at modulation frequencies corresponding to different engine orders reveal additional important information for the root cause analysis and the optimization process.

3.2 Relation to cylinder firing

It has been shown before that the NBMA analyses sinusoidal amplitude modulations while the Diesel Impulsiveness is based on periodic impulsive signal components caused by the cylinder firing. In order to understand and interpret the NBMA results it is thus necessary to investigate the principle relation between important parameters of the cylinder firing process and the NBMA results

To do so representatives for series of cylinder firings have been synthesized in order to have complete control over the process. No further background signal has been added, so that the input signals to the NBMA were the pure periodic impulsive part of the complete signal.

In the theoretical case that all cylinder firings are completely identical (no cylinder-to-cylinder and shot-to-shot variations) the NBMA renders the results shown in top of Fig. 2 . Here the average modulation indices are shown (NBMI averaged over carrier frequency), since modulation is identical for all carrier frequencies due to the lack of the non-modulated background noise.

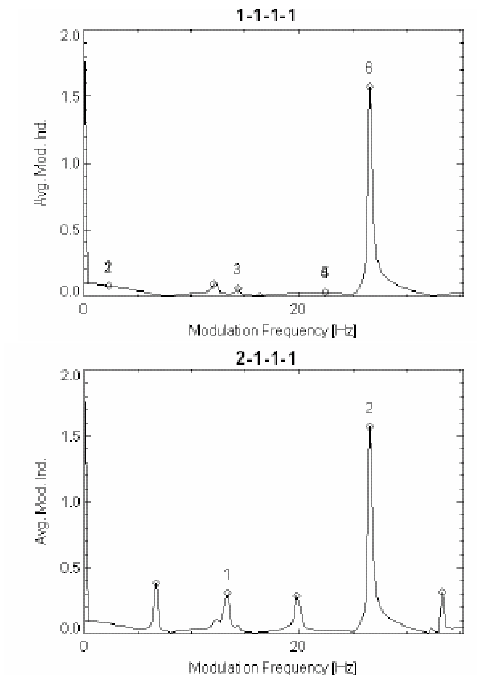

Fig. 2 Average NBMI for simulated cylinder firing.
Top: identical cylinders
Bottom: one cylinder with a different amplitude

It can be seen that modulations occur just at the modulation frequency corresponding to the 2nd engine order. This modulation frequency thus describes the basic impulsive structure of the diesel sound.

The bottom graph in Fig. 2 shows the result if one cylinder fires with a different amplitude than the other three. The basic modulation is unchanged while now modulations at modulation frequencies corresponding to multiples of the half engine order occur in addition. This is due to the fact that now additional periodicities are added to the signal, each fourth firing is now also identical. These differences between cylinder firings change the character of the Diesel Impulsiveness.

Shot-to-shot variations can be interpreted as a statistical uncertainty of the firing parameters. They result in deviations from the fixed time structure, so that e.g. temporal variations reduce the modulation index at the base modulation frequency.

The suitability of the NBMA to evalualte diesel sound becomes obvious when spectral differences between cylinder firings are investigated. Fig. 3 shows the results for a firing series where a small spectral reduction in the carrier frequency band between 0.6 and 2.5 kHz was introduced at the firing of one cylinder.

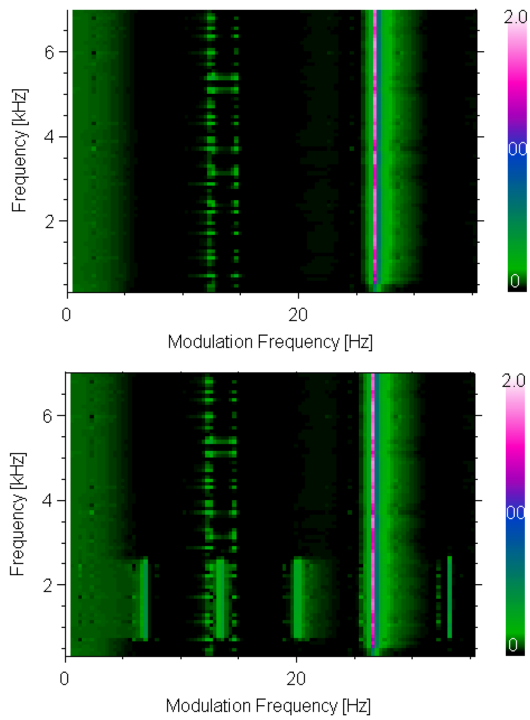

Fig. 3 NBMI of simulated cylinder firing.
Top: all cylinder identical
Bottom: one cylinder with a spectral reduction at carrier frequencies between 0.6 and 2.5 kHz

It first can be seen in the top graph as stated above that the modulation at the base modulation frequency is identical for all carrier frequencies.

In the bottom graph it is interesting to note that modulations at modulation frequencies corresponding to multiples of the half engine order occur just in the frequency band in which one of the four cylinders had a different spectrum. In this frequency band the NBMA thus renders the same results as in bottom of Fig. 2 , where one cylinder has a different amplitude - which is the case for this narrow carrier frequency band.

The NBMA is thus able to resolve differences in the firing of cylinders and is a powerful tool to render important information on the origin of Diesel Impulsiveness.

3.3 Diesel Impulsiveness metric

It has been shown above that the NBMA is able to give a detailled insight into Diesel Impulsiveness perception. In order to quantify Diesel Impulsiveness single value metrics were developed based on the NBMA results.

This development is based on extensive perceptual investigations of various interior and exterior diesel sounds in different conditions. Real vehicle drives, test bench drives and laboratory investigations have been performed with both, experts and customers. The laboratory investigations have been performed with headphone representations of artificial head recordings and applying the individual test presented in [2] . concepts of the customer evaluation are presented in [3] .

The first index quantifies the pure Diesel Impulsiveness. This so-called M-DKI combines the modulations at modulation frequencies corresponding to multiples of the half engine order up to the base modulation frequency in a specified band of carrier frequencies. This metric is suitable to quantify any type of signal, exterior, interior and even structure borne sounds.

In order to reproduce the subjects ratings for interior Diesel Impulsiveness in the idle condition the DKI was developed. This metric is based on the M-DKI but consideres in addition that the level of signal components have an influence on the interior vehicle rating. It thus combines the M-DKI with the signal level in a specific frequency range. The correlation of the DKI to ratings of interior vehicle sounds reaches a value of 0.96 and is opposed to the subjects ratings in Fig. 4 .

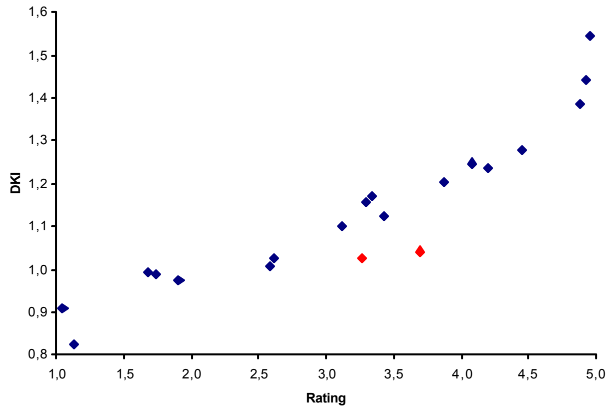

Fig. 4 DKI vs. subjects ratings of Diesel Impulsiveness for interior vehilce recordings in idle. Correlation is 0.96

Due to this high correlation the DKI can thus be used to predict the rating of Diesel Impulsiveness for the idle condition. This prediction was determined by a fitting of a 2nd order polynom. The correlation between the real subjects ratings and the automatically predicted rating was found to 0.97, and reaches a value of 0.99 if two artificial sounds are not considered. Real and predicted ratings are opposed in Fig. 5 .

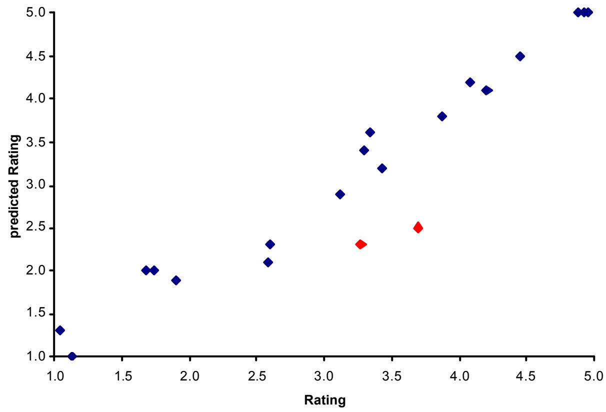

Fig. 5 Comparison of automatically predicted rating and subjects rating of Diesel Impulsiveness of interior vehicle sounds in idle. Synthetical signals are marked in red. Correlation is 0.97 (0.99 without synthetic signals).

4 Summary

The method presented in this paper allows an efficient and detailled analysis of diesel sounds. The characteristic and perceptually relevant features of Diesel sounds can be identified and quantified.

Single value metrics have been developed to quantify Diesel Impulsiveness for interior, exterior and structure borne Diesel sound.

For idle, which is the percetually most releveant condition, a quantification and prediction of the rating of interior Diesel Impulsiveness is possible with a high correlation.

Literature

[1] Bodden, M.; Heinrichs, R., 'Analysis of the time structure of gear rattle'. *Proceedings of the Internoise 99*, Fort Lauderdale, USA, 1273-1278 (1999).

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