Periodic Impulsiveness - Perception and metric

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Introduction

A process and metric to tackle Diesel Impulsiveness (Diesel knocking) has been developed and presented in former publications (e.g., Bodden & Heinrichs, Forum Acusticum 2005, Internoise 2007). While vehicles with gasoline engines did not show any similar behavior in the past, the introduction of direct injection engines let to the fact that nowadays also these engines produce a typical periodic impulsiveness (tick).

The aim of the work presented here is to develop a unique and global process and metric to quantify general periodic impulsiveness. Extensive listening clinics have been performed on all levels, vehicle interior, exterior, and powertrain cell level to get insight into the perception of periodic impulsive signals. A corresponding metric has been developed which can be used on all levels for engineering purposes and for target setting on vehicle and system level.

Review of the metric for diesel impulsiveness

The metric for diesel impulsiveness was first developed to reproduce customer perception for the most important condition, idle interior. Within the years this metric has been extended to cover multi-cylinder engines architectures (I3 to V10), to include exterior and powertrain levels, consider transfer paths and to be applicable for off-idle ([1 - 3]).

Diesel impulsiveness is analysed via the specifically developed Narrow Band Modulation Analysis method ([1]). From the resulting modulation spectrum modulations caused by the engine orders are extracted and combined to form the metric mDKI, a metric describing the modulation content and thus the time structure of the signal. In the orthogonal approach the bandlimited level determines the influence of the signal level, and combining both results in the customer-representative metric DKI which quantifies diesel impulsiveness.

The resulting metric shows a high correlation to subjective evaluations, e.g., an R^2 of 0.94 for interior idle.

This base approach was followed by others later on (e.g., [4])

A universal metric for periodic impulsiveness

While the specific type of periodic impulsiveness was unique for vehicles with a diesel engine in former times, todays modern gasoline engines show a similar effect. With the introduction of direct injection principle a periodic tick component can be observed. This component shows a similar time structure as the diesel impulsiveness, so that the same analysis principle can be used to quantify it. Nevertheless a gasoline engine still sounds significantly different compared to a diesel engine, so that a metric which should cover both engine types needs to be adopted.

Requirements of the metric

The metric should serve as a universal metric for periodic impulsiveness on all levels and for all applications as shown in Fig. 1.

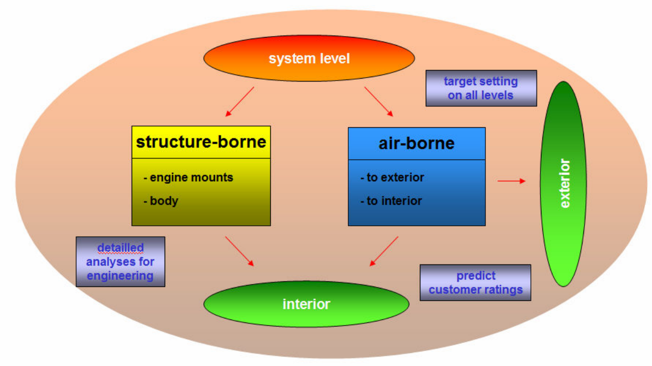

Figure 1: Applicability of the metric.

The metric should

- represent the customer perception for interior and exterior
- allow quantification on system level and on transfer paths
- cover all operating conditions (idle - off-idle)
- be applicable for target setting on all levels (int, ext, system level) and for guided engineering purposes (origin analysis, countermeasure development and quantification)
- be applicable for all types of combustion engines (diesel, gasoline, I3 to V10).

Development of the metric

In order to develop a corresponding universal metric extensive listening clinics on all levels are required. Nine different clinics have been performed mostly on two continents, Europe and North America. It is interesting to note that impulsiveness perception is quite similar on both continents, although differences could be expected due to the fact that diesels are very unfamiliar in die US.

The results of the listening clinics build a comprehensive base to the adjustment of the metric. The comparison of the data analysis to the subjective ratings showed that three major topics had to be tackled which will be discussed in the following paragraphs.

Inter-orders

A base assumption of the performed analysis is that modulations which are multiples of the half engine order contribute to impulsiveness. The periodicity in the signal is directly caused by the firing of the cylinders and the initiated mechanical processes.

In contrast some gasoline engines show a different behaviour, resulting in a strange 'a-rhythmical' impulsiveness. For these engines impulsiveness occurs with a periodicity which is not necessarily linked to the half-order rhythm. This can be caused by a component which is driven by a different mechanism (e.g., a pump with a different rpm). Fig. 2 shows a typical NBMA plot of a corresponding sound.

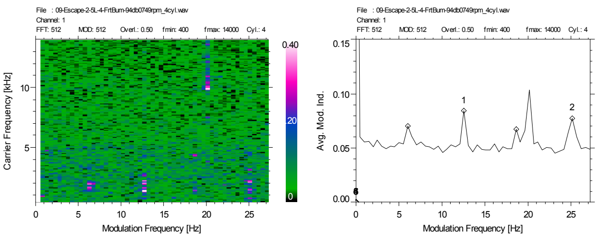

Figure 2: NBMA plot (left) and average narrow band modulation index showing a strong inter-order

A clear and strong modulation contribution can be observed at a modulation frequency of 20 Hz at higher carrier frequencies which corresponds to the 1.6th engine order.

This inter-order was not considered by the metric formulation of the mDKI, but it influences the perceived impulsiveness. Thus a mechanism was developed to detect inter-orders and to apply a penalty to the resulting metric.

Spectral weighting

The orthogonal approach explicitly separates modulation and level, and the modulation index is used to determine the mDKI. Diesel engines usually contain a significant low frequency knock component with a high level, but gasoline engines often contain just high carrier frequency tick components at a rather fable or low level. These high frequency ticks can show very strong modulation indices, so that the resulting mDKI would over-predict the impusliveness. Fig. 4 shows a corresponding example.

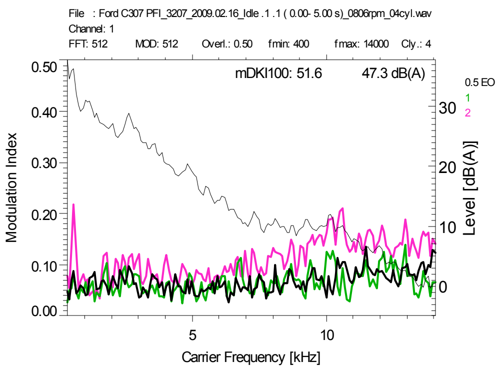

Figure 3: Engine order modulation cuts for a gasoline exterior sound with just high frequency tick

In order to consider this influence a specific spectral weighting function was introduced into the metric.

Overall alignment

The original definition of the mDKI and DKI was purely based on the results of a listening clinic for interior diesel idle. Although it was extended later to exterior and system level data the main formulae kernel was not modified.

Extending the metric to gasoline vehicles and using the results of the nine different comprehensive listening clinics a fine alignment to the complete dataset was possible. The kernel of the metric and the orthogonal approach were not changed, but parameters and internal weightings, e.g. the influence of the level on the metric, adopted.

The resulting universal metric for periodic impulsiveness is the TKI (Tick-Knock-Index) which is composed of the mTKI (modulation contribution) and the band-limited level.

The correlations of the TKI to the nine different listening clinics is summarized in Fig. 4.

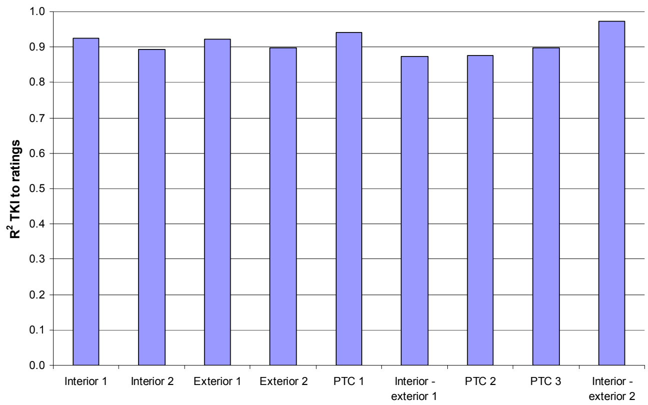

Figure 4: Correlations of the metrics to the nine different listening clinics.

The average R^2 of the metric to the subjective ratings is 0.91, thus guaranteeing high correlations for all application scenarios from interior over exterior to system level.

Application of the metric

Equal TKI curves

In order to compare different vehicles or to trace the walk from PT to exterior/interior a graphic representation in form of equal TKI curves are used. Fig. 5 shows an example.

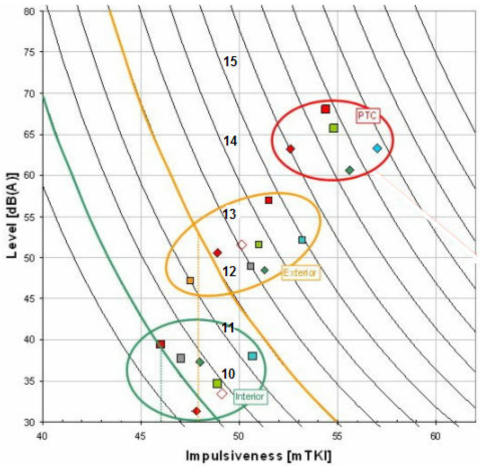

Figure 5: Presentation of the metrics in the equal TKI plot

In this graph the TKI is plotted with its mTKI and band-limited level. The background curves show curves for identical TKI, and thus identical periodic impulsiveness rating. Target curves can easily be added to that presentation.

Detailed analysis Diesel vs. Gasoline

As stated above, Diesel engines mostly contain thy typical lower carrier frequency knock component while gasoline vehicles contain higher frequency tick components. But, the separation is not so strict since both types of engines can contain both types of periodic impulsiveness.

Fig. 6 shows a comparison of a diesel and a gasoline vehicle for the idle interior case.

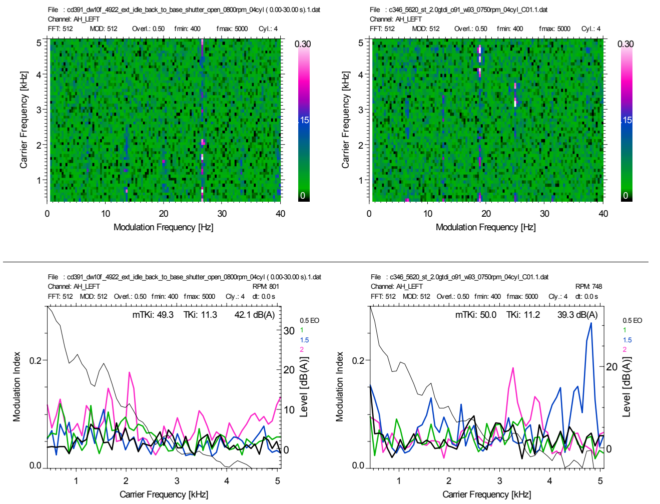

Figure 6: Comparison Diesel (left) to Gasoline (right) interior. Top: NBMA plot; bottom: order cuts.

It is obvious that the diesel vehicle contains stronger modulation at lower carrier frequencies (up to 2 kHz), but also at higher carrier frequencies modulations can be observed.

The gasoline vehicle contains dominant high carrier frequency modulation. In addition, the special typical role of modulations at the 1.5th engine order can be observed. This modulation is in a carrier frequency region (4-5 kHz) which is different from the other modulations, showing that it is originating from a different process. In this case it is periodic impulsiveness caused by the fuel pump which is not directly driven by the same rpm.

Fig. 7 shows the corresponding data for the exterior idle case.

Still the Diesel vehicle contains strong low carrier frequency modulation as seen in the interior, but here also clear and strong high carrier frequency modulations (tick components) can be observed (e.g., 5 and 8 kHz carrier frequency).

The gasoline vehicle shows the dominant tick as in the interior (3-4 kHz), higher components (~6.5 kHz) and the strong 1.5th order driven modulation at 5 kHz carrier frequency.

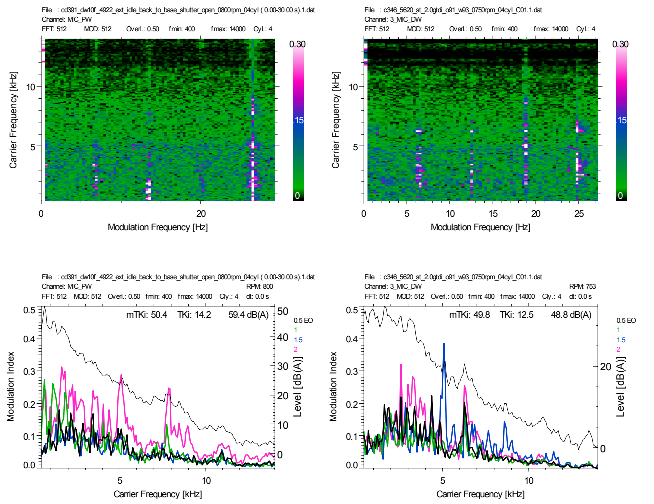

Figure 7: Comparison Diesel (left) to Gasoline (right) exterior. Top: NBMA plot; bottom: order cuts.

Gasoline and Diesel engines thus show typical and characteristic features, but also a lot of common behaviour with regard to periodic impulsiveness.

Summary

Periodic impulsiveness is an issue for all current combustion engines, diesel and gasoline and has a strong impact on the overall Sound Quality. The proposed metric realizes a universal approach to quantify the underlying perception of periodic impulsiveness. It can be applied to diesel and gasoline vehicles at interior, exterior, system level, on transfer paths and for all cylinder numbers. The metric shows a high correlation in all application scenarios as thus can be used for target setting on all levels.

References

[1] Bodden, M., Heinrichs, R.: Diesel Sound Quality analysis and evaluation. Proc. of the Forum Acusticum 2005, Budapest, 1161-1164.

[2] Heinrichs, R., Bodden, M.: Diesel Impulsiveness Part I: customer perspective. Proc. of the Internoise 2007, Istanbul, paper no 282.

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[4] Richter, S., Svensson, C.: Analysis of the interior noise quality of a diesel vehicle using time based transfer path analysis and objective indices. Proc, of the Aachen Acoustic Colloquium 2009, Aachen.