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The application of a new software tool for separating engine combustion and mechanical noise excitation

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ABSTRACT

The optimization of engine NVH is still an important aspect for vehicle interior and exterior noise radiation. To optimize the engine noise / vibration contribution to the vehicle, a complete understanding of the excitation mechanism, the vibration transfer in the engine structure and the radiation efficiency of the individual engine components is required.

Concerning the excitation within the engine, a very efficient analysis methodology for the combustion- and mechanical excitation within gasoline and diesel engines has been developed. Out of this methodology a software tool has been designed for a fast, efficient and detailed evaluation of the combustion- and mechanical excitation content of total engine noise. Recently this software tool has been successfully applied in engine NVH optimization work for defining the best optimization strategies for engine NVH reduction and noise quality improvement especially with respect to combustion excitation.

In this paper a brief description of the methodology which forms the basis of the software tool is presented apart from a detailed discussion of a number of results obtained with this software tool on gasoline and diesel engines.

INTRODUCTION

Optimization measures performed directly on the excitation sources are most effective for reducing engine noise and improving noise quality. Therefore, the precise knowledge of the contribution of the different excitation phenomena to total engine noise / noise quality is of great importance.

Several methodologies have been developed in the past to obtain this information. [1/2/3/4/5/6/7]. Within the work reported here, an efficient methodology has been developed which gives accurate enough information while requiring very little analysis effort.

Based on a literature survey of published methodologies for the evaluation of combustion and mechanical excitations, these methodologies were developed, evaluated and tested on engines with respect to their performance. Based on this knowledge the new methodology was defined and developed with respect to accuracy and minimum analysis effort.

BASIC ASSUMPTIONS

In order to define the noise contributions from different excitation mechanism in an engine, the following basic assumption has been made in this project for the methodology development:

$$TN = MN + CEC + iMN$$

- TN Total engine noise
- MN Engine noise at motoring
- CEC Combustion excitation content of TN (combustion noise)
- iMN Further increase of above defined motoring noise (MN) by mechanical excitation due to combustion excitation (increase of motoring noise)

It has to be noted that this assumption / definition is arbitrary and could be made in some other way if required for such kind of project.

For the analysis of the 3 different components of total engine noise, the analysis of TN, MN and CEC is straight forward according to our assumptions. For the definition of the component iMN (which can be obtained by iMN = TN – MN - CEC) different additional analysis techniques were used to verify its contribution with respect to CEC. [8]

METHODOLOGY DEVELOPMENT FOR THE SPLIT OF MECHANICAL AND COMBUSTION EXCITATIONS

For the methodology development first tests were performed on a 4 cyl. diesel engine with 2 ltr. displacement. The work was started with an analysis of “mechanical noise” (mN), based on the methodology published in [1/2] which we named “conventional approach”. Here in a diesel engine the injection timing is varied to decrease and increase the combustion excitation. If the engine noise stays constant at decreasing combustion excitation this value is called “mechanical noise” (mN) and is assumed to stay constant over load for this speed condition (which is an approximation). However, this “mechanical noise” (mN) tends to lower values than the actual mechanical noise under real operating conditions since it is obtained at very low combustion excitation. Therefore, the calculated “combustion noise” cN (cN=TN-mN) is somewhat higher than the actual combustion noise under real operating conditions. This can be seen in Fig. 4, when comparing the combustion noise results of the coherence (assumed to be the actual combustion noise) and the conventional approach. The analysis using this conventional approach is very time consuming since for each engine speed operating condition the variation of injection timing is necessary and an “open ECU” is required as well.

In a next step the methodologies reported in [3/4/5] were analyzed. The regression approach is basically based on a regression analysis of cycle-to-cycle fluctuations in combustion excitation and engine airborne noise for each third octave band. Here the combustion excitation content (CEC) of TN can be determined quite simply from cylinder pressure and airborne noise analysis without changing combustion excitation at the different operating conditions.

In a final step the coherence approach reported in [6/7] was evaluated. Between the combustion excitation and airborne noise signal the coherence is computed. Again only a quite simple analysis process is required.

For the methodology to be reported, the coherence method was selected based on its performance potential and further developed and optimized. Among other aspects the time delay between combustion excitation and airborne noise as well as the signal duration over degree crankangle was investigated and optimized to obtain the most accurate CEC content of TN.

As an example, between the cylinder pressure signal and the air borne noise signal an average time delay of 5ms has to be considered quite independent of engine speed and load (see Fig. 1).

For obtaining CEC from measurements, all microphone signals around the engine (normally 4 in a semi anechoic chamber) and the combustion excitation in each cylinder is used. However, due to the quite good stability of the combustion excitation in Diesel engines, combustion signals of an arbitrary number of cylinders or even of one single cylinder gives sufficient accuracy if duplicated to represent the real ignition sequence.

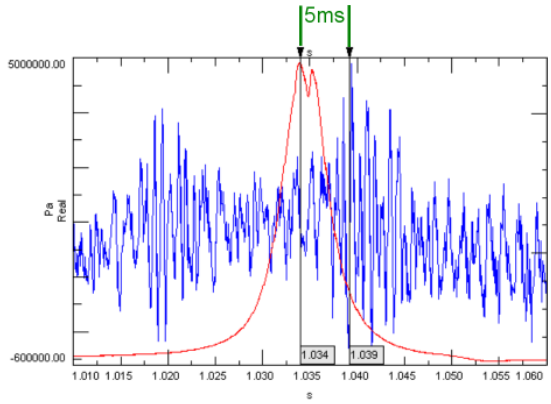

Fig. 1: Time signals of cylinder pressure (red) and air borne noise (blue); time delay 5ms

Before the coherence calculation can be started, some signal processing has to be done, to prepare the data. The coherence method is using only parts of the combustion excitation signal. These are floating time windows, centered to the combustion cylinder pressure peak. (see Fig.2) Several consecutive peaks are used for the analysis.

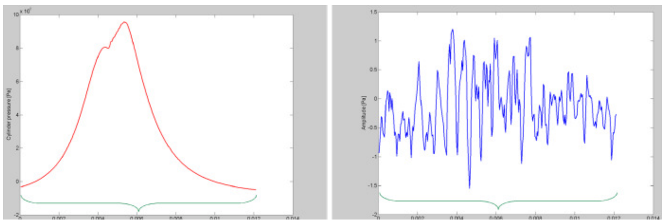

Fig. 2: Coherence method; input data: combustion (left), air borne noise (right); time delay already considered

An important step is the transformation of the signals from time domain to frequency domain. For this a window called “Tukey” has been proven to be the best compromise, (see Fig. 3), which allows to use a plateau with different lengths.

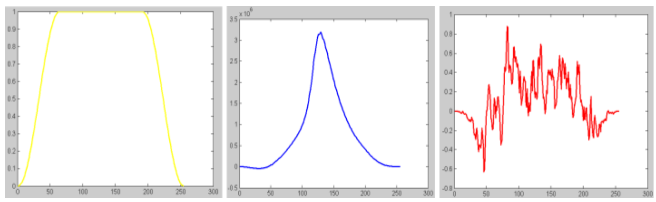

Fig. 3: Tukey FFT window (left-yellow), time signals after multiplying with the Tukey window: combustion (middle-blue), air borne noise answer (right-red)

Now, between the cylinder pressure and the air borne noise signal a magnitude squared coherence is computed using cross power spectrum density.

$$Cxy(f) = \frac{|Pxy|^2}{Pxx(f)\ Pyy(f)}$$

Cxy(f) coherence for the combination cylinder pressure – 1meter microphone
Pxy(f) mean crosspower of all relevant couples cylinder pressure - air borne noise answer
Pxx(f) mean autopower of all cylinder pressure signals
Pyy(f) mean autopower of all air borne noise signals

RESULTS OBTAINED WITH THE NEW METHODOLOGY

To present the performance of our coherence approach, some results for diesel- and gasoline engines are presented.

In Fig. 4 a comparison of results is shown as an example for a 2 ltr. diesel engine for the operating condition 2400 rpm, 50 % load. As can be seen, the "combustion noise" (cN) from the conventional approach and the CEC from the regression and the coherence approach with respect to TN is plotted against each other.

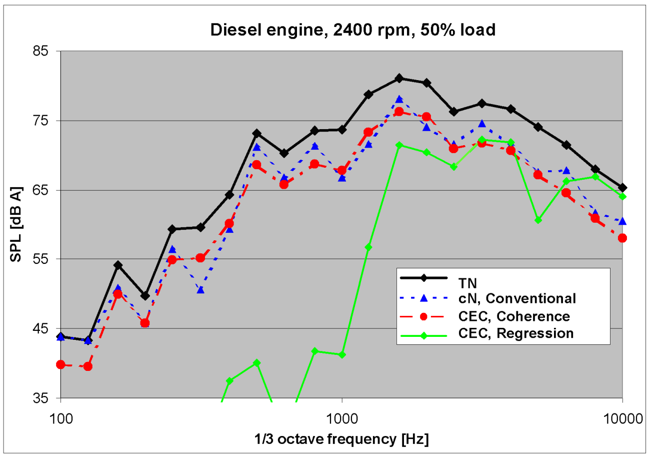

Fig. 4: Comparison of combustion excitation content of TN for conventional, coherence and regression approach.

As mentioned before for the conventional approach, the "combustion noise" (cN) is not directly obtained but is calculated via the "mechanical noise" (mN) and total airborne noise (TN) which yields a little higher "combustion noise" (cN) as actual present. Therefore these results obtained are only used for reference.

The results of the "conventional approach" and the coherence method show quite reasonable data, the regression results can not match the other results due to a flat slope of the regression line for the 1/3 octave bands at low frequencies up to 1 kHz (see Fig. 5). These flat slopes arise due to small fluctuations in combustion excitations of the diesel engine. For a gasoline engine the regression approach will produce better results as shown later in this publication since here the combustion fluctuations are normally larger.

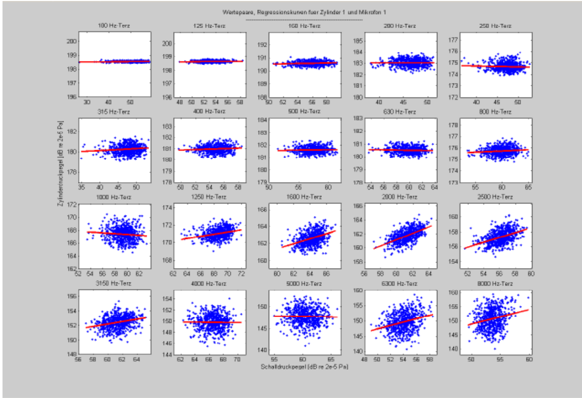

Fig. 5: Result of 1/3 octave regression analysis between CE and TN

In the following figures some results of a passenger car diesel and gasoline engine are shown by using our coherence approach. Fig. 6 shows the highest levels for combustion noise (CEC) at high frequencies. The derived increase of mechanical noise due to combustion (iMN) can be seen in the same magnitude as the mechanical noise (MN) above 1.5 kHz. This result is quite plausible since the impacts due to combustion of piston and cranktrain will yield a response of the structure in this frequency range.

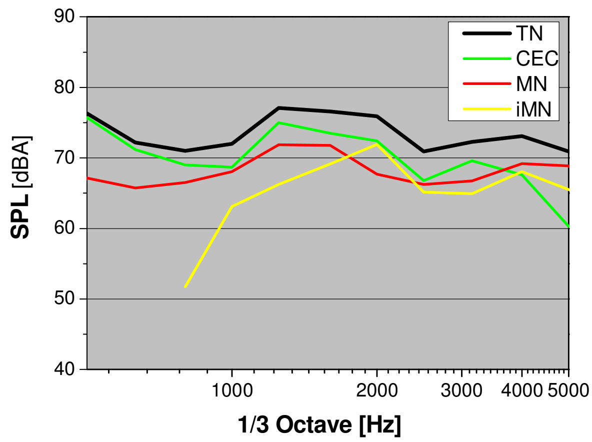

Fig. 6: Result for a 2 ltr. diesel engine at 2000 rpm and 50 % load

For a higher engine speed condition the level of combustion noise (CEC) is in the same range as the mechanical noise (MN) -Fig. 7. Due to this fact, the calculation of the increase of motoring noise due to combustion (iMN) produces only above 4 kHz useful results.

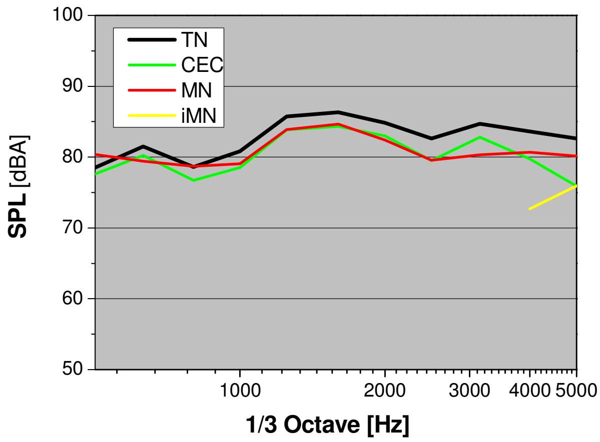

Fig. 7: Result for a 2 ltr. diesel engine at 4000 rpm and 50 % load

The coherence method was also applied on passenger car gasoline engines. Fig. 8 shows the results at 3000 rpm, 50 % and 100% load for a 1.8 ltr. gasoline engine.

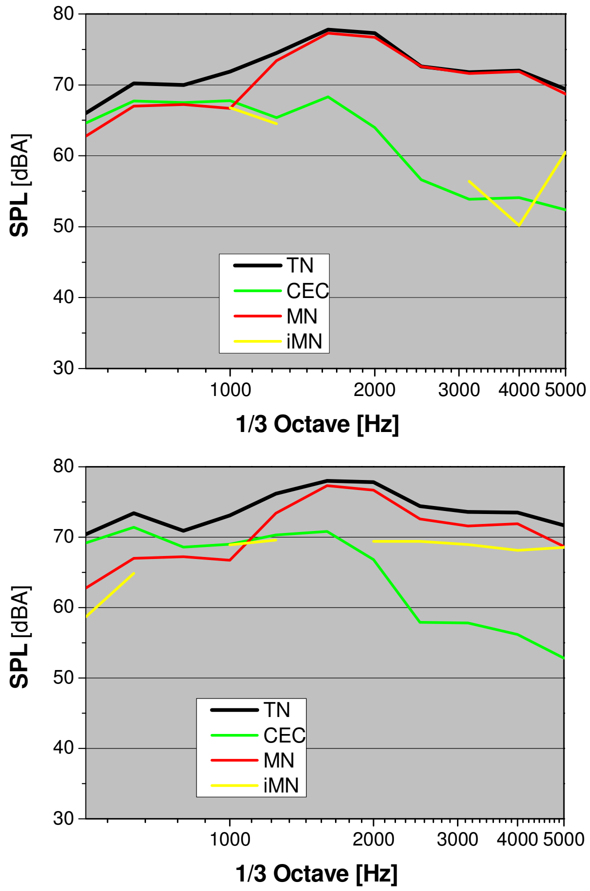

Fig. 8: Results of coherence method for a 1,8 ltr. gasoline engine, 3000rpm, 50% load (upper part), and 100%load (lower part)

From these results (Fig. 8) it can be seen, that up to 1200 Hz, combustion excitation content (CEC) of TN is dominating. Above 1,2 kHz, the TN is determined by the mechanical noise (MN) for both load conditions. However, it can be noticed, that at 100% load the derived increase of mechanical excitation due to combustion (iMN) is relevant over the frequency range, while at 50% this noise source is less important.

Fig. 9 shows a result at 5000 rpm and 100% load. Again, up to 1,3 kHz CEC is dominating the TN and above this frequency MN is determining the TN while the increase in mechanical excitation due to combustion (iMN) is increasing with frequency.

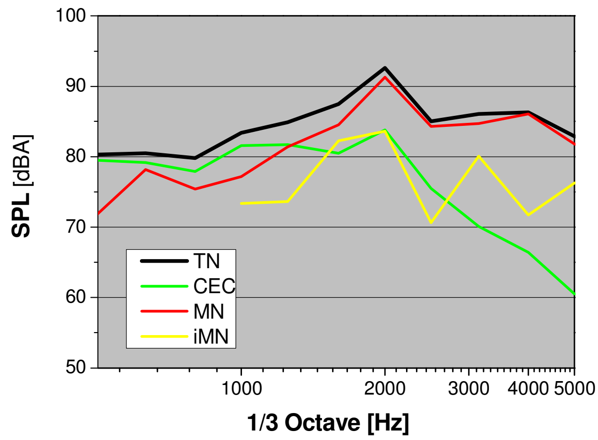

Fig. 9: Results of coherence method for a 1,8 ltr. gasoline engine, 5000rpm, 100%load

Cycle to cycle fluctuations of the cylinder pressure in gasoline engines allow also to apply the regression method, for obtaining quite useful results however only at higher frequencies. Thus, the coherence and the regression results are compared in Fig. 10 for the 1,8 liter gasoline engine.

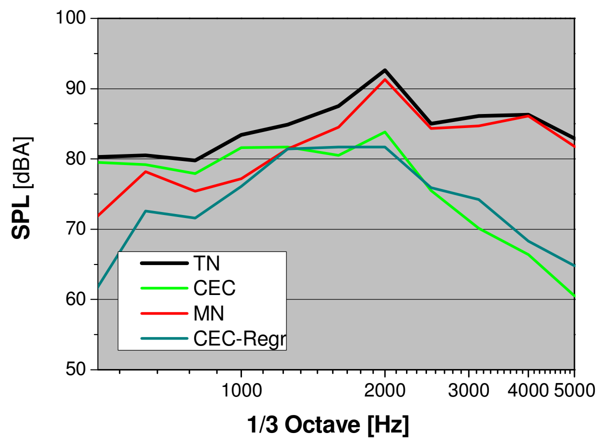

Fig. 10: Comparison of CEC values from regression method (dark cyan) and coherence analysis (green) for a gasoline engine at 5000rpm and 100%load

Fig. 10 shows that the CEC results of the two methods match one another quite well in the frequency range above about 1 kHz. In general, the results of the coherence method look more plausible than the ones of the regression method, because they tend to follow the TN in the lower frequency range. Nevertheless, it can be seen that contrary to the application on a diesel engine the regression method works better for gasoline engines in the higher frequency range. Further results of our coherence method for Diesel engines were published in [8].

All applications up to now show that the effort for the coherence approach is much smaller than the effort for the conventional one, since only microphone and cylinder pressure measurements are necessary, which are obtained in NVH work, anyway. Furthermore, no "open ECU" providing different combustion timings over a number of operating conditions is necessary.

VALIDATION OF THE COHERENCE APPROACH VIA STRUCTURE RESPONSE RESULTS

A validation of the coherence approach can also be performed by the structure response results of engines with respect to combustion excitation. This engine structure response is defined as

$$SR = CEC / CE$$

SR structure response of engine
CEC combustion excitation content of total engine noise (TN) obtained by the coherence approach
CE combustion excitation within cylinder

Basically, such an average ("reference") structural response of a number of Diesel engines is used in the Lucas and AVL Noise Meters [11, 12], for calculating an overall "reference" combustion noise in dBA using combustion excitation measurement inputs. However, the structure response shown in the following figures 11 and 12 are obtained from two specific engines. Therefore, they will not be the same as the ones used in the Combustion Noise Meters mentioned above.

If CEC is obtained via the reported coherence approach and divided by the measured combustion excitation CE (obtained via pressure transducer) the SR can be calculated.

As can be seen in Fig. 11 the SR of a 2 ltr. diesel engine is shown for different operating conditions. The spread scatter obtained is quite small despite a certain non-linearity of the transmission path between the combustion chamber (measurement of CE) and the airborne engine noise (TN) from which CEC is obtained. This result verifies as well the quality of the coherence approach developed with this project for the determination of CEC and iMN.

For a further validation, the structure response was analysed for a 1,9 liter passenger car Diesel engine.

As in Fig. 11, for different engine operating conditions, different levels of the structure response over the frequency range can be observed in Fig. 12. The differences are mainly again due to the non-linear behavior of the oil film between rotating and sliding engine parts, e.g. in the oil films of the crank train slider bearings and the oil film between piston and liner. The stiffness and damping characteristics of theses oil films are highly non-linear with speed and load effecting the noise and vibration transfer through the running engine. According experimental results have also been reported in [10].

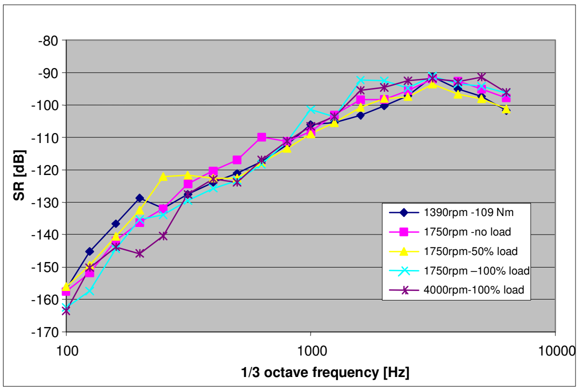

Fig. 11: Calculated structure response of a 2 ltr. diesel engine for different operating conditions using CEC

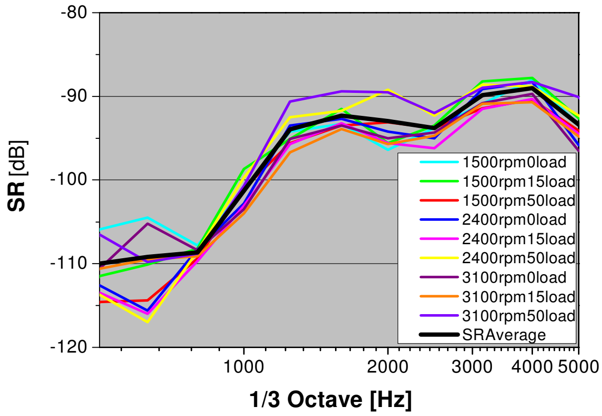

Fig. 12: Calculated structure response of a 1,9 ltr. diesel engine for different operating conditions using CEC

Simulation results of surface noise of other engines by means of FEM + MBD (combined finite element method and multi-body dynamics) [9], showed as well the effect of the non-linear transfer behavior on structure response. According to other results obtained [10], a scatter band of simulated SR values due to non-linearity of up to 5-10 dB can be expected.

CONCLUSIONS

In the work reported, a methodology / software tool was developed for the detailed analysis of engine mechanical and combustion excitation contents of total engine noise. The methodology has been developed and verified on gasoline- as well as on diesel engines. Out of this methodology a software tool has been designed for application in engine noise reduction and noise quality optimization work.

The benefits of this new software tool are good accuracy, very little analysis effort and good separation of the different excitation phenomena. This software tool can therefore be applied to separate very fast and accurately the contributions of mechanical and combustion noise as well as for the evaluation of the engine structure response out of microphone and combustion excitation signals only at any engine operating condition. No open ECU for modifications of combustion excitation at different operating conditions is required any more.

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APPENDIX

TN	Total engine noise
CE	Combustion excitation within cylinder
CEC	Combustion excitation content of total engine noise (TN)
MN	Engine noise at motoring
iMN	Increase of motoring noise (MN) by mechanical excitation due to combustion excitation (CEC)
mN	“Mechanical noise” according to conventional methodology [1/2]
cN	“Combustion noise” according to conventional methodology [1/2]
SR	Structure response of engine

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