# ANALYSIS OF THE TIME STRUCTURE OF GEAR RATTLE

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## INTRODUCTION

The sound of a vehicle is composed of a variety of different components. Besides the major contributors such as engine, wind and tire noises several other sources might contribute to the overall audible sound, and thus influence the overall Sound Quality impression of the vehicle.

One of these specific noise components is gear rattle. This is a noise which is produced by the gear, and which might be audible in specific driving conditions in the interior of the vehicle. Once it is detected, this gear rattle can reduce the overall Sound Quality impression significantly, or it can even be associated to a technical defect.

It has been shown in a previous paper [1] that spectral cues can be used to analyse and quantify gear rattle for vehicles with a diesel engine. A new spectral metric has been developed which allows to predict the rating of gear rattle from an artificial head recording of the interior vehicle noise in a defined driving condition. But, a closer look to the characteristics of gear rattle shows that besides spectral cues also the time structure of the sound carries perceptual relevant information. In this paper a new method to analyse gear rattle and to predict the rating of subjects will be presented which is based on an analysis of the time structure.

## GEAR RATTLE

Gear rattle is a phenomenon which is not constantly audible in the interior vehicle sound, but which can be detected in specific driving conditions. In [1] we have defined a driving condition that is typcial for a situation in which a customer might detect the gear rattle. This driving condition is depicted in the top of Fig. 1 and consists of two phases, representing a stop and go situation of a traffic jam. In the first phase the car is creeping in the 2nd gear driving with constant speed at low rpm with the clutch engaged. In the second phase the driver disengages the clutch, so that the car is slowly decelerating at about the same rpm. Gear rattle can only occur in the first phase, since in the second one the complete gear system is not connected to the engine. The driver of the vehicle thus can perform a direct comparison of the situations with gear rattle and without gear rattle. Since the human auditory system is very sensitive to changes in sounds the attention of a listener is automatically focussed towards the gear rattle in this situation.

It has been shown in [1] that spectral cues represent important perceptually relevant information to describe the gear rattle. Since the driving condition defined above allows for a direct comparison of the two phases, the newly developed spectral metric also takes the spectral

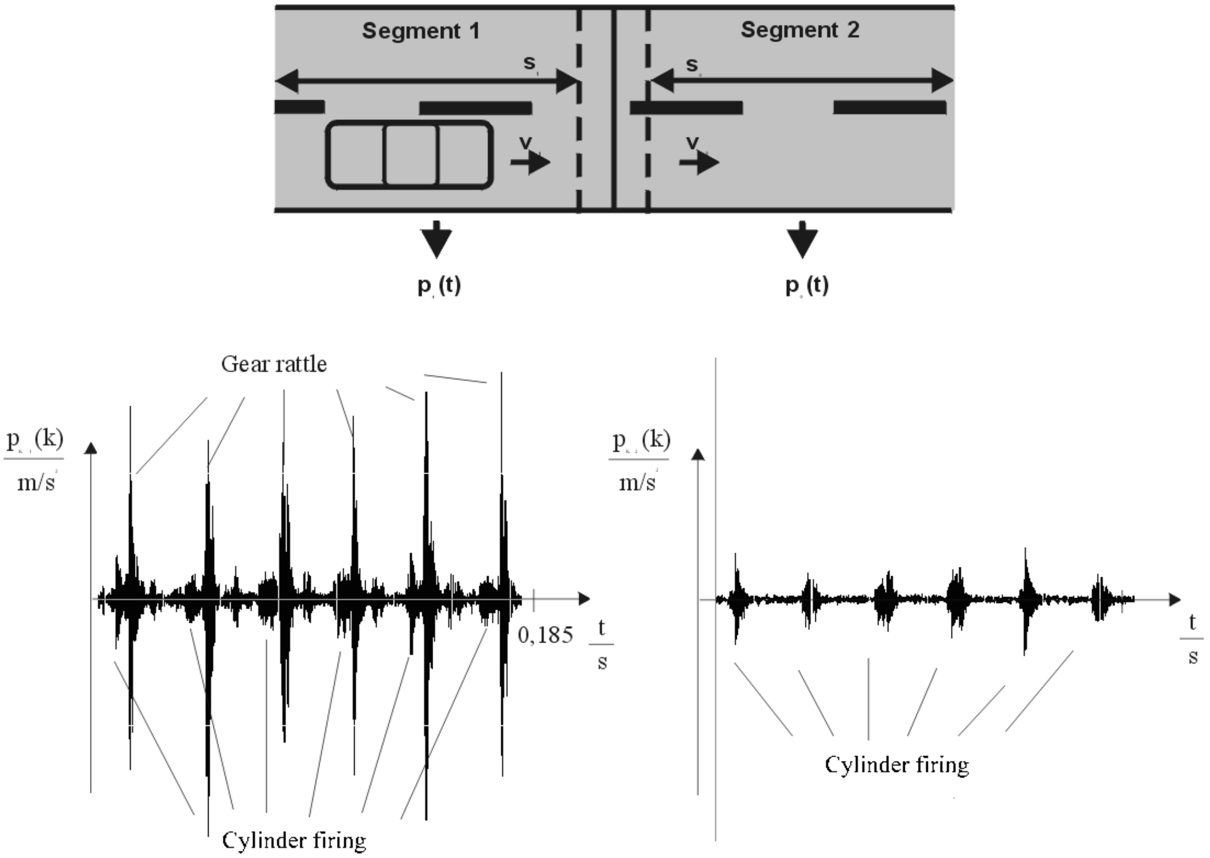

**Fig. 1** Schematic representation of the driving condition to investigate gear rattle (top) and the corresponding structure-borne noises recorded at the surface of the gear system (bottom). Gear rattle can only occur in segment 1 where the clutch is engaged.

differences of the two phases into account. But, a comparison of the time signals of the two phases as depicted in the bottom of Fig. 1 indicates that also the time structure carries important information. In this graph the stucture-borne noise measured at the surface of the gear system is depicted for both driving conditions, clutch engaged and clutch disengaged.

It can be seen that without gear rattle (right graph) peaks occur which are caused by the subsequent firing of each cylinder (4-cyl. engine). With gear rattle (left graph) additional strong peaks are present, which occur with a short delay after the firing of the cylinders. Despite of spectral changes the time structure thus is significantly changed by the gear rattle. This difference between the two situations is very clear for the structure-borne noise presented in the figure, but less obvious in the air-borne noise which is recorded in the interior of the vehicle. Nevertheless, differences can be observed in air-borne noise, too. An appropriate method to quantify changes in the time structure is a modulation analysis which will be presented in the following chapter.

## MODULATION ANALYSIS

A powerful method to analyse the time structure of signals is a modulation analysis, in which the envelope of a signal is investigated. If this envelope shows a periodic behaviour, the signal is modulated with the frequency corresponding to this period. The modulation analysis can either be applied to the envelope of the time signal to determine overall modulation, or to the envelope of bandfiltered signals to determine the modulation as a function of carrier frequency.

For the application presented here modulation is calculated from the spectrogram of the signal. The spectrogram is calculated as a series of subsequent spectra as follows:

$$P(n, l) = \frac{1}{N}\sum_{k = l \cdot N \cdot (1-o)}^{l \cdot N \cdot (1-o) + N - 1} p(k) \cdot e^{-j2\pi\frac{k \cdot n}{N}} \cdot w(k - l \cdot N(1-o)) , \qquad \textbf{(1)}$$

with
$p(k)$: time signal at sample k
$N$: FFT-length
$n$: frequency index
$o$: Overlap between subsequent frames
$l$: index for spectrum no. (time index, $l = 1...L$)
$w$: weighting function (Hamming)

Each frequency index in the spectrogram now represents the behaviour of the envelope at the corresponding carrier frequency. The modulation spectrum $P_m(n, m)$ is thus calculated here by means of applying FFTs to the time series of the absolute values of $P(n, l)$ at each frequency index:

$$P_m(n, m) = \frac{1}{M}\sum_{l = 0}^{M-1} |P((n, l) \cdot w(l))| \cdot e^{-j2\pi\frac{k \cdot m}{M}} , \qquad \textbf{(2)}$$

with
$m$: modulation frequency index,
$M$: FFT-length of FFTs applied to each frequency index n, $M \le L$

and the modulation index $P_{mi}(n, m)$ is calculated by normalization:

$$P_{mi}(n, m) = \frac{P_m(n, m)}{P_m(n, 0)} . \qquad \textbf{(3)}$$

The resolution $\Delta f_m$ of the modulation frequency then is

$$\Delta f_m = \frac{1}{T_l} = \frac{f_s}{N \cdot (1-o) \cdot M} . \qquad \textbf{(4)}$$

Besides the sampling frequency $f_s$ the resolution with regard to the modulation frequency thus depends on the FFT length *N* and the overlap *o* of frames. As a consequence the maximal modulation frequency $f_{m, max}$ which is analyzed is

$$f_{m, max} = \Delta f_m \cdot M = \frac{f_s}{N \cdot (1-o)} . \qquad \textbf{(5)}$$

The modulation index of an interior vehicle noise with gear rattle is shown in the top graph of Fig. 2. The Modulation Index represents complete information including which carrier frequency is modulated with which frequency. If we take a look at this modulation representation of a gear rattle signal we can see that information can be presented in a more condensed way. It can be seen that vertical lines occur in the modulation spectrum, meaning that carrier frequencies are modulated with the same frequency. But, it can also be seen that not all carrier frequencies are modulated, but that mainly frequencies above a lower cutoff frequency (around 500 Hz) and below an upper cutoff frequency (about 7 kHz) are modulated. This corresponds well to the findings concerning the spectral cues of gear rattle, which showed that the rattle contributions are in the range between 500 Hz and 5 to 7 kHz. Thus we define the average modulation index $\bar{P}_{mi}(m)$ as the average of the modulation index within a limited frequency range:

$$\bar{P}_{mi}(m) = \frac{1}{n_o - n_u} \sum_{n = n_u}^{n_o} P_{mi}(n, m) \quad . \tag{6}$$

The average modulation index is dipicted in the middle graph of Fig. 2. Clear peaks occur at modulation frequencies which are at multiples of the half of the engine order, while in between no significant modulation can be observed. The average modulation index can thus be simplified by just selecting modulation frequencies which correspond to multiples of the half engine order.

The modulation frequency index $m_{eo}$ corresponding to the engine order is

$$m_{eo} = \frac{f_{eo}}{\Delta f_m} = \frac{rpm}{60} \cdot \frac{N \cdot (1 - o)}{f_s \cdot M} \quad . \tag{7}$$

The resulting average engine order modulation index is depicted in the bottom graph of Fig. 2 for both conditions, clutch engaged and clutch disengaged.

The figure shows the typical behaviour of the modulation at the different engine orders. When gear rattle is present modulation increases at the second engine order, remains constant at the 4th engine order, and decreases at all other orders. Since the specified driving condition allows for the direct comparison of the conditions with and without gear rattle, we can also define the difference of the average engine order modulation indices of these two conditions:

$$\Delta\bar{P}_{mi}(m_j) = \bar{P}_{mi,1}(m_j) - \bar{P}_{mi,2}(m_j) \quad , \tag{8}$$

with $j$ being multiples of half of the engine order. Based on the above described behaviour of the modulation with frequencies corresponding to engine orders the Diesel Rattle Modulation Index *DRMI* is defined as:

$$DRMI = \Delta\bar{P}_{mi}(m_2) - \sum_{j = 0.5}^{4} \Delta\bar{P}_{mi}(m_j) \, ; \; j \neq 2 \quad . \tag{9}$$

Using this *DRMI* an instrumental method to predict the gear rattle evaluation has been defined. Like for the spectral metric, polynominal fits were calculated, and the least squares method was applied to identify the optimal degree and the corresponding coefficients. The best correlation was found for a 2nd order polynom, so that the predicted evaluation $E_{DRMI}$ is calculated from the *DRMI* as follows:

$$E_{DRMI} = a_m \cdot DRMI^2 + b_m \cdot DRMI + c_m \tag{10}$$

with $a_m$, $b_m$, and $c_m$ being the coefficients determined by the polynominal fit. Fig. 3 shows the predicted evaluation versus the evaluation of subjects for a rating of 19 different vehicles. The correlation between the ratings is 0.95.

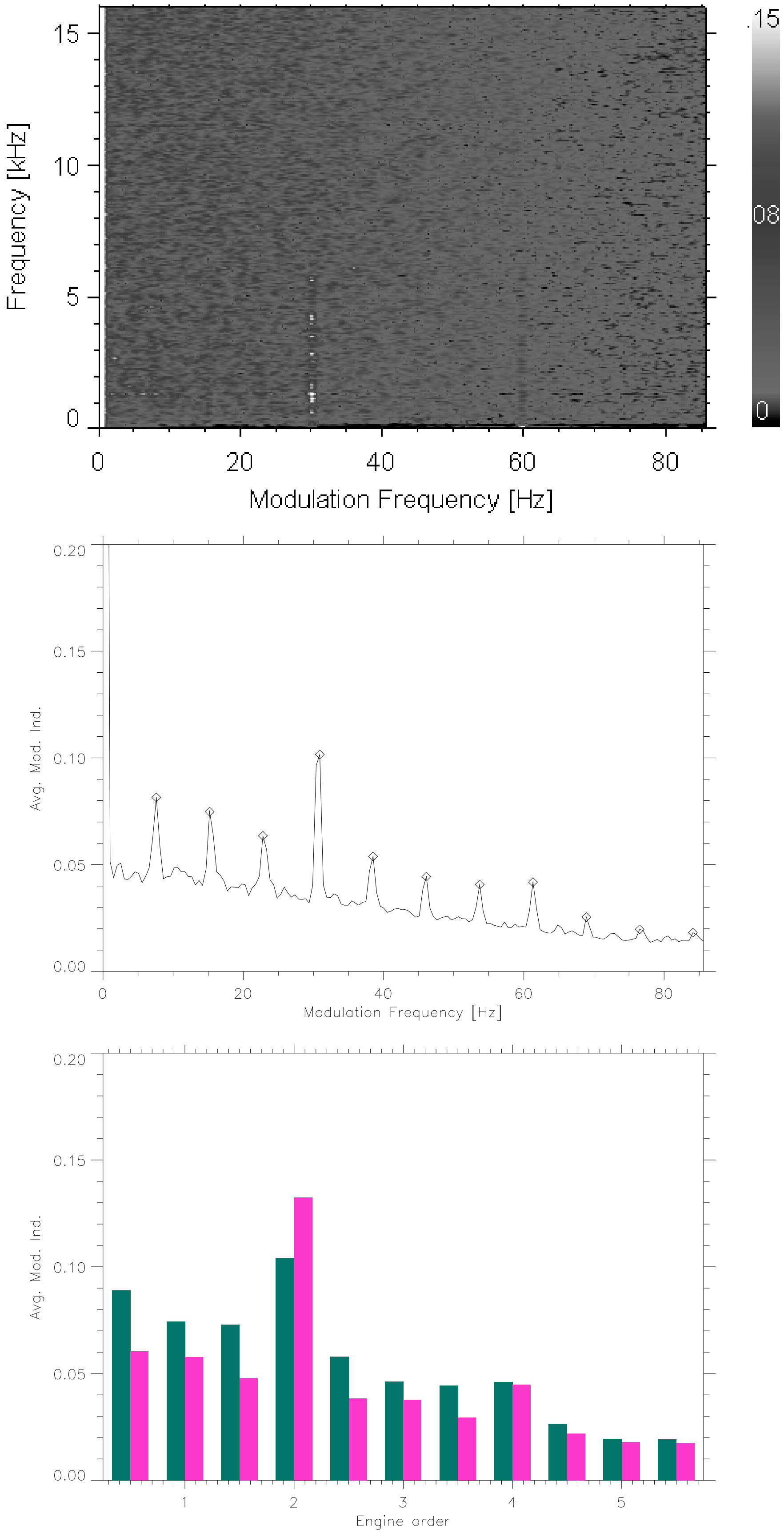

**Fig. 2** Modulation analysis of an interior vehicle noise with diesel engine and gear rattle. Top: Modulation Index; Middle: Average Modulation Index; Bottom: Average Engine Order Modulation Index (dark: no gear rattle; light: with gear rattle).

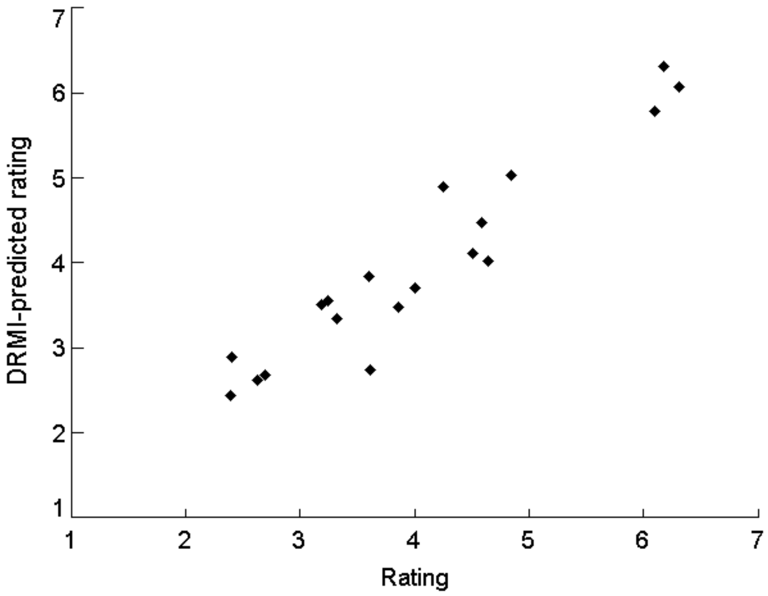

**Fig. 3** Predicted rating versus subjects rating of the gear rattle of 19 vehilces

## SUMMARY

A new instrumental method to predict the rating of gear rattle from an artificial head recording of the interior vehicle sound in a defined and representative driving condition is presented in this paper. The method is based on an evaluation of specific cues in the time structure of the noise. Using this method, a correlation of 0.95 between predicted ratings and ratings of subjects was achieved. This correlation is slightly higher than the one achieved with the spectral metric proposed in [1], where a value of 0.92 was observed. Since these two methods evaluate different sound characteristics, it can be expected that their combination will guarantee a very accurate and robust prediction of the sound quality of gear rattle.

## REFERENCES

1. „*Perceptual and instrumental description of the gear-rattle phenomenon,*“ R. Heinrichs, M. Bodden, Proc. Int. Congress on Sound and Vibration, Copenhagen, Denmark, 3103-3112.