# TIME FREQUENCY ANALYSIS
# OF TRANSIENT NVH PHENOMENA IN VEHICLES

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SUMMARY: The NVH (Noise, Vibration, Harshness) development of modern passenger vehicles requires the optimization of all sounds, which are perceivable by customers. Especially the sound design of door closing sound, seat adjusters and electronic direction indicators require the application of high sophisticated analysis tools. The standard Fourier Transformation (FT) is not suitable for the analysis of those transient sounds as the signal content is changing too rapidly. Alternative methods like Short-Time Fourier Transformation (STFT) or wavelet analysis are better suited. These methods require a higher degree of sophistication by the users. In addition special considerations with to regard to the setting of objectives during the NVH development process are to be taken into account. This paper summarizes the basic ideas of these alternative methods. For the example of door closing sounds the potential of these methods as well as the importance of the documentation of the selected analysis parameters are presented.

## INTRODUCTION

The Fourier Transformation (FT) as standard method for signal analysis is not suitable to analyse transient signal as the time information is lost during the transformation process.

The aim of this paper is to summarize the theory of methods for time-frequency analysis like Short-Time Fourier Transformation as well as for Wavelet Transformation. These methods are suitable to analyse transient NVH phenomena in vehicles. In this paper door closure sounds are investigated as an example.

As part of a benchmarking project door closing sounds of nine different saloon cars from five different manufacturers were recorded and analysed. The recording of the sounds were made in the showrooms of the dealers, which already lead according to their different reverberation properties to different subjective quality impressions of sound events.

The focus is set on the application of these methods to practical examples as well as the potential usage and risks for the target setting process during a vehicle development program.

## THEORY

*Short-Time Fourier Transformation:* Many signals are non-stationary; they contain for example impulses or recent changes of the frequency content. For the analysis of these characteristics the Short-Time Fourier Transformation (STFT) is used in order to overcome the lack of information on the time scale from the standard Fourier Transformation [2], [3]. In principle the signal is analysed in narrow windows with the assumption that the signal is stationary within this window. The mathematical formulation of the STFT is expressed as follows:

$$\underline{X}(\omega,\tau) = \int_{-\infty}^{\infty} x(t)w(t-\tau)e^{-j\omega t}\mathrm{d}t, \qquad (1)$$

where, $\underline{X}(\omega,\tau)$ is the Fourier Transformation. The localised window function $w(t-\tau)$ is shifted over the time signal $x(t)$ to divide it into consecutive parts. A Fourier Transformation is performed for each windowed part of the signal. The window function and an overlap can be selected in the same manner as for the standard Fourier Transformation. These individual spectra are plotted in a three-dimensional plot as a function of time and frequency. Alternatively the squared magnitude $\left|\underline{X}(\omega,\tau)\right|^2$ is plotted as the so-called periodogram or spectrogram, which roughly shows the energy distribution over time and frequency [2].

The main issue with the STFT is the fixed ratio between the time and the frequency resolution. An increase in the frequency resolution leads simultaneously to a deterioration in the time resolution. The STFT provides some information on time location as well as on the frequency content, but only in time intervals and frequency bands. There is always the problem to find the best compromise by selection of the suitable window length as the sampling frequency is usually already fixed during the recording of the signals. In case of well separated frequency components in the signal, which is to be analysed, it is possible to sacrifice some frequency resolution for a better time resolution by means of a smaller window, since the spectral components are already well separated. If the focus is on the frequency identification, it is necessary to lose some time information by means of a larger window size. Another feature of the STFT is that the chosen time window length is constant and applied to the complete signal. Hence, all frequencies all analysed with the same window and with the same compromise between time and frequency resolution. In many cases the signals require a more flexible approach, where a variation in the window size is possible in order to determine more accurately either time or frequency. This flexibility is provided by Multi-Resolution Analysis (MRA) [3].

*Wavelet Transformation:* The basic characteristic of MRA is that different frequencies are analysed with different time windows. The MRA provides at high frequencies good time resolution at the expense of a reduced frequency resolution. On the other hand, a good frequency resolution is provided at low frequencies at the expense of a worse time resolution. This limitation is acceptable because low frequency phenomena change only slowly in time. Therefore, a good resolution in time domain can be sacrificed for a high frequency resolution. Conversely, high frequency phenomena change more rapidly with time. Thus, the time becomes the more important dimension. The MRA increases the time resolution at the expense of a reduced resolution in the frequency domain under these conditions.

The Wavelet Transformation (WT) is a form of MRA, which is well suited for the analysis of non-stationary signal. The so-called Continuous Wavelet Transformation (CWT) is defined as [1], [2]:

$$C(s,\tau)=\frac{1}{\sqrt{|s|}}\int_{-\infty}^{\infty}x(t)\psi\left(\frac{\tau-t}{s}\right)\mathrm{d}t. \qquad (2)$$

The Wavelet coefficient $C(s,\tau)$ is a function of a scale parameter $s$ and the shifting parameter $\tau$. This shifting parameter $\tau$ can be seen in the same way as in the STFT and hence represents the time location of the analysed time window. However, instead of a frequency there is a scale factor $s$, which is proportional to the inverse of the frequency $f$:

$$s\sim\frac{1}{f}. \qquad (3)$$

The weighting function $\psi(\frac{\tau-t}{s})$ is the so-called mother wavelet. This function has only mild conditions to meet: it has to be ensured that the mother wavelet has zero mean and it should also have finite energy [1]. In general an infinite number of wavelet function can be constructed artificially as mother wavelets. This mother wavelet is use as a prototype wave and by application of the scaling factor several scaled windows are generated and applied during the Wavelet Transformation. The dilation of the mother wavelet is determined by the scaling factor $s$. Scaling simply means that the mother wavelet is stretched, $s > 1$, or compressed, $s < 1$. Higher scale parameters correspond to stretched wavelets. Simultaneously the portion of the analysed signal window becomes longer. Thus, lower frequency components are analysed with a wider time window. This is realised by a compression of the wavelet with lower scale parameters. Therefore, high frequencies are analysed in a narrow window. In the same way as the Fourier Transformation represents the original signal as a sum of constituent sinusoidal components, the CWT yields the constituent wavelets of the original signal. Usually, the squared modulus $|C(s,\tau)|^2$ is plotted in the so-called scalogram [1].

As the parameter $s$ and $\tau$ can continuously take any value the transformation is called the CWT. With digital signal processing the user can prescribe the values of these parameters with a selectable resolution. As the calculation (2) has to be conducted for each parameter set of $s$ and $\tau$, the CWT requires a large amount of computation time. Alternatively the value of $s$ can be prescribed by values as a power of 2. This leads to an efficient algorithm, which has been proposed by Mallard in 1988. This scheme is known as Discrete Wavelet Transformation (DWT).

An alternative explanation of the DWT is the application of complementary high and low pass filters [3]. In summary the DWT is more efficient than the CWT, but loses some detail of the CWT. Both, CWT and DWT, operate of the digitised time signal, however, the CWT uses a nearly continuous range of scales, whereas the DWT operates with discontinuous frequency bands where the level of discontinuity is defined by the number of filtering operations applied. In the following analysis the DWT was applied.

## RESULTS

As an example for the time-frequency analysis of transient NVH phenomena in vehicles in this section door closing sounds are analysed. The importance of the first acoustical impression of a customer to a vehicle of his interest prior to his buying decision is to be emphasized. In most cases the door closing sound in the showroom is the first perceived noise.

The analysis of door closing sound is reported in several papers [5], [6]. An example of the time signal of a door closing sound is shown in Figure 1. The sounds start with a first impact, which is caused by the contact of the latch to the striker. This impact excites a number of vibrating systems and components in the vehicle. Examples are the rattle of the springs in the latch, the mechanical resonances of the door panels, the first torsional modes of the body structure and acoustic resonances of the air cavity in the vehicle interior.

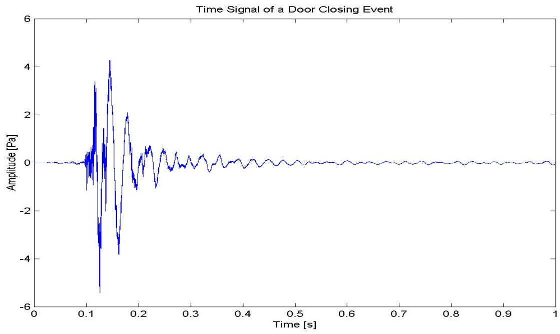

Figure 1:Time signal of a vehicle door closing sound

Each of these systems may have a different damping and hence a different time duration. Typically they last longer than the first initial impact. However, the duration of the entire event of door slam lasts only around half a second. In order to understand the complex nature of the door closing sound, an analysis of the measured sound pressure signal by means of Time-Frequency-Analysis is necessary.

*Short-Time Fourier Transformation of a Door Closing Event:* The results of a STFT analysis of a door closing sound is shown in Figure 2. The parameter for the STFT was selected with a window length $T_w$ of 0.1 seconds, which leads to a frequency resolution $\Delta f$ of 10 Hz. There has been no additional weighting function applied to the time windows. The abscissa axis of the colourmap shows the time in seconds, the ordinate axis the frequency in Hz and the colour stains represent the amplitude value of the Sound Pressure Level (SPL) in dB defined by the colourbar.

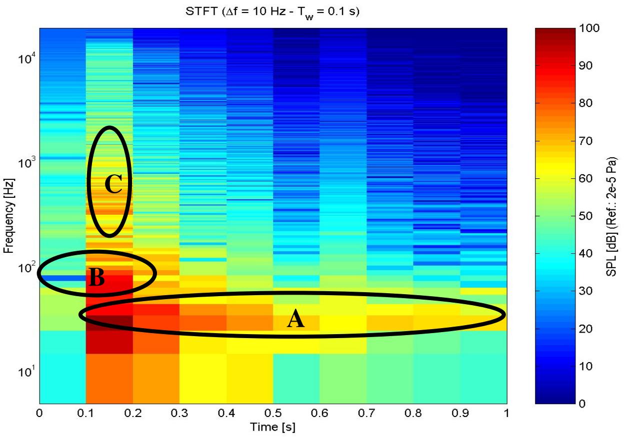

Figure 2: Short-Time Fourier Transformation of a vehicle door closing sound

The range around 30-40 Hz, indicated with mark A, is possibly caused by the excitation of the first torsional mode of the body structure or one of the first acoustical modes of the air cavity in the vehicle interior. Mark B indicates the range around 60-70 Hz, which is probably the first resonance frequency of the door panel. The very broad frequency range marked by C is likely to be caused by the first initial impact at the beginning of the door closing event. It has stated that the pattern shown in figure 2 is similar for all recorded sounds although the sounds are subjectively perceived with quite different sound qualities.

*Wavelet Analysis of a Door Closing Event:* The results of a Discrete Wavelet Transformation (DWT) of the same door slam, which was analysed above, is illustrated in Figure 3.

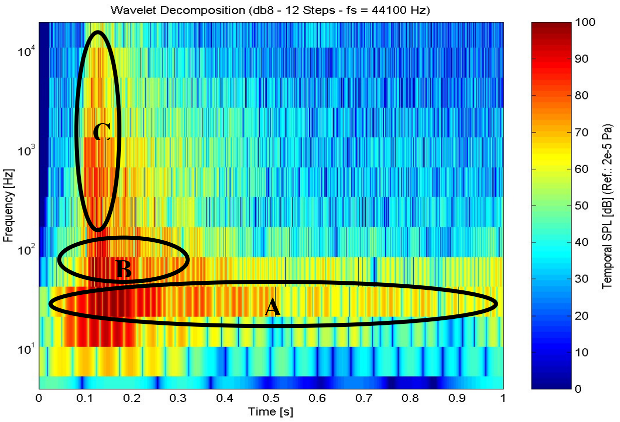

Figure 3: Discrete Wavelet Transformation of a vehicle door closing sound

The original time signal of the door slam was recorded with a sampling frequency of 44100 Hz. The wavelet analysis was conducted by application of the 'db8' wavelet in 12 decomposition, or filtering, steps. Figure 3 shows the same typical time-frequency characteristic of a door slam in form of a foot plus toe [5], [6] as in Figure 2. Nevertheless the DWT representation has the clear advantage that the time resolution is increasing versus higher frequencies. It is now possible to distinguish the low frequency content, marked with A, better from the one of the door panel, indicated with mark B, although only 12 decomposition steps have been used. In addition the frequency content above 500 Hz can be clearly much better resolved in time, see mark C.

For a similar result with the STFT at least two colourmaps are required. Thus, the DWT provides a more compact time-frequency representation of transient signals.

*Comparison between the Objective and Subjective Evaluation:* The sections above show that the Wavelet Analysis reveals the details of the frequency content of the transient signal more clearly than the Short-Time Fourier Transformation. In this section a comparison is made between the objective analysis of two door closing sounds and the subjective evaluation by customers.

In a subjective evaluation vehicle A receives a higher rating of customer satisfaction than vehicle B.

Vehicle A subjectively offers a very compact sound with a short duration. It sounds tremendously dark, which is determined by a low frequency content. This type of sound is associated with upper class vehicles and a high expectation of quality by the customer. Oppositely, the door slam of vehicle B sounds more tinny and light. It has a high frequency content, which lasts quite long. The subjective perception allocates this sound to a low-budget vehicle with a lower level of quality than vehicle A. It has to be remarked that both cars were measured in different show rooms of different dealers. Hence in both cases there were different reverberation times in the showrooms. This has an additional effect on the subjective perception and evaluation of the door closing events.

Figure 4 illustrates the results of the signal decomposition by application of the DWT. The comparison of the two colourmaps clearly shows differences between the two sounds. For vehicle A the high frequency content is limited to a short duration time and in the low frequency range the contribution is reducing slowly.

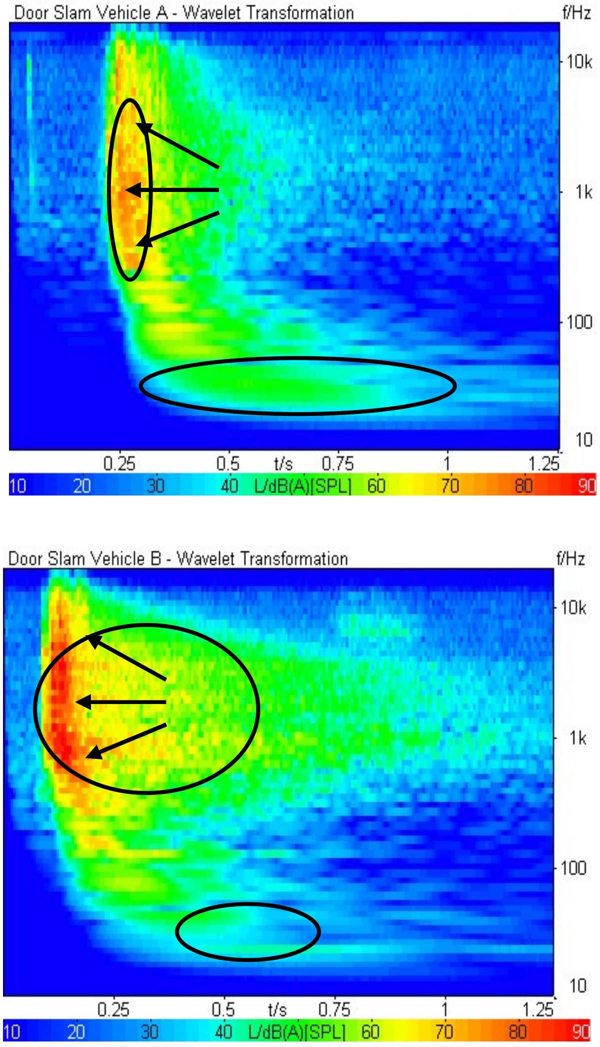

Figure 4: DWT of vehicle A and vehicle B door closure Sounds

Vehicle B shows instead higher sound pressure levels in the high frequency range. In addition these frequencies are occurring for a much longer time. This high frequency content is responsible for the more tinny character of the vehicle B sound and a graphic visualisation of the subjective perception of the reverberation. The solidity of the sound of vehicle A, which is caused by the content in the low frequency range, is not found in this frequency range for vehicle B.

In the vehicle development process the setting of objectives is meanwhile widely used in order to optimise the NVH performance of vehicles and their components. In Figure 5 a possible strategy for target setting of door closing sounds is shown [5].

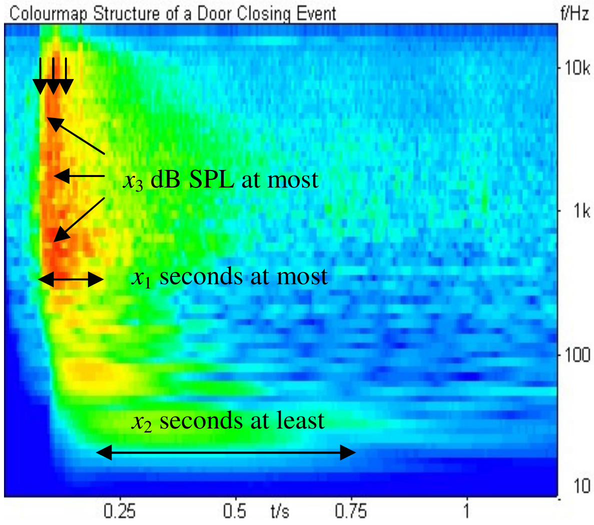

Figure 5: Target setting for door closing sounds

The duration of the impulse at the frequency range above 500 Hz could be defined by a maximum limit of $x_1$ seconds. In the same manner the duration of the pulse in the low frequency range around 50 Hz could be defined with a minimum duration of at least $x_2$ seconds. A sound pressure level of $x_3$ dB would limit the maximum level, which could be allowed in the frequency range above 500 Hz. The exact values need to be developed by a benchmarking process.

Nevertheless these target values need to be accompanied by an exact definition of the analysis parameters of the DWT. Figure 6 shows the same door closure sound analysed by DWT with slightly modified parameters.

These analyses are conducted with a commercially available tool, which is widely used in the automotive industry. The wavelet analysis is realized by application of a number of band-pass filters to the signal. In order to ease the usage of the wavelet analysis for the user only a few parameters for setting of the band-pass filters need to be set. In this case the wavelet decomposition has

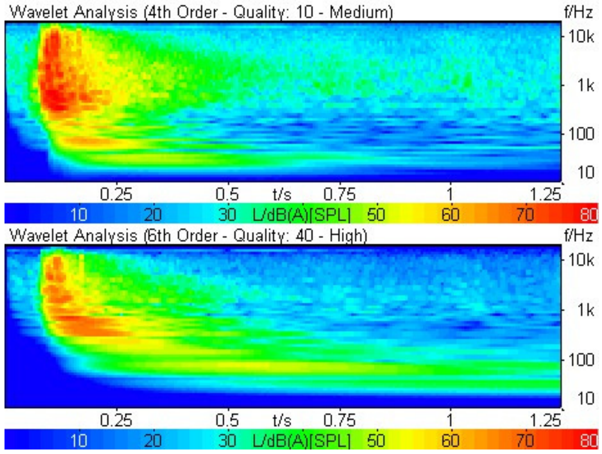

Figure 6: DWT of one door closure sound analysed with modified filter parameters

been conducted with a Butterworth filter type, but different orders. An increase in filter orders coincides with an improved steepness of the filter characteristics. The quality of the filter, the so-called Q-factor, describes the width of the pass-band of the filters. The number of filters applied to the signal is controlled via the resolution parameter. In this case “Medium” and “High” were selected. In general there is no recommendation for an optimal combination meaningful.

Figure 6 clearly reveals that the setting of the analysis parameters is a major contributor to the pictures of the colourmaps and not only the signal content. With regard to the application of the DWT in a target setting process each target value out of a DWT colourmap would need to be accompanied by an exact definition of the analysis parameters. Experiences from the daily business show that in most cases the boundary conditions for target values are often omitted. In case of the need for the comparison of analysis results obtained on one hand for one vehicle from source A, e.g. a vehicle OEM, and on the other hand, for another vehicle from source B, say an engineering consultant, there is a high risk, that the analysis algorithms used and/or the analysis parameters were set different. This may lead to completely wrong interpretations of analysis results as shown above. Finally it has to be stated that the same risk applied to the standard FFT. As long as just the approximate frequency content is the matter of interest the risk of creating false results is a bit lower than with the wavelet analysis.

## DISCUSSION AND CONCLUSIONS

For the analysis of transient signals like door closure sounds the usual Fourier transformation (FT) is not suitable. The time content of the signal is lost during the transformation process. As an alternative the Short-Time Fourier Transformation (STFT) is offering the potential to analyse signals by consecutive application of FT, so that the frequency spectrum can be allocated to a time. However, the drawback of the STFT is that the ratio between time and frequency resolution is fixed across the whole frequency range. A Multi-Resolution Analysis like the Wavelet Transformation (WT) offers the ability to analyse a signal in time and frequency with a variation in time and frequency resolution.

Beside an overview on the theory of both methods, STFT and WT have been applied to the practical example of door closure sounds. The Wavelet Analysis offers more details, which coincide with the subjective perception of these sounds by the customer.

Additionally it has been shown, that the usage of parameters of a Wavelet Analysis for target setting in the vehicle development process need to be accompanied by a clear and well defined documentation of the analysis parameters.

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