



This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



CC creative commons
COMMONS DEED

Attribution-NonCommercial-NoDerivs 2.5

You are free:

- to copy, distribute, display, and perform the work

Under the following conditions:

BY: **Attribution.** You must attribute the work in the manner specified by the author or licensor.

Noncommercial. You may not use this work for commercial purposes.

No Derivative Works. You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

Your fair use and other rights are in no way affected by the above.

This is a human-readable summary of the [Legal Code \(the full license\)](#).

[Disclaimer](#) 

For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

WAVELET ANALYSIS OF VEHICLE DOOR CLOSURE SOUNDS

J Niermann Vehicle Engineering, University of Applied Sciences, Cologne, Germany
S J Walsh Dept. of Aeronautical and Automotive Engineering, Loughborough University, U K
K Becker Vehicle Engineering, University of Applied Sciences, Cologne, Germany

1 INTRODUCTION

The good impression of sound quality has a large impact on the subjective feeling a potential customer gets from a vehicle. The sound quality of a vehicle is the composition of many kinds of noises, for instance, wind noise, road noise, combustion noise of the engine, and transient NVH phenomena. Transient NVH phenomena like door closing events, central locking noise and engine knocking have a significant influence on the sound quality of a vehicle, which the customer notices. Therefore, the task of an acoustic engineer is to analyse the transient noise, so as to understand the noise generating mechanism and then to improve the design of the system in such a way that the sound quality is enhanced. However, not every signal analysis method is suitable to analyse transient signals. The standard Fourier Transformation (FT), for instance, is not appropriate because transient signals are not stationary. Alternative signal processing applications like Time-Frequency-Analysis are more suitable for the analysis of these sorts of signals. The aim of this paper is to apply two such methods, the Short-Time Fourier Transformation (STFT) and the Wavelet Transformation (WT) for the investigation of transient NVH phenomena in vehicles. Section two outlines the basic theory of the STFT and Wavelet Transformation. In section three it is shown that Wavelet analysis can reveal information about the signal that the STFT obscures. It is also shown that this additional information is noticeable in the subjective impression of the sound. Section four discusses some of the advantages of the WT and suggests some areas for future application of the WT when analysing door closure sounds.

2 THEORY

2.1 Short-Time-Fourier-Transformation

Many signals are non-stationary; they contain a lot of transitory characteristics like drifts, trends, abrupt changes, beginnings and ends of events. To analyse these important characteristics, the Short-Time-Fourier-Transformation (STFT) is applied in an attempt to overcome the lack of information on time locality in the usual Fourier Transformation¹. The approach is to look at the signal from narrow windows and to assume the signal within the window is stationary. The STFT is expressed in the following equation:

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

where, $\underline{X}(\omega, \tau)$ is the Fourier Transformation. The localised window function $w(t - \tau)$ is slid over the time signal to divide it, and a Fourier Transformation is performed for the signal cut in the window.

The single spectrum results of every section are plotted in a three-dimensional plot as a function of time and frequency.

The main disadvantage with the STFT is the difficulty in obtaining satisfactory resolution in both the time and frequency domains. The STFT provides some information on both time locality and frequency content, but only in time intervals and frequency bands. The precision of the provided information is limited and is determined by the size of the used window. Therefore, there is always the problem of the correct selection of the window size in the STFT. If the frequency components are well separated from each other in the original signal, 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 interest concentrates more on the frequency resolution, it is necessary to lose some time information by means of a bigger window size. Thus, there is always a compromise between the time and frequency resolution. Another feature of the STFT is that once the time window is chosen it is applied during the entire analysis. All frequencies are analysed with the same window and with the same compromise between time and frequency resolution. Many signals, however, require a more flexible approach, where it is possible to vary the window size to determine more accurately either time or frequency. This flexibility is provided by Multi-Resolution Analysis¹.

2.2 Wavelet Transformation

In Multi-Resolution Analysis (MRA) different frequencies are analysed with different time windows. At high frequencies MRA provides good time resolution at the expense of poor frequency resolution. On the other hand, at low frequencies it provides a good frequency resolution at the expense of a worse time resolution. This approach makes sense because low frequencies are phenomena that change slowly in time. Therefore, a good resolution in time domain can be sacrificed for a high frequency resolution. Conversely, high frequency phenomena behave more rapidly with time. Thus, time becomes the more important dimension. So the MRA increases the time resolution at the expense of resolution in the frequency domain for these conditions.

Wavelet Transformation¹ (WT) is a form of MRA well suited for the analysis of non-stationary signals. The Continuous Wavelet Transformation (CWT) is defined as:

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

The Wavelet coefficient C is a function of the scale parameter s and the shifting parameter τ . The shifting parameter, τ , can be regarded in the same manner as in the STFT. Thus, it represents the time location of the window. However, there is no longer a frequency parameter as in the STFT. Instead there is a scale factor, s , which is proportional to the inverse of the frequency, f :

$$s \sim 1/f \quad (3)$$

The term $\psi\left(\frac{\tau - t}{s}\right)$ is called the Mother Wavelet. It is a prototype wave used to generate the several scaled window functions that are applied during the Wavelet Transformation. The length of the window function is determined by the scaling factor s . Scaling a wavelet simply means to stretch or to compress the wavelet. Therefore, a scale parameter, s , greater than one expands the Wavelet function, whereas, a scale parameter less than one compresses it. Higher scale parameters correspond to the stretched wavelets. The more the Wavelet is stretched, the longer is the portion of the signal with which it is compared. Thus, lower frequency components can be analysed with a wide time window. Lower scale parameters compress the Wavelet, so shorter portions of the signals are within the window. Therefore, high frequencies are analysed in a narrow window. In the

same way that the Fourier Transform represents the sum of the constituent sinusoidal components of a signal, the CWT yields the constituent wavelets of the signal.

The disadvantage of the CWT is that it requires a large amount of computation that makes it very slow. By applying complementary high and low pass filters the Discrete Wavelet Transform¹ (DWT) is more efficient but loses some of the detail of the CWT. Both the CWT and the DWT operate on digitised time signals, however, the CWT provides a continuous range of scales, whereas the DWT provides a discontinuous frequency where the level of discontinuity is defined by the number of filtering operations applied. For the following analysis the DWT was used.

3 RESULTS

In this section Time-Frequency-Analysis is applied to a practical application, the analysis of transient NVH phenomena in vehicles. One of the most important transient sounds in a vehicle is the door closing sound. It is often the first sound of the vehicle that a potential customer hears when in the showroom of a car dealer or at the beginning of a test drive.

An analysis of door closure sound is given in references^{2,3}. An example of car door closure sound is shown in Figure 1. The sound starts with a big impact that is a result of the mechanical impacts between the latch and the striker. This impact excites a number of resonances in the vehicle. For example, the rattle of the springs in the latch, the mechanical resonances of the door panels, the first torsional mode of the body structure and acoustic resonances of the interior air volume. Each of these resonances may have a different time duration and typically lasts longer than the first big impact. However, the entire event of the door slam lasts only around half a second. In order to reveal the complex nature of the door closing sound, it is necessary to analyse the measured sound pressure signal by means of Time-Frequency-Analysis.

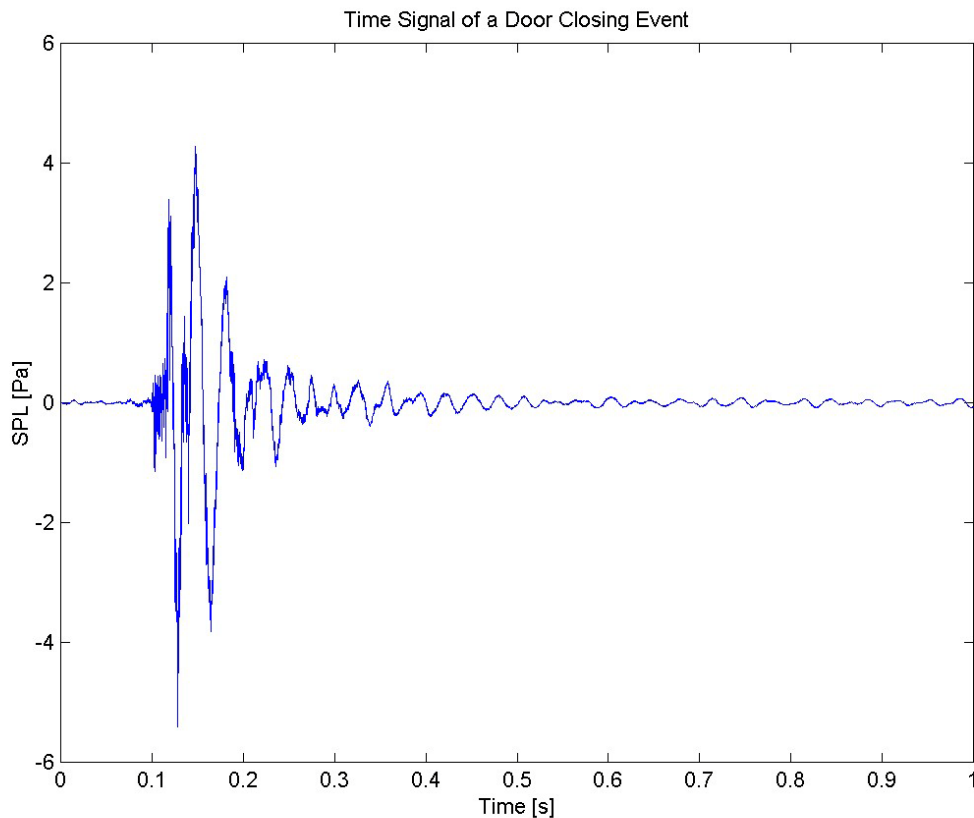


Figure 1: Time signal of a vehicle door closure sound.

3.1 Short-Time-Fourier-Transformation of a Door Closing Event

Figure 2 shows the result of a STFT on a recording of the sound of a vehicle door closing. The vehicle was one of nine different saloon cars from five different manufacturers. Each recording of door closure sound was made in the showroom of the respective car dealer. The STFT has a window length, T_w , of 0.1 seconds, which results in a frequency resolution, Δf , of 10 Hz. The x-axis of the colourmap represents time, the y-axis frequency on a logarithmic scale and the colour stains represent the amplitude values of the Sound Pressure Level defined by the colourbar. The frequency component in the area of 30-40 Hz with the long duration, indicated with mark A, is possibly the first torsional mode of the whole body structure or one of the first in-vehicle cavity modes excited by the door closure. Mark B indicates what is probably the first resonance frequency of the door panel as this resonance usually occurs at around 60-70 Hz. The very broad frequency range within the first tenth second, indicated with mark C, is likely to be a result of the first big impact at the beginning of the door closing event. It is worth noting that all the door slams had the time-frequency characteristic of a broad frequency content at the beginning with a subsequent toe in the lower frequency region of the figure. However, every door sounded different.

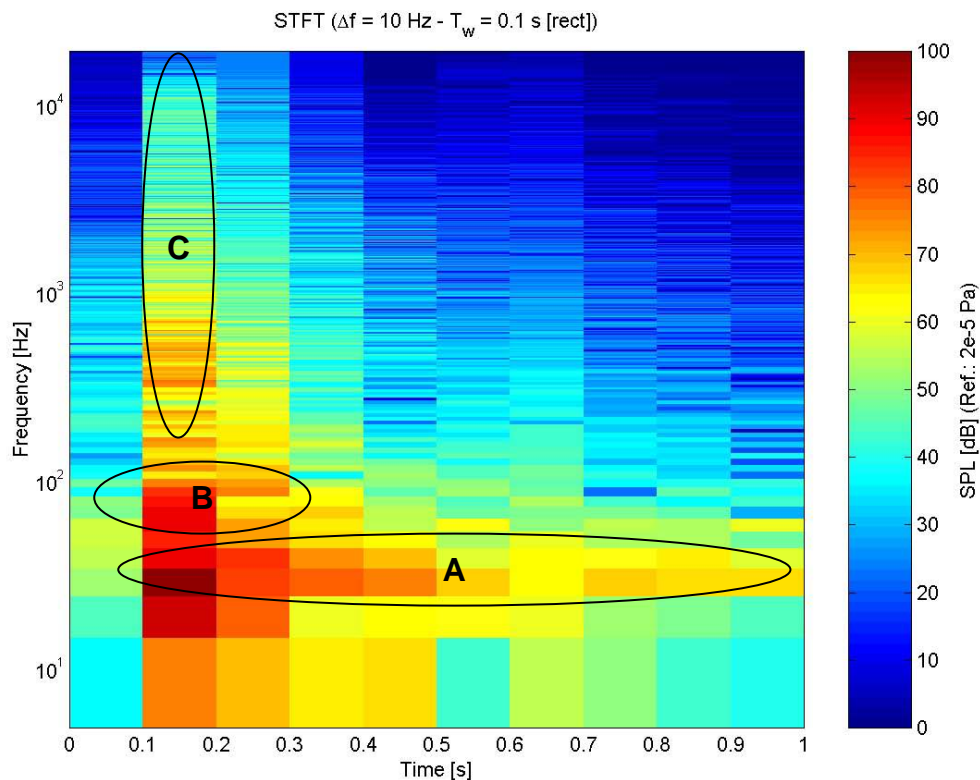


Figure 2: Short-Time-Fourier-Transformation of a vehicle door closure sound.

3.2 Wavelet Decomposition of a Door Closing Event

Figure 3 illustrates a Wavelet Decomposition of the same door slam that was analysed in the section above by means of the STFT. The original time history of the door slam was sampled at 44100 samples per second. The wavelet analysis was calculated by applying the filter coefficients provided by the 'db8' wavelet in 12 decomposition, or filtering, steps. Figure 3 shows the typical time-frequency characteristic of a door slam in form of a foot plus toe^{2,3}. However, the WT representation has an advantage over the STFT representation shown in Figure 2. Firstly, even though only 12 decomposition steps have been used, it is possible to distinguish the low frequency resonance, indicated with mark A, from that one of the door panel, indicated with mark B. Secondly,

the frequency content above 500 Hz due to the impulse at the beginning of the door closing event is far more clearly resolved in time (mark C). Thus, the Wavelet Decomposition provides a more compact time-frequency representation of a door slam using one colourmap only. To gain the same amount of information using the STFT it is necessary to calculate at least two colourmaps.

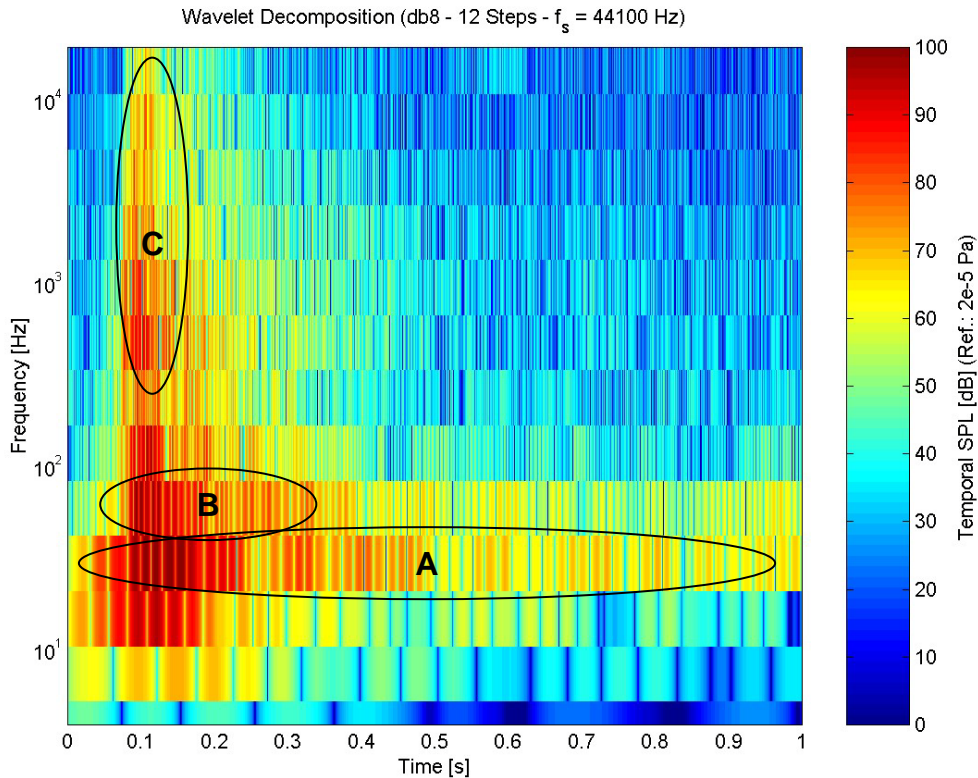


Figure 3: Wavelet decomposition of a vehicle door closure sound.

3.3 Comparison between the Objective and Subjective Evaluation

The previous section showed that Wavelet Transformation of a door slam can present more precise time-frequency than the STFT. In this section a comparison is made between the objective results provided by WT and STFT respectively, and the subjective impression of the door slams of two different vehicles. If human hearing is not very sensitive to the extra frequency content that is only objectively visible in the Wavelet Transformation, then it will not be necessary to analyse the door slam by means of this approach. On the other hand, if the frequency content detected only in the Wavelet Transformation is very meaningful for the subjective impression of a door slam, then the additional information provided in the WT can reflect more closely customer satisfaction.

In this section the door closure sound of two different vehicles, vehicle F and vehicle E, are compared using the STFT and the WT. In a subjective evaluation the sound of vehicle E door closing received a higher satisfaction rating than vehicle F. The general impression of the door slam of vehicle E was that it sounded tremendously dark, determined by a low frequency content. This kind of sound characteristic is associated with a big and solid limousine, a very expensive car, and a car with a high level of customer satisfaction. The general impression of the door slam of vehicle F was that it sounded light, tinny, not very solid and more clattered with a higher frequency content. For some human beings, this impression can lead to the description that the door sounds very cheap and so they associate a worse car with this door, a car with low customer satisfaction. However, it is worth noting that the two cars were measured in the different show rooms of the two car dealers. The different halls provide different environment conditions with different reverberation

times. This may have had an effect on the subjective comparison and evaluation of the two door closing events.

Figure 4 illustrates the STFT of the two door slams. The two colourmaps reveal minor differences. Firstly, the beginning impulse of vehicle F is more lively in the frequency range from 500 to 5000 Hz (see mark A). Secondly, the decay of the vehicle F sound involves more high frequency content than the vehicle E (see mark B). This may be due to the larger reverberation content in the vehicle F sound caused recording in a different show room. Otherwise, both colourmaps seem to be very similar. However, subjectively, each door slam had a distinct sound. This is not clearly indicated by the STFT.

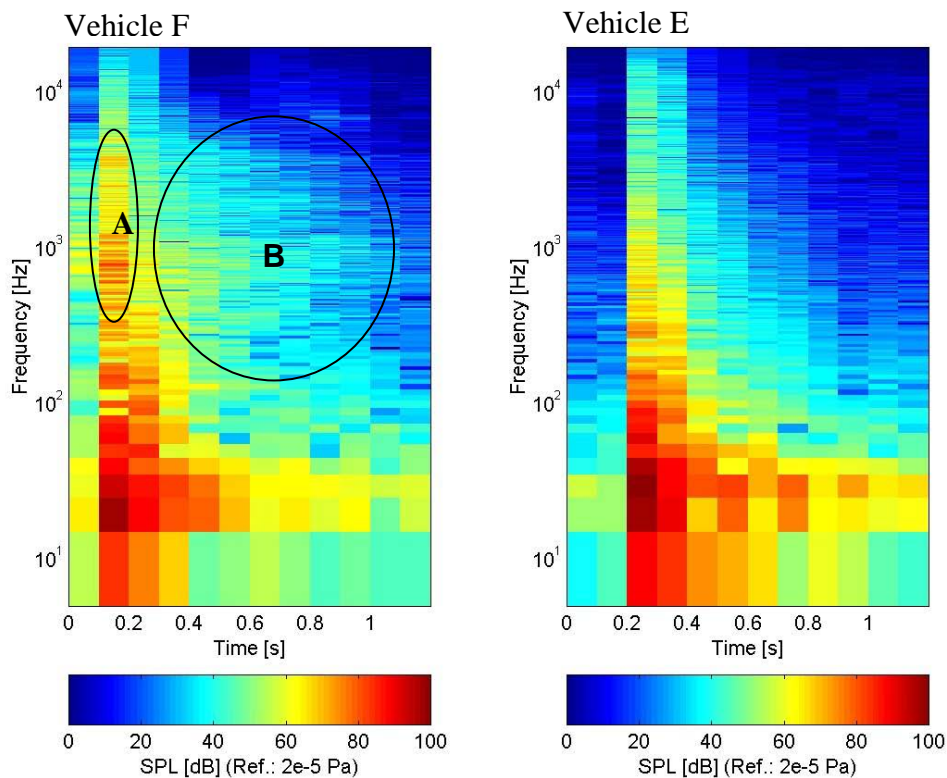


Figure 4: STFT of vehicle F and vehicle E door closure sounds.

Figure 5 illustrates the results of the signal decomposition performed by the Wavelet Transformation. A comparison between the two colourmaps shown in Figure 5 and the corresponding colourmaps shown in Figure 4 indicates that the Wavelet Transformation makes the difference between the two door slams more obvious than the STFT does. In Figure 5 the reverberation of the vehicle F door slam is more clearly visible (see mark B). Furthermore, the impulse at the beginning of the event is more pronounced along a wide frequency range from 500 Hz to 10 kHz (see mark A). This higher frequency content can be responsible for the more tinny and cymbal sound characteristic of the vehicle F door closure sound. Moreover, the decay of the middle frequency content around 100 Hz lasts longer in the vehicle F door closing sound compared to the vehicle E door slam sound (see mark C). Thus, the Wavelet Transformation can indicate more relevant time-frequency information for the subjective feeling of a door slam than can be discovered immediately by means of the STFT.

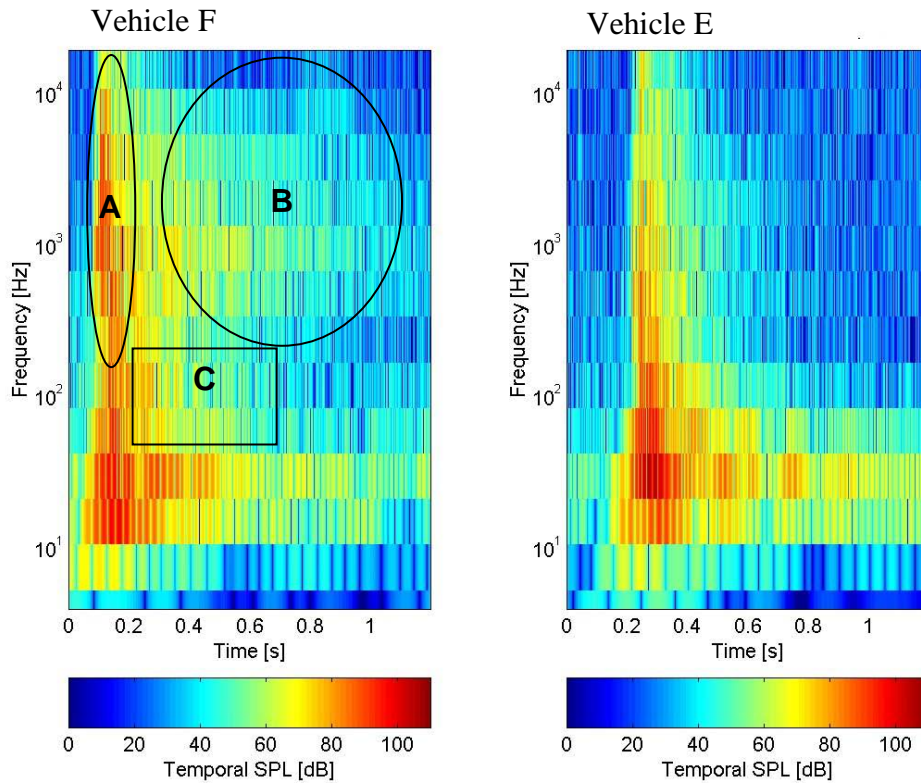


Figure 5: Wavelet decomposition of vehicle F and vehicle E door closure sounds.

4 DISCUSSION AND SUMMARY

It is well known that the usual Fourier Transformation (FT) is not suitable for the investigation of non-stationary signals. The FT does not provide any information about the time instant in which resonances in the structure appear nor about their time duration. The Short-Time-Fourier-Transformation (STFT) is able to furnish a frequency spectrum that includes information on the time locality of the resonant behaviour. However, the drawback in the STFT is that all frequency ranges are analysed during the entire analysis with a fixed window size. A Multi-Resolution Analysis like the Wavelet Transformation (WT) allows a signal to be analysed in time and frequency with varying time and frequency resolution.

In section 3 it was shown that it is possible to analyse a complicated signal like the door slam in one step. The complete time-frequency representation can be provided in only one colourmap. By contrast, the STFT can only provide this information using several investigation steps with a varying window size. It was also shown in section 3 that the subjective sound quality of a door slam can be better represented by a WT than by a STFT.

For the future it would be interesting to correlate the objective sound attributes of the WT with the subjective impression of the sound quality based on psycho acoustical quantities like loudness, roughness and sharpness⁴. This approach may provide further explanations between the objective and subjective impression of an impulsive sound event such as a door closure sound.

5 REFERENCES

1. R. Polikar. The Wavelet Tutorial. Ames, USA, Cyberdomain Root Page (1996).
2. A. Petniunas, N. C. Otto, S. Amman, R. Simpson. Door System Design for Improved Closure Sound Quality. SAE Technical Paper Series 1999-0-1681, Michigan, USA (1999).
3. D. Hamilton. Sound Quality of Impulsive Noises: An Applied Study of Automotive Door Closing Sounds. SAE Technical Paper Series 1999-01-1684, Michigan, USA, (1999).
4. E. Zwicker and H. Fastl. Psychoacoustics: Facts and Models, 2nd edition, Heidelberg, Springer Verlag (1999).