Precise Characterization of Structure-Borne Sound Transmission Applied on Crash Sensing Technologies

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1 Introduction

The non-destructive prospection by ultrasonic or structure-borne waves within solids is a common indirect measurement technique beside the conventional body acoustic. It is used for quality control during the production cycle or online surveillance of tools, bearings, engines and machine structures by detection of defects or location of faults like unbalanced masses.
In the frame of a car safety system the structure-borne sound method is used to distinguish crash situations in civil cars [1]. The device uses the information on the crash that is decoded in the high frequency range of the structure-borne sound caused by the deformation in the first few milliseconds of the impact. Usually the corresponding acceleration-sensor is placed in a central processing unit in the middle of the car. Hence the sensor position is not in the deformation zone, the impact-deformation sound signal is affected on its propagation through the car structure. In order to detect the signal beside multiple disturbing signals and to distinguish different crash situation, the characteristics of the propagation path within the car body need to be known.
On one hand these techniques require a sophisticated signal analysis (signal and pattern recognition) and on the other hand the wave behaviour and especially the influence of dispersion within the complex technical structure (system) need to be known with a high precision.
In order to design such prospection and surveillance sensor systems a tool is needed to estimate the behaviour of structure-borne sound propagation within a large scale structure. Further an appropriate simulation technique is indispensable in an early stage of the design process considering the development of structure-born sound based inspection sensors and their integration as a new technology into car. The description of the high frequency wave effects is either solved by simple linear models or enhanced FEA-simulation (Finite-Element-Analysis). Even if FEA-simulations are necessary in case of very complex structures they can perform calculation on a small scale only (due to the rising number of elements) and are not applicable to real time tasks up to now. That's why alternative approaches like linear modelling are used to describe the elastic sound propagation - with a precision needed for signal analysis.
The current paper discusses such a linear approach building on the transmission line method [1, 2] and a linear model (e.g. Mason-theory [3]). Here the crucial step in developing a fast and effective simulation method for the prediction of the sensor signal during a crash - in the last case - is the reduction of the complexity of the physical system (chapter 3.1). Using the Mason-theory and mason graph it is possible to get a semi-analytical solution of an acceleration wave transmitted from the excitation to an arbitrary point in the structure (chapter 3.2). With the including of the dispersion, one of the main dominant physical effects will be taken into account (chapter 3.3). The validation of these assumptions is shown by comparing the linear solution with FEA-simulations and simulation of corresponding structures with the new technique (chapter 4). In the following the assumptions and the characteristic behaviour are related to measurement results of a real car structure (chapter 5). At the End a conclusion and an outlook for further optimization of the simulation technique will be given (chapter 6).

2 Motivation: Inadequacy of actual Crash-FEA-Simulations

The FEA is the standard technique in simulation of crashes [4], but due to the usual wavelength to minimum element size ratio it only regards the deformation and corresponding acceleration of the car structure, including its transmission, up to a frequency range of 2 kHz [5]. The higher frequency range up to 20 kHz which holds the main information on the characteristics of the crash is not processed, even not in other simulation techniques [6].

Up to now the simulation time and amount of data due to rising element number of FEA-simulations would be unacceptable for the car design process [1]. Hence, the research focuses on a fast method to predict this high frequency range signals. The scope is not to replace the FEA-crash simulation – further the solution should be extended. More the FEA still is essential in predicting the excitation signal during a fast deforming of the crash elements in the car front structure [7]. The signal evolved by FEA-simulation is still used as an input for the model calculating the propagation of structure borne waves on a large scale.

3 Linear modelling and signal prediction, assumptions and restrictions

The linear model is able to estimate the propagation of any kind of physical wave. It can be used for acoustic and electromagnetic waves as well [8]. The precision of the solution is affected by the level of the modelling. Here the important variables are the properties of the solid materials where the mechanical impedance, the frequency dependent propagation speed (dispersion) and the transmission and reflection dependent on the geometry of the junctions between different structures are counted among. The precise information on these factors would lead to an accurate image of the wave propagation. Since these values are not a priori known either effective values or an iterative solution with predicted starting values have to be used. The presented approach uses effective values of the impedance and the reflection factors. An iterative adaption is neglected in first step. The following chapters describe the derivation of the model equation and its solution.

Since a physical image of the wave propagation in small scale is needed, FEA-simulations have to be used. Further if, such a detailed description of real physical phenomena is not needed, a linear signal orientated model may already deliver the necessary information in a reduced way. Due to the complexity of real car structures – the whole signal could not be reconstructed without sophisticated FEA-models. But the main signals aspects can be predicted by simple models.

The task is to reduce the physical system to its main parameters, which are needed to estimate the impulse signal at the sensor position within the precision range of the application. In case of a car safety system the prediction of the signals envelope, its maximum amplitude and the centre of gravity are adequate to discriminate different crash situations. The model has to calculate these parameters – while others can be neglected. In the frame of such simplification of the real physical phenomena, only the dominant effects and structure parts need to be regarded likewise.

The following chapters mainly discuss the usability and performance of such linear modelling in estimating the propagation of structure borne sound signals up to a high frequency range.

3.1 Model equation of the wave propagation

The signal oriented linear modelling is adequate to describe the structure-born acoustic-mechanical impulse concerning multiple reflection and dispersion within a complex car body. The estimation of wave phenomena on certain propagation path is done by using the Mason-theory [3], assuming elastic structures without deformation (which comply in the first few milliseconds of an impact or car crash [9]) and linear material properties.

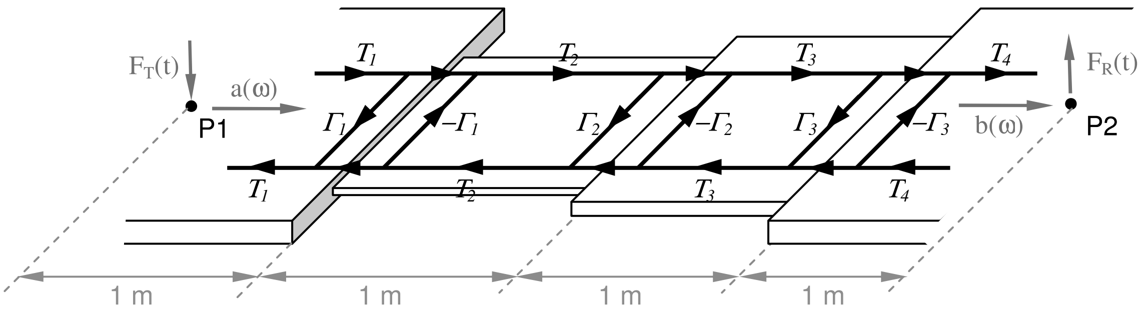


Fig. 1: Simple example of 4 thin plates of different size and thickness with corresponding network representation of the normalized wave propagation through the layers including reflection at the joints and transmission based on the Mason-theory

The principle of the linear modelling by Mason-graph is exemplified on a simplified structure made of four different elastic plates (figure 1) which may represent a bottom plate of a car.

Based on that Mason-graph a semi-analytical solution can be derived to calculate either the transmitted signal from the excitation (impact) point to an arbitrary point in the structure or the reflected signal with an expected precision in a split second.

In figure 1 a(ω) and b(ω) represent normalized acceleration waves in frequency domain at the excitation point P1 and the measurement point P2. The corresponding forces F_T and F_R can be calculated by multiplying the mechanical impedance. The propagation paths along the plates are described by complex transmission function $T_i(\omega)$.

$$T_i(\omega) \approx T(\omega) \cdot e^{-j\omega\tau(\omega)} e^{j\sigma} \tag{1}$$

Where T is the real transmission factor, τ(ω) the dispersive travel time and σ and effective spreading loss and damping factor. The behaviour between structure elements of different geometry or impedance is represented by complex reflection functions $\Gamma_i(\omega)$ as well. Depending on the type of wave and the model used the reflection coefficient can be calculated with the mechanical impedance by (assuming a planar wave front):

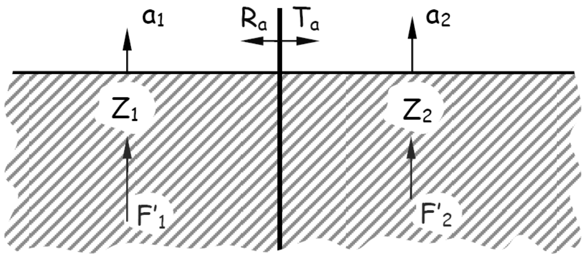
$$\Gamma_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \tag{2}$$

Considering all path in the graph (Figure 1) an analytical equation, which describes the wave propagation from P1 to P2, can be derived:

$$G_T = \frac{b}{a} = \frac{T_1\sqrt{1-\Gamma_1^2}\,T_2\sqrt{1-\Gamma_2^2}\,T_3\sqrt{1-\Gamma_3^2}\,T_4}{1 + T_2^2\Gamma_1\Gamma_2 + T_3^2\Gamma_2\Gamma_3} \tag{3}$$

3.2 Effective impedance and reflection and transmission parameter

In the sensor application the detection of the impulse signal is hardened because it is usually masked by clutter, noise and multiple reflections. Considering typical mechanical wave velocities in relation to the car dimensions, multiple round trip reflection may occur during the surveillance window which is normally required to characterize a wideband impulse signal. That’s why the roundtrip propagation and reflection of the bending waves (asymmetric lamb wave) in the car is an important physical effect that has to be taken into account.
This model (3) suffices to calculate all wave components travelling in both directions perpendicular to the junction. The transmission within the elements, the reflection at the joints and the damping due to spreading loss are included. The main sources of deviations to the real measurable signals are the open boundary conditions with infinite elements. On this account reflections at the outer boundaries and non-planar waves are not regarded as well as the mode conversions. Thus the model only complies in a short time window with the real occurring waves. The time length needed is mostly assigned by the permitted deviation and the level of modelling.



$$a_2(\omega) = T(\omega)\frac{Z_1(\omega)}{Z_2(\omega)} \cdot a_1(\omega) \qquad Z = \frac{\dot{F}(\omega)}{a(\omega)}$$

$$T_a(\omega) = T(\omega)\frac{Z_1(\omega)}{Z_2(\omega)} \qquad \dot{F}(\omega) = Z \cdot a(\omega)$$

Fig. 2: Definition of the equivalent impedance of a junction, based on a acceleration measurement on the surface of the transmission path in the near of the junction

Here, “the level of modelling” means the determination of material parameters. The transmission and reflection depend on the mechanical impedance and the geometry. Since the wave behaviour at joints between different construction elements is a priori unknown, it is appropriate to deal with effective values.
Normally the reflection is described by the mechanical impedance [10] whose determination on real structures often is hardened. Even if one regards simple plate or beam elements, its impedance can vary by inhomogeneities, junctions to neighbour elements, welds or coating materials, which are often used in acoustic noise reduction. Hence instead of determine the physical impedance along the whole element it is more efficient to define an effective or equivalent impedance at both junction sides (figure 2) derived from the acceleration a(ω). This acceleration perpendicular to the surface on thin structures can be measured with piezoceramic sensors. The inhomogeneities within the element itself need to be neglected or are described by the complex transmission function either.

3.3 Modelling the dispersion effect.

In current structure borne sound application especially in the car safety system the characteristics of the envelope (max. amplitude, position of the centre of gravity and width of the impulse and perspectively the rising time) are used for signal discrimination. As one can see on the comparison of two border cases (Figure 3) the dispersion of different mechanical elements have a crucial influence on these parameters already. That's why beside the multiple reflections the dispersion is one of the major effects which need to be regarded in the model.
Theoretical investigations and studies on typical car structures in the frequency range up to 30kHz have shown, that the asymmetric lamb wave (A0) is the dominant mode. The symmetric lamb wave (S0 – longitudinal wave) - containing less energy - can be neglected. The A0-mode shows a typical $k\sqrt{\omega}$ dispersion behaviour, whose factor k depends on the geometry of the element. Figure 3 illustrates the impulse response function of the same gauss excitation first travelling through a plate and second travelling through a beam structure. Both cases deliver a difference in travel time, max. amplitude, position of centre of gravity and spreading of the signal.

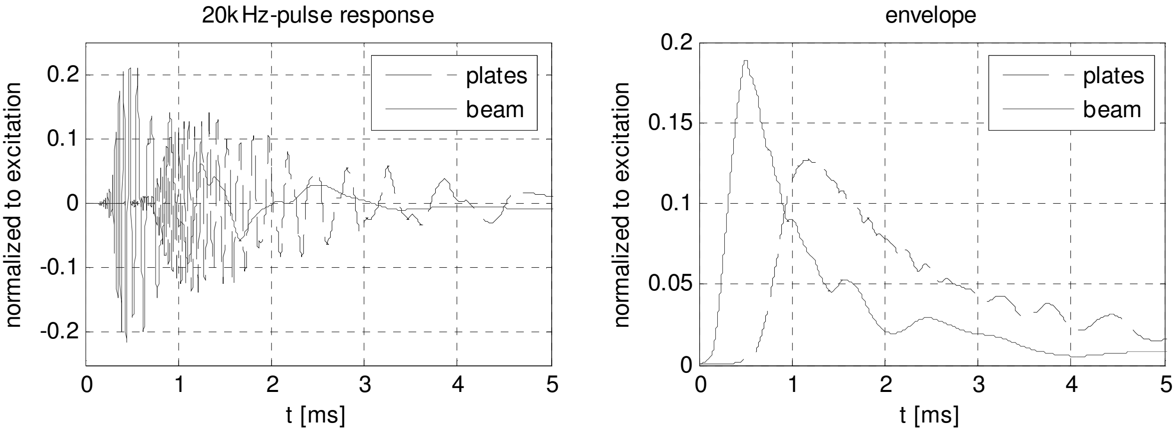


Fig. 3: Single 20kHz impulse response of a simple plate and beam structure (left) with comparison of the corresponding envelope (right)

Since there is a markable variation in those parameters, the model has to take different propagation path into account.

4 Validation with the simplified structure

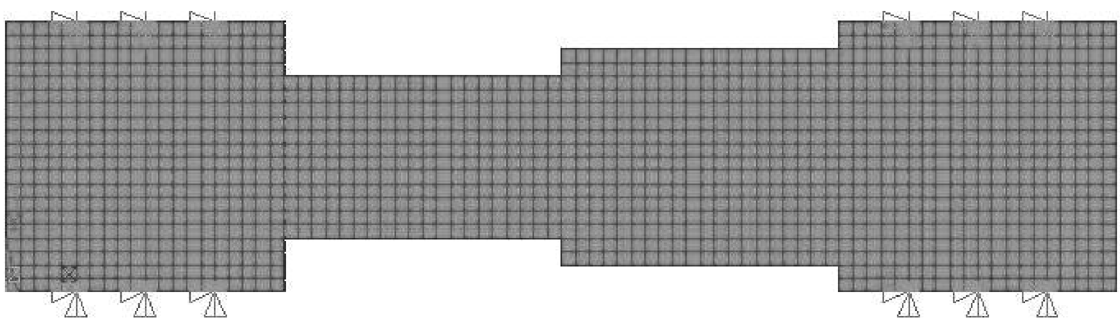


Fig. 4: FEM representation of the example structure made from shell elements with different thickness and different impedance

The validation of the linear model is done by comparing it with simulated reference data. Therefore the simple structure from figure 3 was simulated with the new method based on mason theory and with a standard FEA-tool. In the FEA-representation the geometry is defined by shell elements with the corresponding thickness of the parts and a short element length favouring reproduction of the high frequency bending waves [5] (figure 4).
Both results are shown in figure 5. Here it is obvious, that the principal signal behaviour can be simulated satisfying, because for the application structure-born sound sensing it is only necessary to get the envelope of the signal (figure 6) and the centre of gravity of this envelope. Especially the early time response (t<5ms) complies with the FEA-Simulation (figure 6).

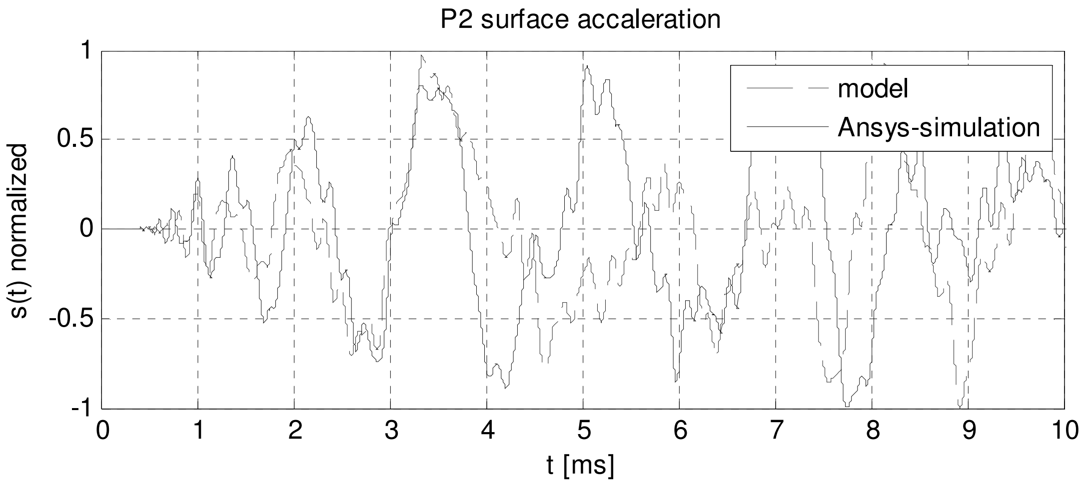


Fig. 5: Comparision of the FEM-simulated dynamic behaviour of the structure and the Mason-simulated dynamic behavior

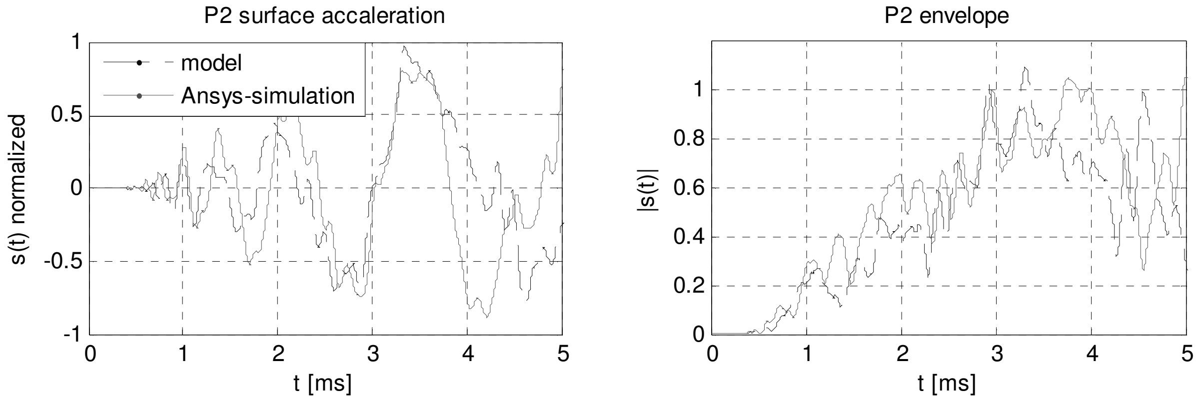


Fig. 6: The early time response (left) shows very good agreement, this is also valid for the envelope which is very important for the application crash detection

The main parameters of the centre of gravity and the envelope of the early time response (figure 6) are quite the same for both solutions. But, as one can see, both traces (figure 5) do not fit within the whole prospection window. The difference rises with the simulation time. The deviation between FEA-simulation and the developed mason-representation is mainly based on the one dimensional behaviour of the mason-model and the two dimensional structure in the FEA-analysis. There were reflections on the sides of the plates, which are not represented in the linear model. Also the boundary conditions of the FEA-model are missing in the mason-representation and lead to another uncertainty. Thus the solutions fit until the roundtrip wave from the outer boundaries reoccurs in the prospection window (t<5ms) and influences the FEA-simulated signal.

5 Comparison with a real car structure

As it can be seen on the example of a simple structrue, the new simulation method is adequate to estimate the impulse signal within a short time window, which is used for fast structural sound sensing technologies. Further, investigations on real car structures show, that also for the application system (car body) the basic assumption are valid.

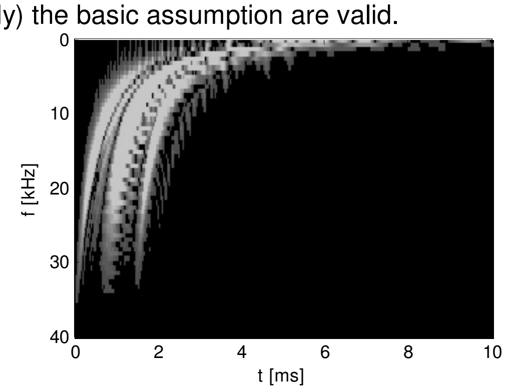


Figure 7a: time frequency representation of model; combination of different propagation path on plate and beam structures.

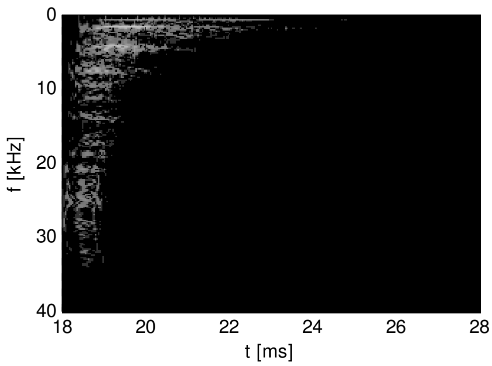


Figure 7b: time frequency representation of impulse signal on real car structure (measurement)

Due to the mechanical complexity of a car, the transmission signal is the superposition of different single propagation path (3) with dispersion effects and multiple reflections on beam and plate structures. The comparison of a real car structure borne sound signal and a multiple path model signal in the time frequency domain illustrates both the influence of the dispersion and the reflections (figure 7).
The dispersion of the dominant bending wave (trace proportional to $\sqrt{\omega}$) and the occurrence of multiple reflections noticeable by the fluctuating density spectra are visible. In the real measurement data (figure 7 b) multiple propagation path, which are not considered in the corresponding model, lead to a spreading of the spectra however three single branches are visible in the spectra of the model (figure 7 a). Thus exemplifies, that the measurement signal could be iterativly approximated by starting with simple transmission path growing in complexity. Therewith depending on the dimension of the structures the early time response up to several miliseconds can be estimated. The measurements in the car are masked by additional clutter signals and reflections from signal path, which are not regarded by the current model.

6 Conclusions and Outlook

The presented simulation technique can be used for a fast estimation of the sound propagation in real car bodies and the expected sensor signals. It is possible, to get a basic knowledge over the structure-born sound transmission behaviour in an early stage without cost intensive measurements or time harvesting FEA-simulations. Therewith the effects of multiple reflections, the spreading loss and the spreading of the signal due to dispersion could be calculated in a split second. The solution of complex systems can be derived by iterative combination of different single path. Here the gainable precision of the estimates mostly depends on the complexity of the model including the length of the transmission path and the application of multiple path in parallel. Thus it is possible to enhance the precision in accepting higher effort in predicting the models parameter.
Although even if the longitudinal wave (symmetric lamb wave) carries less energy, its implementation by a second parallel transmission network would improve the estimate of the rising impulse flank and the smaller oscillation superposing the main signal. Based on the fact that each joining can converse bending waves into longitudinal waves and vice versa this would result in very complex networks. The inclusion of multiple reflections at the outer boundaries, mode conversion, secondary wave modes and non-linearities would enhance the quality of solution further so this simulation technique will get a useful tool in the investigation of structure-born transmission in complex systems.

Acknowledgement

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