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GENERATION AND VALIDATION OF ACOUSTIC 3D WBT MODELS OF A SUV DRIVER COMPARTMENT FROM SEA MODELS

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Abstract

The wave based technique (WBT) constitutes an upcoming simulation technique which results in reduced simulation time and reduced simulation errors compared to finite element (FE) approaches for solving Helmholtz problems. The finite element analysis represents a method which basis functions approximate the boundaries exactly. On the other hand the WBT basis functions are a solution of the Helmholtz equation but its weighted superposition fulfil the boundaries only approximately.

However it takes much time to generate a WBT model of a driver compartment of complex vehicle interior geometries because of the requirement that each WBT domain must be a convex volume. Therefore a compromise has to be found between real vehicle surface geometry and its simplifications to coarse box models. A process is introduced which allows the generation of WBT models including the set up of the required boundary conditions based on complete vehicle AutoSEA models.

As an example the WBT analysis is applied for a complex SUV driver compartment and validated. The model is used to calculate the over all damping factor of the cavity and the acoustic performance of a head liner is analysed with respect to human in-cabin communications.

1. INTRODUCTION

The spatial distribution of a harmonic acoustic pressure field within a domain G assuming adiabatic conditions is defined by a boundary value problem at the surface Ω_p of G of the inhomogeneous Helmholtz equation

$$\Delta p + k^2 p = -j\omega\rho q\delta, \quad \{p = p_0 | \forall x, y, z \in \Omega_p\} \tag{1}$$

where the harmonic pressure is defined as $\hat{p}(x, y, z, t) = p(x, y, z)e^{j\omega t}$, Δ means the Laplace operator, $k = \omega/c$ the wave number, c the acoustic phase speed and ρ the density. In finite element based solutions the variation problem of the homogeneous problem of 1 is solved using the Ritz-method where the used basis functions are typically not solutions of 1 but satisfy the boundary conditions instead. A contradictory approach was first introduced by E. Trefftz, [1] which is the foundation of the Wave Based Technique (WBT) which was first introduced by W. Desmet in 1998 [2]. The WBT uses basis functions which fulfil the homogeneous Helmholtz equation but which do not fulfil the boundary conditions. The following section provides a short introduction to the Wave Based Technique for uncoupled acoustic problems.

Given a bounded domain G, the harmonic pressure field is governed by 1. Let $\Omega_p \uplus \Omega_v \uplus \Omega_Z$ = Ω be a partition of the boundary surface of G which fulfils the surface boundary conditions

$$p_0 = p, \text{ at } \Omega_p, \quad \mathbf{v}_{n,0} = \frac{-1}{j\omega\rho}\frac{\partial p}{\partial \mathbf{n}}, \text{ at } \Omega_v, \quad p = \frac{-Z_{n,0}}{j\omega\rho}\frac{\partial p}{\partial \mathbf{n}}, \text{ at } \Omega_Z. \tag{2}$$

When domains needs to be split apart in convex sub-domains then the impedance boundary condition

$$\frac{j}{\rho\omega}\frac{\partial p_1}{\partial \mathbf{n}_1} - \frac{1}{Z_f p_1} = \frac{j}{\rho\omega}\frac{\partial p_2}{\partial \mathbf{n}_2} - \frac{1}{Z_f p_2} \tag{3}$$

is applied. $p_{1,2}$ are the pressures of the domains 1 and 2 at the mutual boundary surface and $Z_f = \rho c$ is the fluid impedance. The WBT basis functions ϕ_n for each solid are defined by a homogeneous Helmholtz problem of a box with the dimension $L_x \times L_y \times L_z$ which surrounds the solid with the boundary conditions

$$\frac{\partial p(0,y,z)}{\partial x} = \frac{\partial p(L_x,y,z)}{\partial x} = 0, \quad \forall y \in [0,L_y], z \in [0,L_z] \tag{4}$$

$$\frac{\partial p(x,0,z)}{\partial y} = \frac{\partial p(x,L_y,y)}{\partial y} = 0, \quad \forall x \in [0,L_x], z \in [0,L_z] \tag{5}$$

$$\frac{\partial p(x,y,0)}{\partial z} = j\rho\omega V_2(x,y), \ \frac{\partial p(x,y,L_z)}{\partial z} = -j\rho\omega V_1(x,y), \quad \forall x \in [0,L_x], y \in [0,L_y] \tag{6}$$

Applying $p(x,y,z) = X(x)Y(y)Z(z)$ and with the wave number $k = 2\pi f/c$ the following basis function set is found

$$\phi_{rs} = cos(k_r^x x)cos(k_s^y y)e^{-jk_{rs}^z z L_z}, \ [k_r^x, k_s^y, k_{rs}^z] = \left[\frac{r\pi}{L_x}, \frac{s\pi}{L_y}, \pm\sqrt{k^2 - (k_r^x)^2 - (k_s^y)^2}\right] \tag{7}$$

$$\phi_{tu} = cos(k_t^x x)cos(k_u^z z)e^{-jk_{tu}^y y L_y}, \ [k_t^x, k_{tu}^y, k_u^z] = \left[\frac{t\pi}{L_x}, \pm\sqrt{k^2 - (k_t^x)^2 - (k_u^z)^2}, \frac{u\pi}{L_z}\right] \tag{8}$$

$$\phi_{vw} = cos(k_v^y y)cos(k_w^z z)e^{-jk_{vw}^x x L_x}, \ [k_{vw}^x, k_v^y, k_w^z] = \left[\pm\sqrt{k^2 - (k_v^y)^2 - (k_w^z)^2}, \frac{v\pi}{L_y}, \frac{w\pi}{L_z}\right]. \tag{9}$$

Therefore the wave field can be approximated by

$$p = \sum_r^{n_r}\sum_s^{n_s} p_{rs}\phi_{rs} + \sum_t^{n_t}\sum_u^{n_u} p_{tu}\phi_{tu} + \sum_v^{n_v}\sum_w^{n_w} p_{vw}\phi_{vw} + p_p = \sum_a p_a\phi_a + p_p, \tag{10}$$

where p_p means a particulate solution of 1. A weighted residual formulation [2, 3] of the direct sum of all boundary conditions is solved for the coefficients p_a. The pressure field can then be

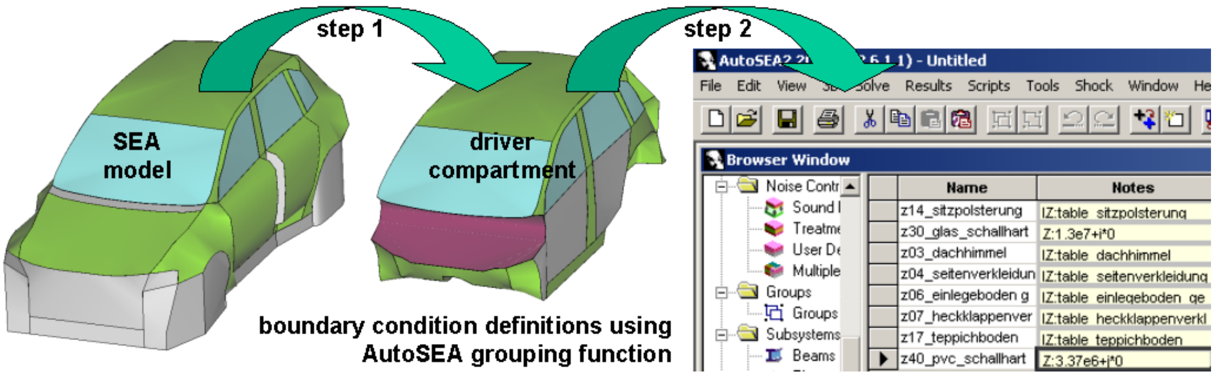

Figure 1. AutoSEA's neutral file format is used to create and save WBT pre-models. Cavities are extracted from a SEA model and AutoSEA's grouping function is used for the definition of boundary conditions.

approximated using 10 at an arbitrary location within the domains.

The actual WBT code described in [3] which is the base of this work was developed within an austrian governmental funded cooperation between the Acoustic Competence Centre (ACC), MAGNA Steyr Fahrzeugtechnik and AVL. This code is capable of 3D acoustic simulations of complex domain decompositions taking under consideration point sources and different boundary conditions like surface impedances, normal pressures and velocities and normal velocity fields which are helpful for the investigation of the radiation of structural vibrations.

2. FROM A SEA TO A WBT MODEL

The acoustic domain of a WBT model needs to be a convex volume [2] in order to gain an unique solution of the pressure distribution. Therefore no incident edge nodes are allowed at the surface of a WBT domain. In case of a complex vehicle drivers cabin including seats therefore the volume needs to be decomposed into several sub domains until the convexity requirement is preserved again. On the other hand the simulation effort is drastically increasing with the number of solids of the complete model. Therefore the number of solids needs to be held small.

Within virtual phases of a complete vehicle development all simulation models in order to optimise crash, fatigue NVH, etc. behaviour are build up from CAD models. In NVH simulation usually three different types of simulation models are used in order to cover the important vibro-acoustic phenomena in the range between 1Hz-10kHz. Acoustic phenomena are investigated based on finite element models (FEM) for frequencies below 300Hz and above 400Hz the statistical energy analysis (SEA) is used. Compared to FE models geometry based SEA models are showing by far less details of its cavity surfaces. Furthermore surface impedance/absorption data is usually integrated into SEA models because the absorbing effect of most trim materials like seats, carpets head liners etc. usually starts at high frequencies which are subject to a SEA model.

Therefore a WBT modelling process based on SEA models created from AutoSEA was developed. The software AutoSEA constitutes a quasi standard in the SEA world at time.

AutoSEA models are based on simple structures like plate faces, singly curved faces, and doubly curved faces. All face elements are defined as a polygon of subsequent surrounding nodes written in a node list. For doubly curved faces so called node rings and a tip node is defined. All plate structures define non plane surfaces which is not allowed within the used WBT code. Cavity elements are build up by defining a surface from plate elements.

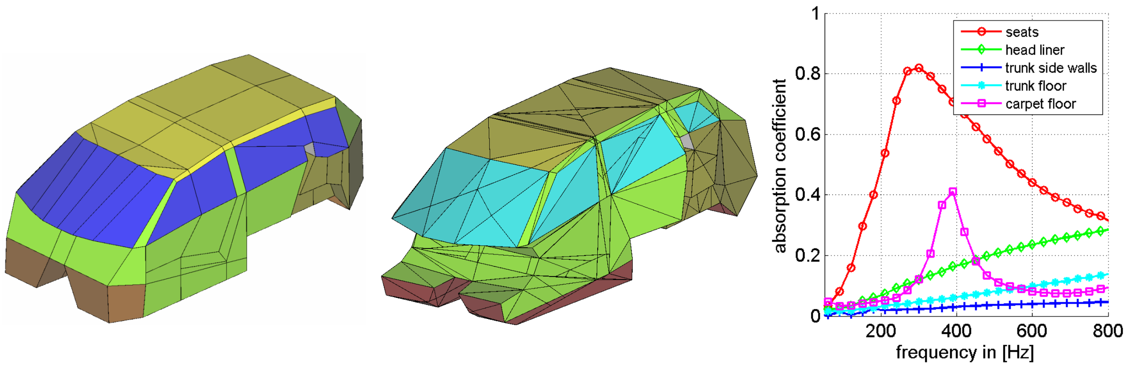

Figure 2. shows the manual build WBT model, a semi-automatic build up model of a SUV with surface colours according to different impedances and the absorptions of all used materials.

WBT pre-models are created based on AutoSEA models according to the process depicted in figure 1. The process starts with the extraction of the cavities of interest, usually the driver cabin and all surrounding structure elements. The surface is grouped into all classes of occurring surface impedances and a WBT boundary condition type identifier is put into each "note" property of the groups. Therefore a WBT pre-model is created which can be viewed within the AutoSEA software.

The final WBT model file is created using MATLAB in-house tools:

- Load xml WBT pre-model into MATLAB, mesh all surface faces into triangle elements so that all surfaces are even and preserve grouping for boundary conditions.
- Identify incident edges in solids and apply WBT meshing algorithm [4] as long as all solids are of convex type, see middle plot of figure 2.
- Mesh all higher polygon surfaces to triangle or quadrille elements.
- Merge together close nodes and eliminate triangle with small areas.

Finally an ASCII based WBT model file is generated which contains the geometry of the problem, the boundary conditions and references to related impedance spectra. For a manual WBT model, see left hand side of figure 2, typically 4-5 weeks time is needed as many failure are only detected very late and their fixture very often draws you back to very early modelling stages. The application of the automated process provides results after 3-5 days work.

Compared to manual modelling a by far more detailed surface can be achieved. Therefore prediction results should come closer to the reality but on the other hand the simulation effort is increasing drastically. While the manual WBT model consists out of 37 solids and 276 faces the semi-automatic model has a size out of 112 solids and 1877 surfaces. The computation time at $f = 100\text{Hz}$ is increased by factor 23 for the large model.

3. WBT VALIDATION RESULTS AND PRESSURE DISTRIBUTIONS

The validation of the WBT solver code and the theory [3] took place by extensive testing based on trivial domain decompositions, e.g. [5] but its performance for complex domain decompositions is not tested yet. Therefore as a validation example the drivers cabin of a SUV is analysed and compared to measurements. In figure 2 the outer surface of the WBT model including seats but excluding the cockpit is depicted. The cockpit is not implemented and therefore the volume

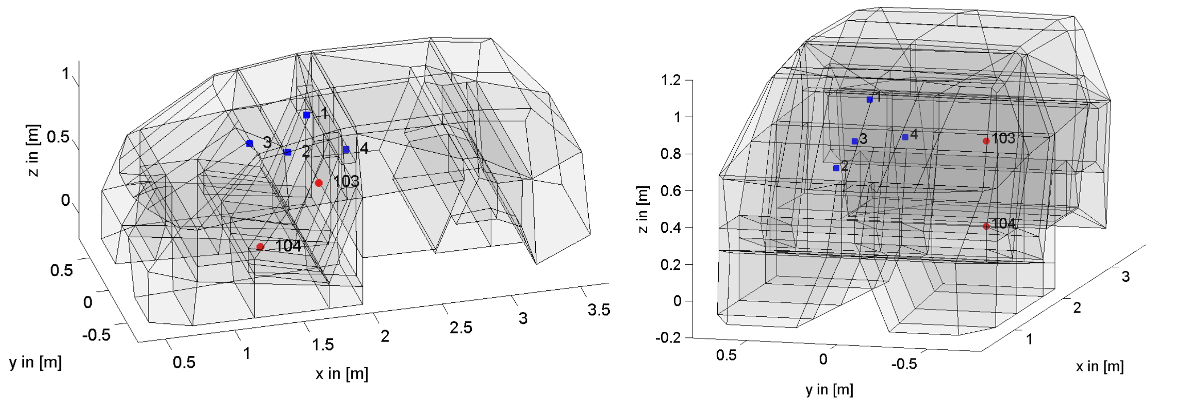

Figure 3. shows locations of excitation (red) and response points (blue) for measurement and simulation.

is approximately $0.21m^3$ too large. Especially around the seats the surface shape is preserved not better than ± 10cm. These simplifications where necessary in order to reduce the number of resulting WBT domains and therefore enable the calculation up to 750Hz on a 32 BIT hardware (RAM allocation limitations). All mentioned compromises have a high impact on the exact location of sound pressure level (SPL) extrema within space. The coloured surfaces of the WBT domains are indicating different impedances which are depicted in figure 2. Therefore high absorptions occur because of seats and head liner and the floor carpet in the regarded frequency range. All absorptions are measured using an impedance tube. For all glass surfaces the frequency independent impedance $Z = 1.3 \cdot 10^7$Ns/m and for all PVC surfaces the impedance $Z = 3.37 \cdot 10^5$Ns/m is applied.

For validation a reference measurement using a volume source was carried out in the real

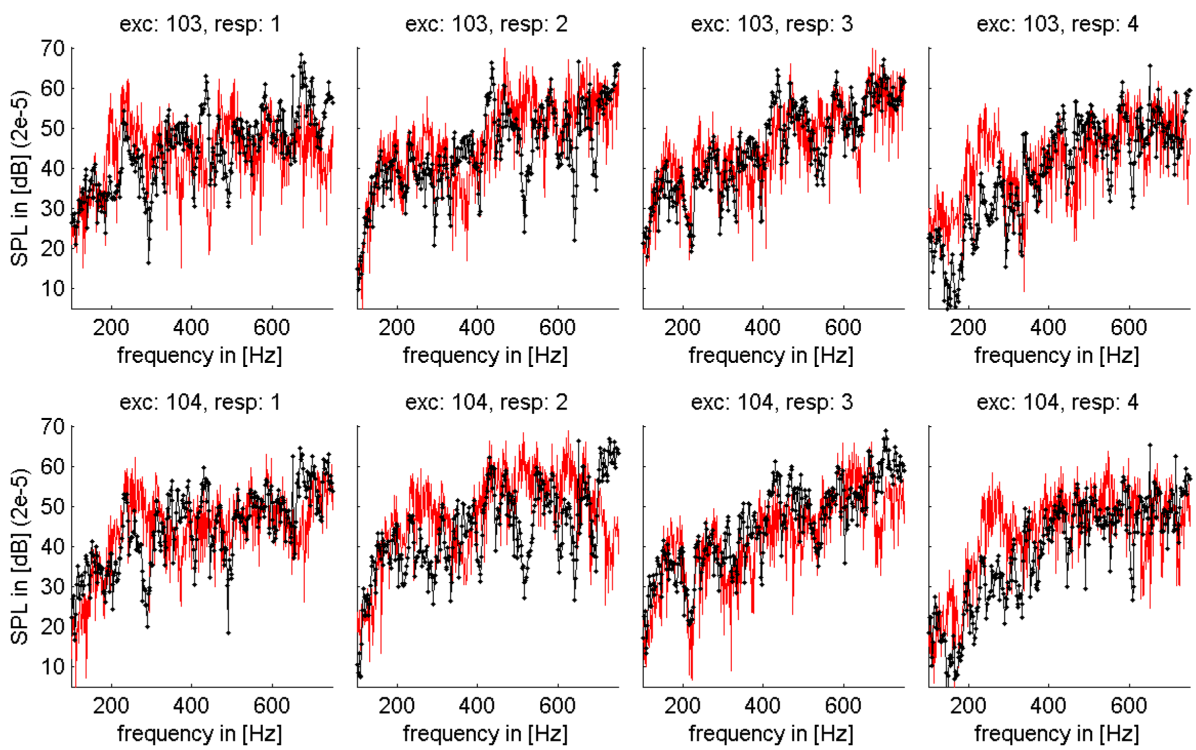

Figure 4. shows the comparison between measured and simulated SPLs (black) between 100Hz - 750Hz.

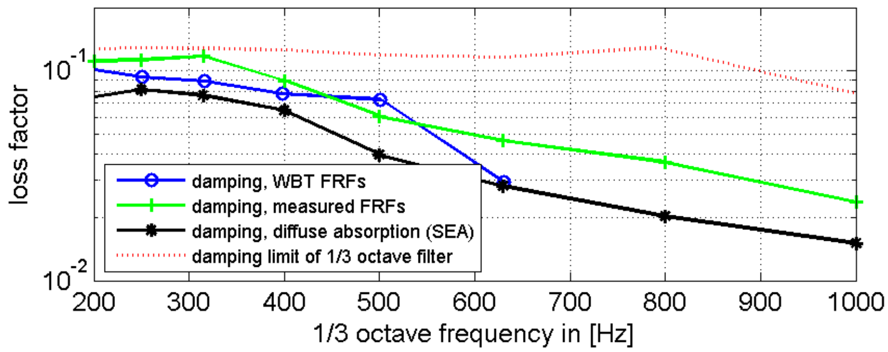

Figure 5. shows a comparison of damping between measurement, WBT and SEA simulations.

vehicle. The approximate excitation (red) and response points (blue) within the driver cabin are depicted in figure 3. The accuracy of all locations in the model compared to the measurements is approximately $\pm$5cm. SPLs at four response points and two excitation points are measured (red) and simulated (black). The comparison is depicted in figure 4 in the frequency range between 100Hz - 750Hz. Figures in the upper trace are showing the SPLs due to an excitation near the drivers head while figures lower trace are SPLs from an excitation just above the seat surface of the drivers seat. Except distortions at single narrow frequencies ranges and deviation between 200Hz -350Hz the agreement is approximately below 10dB. In general the measured trend is followed well by the simulation results. The observed misalignment of the measurement might be because of:

- Missing cockpit, imprecise head rest modelling and general geometrical differences between vehicle and model (compromises in order to reduce the DOFs of the model)
- Impedance measurement does not take into account inhomogeneous properties especially of the seat and the carpet
- Leakage of seals, air evacuation path and Helmholtz resonators are not modelled

4. CAVITY DAMPING AND HEAD LINER ABSORPTION

Based on FRF simulation results the in-cabin damping of the WBT model is calculated. In total 33 FRF with 3 excitations and 11 response points (spatial statistically distributed) are calculated. A Schröder - Hilbert decay rate estimation method is applied to each inverse Fourier transformed and 1/3-octave band filtered FRFs and all decay rates β are averaged. The damping $\eta = \beta/(2\pi f_c)$ is calculated where f_c means the centre frequency of the 1/3-octave band. The results are depicted in figure 5. The green curve shows the in-cabin damping curve of the regarded SUV vehicle which was derived from 165 measured FRFs while the black curves shows the volume averaged damping results derived from an equivalent SEA model with diffuse absorption modelling applied. The dotted red curve shows an upper damping limit according to the maximum decay rate of the used 1/3-octave Butterworth filters. One can see a good agreement between WBT simulation and measurements. The WBT FRFs show single peak values at frequencies above 550Hz which are the reason for non decaying FRFs in the 630Hz 1/3-octave band. Therefore the 630Hz damping value is uncertain. The comparison with the internal loss factor from SEA shows much higher differences compared to the measurement which indicates that the relationship between average surface absorption $\alpha_m = \eta(\omega_m)4V\omega_m/(Ac_0)$ and the internal loss factor η is not valid for arbitrary cavity geometries.

Usually the absorption of a cavity is designed using e.g. SEA analysis or T60 measurements. Both methods have the disadvantage that only the overall absorption of the whole cavity can be designed and no information about local transfer paths at certain frequencies are resolved. Therefore the WBT is applied in order to estimate the influence of a head liner absorption with respect to human in-cabin communication. In the WBT SUV model a point volume source was placed near the mouth of the drivers head and all responses are calculated in the xy-plane near the ears. All FRFs are calculated within 10Hz - 750Hz. This simulation was repeated for different absorptions. In the upper trace the results of the complete model with standard head liner is depicted. The middle trace shows results when the head liner was replaced by a PVC layer and the bottom trace shows the results when the complete model is regarded reverberant. Displayed are FRFs scaled to dB in the range between 60dB (blue) to 100dB (red) at certain frequencies. The influence of trim absorption is apparent when the reverberant model results are compared to the two trimmed models. With increasing frequency and distance from the source the damping becomes increasingly effective. In general the transmission between driver and co-driver is good except at the 550Hz frequency. In all other depicted frequencies there are sufficient SPL maxima close to the head of the co-driver. The transmission between driver and left rear position is worse for all selected frequencies except at 350Hz. A comparison between standard head liner with absorption and PVC with no absorption reveals only very small differences with respect to the spatial distribution. Especially at 550Hz and 750Hz it turns out that the FRF minima are less dominant which is an advantage for the PVC version. The bottom trace clearly indicates highest FRFs for all passenger positions as the damping is minimal. On the other hand annoying noise will be insufficiently suppressed.

In contrast to a spatial view the FRFs are depicted in the whole frequency range in figure 7 at certain vehicle passenger locations. Red curves are related to the model with standard head liner, green curves are related to a model with PVC head liner and blue curves are related to

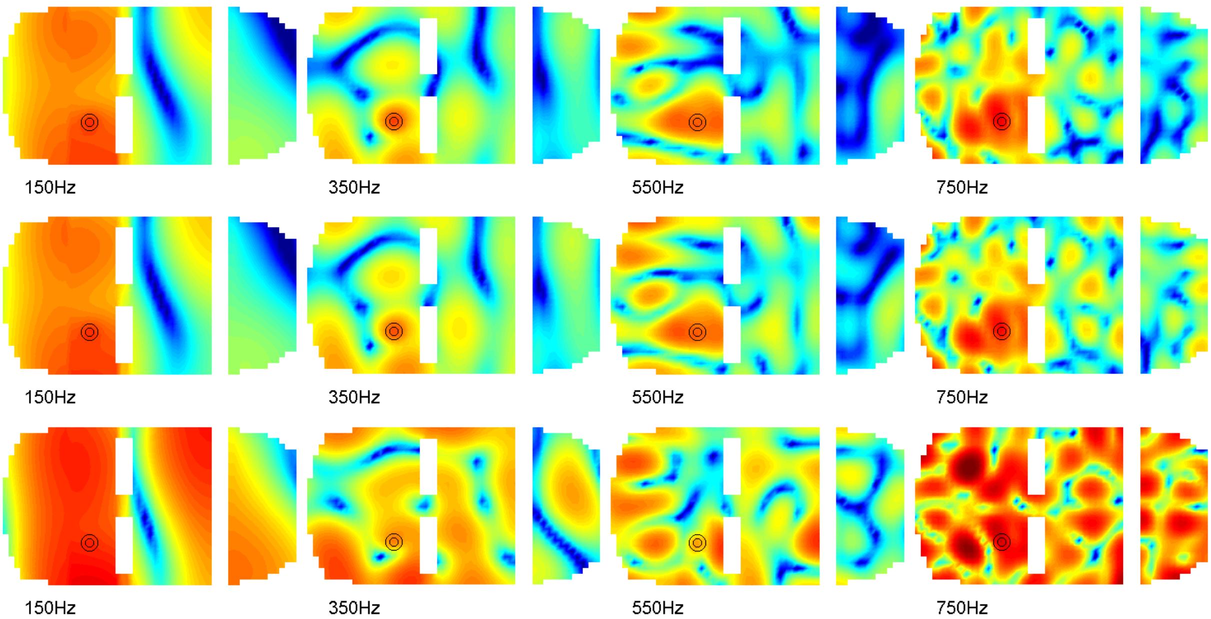

Figure 6. shows FRFs in the xy-plane at height of the human ear using the standard head liner (upper trace), a PVC head liner (middle trace) and a reverberant model (lower trace) (blue=60dB, red=100dB).

the reverberant model. A comparison between the standard head liner and the PVC head liner indicates an increase of the modulus of the FRFs for most frequencies above 200Hz between 1-5dB. Especially the FRF of the rear right position is increased between 5-10dB for frequencies between 550Hz - 700Hz. The frequency view in general indicates very low FRFs around 400Hz which is an important frequency for human communication.

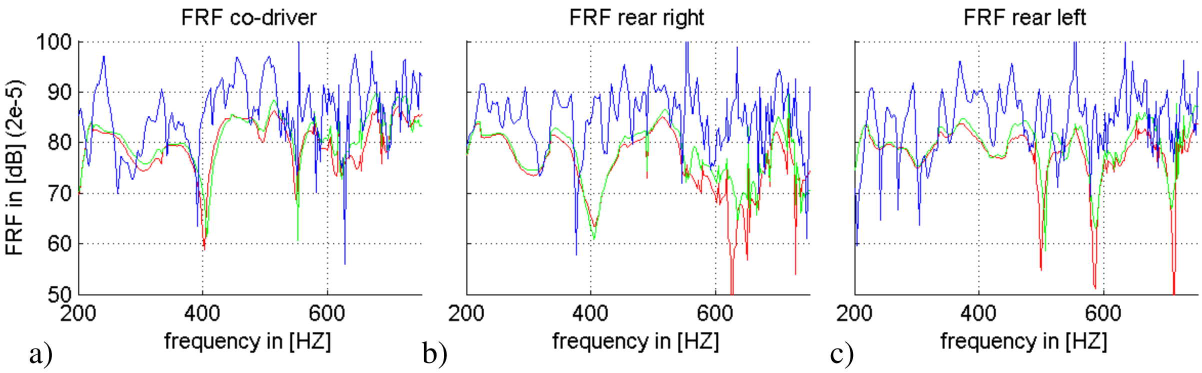

Figure 7. shows the FRFs of the model with standard head liner (red), of PVC head liner (green) and FRF of the reverberant model (blue). The PVC head liner shows the best transfer performance.

5. CONCLUSION

The WBT is a method which can successfully be used in order to apply acoustic analysis of complex cavities. It is shown that validation results are acceptable and that damping estimates are valid. A head liner absorption analysis revealed advantages for a PVC head liner. Therefore the WBT might be a useful tool which expands the possibilities of SEA analysis. On the other hand experience shows that the computation speed advantages of the WBT drastically decreases and might comes close to FEA when more complex geometries are analysed. Therefore the development of efficient algorithms which decompose WBT domains into a low number of convex sub domains seems to be important for a practical implementation of the WBT.

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