Use of the ray tracing based solver BEAM for the evaluation of transfer functions within the time domain

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ABSTRACT

As part of the research project "Computational Acoustics", the ray tracing-based solver BEAM has been developed in recent years to determine the backscattered sound pressure in the far field. This solver is able to calculate the scattering of complex structures composed of fluids and / or elastic materials (in the form of thin layers). Due to its high computing speed, it is therefore well suited for sweeps over a given frequency range.

The paper introduces an extension of the postprocessor, which converts a transfer function into a temporal or spatial impulse response by means of the FFT and displays it graphically, also in 3D. This representation allows the user a visual assignment of the signals to the external and possibly internal structure of the objects observed.

Using a complex structure with different material combinations, first results for the backscattered sound field are presented, analyzed and, if available, compared with results of BEM and FEM calculations.

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1 INTRODUCTION / BASICS OF THE BEAM PROCESS

The BEAM method[3] is a ray tracing-based solution method, which uses a plane wave sound source to determine the "start" beams incident on a structure. It is possible to use rays of fixed "size" (resp. area) or element-specific rays (one per element).

The ray tracing takes place up to a level $L_{b,\ max}$, taking into account shell boundary conditions, transmittance and/or reflection factors, and determines therefrom transmitted or reflected "child" rays and their pressure components.

An example of the ray path within a test structure up to a level $L_{b,\ max} = 5$ is shown in Figs. 1 (2D) and 2 (3D). The outer shell is having a transmission and a reflection factor, while the inner angle (yellow) is sound-hard and thus fully reflecting. “T” marks a transmitted, “R” a reflected beam and the numbers represent the tracing level (beginning at 0 for the initial “start” beam).

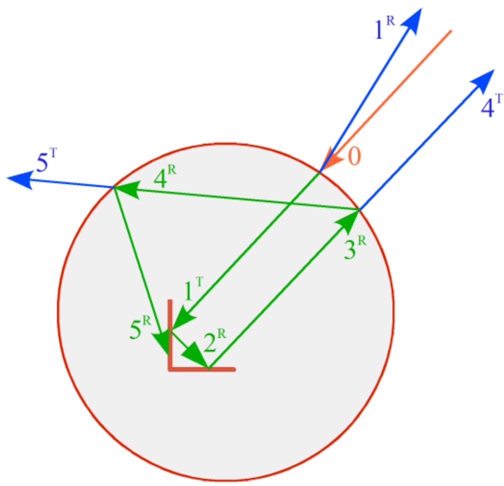

Fig. 1 – 2D ray tracing (maximum level 5).

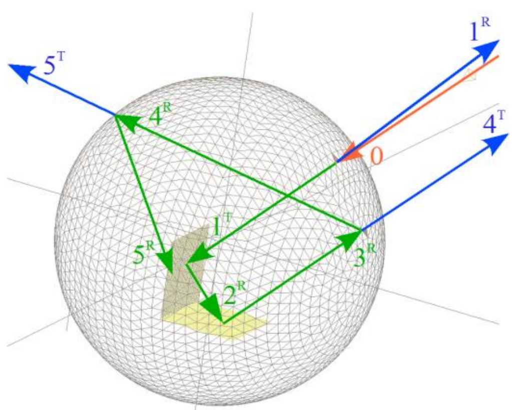

Fig. 2 – 3D ray tracing (maximum level 5).

In order to find the elements hit by a beam without having to perform a time-consuming $1{:}N_{elem}$ comparison, a boxing method from the Fast Multipole Method[1,2] is used to detect the appropriate elements.

A post processing calculation provides the values of the backscattered sound in the far field at given evaluation points.

2 SAMPLE MODEL

The model used consists of a spherical surface cut-out ("outer shell") and a cone shell, which is covered with a round plate (in total 13,084 elements). Figs. 3 and 4 show the model in 3D (shaded) and as a partial 3D grid model to clarify the construction.

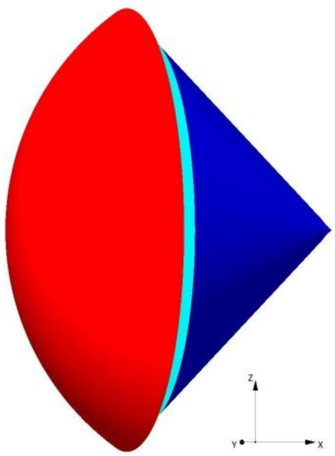

Fig. 3 – shaded 3D model.

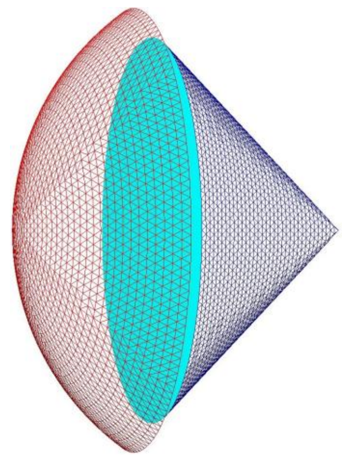

Fig. 4 – partially rasterized 3D model.

Fig. 5 shows a cross section of the model and the relevant materials and dimensions. Inside and outside the structures there is water (speed of sound c_{water} = 1,500 m/s).

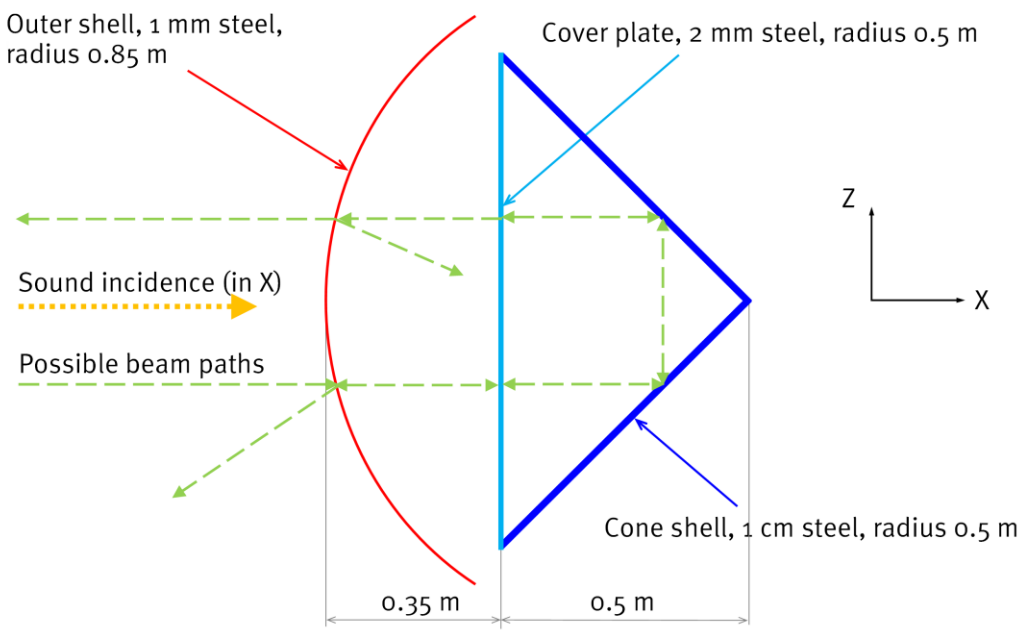

Fig. 5 – Cross section and dimensions of the model used.

The incident sound travels in positive X-direction and thus hits perpendicular to the outer shell. For ray tracing, this results in a large number of possible paths, so that a maximum tracing level with $L_{b,\,max}$ = 9 has been used for this model.

3 CALCULATION OF THE TRANSFER FUNCTION (FREQUENCY SWEEP)

The BEAM method was used to calculate the backscattered sound pressure in the far field for a frequency range between 2 Hz and 100 kHz with a step size of Δf = 2 Hz (N_{freq} = 50,000).

Fig. 6 represents the transfer function for a monostatic evaluation point at x = -10 km, whereby in all the following figures the normalized pressure (TES, target echo strength, recalculated to a distance of 1 meter) is given. Fig. 7 shows a section of it up to 10 kHz.

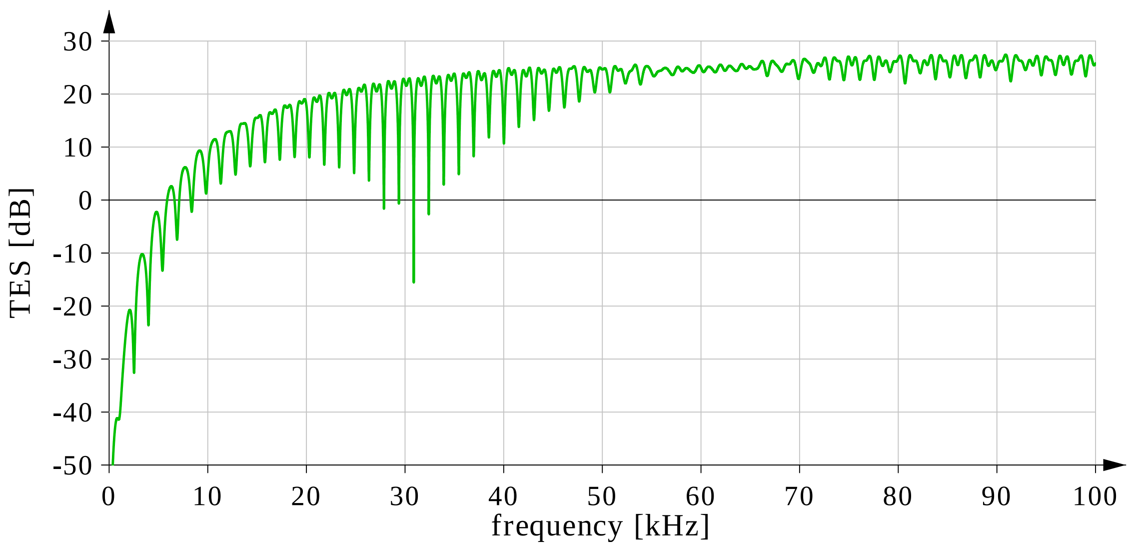

Fig. 6 – TES level in the far field, f = 2 Hz ... 100 kHz, BEAM solver (computing time: approx. 108 s).

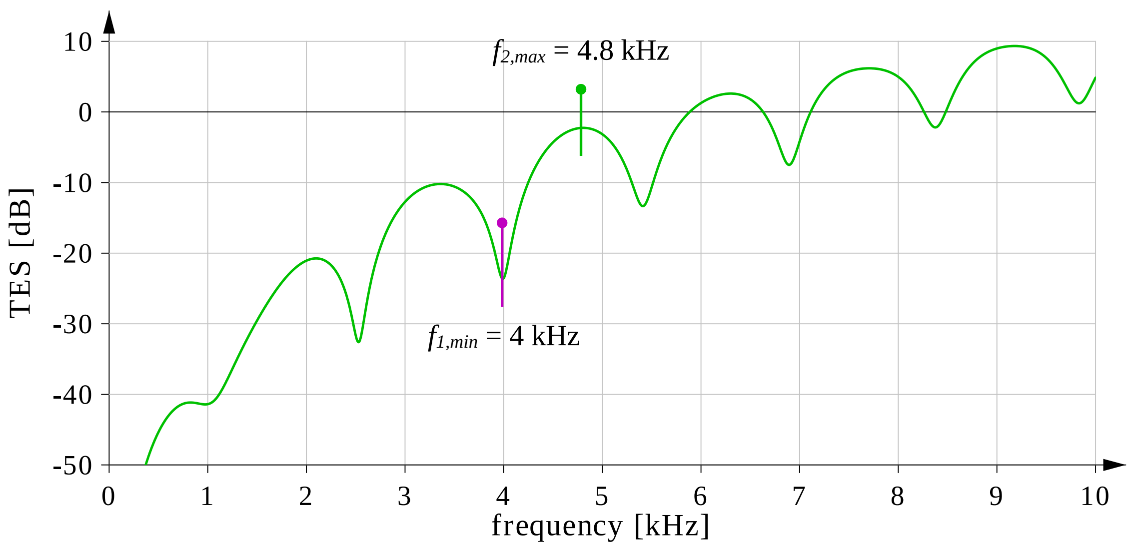

Fig. 7 – TES level in the far field, f = 2 Hz ... 10 kHz (section of Fig. 6).

In Fig. 7, two frequencies $f_{1,min}$ = 4 kHz (green) and $f_{2,max}$ = 4.8 kHz (purple) are marked, which represent a minimum resp. maximum in the transfer function and which are used in the following section.

4 CALCULATION OF THE IMPULSE RESPONSE BY MEANS OF FFT

By means of the FFT and the desired transfer function in the frequency domain, a corresponding impulse response in the time domain is generated from a simple sine pulse of a given duration (Δt_{in} = 2 ms, see Fig. 8) and fixed frequency.

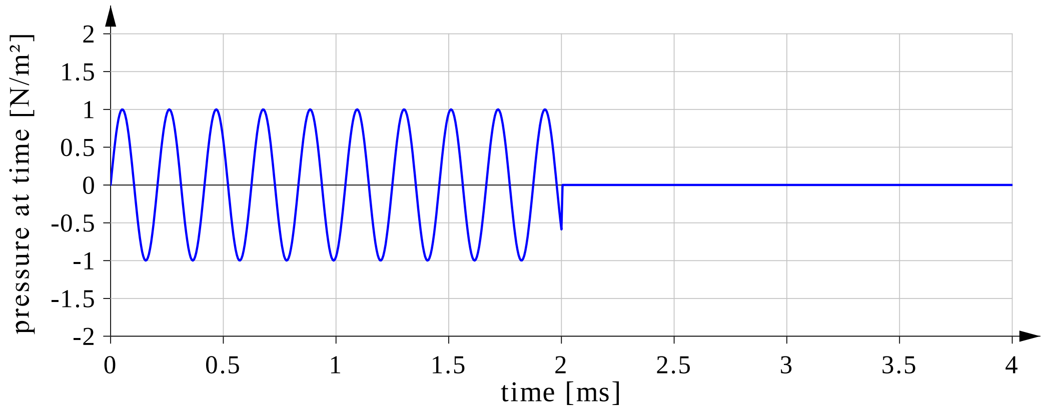

Fig. 8 – Excitation pulse, Δt_{in} = 2 ms, f = 4.8 kHz.

As already indicated in Fig. 7, $f_{1,min}$ = 4 kHz and $f_{2,max}$ = 4.8 kHz were chosen as examples of excitation frequencies, since there exists a minimum resp. maximum in the transfer function. The time assignment of the pressure in the following figures was distance-corrected according to the evaluation point so that the time point t = 0 corresponds to the "beginning" of the response.

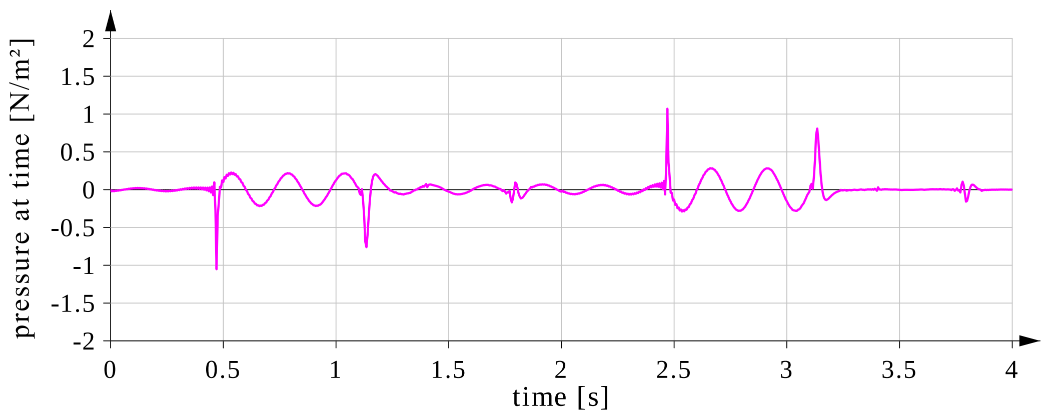

Fig. 9 – Impulse response for $f_{1,min}$ = 4 kHz (pressure over time).

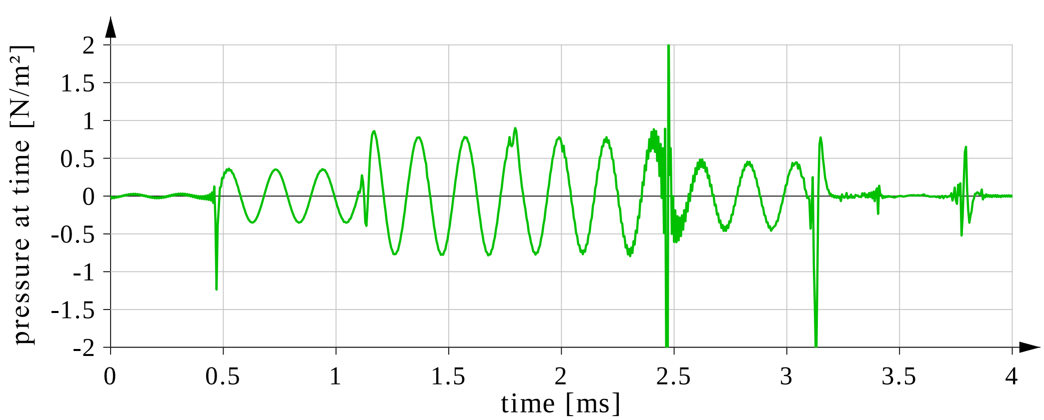

Fig. 10 – Impulse response for $f_{2,max}$ = 4.8 kHz (pressure over time).

The differences in the amplitude of the impulse response for both frequencies, especially in the range between 1.1 and 2.5 ms, corresponds to the expected minimum at $f_{1,min}$ = 4 kHz resp. maximum at $f_{2,max}$ = 4.8 kHz in the transfer function in the frequency domain (Fig. 7).

A time interval of 1 ms when using c_{water} = 1,500 m/s corresponds to a running distance of approx. 0.75 m (round trip). Accordingly, the pressure profile over the distance can be displayed (Fig. 11).

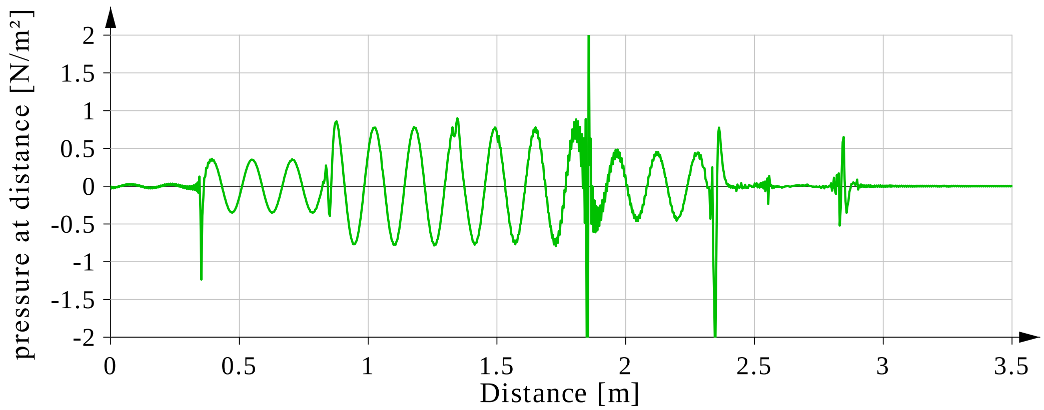

Fig. 11 – Impulse response for $f_{2,max}$ = 4.8 kHz (pressure over distance).

4.1 3D visualization

The postprocessor offers the option of displaying the received impulse responses in the 3D representation (Fig. 12).

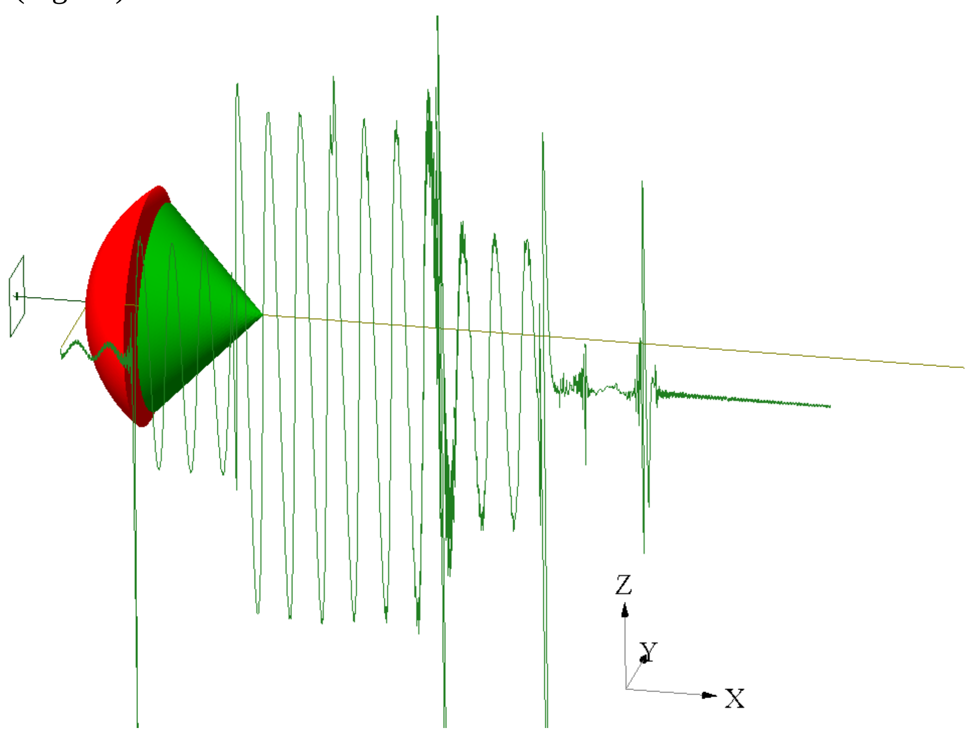

Fig. 12 – Visualization of the impulse response in 3D for $f_{2,max}$ = 4.8 kHz

4.2 Evaluation of the impulse response

If one chooses a suitable viewing plane in the 3D view, then the occurring events, in particular in connection with the "pressure over distance" representation (see Fig. 11), can be identified more easily (Fig. 13, events E1 .. E4).

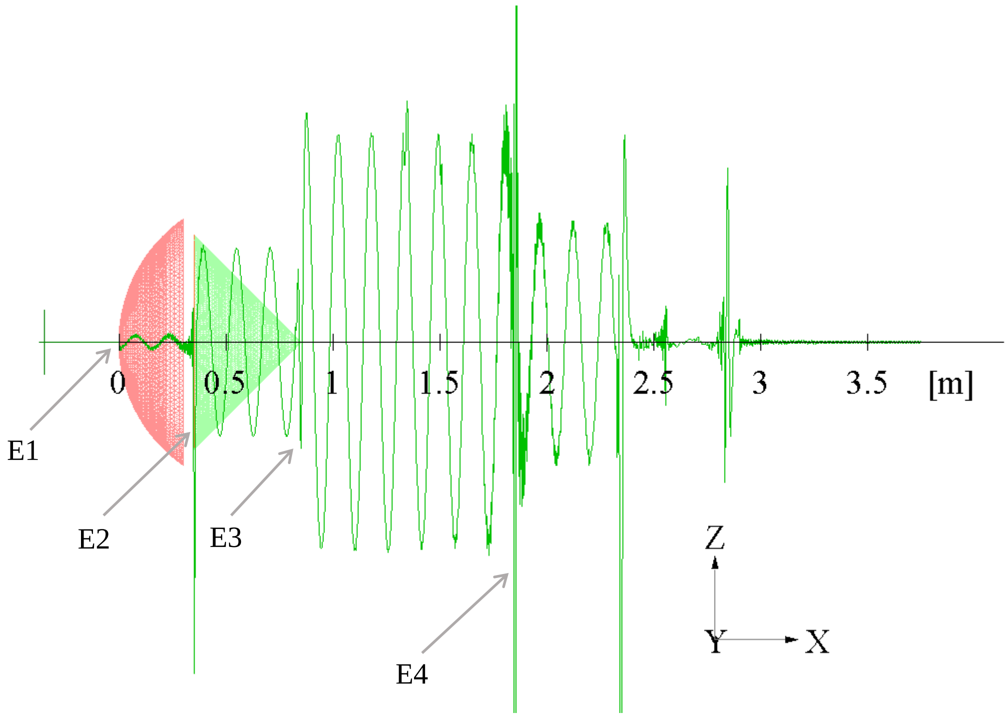

Fig. 13 – Visualization of the impulse response in 3D in the XZ plane for $f_{2,max}$ = 4.8 kHz (numerical values represent the transit distance)

E1: first response of the outer shell

E2: Round cover plate response at approx. 0.47 ms (≙ approx. 0.35 m)

E3: "strong" response of the cone shell ("double mirror"), all running times and distances within the cone are identical (about 1.33 ms ≙ approx. 1 m)

E4: "End" of the path within the cone, decay of the response ($t_{E4} - t_{E2} \approx \Delta t_{in}$ = 2 ms)

5 COMPARISON WITH OTHER CALCULATION METHODS

Particularly in the "low" frequency range (up to approx. 10 kHz in this case), the BEAM method often yields insufficient results due to the far-field approximations used.

Fig. 14 shows a comparison of the transfer functions for a frequency range up to 20 kHz for different calculation methods (BEAM [▬], indirect BEM[4] (IBEM) [▬] and combined with a FEM shell boundary condition for the outer shell [▬]).

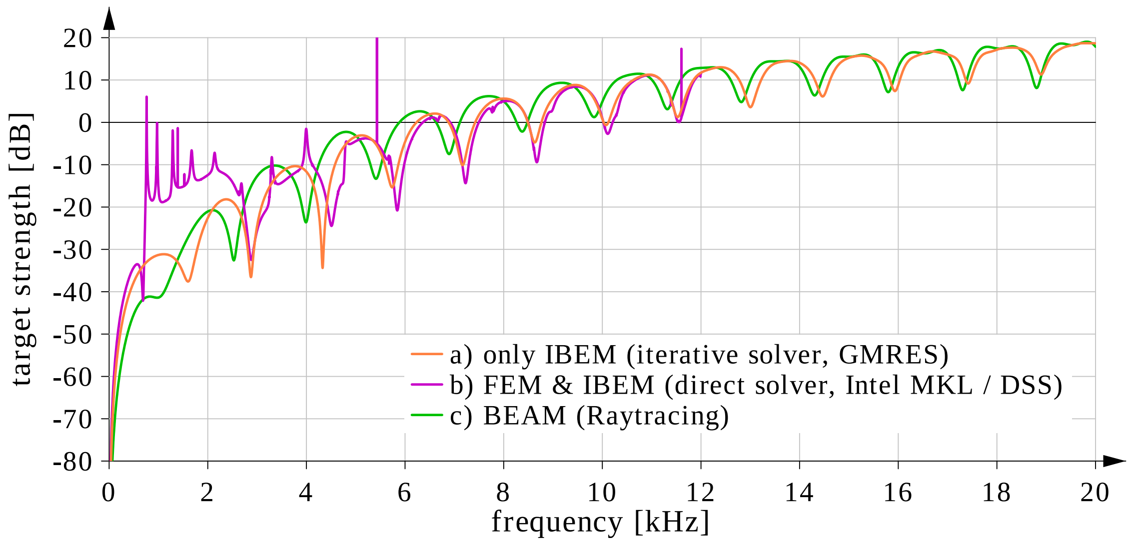

Fig. 14 – Normalized sound pressure level in the range up to 20 kHz using different methods.

Note on the calculation times (6,000 frequencies, up to 12 kHz):

- only IBEM:	approx. 2.5 s per frequency (13,084 degrees of freedom, in total approx. 4:10 h)
- FEM & IBEM solution:	approx. 25 s per frequency (28,218 degrees of freedom, in total 41:45 h)

At lower frequencies, the results of the methods differ more, especially the resonances resulting of the FEM shell are clearly visible. At the higher frequencies, the pressure curves are in better agreement. This offers the generation of a "composite" transfer function.

5.1 "Combined" transfer function

The postprocessor has been extended by a corresponding combining option including a smoothing function, where the frequency ranges or transitions requested can be defined separately. A corresponding result (section up to 20 kHz) is shown in Fig. 15.

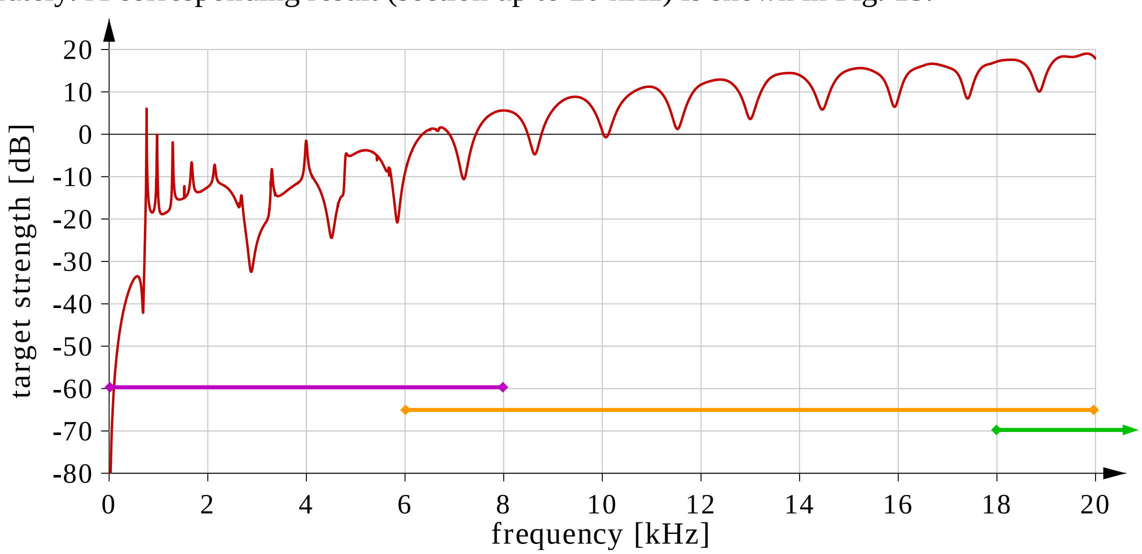

Fig. 15 – Combined normalized sound pressure level (section up to 20 kHz).
FEM [▬]: up to 8 kHz, indirect BEM [▬]: 6 - 20 kHz, BEAM [▬]: 18 - 100 kHz

Results for impulse responses using the combined transfer function were not available at the time of creating this paper, but are expected to be available in the form of an updated version on our website (http://projekt.beuth-hochschule.de/ca, see "Veröffentlichungen, Projekt Computational Acoustics I & II") at the end of August 2018.

6 CONCLUSIONS

The BEAM method is well suited for the rapid generation of FFT-suitable transfer functions (with equidistant frequencies), the resulting impulse responses reflect the expected behavior of the test structure.

A calculation with other numerical methods (conventional BEM, indirect BEM, FEM) is feasible, but requires a much greater amount of computational time and is therefore usually only useful for the low to medium frequency range.

A first option for the creation of a combined transfer function using partial solutions generated with different solving methods has been implemented, but requires further investigation.

7 REFERENCES

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