Detection of radiation-relevant areas using various numerical methods, measurements and sound source types

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Introduction

Reducing the sound reflected by objects under water and thus their "visibility" is a design challenge and requires detailed information about the geometry- and material-dependent backscattering behavior of the structure.

Using various numerical methods and measurements, the radiation-relevant areas of objects are to be determined using generic model examples, taking into account different types of sound sources.

The contribution briefly presents the methods used (boundary element method, ray tracing and hotspot detection), analyzes the results of numerical simulations and compares them with corresponding measurements.

Methods used

Boundary element method (BEM)

The BEM is a widely used numerical method for calculating boundary value problems and requires only the boundaries of the objects under consideration, which are broken down into corresponding three-dimensional surface elements whose size depends primarily on the required frequency.

Combined with additional methods (Burton-Miller method, inertial coupling [1], fast multipole method [2], FEM shell boundary condition [3]), the BEM allows the solution of corresponding acoustic problems on the basis of a fully populated complex matrix of order N^2 (N = i.g. number of elements / unknowns).

This system of equations can be solved using direct solvers, iterative solvers or in combination with approximate methods.

Ray tracing method ("BEAM")

As an alternative to the BEM with its high computational effort and memory requirements, the so-called "BEAM" ray tracing method was developed, which generates "rays" from a sound source that impinge on the object under consideration (for details see [4, 5]).

Complex reflection and transmission coefficients are determined at the hit points, taking into account the specified boundary conditions, and "child" beams are generated which are traced up to a predefined level.

Material-dependent refractions and possible multiple reflections within the structure can be taken into account. A post-processing calculation provides the backscattered sound pressure in the far field at given evaluation points.

This method has been extended so that a monopole source (as an alternative to a plane wave) can also be used. In the examples given, one start beam is generated for each element and tracked further.

An additional advantage is that the same 3D surface models can be used as for the BEM.

Model used

The model used was a "corner icosahedron" consisting of 20 triple mirrors, each with 3 isosceles triangles of the same size (edge lengths approx. 12 & 18 cm, outer diameter: approx. 30 cm). Steel (thickness: 2 mm) was used as the shell material.

Due to its size and multiple symmetries (8-fold symmetry in the 3 main planes (each octant) or 4-fold (90°) in the XY evaluation plane), this model is well suited for numeric simulations and measurements in a water tank [6, 7].

Numerical model

The numerical model consists of 185,814 elements with an edge length of max. 2.5 mm. This makes it suitable for frequencies up to 120 kHz, taking into account the 1/6λ rule ($\lambda_{120\,kHz} \approx 0{,}013$ mm for water).

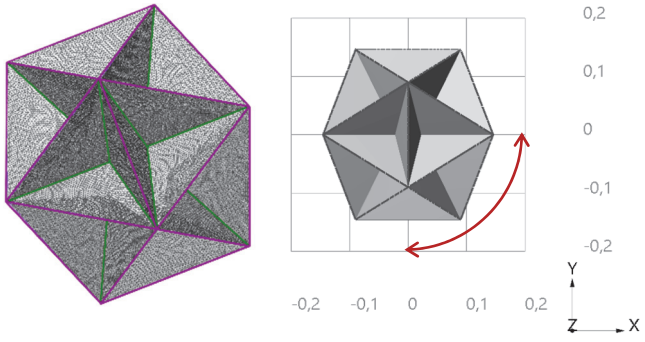

Fig. 1: Icosahedron model with triple mirror corners and its position in the XY plane (the double arrow shows the quadrant symmetry range)

For the BEM, the fluid-structure-interaction was realized by an inertial coupling [1] (without consideration of the stiffness). Mathematically, this corresponds to an impedance boundary condition.

For the ray tracer, the material parameters of the shell are converted into corresponding complex reflection and transmission factors, taking into account the stiffness of the elastic steel.

Real model / measurements

The equivalent real body consists of an air-filled welded steel shell and has a fastening ring on one edge (Fig. 2).

Details of the setup used for the measurements (methodology, transducer model types, size of the water tank, etc.) can be found in [6]. A side-scan sonar ("plane wave") and a spherical transducer ("monopole") were used.

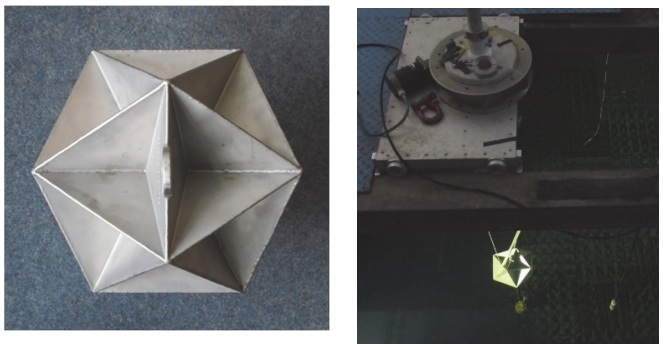

Fig. 2: Real model and its positioning in the water tank for the measurements

Results

The calculations with the specified methods and sound source types were each carried out for 21 frequencies (f = 80 ... 120 kHz, step size 1 kHz) and then averaged (f_{aver} = 100 kHz).

The following figures show the so-called target echo strength (TES, resulting from the backscattered sound pressure) on a circle in the XY plane, whereby only one quadrant is shown for clarity and due to the symmetries.

Sound source: plane wave

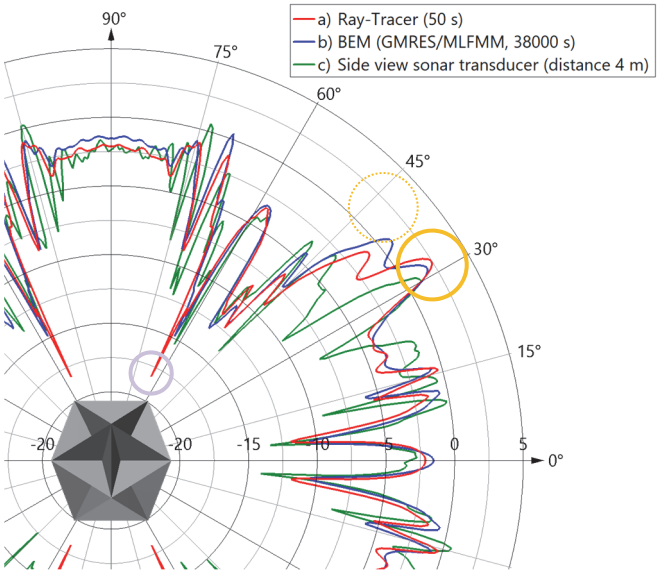

Fig. 3: target echo strength (TES) of the icosahedron, plane wave source, 186k elements, averaged over 21 frequencies (80 … 120 kHz), having a maximum at 32°

The results for the ray tracer and the BEM using a plane wave are mostly in good agreement. At the maxima, the differences are approx. ±1 dB, in some angle ranges up to ±3 dB.

In the measurement result, all significant maxima can be found. However, carrying out the measurement proved to be difficult, particularly due to the required exact positioning of the measurement object (rotation in the tank, post-swing effects) and led to angle-specific shifts in the pressure curves or asymmetries (Fig. 4).

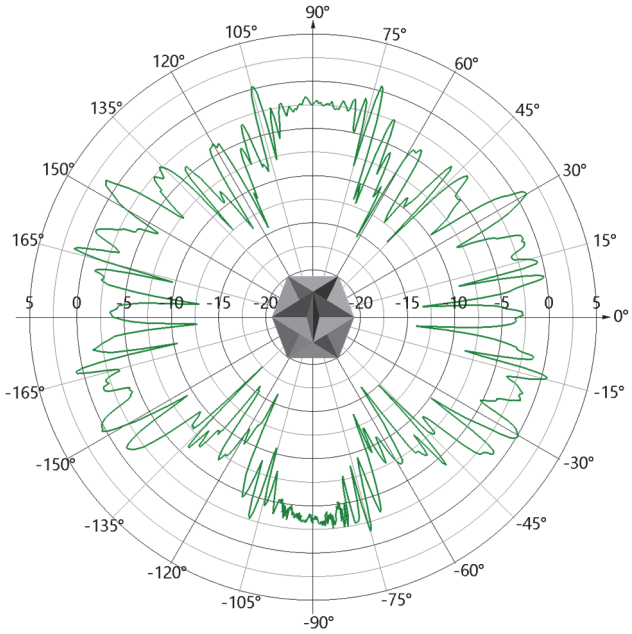

Fig. 4: target echo strength (TES) of the icosahedron, measurement result only, side view sonar transducer, 100 kHz (averaged)

Sound source: monopole, distance 1.2 m

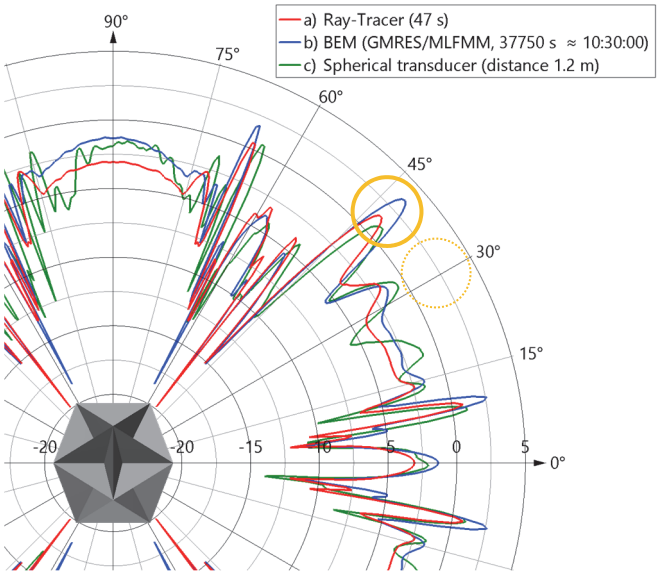

Fig. 5: target echo strength (TES) of the icosahedron, monopole source, distance 1.2m, 186k elements, averaged over 21 frequencies (80 … 120 kHz), maximum at 42°

Even when a monopole sound source is used, the curves agree relatively well. The deviation between the numerical methods (up to 2 dB) is a bit greater than with the plane wave.

Overall, the measurement result with the spherical transducer even agrees slightly better with the simulations results.

Comparison of plane wave and monopole

If we compare the results for the plane wave and monopole, the order of magnitude of the target dimension is comparable. However, angle-specific shifts can be seen at some maxima, particularly at approx. 32° (plane wave) and approx. 46° (monopole, see orange markings in fig. 3 and 5).

The angle-dependent shift of the maxima can be explained by the fact that the spherical wave emitted by the monopole does not represent a “parallel wave distribution” as with the plane wave, due to the small distance between source and object. Accordingly, the double and triple mirrors focus at other angles due to the fan-like sound propagation.

Hotspot detection

The method for so-called hotspot detection is able to visualize radiation-relevant areas outside and inside the structure(s) for selected sound incidence directions, e.g. at maxima of the previously TES levels in the far field [8].

The “beam array” generated by ray tracing is used to sum up the complex pressure component of each ray on so-called “tiles” of a projection plane, using special integration and filter functions, which are then visualized.

Evaluation for a maximum and minimum

To illustrate the hotspot method, this was carried out for the plane wave source at two prominent angles:

a) a **Maximum** at $\alpha_{max} = 32°$ (fig. 3, orange circle)

b) a **Minimum** at $\alpha_{min} = 64.5°$ (fig. 3, light gray circle)

The following figures show the summation of the complex pressure components for the ray tracing reflection levels **1**, **1&2** and **1,2&3** (for details see [4,5,6], higher levels cannot occur due to the geometry of the model), all using the same range of values and the same color scaling.

Summation using absolute values (without phase)

Fig. 6 shows only the absolute value of the far-field summation (without taking the complex phase into account).

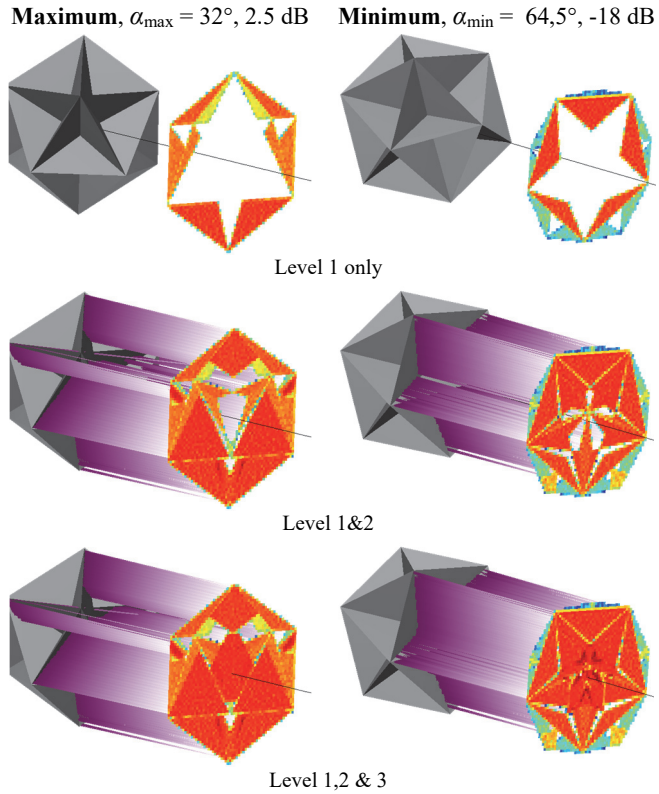

Fig. 6: results of the far-field summation (absolute values, **without** consideration of the phase)

The summation components appear comparable for all levels without taking the phase information into account.

Therefore, this evaluation **does not explain** the significant difference of the TES values at the two specified angles.

Summation using values and phase

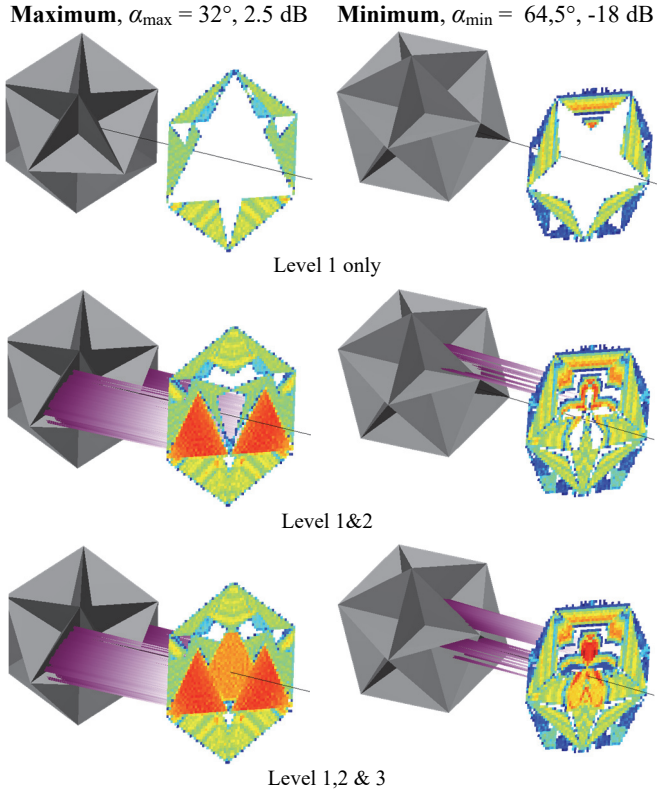

Fig. 7: results of the far-field summation (complex values, **with** consideration of the phase)

If the phase information is included in the summation (Fig. 7), it becomes apparent at the maximum for levels **1&2** that two double mirrors provide the essential components here, as all beams are in phase there, and for levels **1,2&3**, the component of a triple mirror is added.

For the minimum, on the other hand, the absolute values are similar, but due to the different phase position of the backscattered sound, large proportions cancel each other out and thus lead to a significantly lower TES value.

Summary and Outlook

In the investigated high frequency range, the comparison between the BEM, the ray tracer and the measurement results shows that the stiffness does not play a relevant role.

At lower frequencies, e.g. at 20 kHz as in [7], the elastic properties have a much stronger effect. In order to better understand these effects, a full FEM-BEM coupling may be used to simulate the fluid-structure interaction.

First test calculations at these lower frequencies have shown, however, that very strong fluctuations in the target dimension occur even with small frequency changes when using the FEM.

However, due to the fine discretization of the structure required for the relevant frequency range from 80 kHz and

higher and the resulting high memory and computational effort for the FEM-BEM equation system, this cannot be realized with the resources currently available in the project.

For this reason, investigations into alternative methods, particularly for reducing the equation system are planned for the near future.

Project partner

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