SIMULATION BASED DESIGN FOR ACOUSTIC SYSTEM ANALYSIS OF UNDERWATER SENSORS

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Abstract

In the field of underwater acoustics, special consideration has to be given to the problem of interaction of sonar sensors with the platform on which these systems are mounted. An integrated design approach based on numerical simulation tools has been developed. The influence of the acoustical environment with respect to the self-noise level can be analysed in a complex ship's structure using the explicit Finite Element Method. The basics of this method are outlined and results are presented.

I. Introduction

The sonar systems developed by STN Atlas Elektronik for the Navy cover a broad range of frequencies. Thus, for example, a Towed Array Sonar (TAS) has a typical frequency range of 0.1 to 1 kHz, a Cylindrical (or Conformal) Array Sonar (CAS) has a working frequency of approximately 1 to 10 kHz. An intercept passive sonar, on the other hand, operates in a frequency range of approximately 1 to 100 kHz (see Fig. 1). Although the design of these sonar systems differs considerably, their basic structure is very similar:

- a piezoelectric element, active or passive, embedded in a mechanical structure (single transducer)
- an overall sensor or transmitter, consisting of single transducers
- a location on a ship (submarine or surface vessel) or, for a TAS, the connection with a towing cable.

This shows that the surrounding structure plays an important role irrespective of the level on which a sonar or sonar element is considered. In a computational analysis, which is the core element of the Simulation Based Design, phenomena such as scattering, diffraction and general fluid-structure interaction have to be taken into consideration, too. Analytical approaches are extremely difficult, especially where the acoustic wave length is within the spatial order of magnitude of the structure to be analysed. For these problems, explicit Finite Element Methods (FEM) are particularly suitable.

The basic characteristics of this method are outlined in section II, the noise emission of a (submarine) hull test structure, determined by means of computation and measuring technique, is stated in section III as an example of application. Section IV concludes with a short summary.

II. Description of the numerical method

The explicit FE method (for overview refer to [1], for example) is based on the continuum-mechanical equations

$$\begin{aligned} \rho \cdot \underline{a} &= div(\underline{\underline{\sigma}}) \\ \dot{\underline{v}} &= \underline{a} \\ \dot{\underline{x}} &= \underline{v} \end{aligned} \qquad (1)$$

where ρ is the mass density, $\underline{\underline{\sigma}}$ is the Cauchy stress tensor and $\underline{a}, \underline{v}, \underline{x}$ are the acceleration, velocity and position of a point. The dot represents the differentiation in time. For reasons of computational efficiency, a linear interpolation function for displacements and velocities is used in the elements for FEM discretisation. Thus, considering an element, a constant strain and also a constant stress are evaluated by means of time integration of the element strain rate

$$\dot{\underline{\underline{\varepsilon}}} = \frac{1}{2} \cdot (\nabla \underline{v} + (\nabla \underline{v})^T) \qquad (2)$$

so that a spatial 1-point integration is sufficient.
The Cauchy stress tensor $\underline{\underline{\sigma}}$ is divided into a deviator $\underline{\underline{\sigma}}'$, which contains the shear stresses, and a pressure p, i.e. in accordance with

$$\underline{\underline{\sigma}} = \underline{\underline{\sigma}}' - p \cdot \underline{\underline{I}} \qquad (3)$$

where $\underline{\underline{I}}$ is the unit tensor. The sole difference between a fluid element and a structure element is that $\underline{\underline{\sigma}}'$=0 is set for the former and p can be evaluated as a function of the volume strain rate (and generally the specific internal energy of the element). Otherwise, structure and fluid elements are treated in an identical manner. This automatically includes also fluid structure coupling.

The equations stated above permit different types of elements. Thus, volume elements, shell elements, truss and beam elements or, for example, special vibration attenuation elements can be formulated. The use of shell elements for modelling of thin, curved structures such as sonar domes is of particular importance for application of the method in the ship's environment.

Another important aspect is the possibility to keep the FEM mesh sufficiently compact by using so-called absorbing boundary conditions. Interfering reflections from the boundary of the region are reduced by such boundary conditions. Without such an option, the boundaries of the meshed region would possibly have to be expanded to such a degree that the number of the elements then required would make an efficient simulation impossible. Experience has shown that even local absorbing boundary conditions (so-called infinite elements) provide good results. Instead of the velocity change $\Delta v = v^{new} - v^{old}$ of a boundary node as per

$$\underline{v}^{new} = \underline{v}^{old} + \Delta t \cdot \underline{a} \qquad (4)$$

in a time increment Δt to be derived from (1), the node of an infinite element is subjected to a change in normal velocity component as per

$$\underline{v}_n^{new} = \frac{1-d}{1+d} \cdot \underline{v}_n^{old} + \frac{1}{1+d} \Delta t \cdot \underline{a}_n \qquad (5)$$

where the parameter d can be approximated by means of

$$d \approx \frac{1}{2} \cdot \rho \cdot c \cdot \Delta t \cdot A / m \qquad (6).$$

In this case, c is the fluid sound velocity, A the boundary area allocated to the boundary node and m the mass of the node. Equation (5) can easily be implemented as an extension of an existing computer code since a simulation program must already contain a velocity update as per equation (4).

Equation (4) also clearly shows the meaning of the term "explicit" in the description of the FE method: Vector a, evaluated as per equation (1), is evaluated at the previous time step t_{old}. Contrary to the normal FEM, it is now no longer necessary to determine and invert a stiffness matrix. As a price to be paid for this, however, the time increment Δt to be selected must be so small that acoustic waves can pass no more than one element within a time step (so-called CFL stability condition).

III. Example of application for noise emission

Here, the noise emission of a test structure will be described, standing in for the different applications of the simulation method in system analysis and transducer design. This test section with a height of approximately 2 m (see Fig. 2) comprises two curved steel walls which are to be used for approximation of the pressure hull of a real submarine. Now, if a periodic excitation is applied as a load to a wall from the inside (for example, to simulate the effect of machine vibrations), acoustic waves are transmitted into the surrounding water medium due to the vibrations of the steel plates and walls, thus producing a noise level in the water which decreases with the distance to the wall.

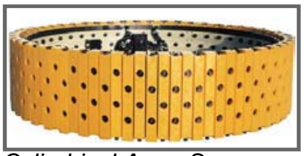
Fig. 3 shows the discretised FEM section model set up for this purpose (consisting of shell elements) and the incorporation of the structure in the surrounding water. For the noise analysis described here, absorbing boundary conditions have been assigned to the surface of the spatial region. (Note: A signal noise analysis of the test section would be performed, for example, by specification of an acoustic wave guide, i.e. reflecting boundary conditions, at the longer sides of the spatial region, the grid has already been prepared for this option).
Fig. 4 shows the relevant comparison of measurement (red squares) and computation (green dots). In this case, the distance-dependent noise level in water is shown for load introduction on a specified point on the plates with a specified frequency spectrum. A remarkable concordance between measurement and computation can be seen. With such a submarine section model, also the improvements by means of insulating measures and the effect of the noise on sensors in the pressure hull area of the submarine can be simulated quantitatively.

IV. Summary

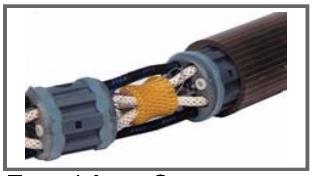
The analysis of wave propagation in the environment of sonar sensors and transducers is an important aspect of the development approach Simulation Based Design for acoustic systems. For this, the explicit FE method as briefly outlined above is particularly suitable. It permits the use of very large computational meshes and thus allows a detailed description of the wave phenomena.

Further reading

[1]: W. Herrmann, L.D.Bertholf:
"Explicit Lagrangean Finite Difference Methods" in
"Computational Meth. for Trans. Analyses",
NorthHolland, 1983



Cylindrical Array Sonar



Towed Array Sonar

Intercept Sonar

Fig. 1: Sonar Sensors

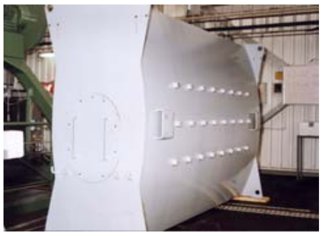


Fig. 2: Test Section

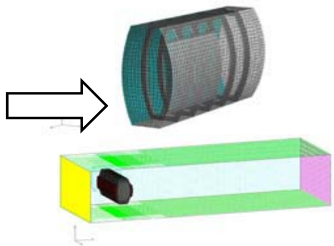


Fig. 3: FEM mesh

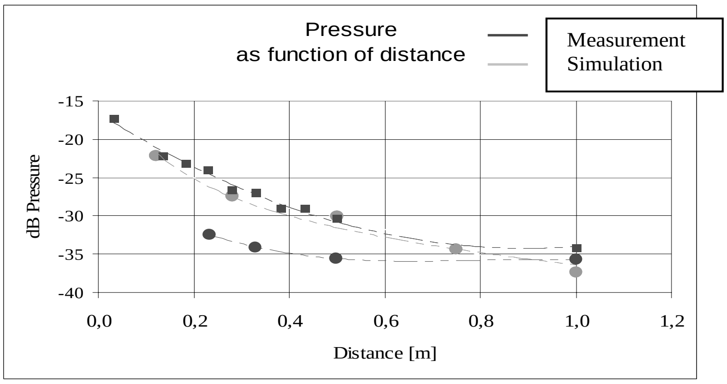


Fig. 4: Comparison of measured and simulated results of noise level (upper two curves)