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Partitioned simulation of the acoustic behavior of flexible marine propellers using finite and boundary elements

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In the last years, classification societies have announced several specifications regarding the , limitation of the noise level of ships. Accordingly, the prediction of the acoustic signature of cavitating propellers, which are the main source for noise generation, has attracted a lot of interest. For an accurate numerical simulation of the underlying physics, the deformation of the propeller has to be taken into account, which results in a fluid-structure interaction (FSI) problem.

In order to utilize different discretization methods for the individual sub-problems, we apply a partitioned solution approach. This makes it possible to use a finite element solver for the structural problem, while a boundary element solver is used for the fluid problem. From the solution of the FSI problem, the acoustic pressure in the far field is obtained using the Ffowcs William-Hawking equation.

1 Methodology

Within the partitioned solution approach, we utilize a staggered coupling algorithm. Focussing on the coupling between the solvers, we abstract the solution process of the fluid subproblem using the boundary element method (BEM) using an operator formulation:

$$\mathbf{t}_n^i = \mathcal{F}_n \circ \mathbf{d}_n^i. \tag{1}$$

Therein, n and i denote the current time step and coupling iteration, respectively. $\mathbf{t}_n^i$ denotes a vector of tractions, evaluated at the locations of the quadrature points of the structural solver. They are the output of the fluid solver $\mathcal{F}_n$ which takes displacements at the location of its mesh's nodes $\mathbf{d}_n^i$ and uses a barycentric interpolation scheme to evaluate the tractions at the desired locations. Similarly, the solution of the structural subproblem using the finite element method (FEM) is denoted by

$$\mathbf{d}_n^i = \mathcal{S}_n \circ \mathbf{t}_n^i. \tag{2}$$

Now, a staggered coupling iteration can be formulated as a modified fixed-point iteration

$$\tilde{\mathbf{d}}_n^{i+1} = \mathcal{S}_n \circ \mathcal{F}_n \circ \mathbf{d}_n^i, \quad \mathbf{d}_n^{i+1} = \mathcal{A}_n^{i+1} \circ \tilde{\mathbf{d}}_n^{i+1}. \tag{3}$$

Accordingly, we start every iteration by solving the fluid problem based on the latest displacements. Afterwards, the structural problem is solved to obtain $\tilde{\mathbf{d}}_n^{i+1}$, which is passed on to an acceleration method $\mathcal{A}_n^i$. Here, the Quasi-Newton least squares method from [1] is used to accelerate the coupling, i.e. to reduce the number of iterations. The iterations start with $\mathbf{d}_n^0 = \frac{5}{2}\mathbf{d}_{n-1} - 2\mathbf{d}_{n-2} + \frac{1}{2}\mathbf{d}_{n-2}$ (a tangent extrapolation method, see [1]) and end once the L_2 norm of the residual

$$\mathbf{r}_n^i = \mathbf{d}_n^i - \mathbf{d}_n^{i-1} \tag{4}$$

falls below $10^{-4}\sqrt{N}$, where N is the number of elements in $\mathbf{d}_n^i$. A detailed investigation of the coupling procedure is given in [2]. The acoustic pressure in the far field is evaluated using on the solution of the fluid solver based on the Ffowcs Williams-Hawkings equation (FWHE). Details about the procedure can be found in [3].

2 Numerical investigations

The simulation methodology presented above can be used in a flexible way to carry out virtual experiments regarding the efficiency and acoustic characteristics of flexible propellers. Usually 3–5 rotations of a propeller are covered by a simulation in order to reach a periodic state. Different wake fields defining the inflow to the propeller can be specified to account for the velocity distribution behind the hull when traveling straight ahead or during maneuvers. Figure 1 (left) shows an overview of

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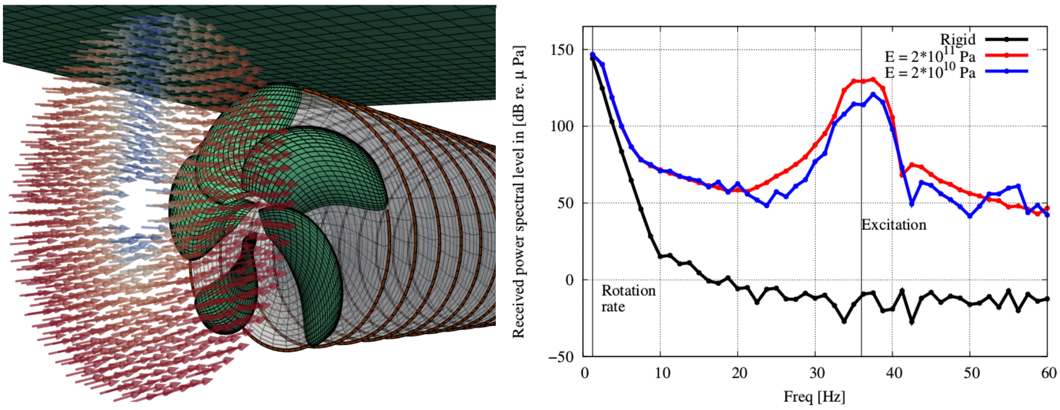

Fig. 1: Snapshot during the simulation of the P1356 propeller. Left: BEM discretization and wake field. Right: Acoustic spectrum for different simulation cases.

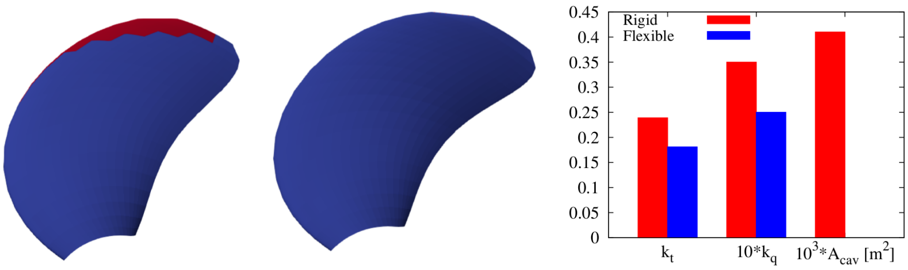

Fig. 2: Effects of blade flexibility on cavitation. Left: Cavitation extend for rigid blade at the 12 o'clock position. Middle: Cavitation extend for flexible blade at the 12 o'clock position. Right: Comparison of the thrust (k_{t}) and torque (k_{q}) coefficients and the cavitation area (A_{cav}).

the discretizations used to simulate the propeller P1356 (see [3] and the references therein), which includes a discretization of the water surface and the propeller's wake. Figure 1 (right) shows the evaluation of the acoustic field. For test purposes, the P1356 propeller was subjected to a periodically varying body load and considered in open water conditions. As expected, a peak is observed in the spectrum at the excitation frequency. The simulation was carried out using a time step size of $5 \cdot 10^{-4}$ s and a rotation of $\Delta\varphi = 2\,°$.

Figure 2 addresses the effect of cavitation, which is considered in the fluid simulations as detailed in [2] and - as illustrated therein - has a severe influence on the acoustic field. Here, we would like to emphasizes, that only by taking into account the blade flexibility (here Young's modulus $2.5 \cdot 10^{10}$), i.e. by performing a fluid-structure interaction simulation, the actual hydrodynamic coefficients can be predicted accurately.

Concluding, it can be stated that the partitioned solution approach is well suited for the assessment of the efficiency and acoustic signature of flexible marine propellers. In a current research project, we will utilize the developed framework for the optimization of propellers made from composite material.

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References

[1] J. Degroote, K. J. Bathe, and J. Vierendeels. Performance of a new partitioned procedure versus a monolithic procedure in fluid-structure interaction. Computers & Structures, **87**, 793–801 (2009).
[2] L. Radtke, T. Lampe, M. Abdel-Maksoud, and A. Düster. A partitioned solution approach for the simulation of the dynamic behaviour of flexible marine propellers. Ship Technology Research **67**, 37–50, (2018).
[3] T. Lampe, L. Radtke, M. Abdel-Maksoud, and A. Düster. A partitioned solution approach for the simulation of dynamic behaviour and acoustic signature of flexible cavitating marine propellers. Ocean Engineering **197**, 106854, (2019).

