Preliminary study on coupling of viscous and potential flow using domain decomposition and relaxation zones

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Introduction

The use of RANS based CFD methods has increased recently in naval and offshore engineering to overcome the limits of classical potential flow methods. The problem of seakeeping with forward speed causes many difficulties even for the linear potential flow methodolgy based on boundary integral equation (BIE) and enormous efforts are demanded when the wave steepness becomes higher, especially when wave breaking occurs. The computing resources becomes more powerful nowadays, and it encourages usage of CFD for naval applications, though it is still demanding. There are still many difficulties for practical application of CFD methods. Generation of meshes is one of those, the discretization of the whole fluid domain makes the modelling of the problem complex and expensive. It is usually concluded that the solution obtained from the finest mesh is chosen as the final value. The wave propagation is also an important difficulty specific to the naval and offshore field. The numerical schemes used in RANS based CFD methods induce numerical damping which added to the physical viscosity. As a result the waves generated by the wave-body interaction do not propagate properly up to far-field. On the other hand, the potential flow methods are quite suitable to propagate the waves up to far-field. However potential flow method becomes complex and difficult to solve when phenomena are highly nonlinear, as it ususally happens close to the body. Considering the characteristics of viscous CFD and potential flow methods, one idea is to combine these approaches to solve typical naval and offshore applications, as done by many researchers over the years [1, 2]. The present study focuses on the advantages and disadvantages of coupling those two methods by introducing two examples: pure wave propagation and a radiation problem (the swaying two dimensional Lewis form). For both problems, several types of outlet conditions of the CFD zone are tested. Those outlet consists of blending zones or mesh stretching and several schemes and target solutions are compared in terms of precision and computational cost.

Description

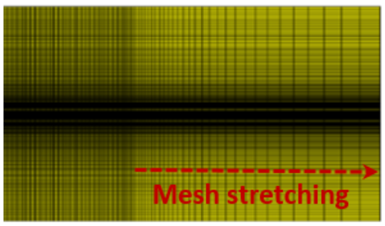
Finite volume method (FVM) based open-source library OpenFOAM is used in the present study. `foamStar` is developped by Bureau Veritas (BV) [3, 4] for naval and offshore purpose. `foamStar` is based on the standard multiphase solver of OpenFOAM (`interDymFoam`) and special modules are included for the generation of waves and floating body dynamics. Generation and absoprtion of waves in `foamStar` uses explicit blending (relaxation) scheme in a defined relaxation zone. The blending equations are given in (1) and (2)

$$\mathbf{u} = (1-w)\mathbf{u} + w\mathbf{u}^{target} \tag{1}$$

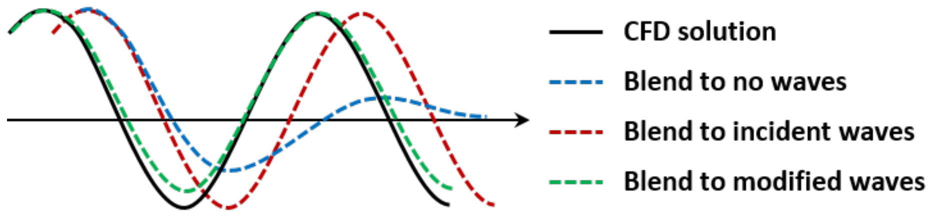
$$\alpha = (1-w)\alpha + w\alpha^{target} \tag{2}$$

where $\mathbf{u}$, α and w is the fluids velocity, volume of fraction and weight function. Target denoted on superscript represents the target value to be blended. The pressure is not blended because of mass conservation.
For the first problem of wave propagation, different outlets are considered: *mesh stretching*, *blending to no waves*, *blending to incident waves* and *blending to modified waves* (simple coupling). The schematic view of the different outlets is depicted in figure 1. *Mesh stretched outlet*, widely used in CFD fields, utilizes numerical damping arising from the stretched mesh, making waves damp out. The conditions *blending to no waves* and

blending to incident waves are given by setting the target values as zeroes and incident waves respectively in the blending equations (1) and (2).
When propagating in the CFD domain, waves change slightly due to numerical effects. Therefore when entering outlet it does not match exactly with the incoming waves. The condition *blending to modified waves* assumes then in the target solution that the waves amplitude and phase change during the propagation in the CFD domain but that the wavelength and period stay constant. Consequently, the change of wave amplitude and phase are computed by Fourier transform over one wave period using the one point measurement located one wavelength before the outlet. The target solution used in the *blending to modified waves* uses the same expression as the one used in *blending to incident waves* but it has time varying wave amplitude and phase.



(a) Mesh stretched outlet



(b) Blending outlet with different target values

Figure 1: Different outlet tested in the wave propagation case

The second test case "swaying two dimensional Lewis form" is considered to remove incident waves and to see the coupling effect on perturbed waves. A schematic view on swaying Lewis form is depicted in figure 2. The considered outlet are in this case *mesh streched outlet*, *blend to no waves* and *blending to potential flow solution*. The potential flow solution is available thanks to Ursell-Tasai's multipole expasion [5, 6].

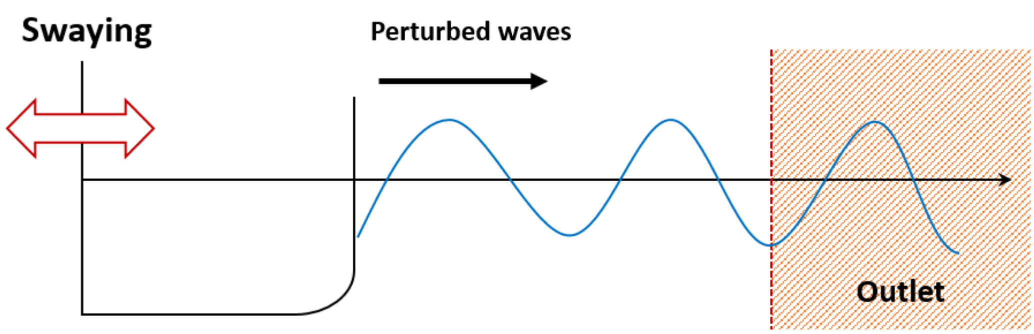
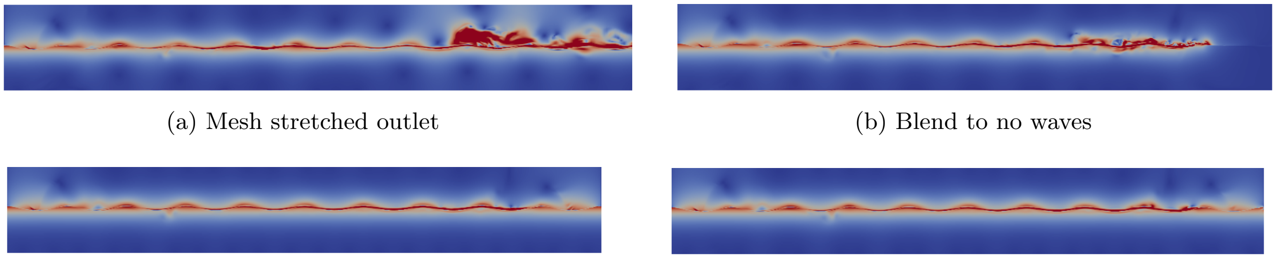


Figure 2: Schematic view of the radiation problem with outlet

Results and Discussion

For the first test case, the velocity fields obtained using the different outlets are shown in figure 3. The instabilities are observed for all outlets. Relatively small instabilities are observed when *blending to incident* and *blending to modified waves* are applied compared with the results obtained with other outlets. The wave reflection coefficients are measured from 250 wave gauges located in the middle of the domain of interest and given in Table 1. All blending schemes give a smaller wave reflection compared with the one obtained with mesh stretched outlet. Comparing the various blending schemes, the smallest reflection is measured when the *blending to modified waves* is used. Comparing with *blending to incident waves*, only a small improvement is observed but it has to be noted that comparing with *blending to no waves* is more reasonable because it is more common and general in CFD methods.



(a) Mesh stretched outlet (b) Blend to no waves

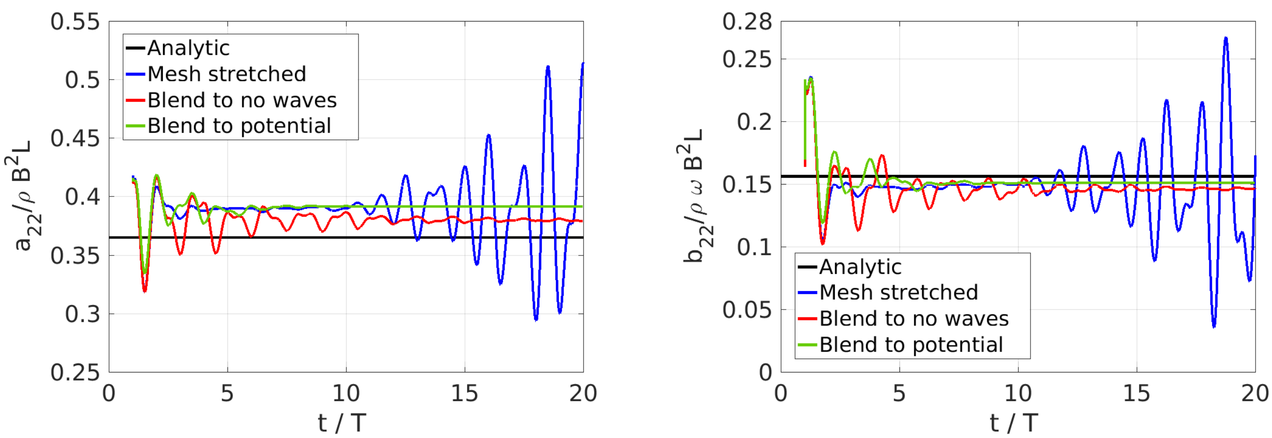
(c) Blend to incident waves (d) Blend to modified waves

Figure 3: Velocity fields obtained with different outlets

Table 1. Reflection coefficient obtained with different outlets

Outlet	Refelection Coef.
Mesh stretched	0.207
Blend to no waves	0.077
Blend to incident waves	0.042
Blend to modified waves	0.039

In the second test case, the total computation domain is expected to be reduced when the target values blended are closer to the values of outgoing waves. The size of the relaxation and pure CFD zone (without blending) are varied and tested with different outlets. For all tests, the computation cells near to the body are always kept of similar size. The results show that having target values similar to the outgoing waves can help to reduce the size of both the relaxation and the CFD zone but it shows also that the computation domain cannot be reduced dramatically. In particular, the radiation forces are more sensitive to the size of the relaxation zone than to the size of the CFD zone. The results about the size of the computational domain will be presented in the workshop. The convergence of the radiation forces acting on Lewis form using the various outlet conditions are shown in figure 4. For the comparison, same size of pure CFD zone is used but the size of the relaxation zone is varied. The radiation forces with mesh stretched outlet start to diverge after some periods and it results from the pressure modulation in the outlet. Comparing the convergence of radiation forces, *blending to potential flow* is faster than *blending to no waves*. Simulation time to get converged values with *blending to no waves* requires three times of *blending to potential flow*.



(a) Added mass (b) Radiation damping

Figure 4: Convergence of radiation forces acting on Lewis form

The radiation coefficients are compared with the analytic values in Table 2. The smallest errors are obtained with *blending to potential flow* even if the smallest relaxation zone is used. However, the increase of accuracy is small comparing with the solution obtained with *blending to no waves*. The total computation time to get converged radiation forces are given in Table 3. The results obtained with *mesh stretched outlet* is excluded because it diverges and a long computation time is required comparing with what is needed with blending schemes. In view of simulation time, the *blending to potential flow* converges faster than *blending to no waves* but the computation time needed for each time step is 5 times longer than with *blending to no waves*. As a whole, the total computation time demanded by *blending to potential flow* is 3 times longer than what needed with *blending to no waves*.

Table 2. Radiation coefficients and errors obtained with different outlets

Coef.	ω	Analytic	Mesh stretched	Blend to no waves	Blend to potential
a'_{22}	2.4	1.304	1.298 (diverge)	1.283	1.316
	4.2	0.136	0.148	0.129	0.141
	7.0	0.365	0.390	0.380	0.392
b'_{22}	2.4	2.169	2.150 (diverge)	2.194	2.185
	4.2	0.798	0.768	0.781	0.798
	7.0	0.156	0.148	0.146	0.151
Error		-	> 13.22 %	9.52 %	9.13 %

Table 3. Total computation time to get converged radiation forces

Cases	ω=2.4 rad/s	ω=4.2 rad/s	ω=7.0 rad/s
Blend to no waves	147,469 s	108,282 s	52,680 s
Blend to potential flow	398,204 s	367,904 s	179,644 s
Ratio of CPU time required	2.70	3.39	3.41

The results show that *blending to outgoing waves* gives a slightly better solution and has possiblity to reduce the computational domain. Many objections are recognized, mainly because the improvements are small and the extra computation time for potential flow makes the coupling unattractive. In addition, the implementation of potential flow with CFD method has also drawbacks. However something might be noted to success in developing a coupling methodology. Firstly, the reduction of potential flow computation time is desired because it contributes large portion of the total computation time. The results show that the solution is relatively sensitive to the blending scheme used in present study and that the relaxation zone can not be reduced less than two wavelengths. Details will be presented and discussed in the workshop.

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