Stabilization of a Fluid-Deforming Structure Partitioned Coupling

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1 Introduction

It is generally accepted that strong partitioned coupling of the fluid-structure systems encounters instability under certain conditions. For the problems which are inherently one-way, this will not occur. While the problem undergoes a two-way physical phenomena, the amount of interaction between fluid and structure increases. As a consequence through the procedure the required rate of exchange of information increases as well. If the coupling is strong, this can be taken care of with sub-iterations, which is the iterations between fluid and structure at each time step until convergence. It is clear that the cost bottleneck of this type of simulations is the number of required sub-iterations. less sub-iterations the better. On the other hand, physics can be even more unfavourable. The rate of information exchange is directly related to the ratio of added mas over structural mass. The amplification factor of the sub-iterative loop should not exceed one, if so the rate need to be relaxed. This is generally called, under-relaxation method. This will automatically slow down the convergence and therefore increase in computation time. This paper is an overview of the aforementioned problem and describing the method proposed to remedy it. The simple two dimensional flexible bottom container case is the numerical test cae.

2 Coupling Scheme

Partitioned fluid-structure system consists of both fluid and structural solver. Those models are independent and only the motion and the loads are exchanged at the interface. In this research the fluid solver is ComFLOW a free surface flow solver developed in university of Groningen and technical university of Delft. ComFLOW is based on finite volume method. The mathematical and numerical methods is comprehensively explained in Wellens, 2012. The structural solver is a one dimensional Euler-Bernoulli beam using Hermite shape functions. In this section, the conventional and the new proposed method are elaborated.

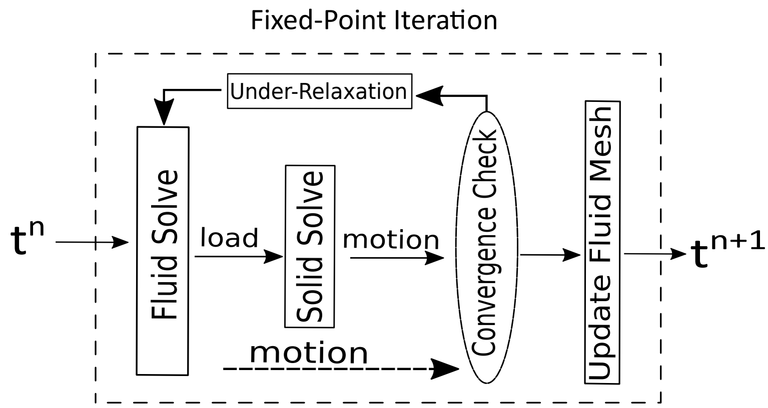


Fig. 1: THE SCHEMATIC VIEW OF PARTITIONED FLUID-STRUCTURE NUMERICAL ALGORITHM.

2.1 Conventional Method

The method of fixed-point iteration is commonly used for the fluid-structure interaction problems. As illustrated in Fig. 1 the so called sub-iterative loop between fluid and the structure continues until convergence is achieved. The convergence criteria is based on the velocities at the interface of fluid and the structure(FS). For in-compressible flows the amount of under-relaxation is related to the ratio of added mass to structural mass as explained in van Brummelen, 2009 . When problems encounters more two-way interaction, more under relaxation need to be applied. The number of sub-iterations per time step directly make the computation more expensive. According to S.M. Hosseini Zahraei, 2017, the origin of this instabilities are the large eigen values of the added mass operator.

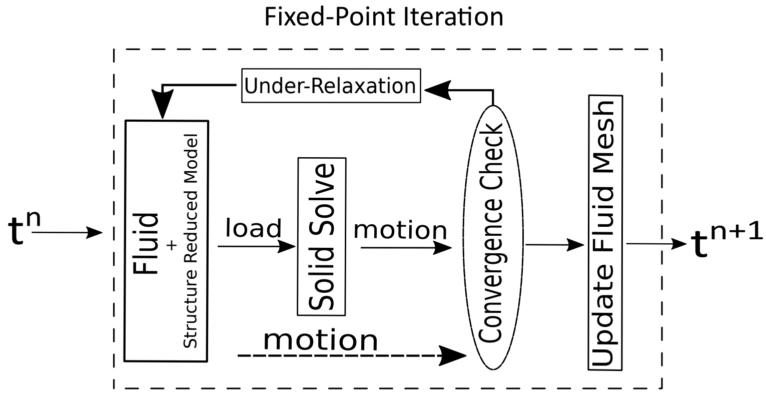


Fig. 2: THE SCHEMATIC VIEW OF QUASI-SIMULTANEOUS PARTITIONED FLUID-STRUCTURE NUMERICAL ALGORITHM.

2.2 Quasi-Simultaneous Method

The new method tries to make most of the advantages of the monolithic approach, while still keeping the system partitioned. This method then can be called quasi-simultaneous. The idea is to make an approximate of the structure, as here it's reduced order model. As illustrated in Fig. 2 this approximate is then solved with the fluid at the same time. The idea of approximate model or also called as interaction law is also present in the work of Veldman, 2009 to couple viscid and in-viscid flows.
According to S.M. Hosseini Zahraei, 2017, the origin of instability is within the most dominant modes of the structure. As those dominant modes are solved with the fluid simultaneously, under-relaxation relief is achieved. this is the moment when the next largest eigen-value of the system takes over, or in other words, the next dominant mode of the structure rules the structural response. Consequently, the amount of under-relaxation required will lower and therefore the convergence will be achieved with less number of sub-iterations.

3 Numerical test Model

One by one meter fluid domain is considered which is 80 percent filled with water. At the bottom of the domain an Euler-Bernoulli beam is placed. The domain dimensions are illustrated in fig3. The beam density is $900\frac{kg}{m^3}$ and it is divided into 101 1D elements. Added mass of the beam can be approximated by the mass of the column of water above the beam which is $0.8 \times 1000 = 800$. Mass per length of beam is $0.05 \times 900 = 45$, therefore the initial ratio of the added mass to the structural mass approximately is $\frac{800}{45} = 17.8$. The beam is initially horizontal and has no deflections. The interaction between fluid and the beam is then simulated. Fluid domain has 101× 41 grids. The solver for pressure Poisson is SOR and the beam fem solver is CG. The time step is 10^{-4} for both fluid and beam. Convergence criteria for the interaction is based on residual of the computed velocities at the interface at each step, as :

$$\frac{\boldsymbol{u}^{n+1} - \boldsymbol{u}^{n}}{\boldsymbol{u}^{1} - \boldsymbol{u}^{0}} \tag{1}$$

4 Results

In this section, first the solution in terms of beam midpoint deflection and total force acting on beam is presented. Next, the relaxation factor required and the effect of it on convergence history is elaborated. In the next part, the interaction law, it's requirements and it's performance under different settings is shown

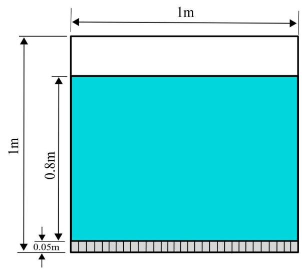


Fig. 3: Dimensional properties of numerical test case

and discussed.

4.1 Coupled Fluid-Beam System Solution

The beam vibrates under the forcing of fluid, as shown in Fig. 4 the midpoint starts to go down and then oscillate until it reaches it's steady deflection under fluid forcing. The force on the beam increases gradually from zero at the beginning and it increase until the beam experiencing it's maximum defection. It oscillates as well as beam deflection until it reaches its final constant value. In the results sown below the simulation is done only for 0.05 seconds.

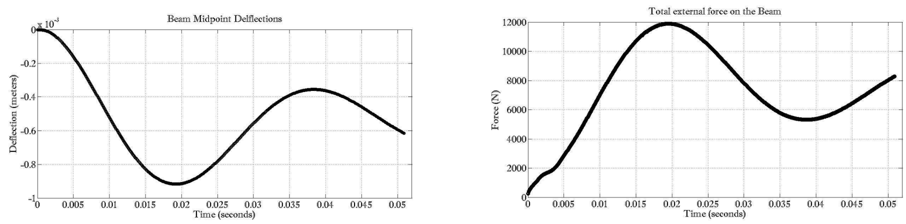


Fig. 4: Beam midpoint defection (top) and tota forrce acting on it(bottom)

4.2 Coupled Fluid-Beam System Convergence

In order to solve for this problem under relaxation should be applied to the rate of load and motion transfer between these two partitions. The added mass ratio as approximated in section one is 18. Theoretically, maximum value for relaxation which can give a stable solution is $\frac{1}{18} = 0.05$. According to simulations, 0.03 already brings a lot of instability. This is due to the fact that the added mass is approximated and the height of the water above the beam varies from one element to the other and also in time. In other words, added mass is also function of time and also fluid free surface. The approximated value of 18 is not exact. The convergence history of the first time step is shown in fig 5. The convergence criteria is as equation 1 and the threshold is set to be 10^{-3}. It is shown that by increasing the relaxation the number of iterations required for the convergence is decreased but also instabilities increased.

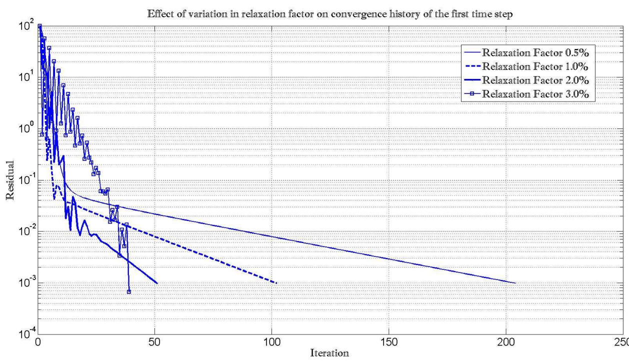
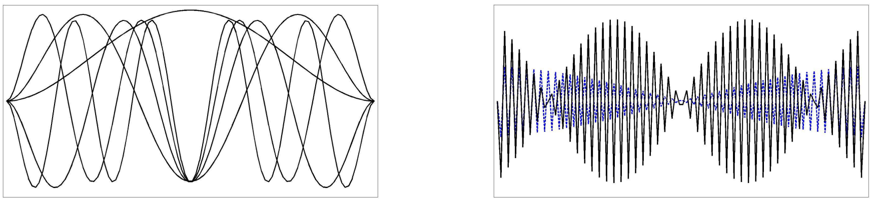


Fig. 5: The effect of relaxation factor on the convergence history for the first time step

4.3 Mode shapes of the beam

All structural eigen-values and eigen-modes are extracted by using the mass and stiffness matrices of the beam and constructing $K^{-}M$ matrix. As an example, the first five mode shapes as well as two higher ones, 101 and 102 are shown in figure 4.3. The shape of higher mode shapes seems to be affected by numerical accuracy of method used to compute them.



4.4 Boundary of Instability

In this section, by keeping the relaxation factor to be 0.03 and plugging in the interaction law with different levels of accuracy, again the convergence history is observed. As illustrated in figure 6, the coupling convergence is affected by the interaction law. It is more stable and the number of iterations is slightly less only for the first time step.

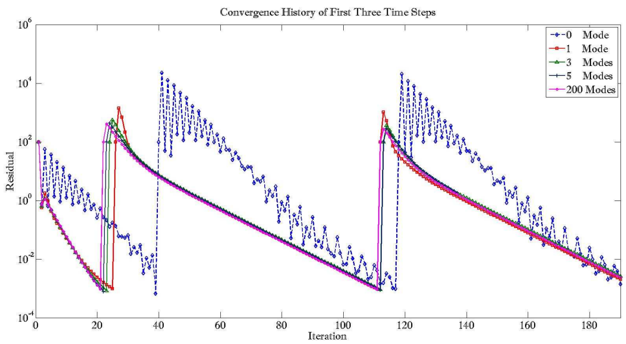


Fig. 6: Convergence history or the first three time steps for different levels for the interaction laws

4.5 Higher relaxation values

In this section the focus is on the number of sub-iterations and the interaction law's influence on reducing the number of iterations. Using the first five modes and applying different relaxation factors, starting from boundary of instability i.e. 0.03, leads in reduction o sub-iterations. The sub-iteration history for first 15 time steps is shown in figure 7 .

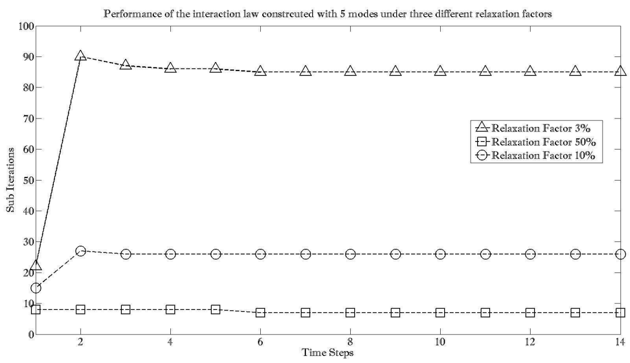


Fig. 7: Interaction law constructed with 5 modes for three different relaxation factors

Using 5 modes, instabilities starts to play a role using 0.50 as relaxation factor, therefore the number of modes is increased to 10. This is sufficient to set the relaxation factor to one. Basically in this case no relaxation is applied. Since the approximate beam inside interaction law is not the same as external beam, still few sub-iterations is needed to achieve convergence. It is also observe that in the first few time steps the number of sub-iterations required is more and that is because more instabilities will occur. The coupling gets more stable as time advances and therefore the number of sub-iterations decreases.

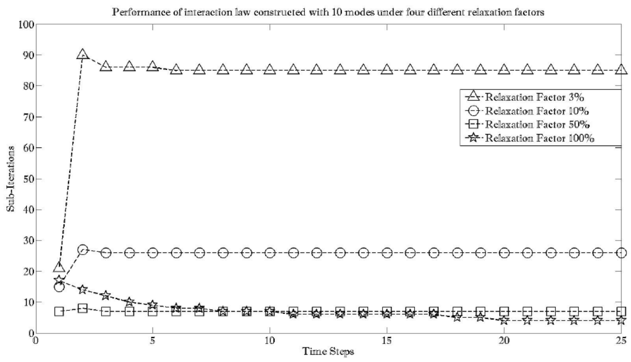


Fig. 8: Interaction law constructed with 10 modes for four different relaxation factors

Adding more modes to the interaction law and keeping the relaxation to be one does not decreases the number of iterations to one. The reason is because of the fact that higher modes are not computed precisely, as shown in figure 5.
It is observed that by decreasing the size of problem and less number of elements the mode shapes are accurate enough to decrease the number of sub-iterations to one. That case will be documented as well.

5 Conclusion

By solving the fluid-structure interaction problem partly simultaneous and choosing the interaction law or the approximate model to be base on dominant structure mode shapes, the coupling scheme speeds up. Specially when there is a strong interaction between fluid and the structure, the quasi-simultaneous method decreases computation time drastically.

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