Analysis of Flexible Plate Motion Based on Co-Simulation of STAR-CCM + and ABAQUS

Linzhao Shu a, Guang Yang b, Nan Ji*, Zhipeng Qian c

School of Shipping and Naval Architecture, Chongqing Jiaotong University, Chongqing, China

*478903658@qq.com
* Corresponding author: 2554617008@qq.com
b815293283@qq.com, c872268573@qq.com

Abstract—By the advantages of the fluid dynamics software STAR-CCM + and the structure simulation software ABAQUS in their respective fields, this paper adopts the FEM algorithm for structural deformation, and based on the RANS equation for fluid simulation, the accuracy of the co-simulation method of Fluid-Structure Interaction(FSI) was proved by comparing the simulation results under typical conditions with the experimental results. Then the deformations of a large flexible plate with fixed bottom end at high flow rate were numerically analyzed. The co-simulation method can obtain more accurate and detailed flow field and structural deformation, and has certain application value for related theoretical research, engineering structure design and safety evaluation.

1. INTRODUCTION
Fluid-Structure Interaction pays attention to the characteristics of fluid and structure simultaneously, can analyze the stress change of solid under fluid action more accurately, also can show the influence of deformation on fluid velocity and pressure. It is more closer to actual physical phenomena, so as to improve the accuracy of numerical calculation.

Ting Long[1] put forward the ES-FEM-SPH method to solve the problem of fluid-solid coupling. Erik Svenning[2] discussed the movement of flexible beam in a sloshing tank. K.Srinivasa Rao[3] observed changes in fluid and structure by changing flow velocity and barrier shape. Shuai Wang et al.[4] studied flapping amplitude of flags and vortex between flags from the number and gap distance.

FSI is complex, and relevant theoretical research is difficult to apply to changeful engineering cases, and single simulation software can not take into account the numerical simulation requirements of fluid-structure interaction according to different emphases. Therefore, numerical analysis is made on the deformation of the bottom fixed large-size flexible plate in high flow rate by using the advantages of STAR-CCM+ and ABAQUS.

2. MATHEMATICAL MODELS AND NUMERICAL METHODS
In order to compare the accuracy of the co-simulation method, the same grid and boundary conditions were used, and the simulation solution was made by using the fluid calculation software STAR-CCM + and ABAQUS and comparing with the experimental data of Tayyaba Bano et al.[5].
2.1 Verification Model
In the co-simulation, the fluid and structure models were established and calculated in STAR-CCM+ and ABAQUS respectively. In STAR-CCM+, because only the fluid domain was contained, only a physical continuum of fluid domains was created. And the corresponding solids structures and properties of flaps were set in ABAQUS, as shown in Table 1.

| Fluid-Glycerin | Structure-Flap |
|----------------|----------------|
| Density        | Density        |
| 1220kg/m³      | 1030kg/m³      |
| Dynamic viscosity | Young’s modulus |
| 1kg/m·s        | 1.23MPa        |

2.2 Border and Grid Settings
According to the literature experiment, this paper calculated the model as shown in the Figure 1. The computation domain of the fluid was a rectangular body, and the flap was fixed at the bottom and its center was at its origin. In order to avoid the backflow effect, the distance between the inlet and outlet flaps was 1.6 m, and the boundary types were respectively set as velocity inlets and pressure outlet. The top and bottom of the computational domain were 0.4 m apart, and the boundary types were respectively set as velocity inlet and slip walls. The flap surface was provided as a non-slip wall surface. The initial velocity of the inlet and the continuous body in the computational domain were ranging from 0.125 to 0.5 m/s, corresponding to Re=3, 6, 9, 12 respectively.

![Fig 1. Flap model calculation domain](image)

![Fig 2. Flap size and grid diagram](image)

In the co-simulation model, the bottom of the flap was fixed in ABAQUS and the boundary conditions in the fluid field were still set in STAR-CCM+. Fluid and flaps were cut into the body grid, the base grid size is 10mm. The flaps are grid-encrypted for movement and surface, and had dimensions of 2.5 mm, as shown in the figure.

2.3 Numerical Verification
In this paper, the calculated results of Reynolds number Re = 12 conditions were compared with the experiment. The observed points were two midpoints of the leading edge and the trailing edge respectively. The Figure 3 was a comparison of experimental and simulation results, which showed that the flaps in a fluid flow velocity of 0.5 m/s are in good agreement with the FSI model used in the literature and experiments. With the exception of this section, the other bending data were obtained from the end of the front edge of flap and all are deformations of flow direction.
3 RESULTS AND DISCUSSION

3.1 Model Introduction

The calculation accuracy and feasibility of the fluid-structure interaction method used in this paper had been verified in the previous paper. Based on this method, the oscillation process and flow field changes of plate in air were discussed. The position relationship between the plate and the flow field was shown as Figure 4. The inlet boundary is set as the velocity inlet, the velocity was 10 m/s. The outlet boundary was set as a pressure outlet; the bottom boundary and the plate surface were provided as non-slip walls surface. The rest of the boundary was provided as a symmetric plane. The bottom of the plate was fixed, and A and B points on the top were selected as observation points as depicted in Figure 5.

| Table 2. Material property of simulation of Plate |
|--------------------------------------------------|
| Fluid-Air | Density | 1.18kg/m³ |
| Dynamic viscosity | 1.85e-5kg·m⁻¹·s⁻¹ |
| velocity | 10m/s |
| Structure-Plate | Density | 4096kg/m³ |
| Young’s modulus | 38.4MPa |
Material properties were shown in Table 2. As shown in Figure 6, the model fluid adopted polyhedron mesh in STAR-CCM+, which was 0.01 m in size, and the mesh around the plate was encrypted to 0.005 m. Structure used hexahedral mesh in ABAQUS, mesh size was 0.005 m, thickness direction of the mesh layer number encryption to 5 layers. Before calculating the dynamic response of flexible plate, the quasi-steady state operation was simulated in advance to obtain the initial flow field. When the initial flow field was obtained, the grid deformers and collaborative simulation in the solver are frozen, and the number of internal iterations of a single time step was increased. After the initial flow field was solved, the initialization step was taken as the starting condition of the simulation solution.

3.2 Plate Stability Analysis
Flexible plate showed obvious periodic oscillation under the action of constant flow of water, and its amplitude was obvious in the early stage and tended to be stable gradually. The force the plate subjected to and the process of oscillating were shown in Figure 7-a,b respectively. The point of flapping was the center of the free end side at the top of plate, and the direction of flapping was the direction of flow movement.

As shown in Figure 7-b, before the plate was subjected to force and the flapping reaches stability, both force and flapping amplitude decreased in a period of about 0.24s until at the 3s reached a stable state. After the plate force enters the stable period, its period is about 0.57 s; The oscillation period is significantly smaller, only 0.05 s, about 1 / 5 of the original period; Before stability was reached, the flapping at both ends of the plate deviated during the third large period, and the phase difference of half a swing period occurred during final stabilization.

3.3 Flow Field Analysis
When the plate reached the stability in the high-speed air, the flow field changed periodically. In this paper, a period of steady time was selected, and the middle and longitudinal sections and sections of the top of plate were illustrated, as shown in Figure 8 and Figure 9. In the vicinity of the plate, the flow velocity decreased from the distal end to the surface, and from top to bottom, to zero. At the top of the
plate, the velocity of flow appeared to vary significantly, and the flow rate increased sharply from the low surface velocity to the high velocity. After the fluid passed through the plate from the top, a distinct low velocity area was formed behind the board. At the top plane of the plate, the flow field changed more obviously periodically. With the periodic stagger of the top two points of A and B on the plate, the low velocity area formed by the backboard flow field moved back and forth between the two points, and the flow fields at a longer distance show the same state.

Figure 8. Portrait flapping flow rate vector

Figure 9. Flow speed vector illustration top of plate
4 CONCLUSION

This paper compares the calculated results with the experimental data by numerical simulation of flaps at different flow rates, and then studies the motion of larger plates in high flow rate air with this method. The following conclusions were reached:

1) The method based on joint simulation is feasible in computation and accuracy.
2) When the external force provided by the fluid is large enough, the motion of the plate is obviously affected by external forces, and the movement period is close to the hydrodynamic period; with the decreasing of hydrodynamic force, the plate itself begins to play the dominant role, and the motion cycle is gradually approaching to the natural frequency and finally reaching the stability.
3) When the oscillation has reached a steady state, the motion of the flow field around the plate also exhibits periodic changes and produces a low flow velocity area at the rear plate.

Based on the Co-Simulation of STAR-CCM+ and ABAQUS for Fluid-Structure Interaction problem, this paper proposes a solution to solve the problem by using the advantages of the two software in the fluid and structure fields respectively, which is more helpful to improve the accuracy of solving the fluid-solid coupling problems and to observe the structural response in a fluid environment.

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REFERENCES

[1] Ting Long, Can Huang, Dean Hu, and Moubin Liu, “Coupling edge-based smoothed finite element method with smoothed particle hydrodynamics for fluid structure interaction problems,” Ocean Engineering, vol. 255, pp.1-17, March 2021.
[2] Erik Svenning, Andreas Mark, and Fredrik Edelvik, “Simulation of a highly elastic structure interacting with a two-phase flow,” Journal of Mathematics in Industry, vol. 4, pp. 1-11, December 2014.
[3] K. Srinivasa Rao, K. Girija Sravani, G. Yugandhar, G. Venkateswara Rao, and V.N. Mani, “Design and analysis of fluid structure interaction in a horizontal Micro Channel,” Procedia Materials Science, Vol. 10, pp. 768-788, June 2015.
[4] Shuai Wang, Jaeha Ryu, Jongmin Yang, Yujia Chen, Guo-Qiang He, and Hyung Jin Sung, “Vertically clamped flexible flags in a Poiseuille flow,” Physics of Fluids, vol. 32, February 2020.
[5] Tayyaba Bano, Franziska Hegner, Martin Heinrich, and Ruediger Schwarze, “Investigation of Fluid-Structure Interaction Induced Bending for Elastic Flaps in a Cross Flow,” Applied Sciences, vol. 10, pp.6177-6177, September 2020.
[6] M.J. Shelley, and J. Zhang, “Flapping and Bending Bodies Interacting with Fluid Flows,” vol. 43, pp. 449-465, January 2011.
[7] T. Sawada, T. Hisada, “Fluid-Structure Interaction Analysis of a Two-Dimensional Flag-in-Wind Problem by the ALE Finite Element Method,” The Japan Society of Mechanical Engineers, vol. 49, pp.170-179, October 2006.
[8] F. Paraz, and C. Eloy, “Schouveiler, L. Experimental study of the response of a flexible plate to a harmonic forcing in a flow,” Comptes Rendus Mécanique, vol. 342, pp. 532-538, September 2014.