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Analysis of compressible fluid flow during the water entry of a body equipped with an air lubrication system: Preliminary CFD results

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1 Introduction

The pressing need to reduce ship emissions has given rise to the emergence of new technologies and methods aimed at either decreasing carbon emissions from ships or reducing power requirements by minimizing ship resistance. The former primarily focuses on ship engines and power generation methods. The latter directly addresses fluid dynamics, particularly turbulent fluid motion around flat plates exposed to viscous fluid streams. The underlying concept behind the latter methods revolves around significantly reducing frictional stresses acting on the ship's surface, which play a crucial role in turbulent fluid flow. To reduce frictional stresses, two commonly employed approaches exist. The first approach involves utilizing polymer covers capable of rendering the solid surface smoother, thereby resulting in reduced frictional stresses within the viscous sublayer. The other method entails gas injection. By introducing gas into the system, microbubbles or a gas layer can form beneath the plate, effectively diminishing normal shear stress.

Since the 1970s, there has been a growing interest in studying the impact of gas injection on fluid dynamics around flat plates towed in water tunnels. Subsequently, further investigations explored the effects of gas injection on the resistance force of ships towed in tanks. It has been discovered that gas injection can reduce the frictional resistance of a flat plate by 80% and decrease ship resistance by 15% (Wang et al. 2022). However, it is important to note that frictional resistance is not the primary contributor to overall resistance, as other factors such as wave making resistance and form drag also play significant roles.

Unsurprisingly, most studies have focused on assessing the performance of ships in calm water conditions (e.g., Zhao and Zong 2022). As a result, there has been limited attention given to the effects of waves on the performance of ships utilizing gas injection systems. One of the primary reasons for deactivating the gas injection system during non-calm water conditions is the substantial motion experienced by ships, which may cause the ship's bow or bottom to exit the water. Accordingly, the injected gas, typically air, undergoes a distinct separation from the water medium, ceasing air-water mixture, which makes it useless. The system may set on in gentle wave condition in random seas, where a sudden large crest may emerge, causing a water exit, which will be followed by a water entry. This scenario gives rise to an aerated water entry problem, wherein the flow of air possibly intensifies the impact pressure. In such cases the wave loads not only induce vibrations upon the ship plate but also impose substantial stress upon the piping system.

Over the years extensive research has been conducted by numerous scholars on the topic of pure water entry (Tavakoli et al., 2023). Theoretical approaches and Green Integration Methods have been employed to address this problem, making assumptions based on potential flow. However, some studies have adopted a viscous assumption, necessitating the use of Computational Fluid Dynamics (CFD) codes. These codes possess the capability to handle highly nonlinear conditions and account for strong turbulent flows that occur when a body deeply penetrates the water. Moreover, they can be easily integrated with computational solid dynamics (CSD) models, thereby aiding in solving flexible water entry problems.

Our current understanding of pure water entry is significant. However, our knowledge regarding aerated water entry remains limited. The complexity of the physics involved may be attributed to this limitation. Insufficient attention has been given to this problem, as most researchers primarily focus on studying drag and resistance reduction caused by the air lubrication systems.

To provide a better understanding of the problem, this brief article discusses the water entry of flat plates equipped with an air lubrication system. As many as five air inlets are placed on the wall of a two-dimensional plate entering water, and the problem is solved by using compressible and incompressible fluid models. The simulations setup is introduced in Section 2. Some preliminary results are presented and discussed in Section 3. Section 4 draws conclusions and future research.

2 Model Setup

2.1 Fluid domain

A rectangular wide fluid domain is considered. A portion of the domain is filled with water. The rest of contains air as shown in Fig. 1. The water is assumed to enter this domain via the lower surface with a speed of u_∞ (inlet). It then slips on the side walls. A plate of length of L is placed in this domain, initially above the free surface. Five different air inlets with a width of $0.025L$ are considered. The air is assumed to flow out with a speed of u_a. Thus, the air flux is $Q_a = 0.125Lu_a$.

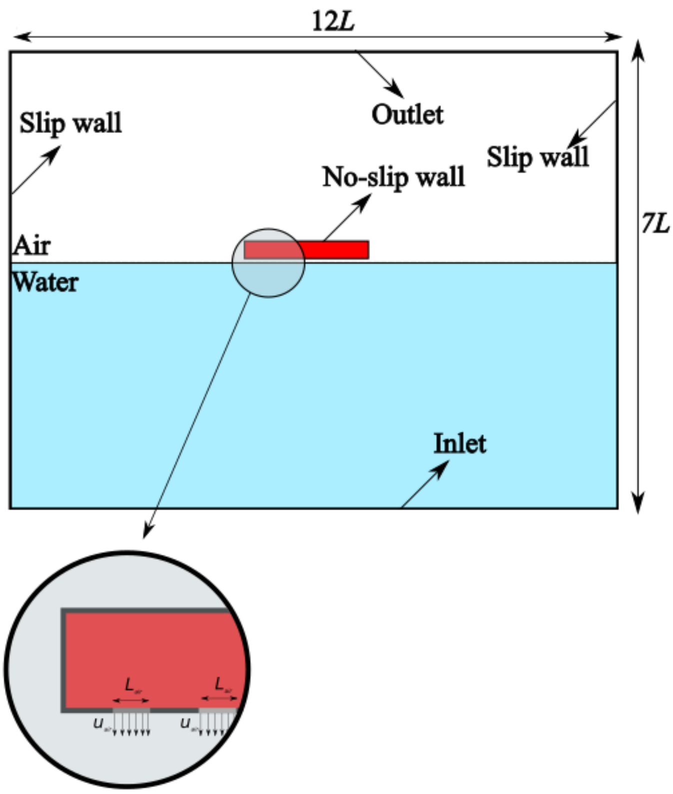

Fig. 1: Problem domain considered in the present research.

2.2 Governing equations

The fluid dynamic problem is governed by Navier-Stokes equations. In the simulations presented the fluid is assumed to be compressible and incompressible. The compressible assumption is expected to lead to more realistic results during aerated water entry (Ma et al. 2016). An energy equation also governs the problem. Two different energy components, including the internal and kinematic energy are considered. To model the two-phase flow, a volume fraction field is introduced, which allows for consideration of an air-water flow. This parameter is governed by a conservation equation.

2.3 Numerical solver and model setup

The present problem is solved by using the OpenFOAM library version 2018-06. To reproduce the problem for the compressible fluid assumption, the compressibleInterFoam solver is used. For the incompressible assumption, the interFoam solver is used. The thermophysical properties of the room temperature are considered for water and air. To treat compressibility the perfect gas state equation is used. Slip boundary conditions are set on the wall of the channel. Extrapolated pressure boundary condition is set on the wall of the plate. Inlet and outlet boundary conditions are set for the upper and lower boundaries of the fluid domain. Zero gradient temperature condition is set for all boundaries of the domain. The initial temperature is set to be 300 K in the whole domain.

The domain is meshed by using the BlockMesh library and a structured approach is employed. The time derivatives of the governing equations are decomposed by using the Crank-Nicolson method and gradient terms are decomposed using a Guess linear scheme. A linear upwind method is used to discretize the divergence terms. The PIMPLE (which is combination of Pressure Implicit with Splitting of Operator Scheme and Semi-Implicit Method for Pressure-Linked Equations Scheme) algorithm is employed for solving the differential equations, and the number of outer correctors is set to be 1. The Courant number is forced to be 0.5 in all simulations.

3 Results and Discussions

3.1 Pure water entry

The pure water entry problem is solved for two different impact speeds of 1 and 2 m/s. The problem is solved using both compressible and incompressible models. Pressure at the middle point is sampled over time and is presented in panels (a) and (b) of Fig. 2. As seen, the pressure predicted using the compressible model and the one predicted using incompressible model do not match. Pressure may peak earlier when the compressible model is used (solid red curves of Figs. 2(a) and 2(b)). In addition, pressure may show some fluctuations before it peaks. This fluctuation is less noticeable for the case with greater impact speed. This observation is subject to further investigation. For the lower impact speed, the peak pressure found through compressible modeling is lower (Figure 2(a)). However, for the greater impact speed, the pressure found through compressible modeling is higher. The pressure found using the compressible model may fluctuate over time. This can be attributed to the reflections from the boundaries of the domain and may not reflect behaviour in real / deep water seas . In a water tank with a limited depth, boundary reflections happen when compressibility is important. The pressure distribution pattern is shown in Figs. 2(c) and 2(d) for the two different instants at which the pressure found using compressible model peaks. As seen, the pressure distribution found using the incompressible case exhibits smoother behavior near the edge of the plate. On the other hand, in compressible simulations, the pressure peaks and gradients are sharp.

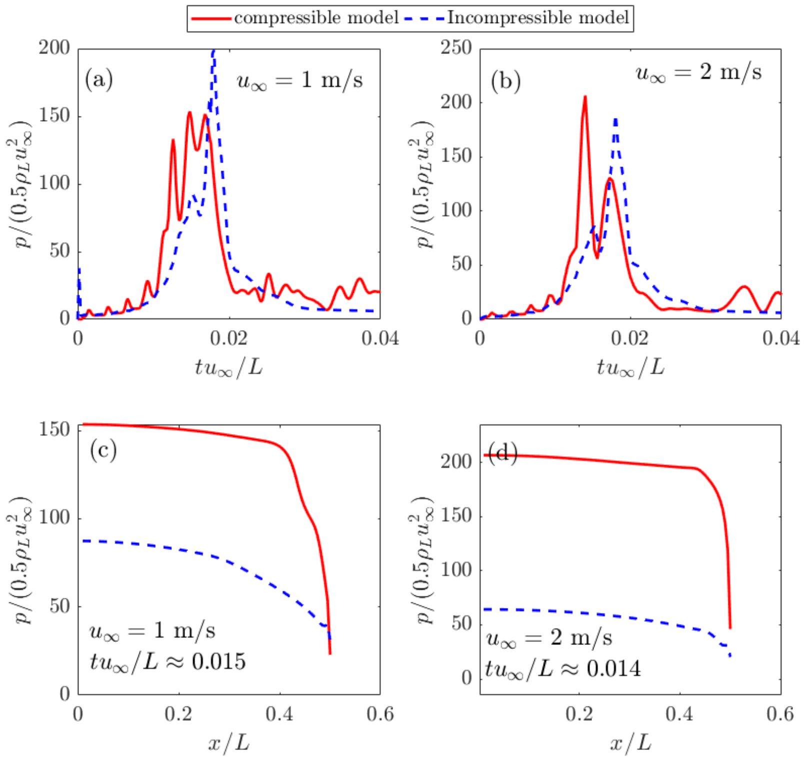

Fig. 2. Panels (a) and (b) show time history of the pressure recorded at the middle point during the pure water entry. Panels (c) and (d) show the pressure distribution along the plate during the pure water entry.

3.2 Aerated water entry

Fig. 3 shows the time history of the pressure at the middle point of the plate equipped with air injections. Two different water entries are considered, and the air injection speed is set to be 0.2 m/s. Compressible and incompressible setups are run, and the results are compared in both panels of Fig. 3. As seen, the compressible setup leads to totally different time history. Two difference crests can be seen in the time history of the pressure corresponding to compressible model and pressure may reach zero. For the incompressible case only one peak emerges, and the pressure never reaches zero. The first peak pressure predicted by the compressible model is much greater than the peak pressure found using the incompressible model. But the second peak found using the compressible model is smaller that the peak found using the incompressible model. For a constant air injection rate, the peak pressure values seem to decrease with the increase in impact speed.

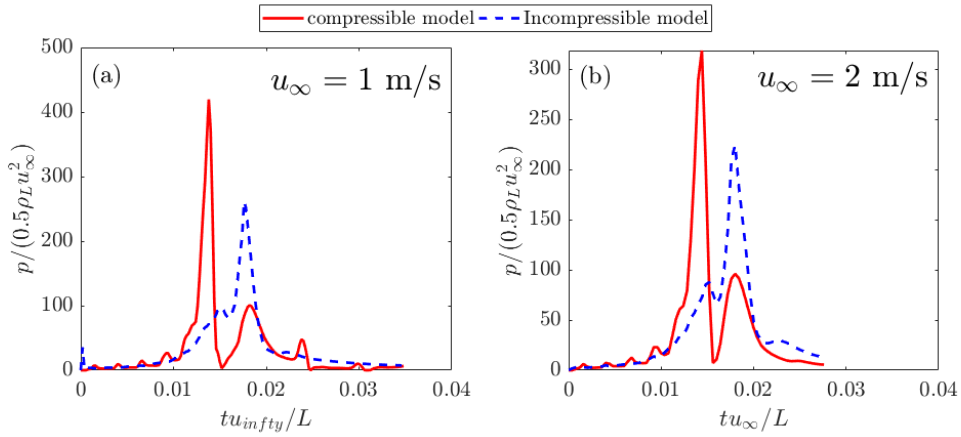

Fig 3. Time history of pressure at the middle point during aerated water entry.

Fig. 4(a) compares the time history of the pressure sampled at the middle point of the plate entering water in pure (solid curve) and aerated (dashed) conditions. Both curves are found using compressible runs. It can be clearly seen that the air flowing out of the inlet patches the plate surface and the peak pressure increases in way of water entry. The next step of this dynamic behavior is a zero dynamic pressure and another peak, which is lower as compared to pure water entry case.

The problem is run for different air flow rates. The air flux is normalized using the water flux ($Q_w = Lu_\infty$). The first peak pressure (green circles) and the second peak pressure (blue diamonds) are found and plotted as a function of the air flux over the water flux ratio (Fig. 4(b)). The peak pressure found in the pure water condition is also plotted in the same Figure. The first peak pressure increases under the increase of the air flux, while the second peak decreases. The first peak emerges as water gets close to the body and impacts its edges (at this stage air flows towards the edges to flow out from the gap between the water and the plate). The second peak happens when an air bubble is formed under the plate. The first peak is mostly affected by the energy of the air flow tending to exit from the gap in between the edges of the plate and the water, which will be energized by the increase in the air flow rate. However, during the second peak, the air bubble may act like a damper and can mitigate the impact loads when water reaches the surface of the plate. For greater air flow rate, the bubble would be larger and can decrease the pressure more significantly. As seen in Figure 3, compressible and incompressible simulations do not give similar results, and no second peak is monitored by the incompressible simulations. There is still an open question whether the results of compressible model are realistic or not. This question can be answered through running other model and performing experiments.

4 Conclusions

This article presented compressible and incompressible two phase simulations of the water entry of a flat plate equipped with an air lubrication system using OpenFOAM. Five different air inlets were placed on the surface of the plate, and the problem was solved for different impact speeds and air flow rates.

The peaks predicted by the compressible model were seen to be larger at greater impact speeds. The pressure distribution pattern corresponding to the compressible case was also seen to be different as compared to that of the incompressible case.

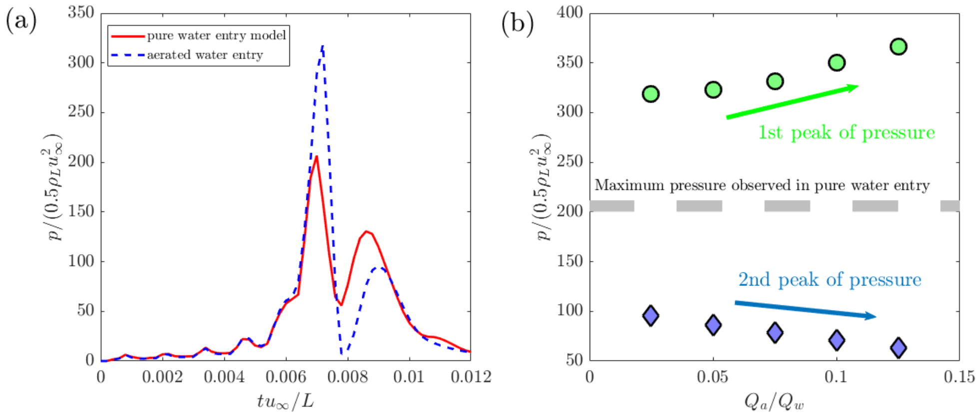

Fig. 4. Effects of air injection on the pressure at the middle point of the plate entering water.

A study on the aerated water entry problem demonstrated that results of compressible and incompressible cases may be considerably different. Through sampling the pressure at the middle point of the plate, two different peak pressures were observed, and a zero-pressure emerging in between them was seen to rise in the compressible runs. For incompressible runs, one peak pressure was observed to emerge in the time history of the pressure sampled at the middle point of the plate. The increase in the air flow rate was seen to lead to an increase in the first peak pressure. The second pressure peak was observed to be dropped by the increase of the air flow rate.

Future research shall focus on simulations using commercial solvers (e.g., StarCCM+) and experiments that will demonstrate the validity of compressible openFOAM simulations.

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