DualSPHysics validation for fluid-structure interaction with floating flexible strucuture in a sloshing tank environment

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I. INTRODUCTION

With the growing interest in offshore renewable energy technologies, the need to accurately design and test these offshore structures is of utmost importance. One of the newest and more complex concepts of harnessing renewable energy sources in offshore locations is the creation of floating photovoltaic farms [1]. It is widely known that offshore structures are submitted to enormous levels of aggression by the elements and so, there are already several types of devices being studied and tested. One way of building these farms to be more resistant to the aggressive ocean conditions, is to build them out of flexible floating materials, able to cope with ocean waves without much tension. This presents a new challenge, where the fluid-structure interaction includes a flexible structure, which is an extremely complex problem to solve with current numerical fluid simulation codes. As the more usual Eulerian methods struggle with very large deformation of mesh (highly flexible structures), in this work, we present a validation for a Smoothed Particle Hydrodynamics (SPH) based code called DualSPHysics, coupled with a novel integrated structural solver for a simple sloshing problem with a flexible floating body. For the validation, experimental results were obtained on a purpose built sloshing tank with several data capturing systems.

II. EXPERIMENTAL SETUP

The choice to build a sloshing tank instead of using an existing wave flume was based on the smaller scale of the sloshing tank. By building a sloshing tank for the purpose of numerical validation, more thought is put on ways to accurately analyze the fluid flow and important parameters for the validation, as discussed by [2].

A. Tank Design

The sloshing tank (see Fig. 1) was built with the interior dimensions of 1m in length, 0.6m height and 0,2 of width. These dimensions were chosen as a good balance between being small enough to use with a stepper motor and large enough to generate a significant wave height. Using a stepper motor ensures a more precise motion of the sloshing tank, therefore providing a good repeatability of results, meaning separate experimental runs with the same conditions provide the exact same results. The motor being used is a Nanotec ST8918L6708 and it is coupled to a 4:1 reduction gearbox. The base of the structure is built of aluminum profile, while the moving and more stress sustaining parts are made of steel and the tank itself is glass. Many design choices were made to facilitate and improve the data gathering systems, such as leaving the bottom and sides of the tank clear of visual objects, to allow the use of laser sheets for Particle Image Velocimetry (PIV) recordings and a direct connection for a rotary encoder to read the tank's position.

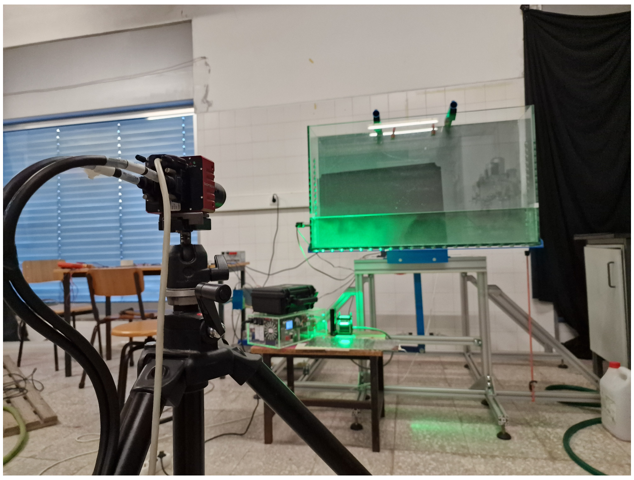

Fig. 1. Experimental Sloshing Tank.

B. Data Gathering Systems

After consulting [3], to fully analyze the fluid flow, three main properties were taken into consideration: pressure; velocity and external applied forces, which are the variables in the navier-stokes equations. Taking these three properties, three separate systems were installed on the tank:

1) Pressure - five pressure sensors were fabricated for this tank. The sensor used is a Honeywell HSCDLNN100MDSA5, with a range of ±100mbar. These sensors can be placed at any of the 50 holes distributed along the sidewalls and bottom of the tank.
2) Velocity - a Particle Image Velocimetry (PIV) code, called QuickLabPIV [4] is used to examine the fluid flow velocities. In this system a high speed camera recording at 405 frames per second (fps) captures the motion of polyamide seeding particles (100µm). The camera used is an Allied Vision BONITO CL-400b.
3) External forces - apart from gravity, the only force applied on the fluid is by the moving tank's walls and bottom. This force cannot be directly measured, however, the motion of the tank is precisely monitored by a rotary encoder connected directly to the tank's center of rotation.

C. Flexible material

Choosing the material for the body was of utmost importance because the required characteristics combined are rare to be found in a single material. The body has the following required characteristics:

- Made from a single material
- Isotropic
- Less dense than water
- Impermeable
- Not too flexible nor too rigid for the scale of the waves

The first materials considered were different types of rubber, but no single material checked all requirements. However, there is a process sometimes used on rubber materials called foaming in which small gas bubbles are formed inside the rubber mixture. Through this process it is possible to obtain closed cell foam, which is a foam with small closed cavities inside the material, so air and moisture are unable to get inside. This process leads to a lower density and higher flexibility of the material. After much consideration, the material chosen was an EPDM (ethylene propylene diene monomer rubber) closed cell rubber foam sheet, with a thickness of 8mm, that follows all the required characteristics.

III. NUMERICAL METHOD

Given the complexity of the interaction between fluid and the highly flexible floating body, mesh-based Eulerian methods were considered incapable of accurately reproducing the desired results, and so a Langrangian approach was chosen for this purpose. DualSPHysics [5] is an open-source computational tool based on the Smoothed Particle Hydrodynamics (SPH) method, which is particularly well-suited for modeling FSI [7]. This particle-based method represents fluids and structures as discrete particles, allowing it to naturally handle complex phenomena such as free surfaces, large deformations, and dynamic interactions. On the other hand, the coupled FEA-based solver handles the flexible structure as Euler-Bernoulli beams.

For this work, involving complex interaction of waves and highly flexible floating bodies, the SPH-FEA coupling [6] offers several critical advantages:

1) Robust FSI Modeling: It captures the complex, nonlinear interactions between waves and flexible structures, which is essential for understanding the behavior of floating systems.
2) Material Flexibility: Through the use of the FEA solver, this coupled code is able to simulate the flexibility of elastic materials, such as the EPDM rubber foam used experimentally, replicating real-world behavior.
3) Validation-Friendly: Its ability to integrate experimental data from the sloshing tank motion ensures reliable calibration and validation, enhancing simulation accuracy.

DualSPHysics bridges the gap between numerical modeling and experimental validation, making it a powerful and adaptable tool for analyzing FSI and has gained a good reputation in the simulation of offshore renewable energy systems. Its scalability, accuracy, and flexibility ensure it is well-suited for advancing the design and optimization of future offshore photovoltaic systems. In every numerical simulation the tank's position and velocity was inputted using experimental data from the installed rotary encoder. This method ensures the maximum similarity of the tank's movement over time between the experimental and numerical runs.

IV. CURRENT RESULTS

The work presented here is part of a larger ongoing study, but has nonetheless provided very promising results so far. As part of the numerical validation there are three main variables being used for comparison between experimental and numerical results:

1) Pressure on the tank's walls
2) Free surface and flexible body elevation
3) Fluid flow velocities

A. Pressure

The pressure sensors have a slight offset from the tank wall and this reflects in the results. Therefore all experimental pressure data is normalized to match the numerical pressure at the start of the runs. In Fig. 2 experimental and numerical pressure results are compared for one sloshing condition at a specific point on the tank's wall, and its observed the results match quite well.

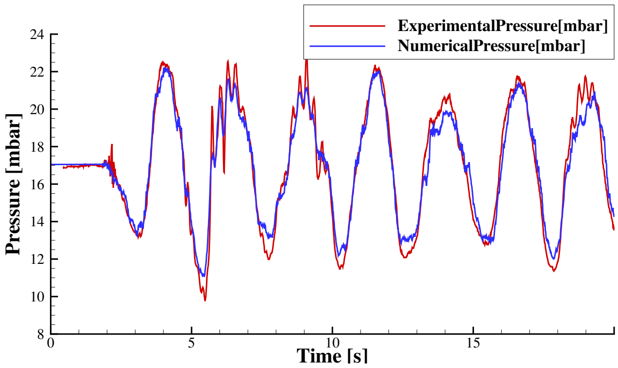

Fig. 2. Comparison of numerical and experimental pressure results of one point on the tank's wall for the same sloshing conditions.

B. *Free surface and flexible floating body elevation*

The elevation of the free surface of the water and (when present) the flexible floating body is a very important validation parameter. This parameter is the only one used to measure the flexing of the floating body and how well the numerical code is capable of processing the complex fluid-structure interaction. A script was created to extract the elevation of the free surface or height of the floating body from the images captured on the high speed camera, however for easier visualization, in fig. 3 a snapshot of the numerical and experimental runs is compared.

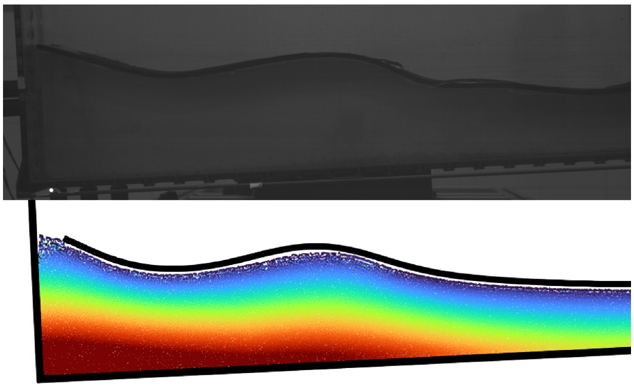

Fig. 3. Snapshot of experimental and numerical runs

C. *Fluid flow velocities*

PIV is a method used to capture the fluid flow velocities at every instant by placing tracer seeding particles in the fluid. The recorded images are then processed in the PIV software QuickLabPIV, outputting a matrix of velocity values for each recorded frame. This is a very powerful validating parameter as the entire fluid flow velocity is well characterized. Fig. 4 shows an example of the velocity on the horizontal axis over time for a single point in space for both the experimental and numerical runs.

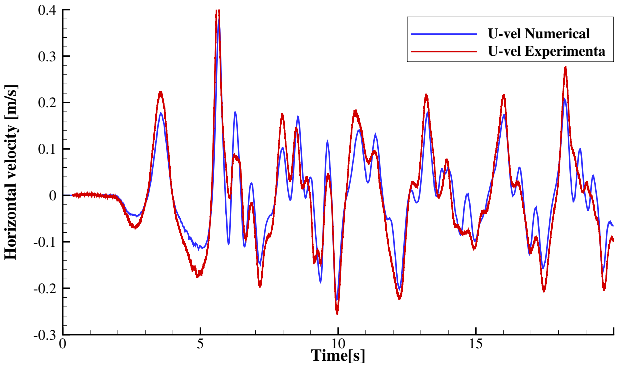

Fig. 4. Comparison of numerical and experimental velocity results of one point in space for the same sloshing conditions.

V. CONCLUSION

This study shows the potential of DualSPHysics, coupled with an FEA structural solver implemented in Chrono, for modeling FSI involving flexible bodies. The validation using a custom-designed sloshing tank emphasizes the code's accuracy in replicating pressure, free surface dynamics, and fluid velocities but most importantly, it guarantees the capability of the code in achieving realistic simulations of complex FSI. While current results are still being worked on, they already validate the model's robustness, and future work will explore more complex settings, extending its applicability to offshore renewable energy systems, particularly floating photovoltaic platforms.

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