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Prediction of Wake Flows Induced by an Offshore Wind Turbine Foundation

Understanding its Environmental Impact - Phase 2: Floating Platforms

Master's thesis in Mobility Engineering(MPMOB)

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

The deployment of Floating Offshore Wind Turbine(s) (FOWTs) requires methods to evaluate their hydrodynamic response and wake characteristics. This thesis applies the Immersed Boundary Method (IBM), implemented as the Virtual Body Method (VBM) in Simcenter STAR-CCM+, to simulate the UMaine VoltturnUS-S semi-submersible platform. The methodology was validated against the dynamic Fluid-Body Interaction (DFBI) with overset meshing technique. For a 2D floating box in waves, the VBM reproduced heave and pitch natural periods with differences of 0.65 % and 0.24 %, respectively, while surge exhibited a 12 % deviation. In 3D free-decay simulations of the UMaine VoltturnUS-S foundation, the platform's heave natural period agreed within 0.73 %, whereas the pitch period deviated by 0.22 % . Even with noticeable deviations, this VBM notably reduced computational costs by nearly 40 % in core-hours per million elements for free decay case, when compared to the DFBI cases with overset meshing. Applying the validated framework to full-scale conditions, multiphase simulations of the platform in a thermally stratified environment were conducted. The results demonstrated that the multi-column structure generates a complex near-wake recirculation zone with persistent flow reversal. Thermal mixing was predominantly observed near the surface, resulting in a maximum mean temperature increase by 5.82 K at a depth of 3.83 m below the free surface, with mixing effects decaying rapidly in deeper waters. The findings validate the VBM as a functional fixed-grid alternative for simulating platform kinematics and provide a baseline for future environmental wake investigations involving FOWTs.

Keywords: Floating Offshore Wind Turbines (FOWTs), VoltturnUS-S Platform, Virtual Body Method (VBM), Immersed Boundary Method (IBM), Computational Fluid Dynamics (CFD), Fluid–Structure Interaction (FSI).

Preface

This report presents the outcome of the Master's thesis project entitled "*Prediction of Wake Flows Induced by an Offshore Wind Turbine Foundation to Understand Its Environmental Impact*", carried out at the Division of Marine Technology, at Chalmers University of Technology. The work focuses on the development and application of a computational framework for simulating floating offshore wind turbine hydrodynamics. Enabling efficient simulation of platform motions and wake development without dynamic mesh deformation. The project has provided valuable experience in computational fluid dynamics, marine hydrodynamics, and numerical modelling, while contributing to the understanding of wake flows around floating offshore wind platforms.

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Yash Vijay Shendokar, Gothenburg, September 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BCD	Bounded Central Differencing
CFD	Computational Fluid Dynamics
CoG	Center of Gravity
CFL	Courant–Friedrichs–Lewy
DFBI	Dynamic Fluid-Body Interaction
DOF	Degree of Freedom
FLNG	Floating Liquefied Natural Gas
FOWTs	Floating Offshore Wind Turbine(s)
FPSO	Floating Production Storage and Offloading
FSI	Fluid-Structure Interaction
FVM	Finite Volume Method
HRIC	High-Resolution Interface Capturing
IAPWS	International Association for the Properties of Water and Steam
IBM	Immersed Boundary Method
IEA	International Energy Agency
IEC	International Electrotechnical Commission
NREL	National Renewable Energy Laboratory
RANS	Reynolds-Averaged Navier–Stokes
RMSE	Root Mean Square Error
TKE	Turbulent Kinetic Energy
VBM	Virtual Body Method
VOF	Volume of Fluid

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables used throughout this thesis.

Indices

i, j, k	Spatial indices (tensor notation)
t	Time index or turbulence-related variable index

Sets

Ω	Fluid domain
Γ	Virtual boundary surface
V	Control volume
A	Bounding faces of the control volume

Parameters

C_d	Coefficient of drag
C_p	Coefficient of pressure
C_w	Constant for the WALE model
c_p	Specific heat
D	Diameter of the monopile
H	Domain height
L	Domain length
M	Structural mass matrix
N	Number of iterations
U_{ref}	Reference velocity
U_R	Ursell number

W	Domain width
y^+	Non-dimensional wall distance
Γ	Diffusion coefficient
Δ	Grid filter
Δr	Cell size
Δt	Time discretization interval
λ	Thermal conductivity
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ	Fluid density

Variables

A	Added mass matrix
B	Hydrodynamic damping matrix
C	Hydrostatic restoring (stiffness) matrix
f_i	Volumetric body force
k	Turbulent kinetic energy
L_u, L_v	Integral lengthscales
$\hat{n}_j$	Normal vector
p	Instantaneous/Thermodynamic pressure
p'	Fluctuating pressure
P_k	Production term of turbulent kinetic energy
R_{ij}	Two-point correlation tensor/Autocorrelation
S	Source term in transport equation
S_ϕ	Volumetric source term for general scalar
S_{ij}	Instantaneous strain-rate tensor
T	Instantaneous temperature
T'	Fluctuating temperature
T_u	Integral timescale
u_i, v_i	Instantaneous velocity vector
u'_i, v'_i	Fluctuating velocity vector
x_i, x_j	Spatial coordinates in Cartesian system
α, α_i	Volume fraction/Phase volume fraction
ϵ	Mean kinetic energy dissipation
$\eta_1 \dots \eta_6$	Platform rigid-body displacement in six degrees of freedom (Surge, Sway, Heave, Roll, Pitch, Yaw)

θ	Angular position
σ_{ij}	Stress tensor
ϕ	General scalar quantity
$\Omega_{i,j}$	Vorticity tensor

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1

Introduction

1.1 Background

Driven by global sustainability goals and the pursuit of net-zero emissions, the shift from fossil fuels to renewable energy has accelerated, with wind power playing a key role in meeting future energy demand. As global energy consumption continues to rise, wind energy, both onshore and offshore, has steadily gained momentum to be a important component of the renewable energy market. As of 2023, the global installed offshore wind capacity reached 75.2 GW. According to Meng et al. [14], industry forecasts project cumulative capacity to grow to around 519 GW by 2035.

Fixed-bottom foundations, including monopiles, gravity-based structures, and jackets, have generally been the preferred solution due to their straightforward construction, ease of installation, and comparatively low operational costs (Malhotra [13]). However, the offshore wind industry is expanding from shallow coastal waters into deeper regions to meet these rising energy demands. Beyond water depths of approximately 50 m, installation, operation and material costs increase sharply, imposing economic constraints on fixed-bottom deployment.

FOWTs have therefore emerged as the natural technological trajectory for deep-water development, drawing on decades of offshore engineering experience with systems such as Floating Production Storage and Offloading (FPSO) and Floating Liquefied Natural Gas (FLNG) units (Zhang et al. [23]). Floating platforms access stronger, more consistent wind resources in deep water while reducing visual and noise impacts near shore. Among the floating foundation concepts presented in Figure 1.1, semi-submersible concepts are expected to play an increasingly important role in future commercial developments. Compared with spar-buoy designs, semi-submersible platforms generally offer lower draft requirements, facilitating assembly and installation. In addition, their relatively large water-plane area provides favourable hydrostatic stability, making them suitable for supporting large-capacity wind turbines. These characteristics make the semi-submersible platform an appropriate object for investigating both floating-platform dynamics and the resulting hydrodynamic flow phenomena.

This thesis employs the UMaine VoltturnUS-S reference platform. This platform developed collaboratively by the University of Maine and the National Renewable Energy Laboratory (NREL) under the International Energy Agency (IEA) Wind

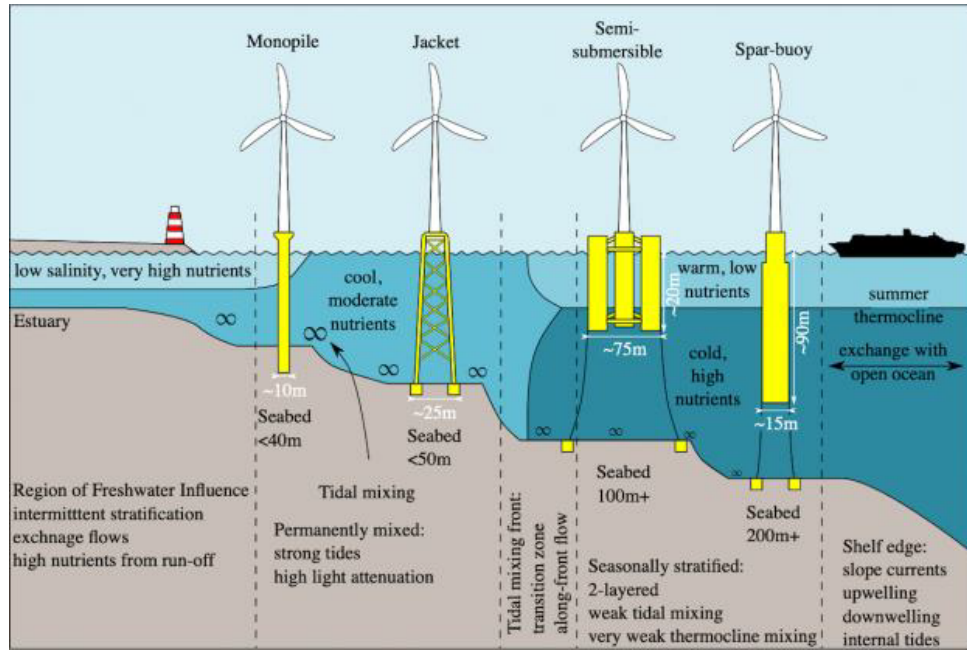


Figure 1.1: Floating wind turbines with different foundation types (Dorrell et al. [5]).

TCP Task 37 (Allen et al. [1]). Designed to support the IEA 15 MW reference wind turbine from Gaertner et al. [8], the platform serves as an open-source, industry-standard benchmark representing the next generation of large-scale floating offshore wind technologies. The VoltturnUS-S platform has been widely adopted within the offshore wind research community as a reference design for numerical and experimental studies. It provides researchers with access to detailed geometric, hydrostatic, structural, and mooring-system properties, enabling direct comparison between different numerical approaches and experiments.



Figure 1.2: The UMaine VoltturnUS-S semi-submersible reference platform supporting the IEA-15-240 wind turbine. Image courtesy of the University of Maine.

Figure 1.2 is the VoltturnUS-S which is a four-column steel semi-submersible com-

prising a central column supporting the turbine tower and three radially spaced outer columns connected by rectangular pontoons (Allen et al. [1]). The structure is in place using a three-line chain catenary mooring system. The physical and hydrostatic properties of the UMaine VoltturnUS-S platform were reproduced to model its dynamic response in the computational domain. The general and hydrostatic properties of the platform, as well as the structural mass distribution are detailed in Table 1.1.

Table 1.1: General system, geometric, and hydrostatic properties of the full-scale IEA 15-MW FOWT on the UMaine VoltturnUS-S platform (Allen et al. [1]).

Parameter	Value	Units
Turbine Rating	15	MW
Water Depth	200	m
Platform Draft	20	m
Platform Freeboard	15	m
Outer Column Diameter (x3)	12.5	m
Central Column Diameter (x1)	10.0	m
Pontoon Dimensions (Width $\times$ Height)	12.5×7.0	m
Waterplane Area	446.7	m ²
Total System Mass	20,093	t
Hull Displacement	20,206	m ³
Roll Inertia (about Center of Gravity)	1.251×10^{10}	kg $\cdot$ m ²
Pitch Inertia (about Center of Gravity)	1.251×10^{10}	kg $\cdot$ m ²
Yaw Inertia (about Center of Gravity)	2.367×10^{10}	kg $\cdot$ m ²

1.2 Previous Work

Allen et al. [1] established the foundational numerical baseline for the UMaine VoltturnUS-S platform using the OpenFAST simulation framework. System hydrodynamics were represented through a potential-flow formulation coupled with quadratic drag forces, enabling the prediction of the platform’s rigid-body response under standard International Electrotechnical Commission (IEC) load cases. This work provided a widely adopted reference model for the IEA 15-MW wind turbine mounted on the VoltturnUS-S semi-submersible platform.

Experimental validation of the platform was subsequently conducted using a 1:70 scale physical model at the COAST Laboratory Ocean Basin. Ransley et al. [16] evaluated the hydrodynamic performance of the system through static equilibrium measurements, free-decay tests in surge, heave, and pitch, as well as focused-wave experiments. By excluding aerodynamic rotor loading, the study isolated hydrodynamic and mooring-system effects, providing a benchmark dataset for validating floating-platform motion predictions and coupled fluid-structure interaction models.

Beyond platform-motion validation, previous work has also investigated environmental flow interactions associated with offshore wind infrastructure. As Phase 1 of the

research project *Prediction of Wake Flows Induced by Offshore Wind-Turbine Foundations to Understand Their Environmental Impact*, Satria Pratama [18] developed a numerical framework for evaluating wake-induced mixing in stratified shelf seas. Using Large Eddy Simulation (LES), the study examined the wake generated by an 8 m diameter bottom-fixed monopile and showed that wake-induced disturbances can modify the local thermocline structure. Furthermore, simulations incorporating temperature-dependent fluid properties demonstrated that buoyancy forces associated with density stratification substantially suppress vertical mixing, highlighting the importance of accurately representing stratified marine environments when assessing environmental impacts.

Recent investigations have further demonstrated that floating offshore wind turbines introduce additional wake complexities compared with fixed-bottom structures. Because floating platforms experience continuous rigid-body motions, their wakes are inherently unsteady and three-dimensional. Rezaeiha and Micallef [17] showed that platform surge motion enhances turbulent mixing and accelerates wake recovery through increased momentum entrainment. Similarly, Arabgolarcheh, Rouhollahi, and Benini [2] reported that pitch motion can generate non-axisymmetric helical wake structures, while Li, Dong, and Yang [12] identified sway-induced wake meandering as an additional mechanism influencing downstream flow development.

Collectively, these numerical, experimental, and wake-focused studies provide valuable insight into the hydrodynamic behaviour of offshore wind structures. However, most existing investigations either focus on the global motions of the VoltornUS-S platform or employ simplified turbine representations when examining wake dynamics. The hydrodynamic wake generated by a floating semi-submersible platform and its interaction with a stratified marine environment remain comparatively unexplored. Consequently, applying a fully resolved multiphase Computational Fluid Dynamics (CFD) framework to investigate the wake of the VoltornUS-S platform represents a necessary methodological advancement and forms the basis of the present study.

1.3 Research Gap

Although the hydrodynamic behaviour of the VoltornUS-S platform have been investigated using potential flow solvers and experiments, the ability of a fully resolved multiphase CFD approach to capture the coupled Fluid-Structure Interaction (FSI) and wake dynamics remains insufficiently explored. Most previous studies have focused primarily on predicting platform motions, structural loads, and overall system performance. Comparatively less attention has been given to the detailed flow field surrounding the platform and the mechanisms governing wake formation and turbulence generation. Furthermore, the applicability of the VBM for modeling floating offshore wind platforms has not been comprehensively assessed. Since the prediction of wake-induced mixing depends strongly on the accurate representation of platform motions and hydrodynamic loading, additional validation of the numerical methodology is required before it can be applied with confidence to environmental flow

investigations. This creates a need for further study of both the numerical framework and the resulting wake characteristics.

In this study, the IBM is used to represent the floating platform and reproduce its wake. This is carried out using VBM framework which is available in CFD commercial software STAR-CCM+. To verify the approach, a simple two-dimensional box-type geometry is simulated using the Virtual Body formulation and compared against the body-fitted Dynamic Fluid-Body Interaction (DFBI) implementation. A detailed description of the IBM and its framework is presented in chapter 3 for this study.

The comparison is performed across three degrees of freedom, heave, surge, and pitch. Accurately capturing the hydrodynamic response and wake behaviour requires a clear understanding of how the virtual boundary interacts with the surrounding fluid pressure field. The accuracy of the predicted loads and wake structures depends on how effectively the method captures momentum exchange across this moving fluid–structure interface. The detailed implementation used in this work is presented in section 3.3.

1.4 Objectives and Limitations

This thesis constitutes Phase 2 of the research project *Prediction of Wake Flows Induced by an Offshore Wind Turbine Foundation to Understand Its Environmental Impact*. Phase 1 Satria Pratama [18] established the numerical methodology for modelling wake-induced mixing in stratified shelf seas, examining the wake downstream of an 8 m diameter bottom-fixed monopile subjected to a steady current. Environmental boundary conditions were based on deep-water field measurements featuring a thermocline at approximately 10 m depth.

Phase 1 demonstrated strong sensitivity to fluid property formulations. Constant-property simulations over-predicted vertical mixing, resulting in a 1.76 °C surface temperature increase 35 diameters downstream. Conversely, applying temperature-dependent properties based on the International Association for the Properties of Water and Steam (IAPWS) formulation, Wagner et al. [22] showed negligible thermocline erosion. This established that buoyancy forces associated with density stratification stabilize the wake and limit vertical mixing interactions.

The aim of this thesis is to numerically investigate wake flows generated by FOWTs and to evaluate the feasibility of applying the IBM (referred to as the VBM within STAR-CCM+) to model their hydrodynamic response. Building on the simulation framework developed in Phase 1 by Satria Pratama [18], the present work extends the methodology to floating deep-water structures in order to predict how their presence and dynamic behaviour may modify natural marine flow conditions. In addition, this thesis seeks to identify and mitigate numerical instabilities and to stabilise the fluid–structure interaction within the computational framework.

The objectives and the approaches applied to achieve these aims are summarized below:

Objective 1: Extend the existing numerical framework from bottom-fixed monopile foundations to multi-degree-of-freedom floating platforms. This is achieved by utilizing an IBM on a fixed Cartesian grid, bypassing the computational expense and quality degradation associated with dynamic mesh morphing. Furthermore, this approach strives to mitigate the instabilities ensuring that the FSI of massive marine structures is resolved prior to analyzing the turbulent far-wake dynamics.

Objective 2: Validate the multiphase wave-kinematic capabilities of the Virtual Body Method by comparing the surge, pitch, and heave responses of a floating box with those predicted using a DFBI solver coupled to an overset mesh. Simulations are performed in regular Volume of Fluid (VOF) waves to assess the ability of the virtual boundary approach to capture air-water interface effects and rigid-body motions. Agreement between the resulting displacement responses provides confidence in the methodology before its application to the three-dimensional VoltturnUS-S platform.

Objective 3: Compare the experimentally evaluated characteristics of the floating platform against the 1:70 scale physical wave basin experiments conducted by Ransley et al. [16]. By simulating rigid-body free-decay tests in a calm numerical wave tank, this stage evaluates the solver’s ability to capture the platform’s response in heave, and pitch. Validating these fundamental kinematic responses ensures that the Virtual Body framework replicates the motion of the semi-submersible, establishing a baseline prior to introducing turbulent flow.

Objective 4: Verify that the Virtual Body model resolves the coupled fluid-structure interaction and rigid-body kinematics to execute the simulations of full-scale wake dynamics. The methodology is applied to the fully three-dimensional VoltturnUS-S platform, employing a Volume of Fluid (VOF) flat waves. Under these dynamic conditions, the surrounding turbulence is rigorously investigated to quantify how the platform’s multi-degree-of-freedom motions dictate the turbulent wake structure.

There are several limitations should be acknowledged when interpreting the results of this study. These limitations arise from modeling assumptions, numerical constraints, and the simplifications adopted to isolate the hydrodynamic behavior of the VoltturnUS-S platform. Understanding these restrictions is important for assessing the applicability of the findings and identifying directions for future improvements and more comprehensive floating offshore wind turbine simulations.

Limitation 1: Limitations of the Immersed Boundary Method While the Virtual Body Method within the IBM framework eliminates the need for computationally expensive dynamic mesh morphing, it introduces several numerical limi-

tations. Simulating massive structures with can trigger instabilities, causing phase lags between the fluid and the structure.

Limitation 2: Omission of the Mooring System A notable limitation of this study is the exclusion of the mooring lines from the computational model. In reality, the VoltturnUS-S platform utilizes a three-line chain catenary mooring system. Neglecting these physical lines means the model does not capture the non-linear restoring stiffness they provide, which is critical for constraining the platform's motion in surge. Further, physical mooring chains contribute their own hydrodynamic added mass and viscous drag, which interact with the platform's wake and provide additional damping to the system. By removing the moorings, the current setup strictly isolates to the bare-hull hydrodynamics.

Limitation 3: Isolation of Platform Hydrodynamics The current simulations focus only on the hydrodynamic response of the floating platform, neglecting a aerodynamic model of the wind turbine itself. In operational floating offshore wind turbines, the rotor assembly introduces severe aero-hydro-servo-elastic couplings. By not actively modeling the rotating turbine and its control system, this study neglects thesis forces and the aerodynamic damping due the blades, which can affect the platform's pitch motions. While this isolation was needed to establish a verified hydrodynamic baseline, it restricts the findings to purely hydrodynamic load cases. Consequently, the results cannot capture the complex, two-way interaction where changinf aerodynamic thrust alters the platform's equilibrium position and wake generation.

Limitation 4: Assumption of a Perfectly Rigid Structure Finally, the fluid-structure interaction framework applied in this thesis evaluates the kinematics of the VoltturnUS-S platform under the assumption that it is a perfectly rigid body. This neglects the actual structural deformation of the pontoons, braces, and columns.

2

Theory

This chapter presents the theory governing the fluid dynamics and numerical models used in this study. It begins with the fundamental conservation laws of fluid mechanics, followed by the turbulence modeling approach required to study wake dynamics in offshore environments. The hydrodynamic and kinematic concepts required to describe floating offshore wind turbine behaviour are then introduced. Finally, the finite-volume framework used to discretize and solve the governing equations is presented.

2.1 Governing Equations

The behaviour of fluid motion is governed by the fundamental conservation laws of mass and momentum.

2.1.1 Conservation of Mass

For a fluid continuum, the differential form of the continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_j)}{\partial x_j} = 0 \quad (2.1)$$

where ρ is the fluid density and v_j is the velocity vector. For incompressible flow with constant density, this reduces to:

$$\frac{\partial v_j}{\partial x_j} = 0 \quad (2.2)$$

2.1.2 Conservation of Momentum

Applying Newton's second law to a fluid continuum yields the Navier–Stokes equations, which describe the conservation of momentum. For an incompressible Newtonian fluid, the momentum equation is:

$$\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 v_i}{\partial x_j \partial x_j} + f_i \quad (2.3)$$

where p is the thermodynamic pressure, ν is the kinematic viscosity, and f_i represents the external body forces. The body-force term forms the fundamental basis of the IBM formulation detailed in Chapter 3.

2.2 RANS Turbulence Model

Offshore wind turbines operate in the ocean and atmosphere, where the flow is strongly turbulent. Turbulence refers to the irregular and fluctuating motion of a fluid, characterised by swirling eddies of many different sizes. Because these motions span a wide range of spatial and temporal scales, resolving every detail of the flow directly is not computationally feasible.

To describe this chaotic flow mathematically, the instantaneous flow is separated into a steady mean component and a fluctuating component. For the instantaneous velocity v_i , it can be decomposed by the Reynolds decomposition as:

$$v_i = \langle v_i \rangle + v'_i \quad (2.4)$$

where $\langle v_i \rangle$ represents the time-averaged mean velocity and v'_i represents the random turbulent velocity fluctuations, as presented in Figure 2.1.

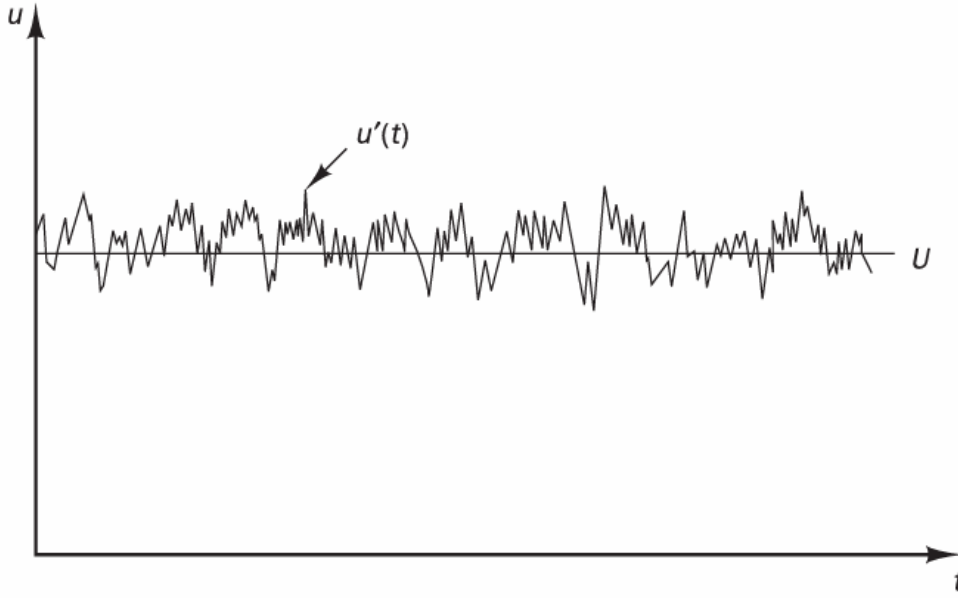


Figure 2.1: General representation of velocity in turbulent flow

Applying the Reynolds decomposition to the velocity in the fundamental continuity and momentum equations and subsequently time-averaging, the Reynolds-Averaged Navier–Stokes (RANS) equations are obtained:

$$\frac{\partial \langle v_j \rangle}{\partial x_j} = 0 \quad (2.5)$$

$$\frac{\partial \langle v_i \rangle}{\partial t} + \langle v_j \rangle \frac{\partial \langle v_i \rangle}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x_i} + \nu \frac{\partial^2 \langle v_i \rangle}{\partial x_j \partial x_j} - \frac{\partial \langle v'_i v'_j \rangle}{\partial x_j} + \langle f_i \rangle \quad (2.6)$$

This time-averaging introduces a new term into the momentum equations $\rho \langle v'_i v'_j \rangle$, known as the Reynolds stress tensor. Because the Reynolds stresses are unknown,

the system contains more variables than governing equations, leading to the fundamental "closure problem" of turbulence mechanics.

To resolve the closure problem, the RANS focuses entirely on computing the mean flow properties while modeling the bulk physical effects of the turbulent fluctuations. The most widely used approach to approximate the unknown Reynolds stresses is the Boussinesq eddy viscosity hypothesis, which assumes the turbulent Reynolds stresses are proportional to the mean rate of deformation (Versteeg and Malalasekera [20]):

$$-\rho\langle v'_i v'_j \rangle = \mu_t \left(\frac{\partial \langle v_i \rangle}{\partial x_j} + \frac{\partial \langle v_j \rangle}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (2.7)$$

where μ_t is the turbulent eddy viscosity, k is the Turbulent Kinetic Energy (TKE), and δ_{ij} is the Kronecker delta. This hypothesis shifts the closure problem to formulate a transport equation for the eddy viscosity.

Because wake development is governed by the transfer of energy from the mean flow to turbulent fluctuations, it is useful to examine the TKE transport equation. A key term appearing in both the mean kinetic energy and TKE transport equations is the production term P_k :

$$P_k = -\langle v'_i v'_j \rangle \frac{\partial \langle v_i \rangle}{\partial x_j} \quad (2.8)$$

When the Reynolds stress ($\langle v'_i v'_j \rangle$) interacts with the mean velocity gradient ($\partial \langle v_i \rangle / \partial x_j$), energy is extracted from the mean flow and converted into turbulent motion (Versteeg and Malalasekera [20]). The velocity deficit created by the platform introduces strong velocity gradients at the wake. Because the production of TKE is driven by mean-flow shear, these gradients act as the source for turbulence generation. Therefore, accurate representation of turbulence generation is required when evaluating the hydrodynamic influence of a floating platform.

2.3 Multiphase Flow and Wave Modelling

While the preliminary stages of this research evaluate the subsurface wake in a single-phase environment, an accurate assessment of FOWTs ultimately requires resolving the complex multiphase interactions at the air-water interface. To track the free surface and simulate the effects of wave-current interactions acting upon the dynamic floating platform, the VOF method is used.

2.3.1 Volume of Fluid (VOF) Method

The VOF model is an Eulerian interface-capturing approach used to represent immiscible phases on a fixed computational grid. The method assumes that the mesh resolution is sufficient to resolve the position and shape of the air-water interface. Instead of explicitly tracking the physical boundary between the fluids, the phase distribution is described using a scalar volume fraction, α_i , defined in STAR-CCM+

(STAR-CCM+ 2506 User Guide [19]) as:

$$\alpha_i = \frac{V_i}{V} \quad (2.9)$$

where V_i is the volume of phase i within a control volume V . For a two-phase system, the volume fractions must satisfy:

$$\sum_i \alpha_i = 1 \quad (2.10)$$

Because the VBM dynamically projects vertices and alters cell shapes at the fluid-structure interface, the VOF conservation equation must account for the local mesh motion to prevent artificial mass generation. For the water phase, the modified transport equation is:

$$\frac{d}{dt} \int_V \alpha_{\text{water}} dV + \oint_A \alpha_{\text{water}} (\mathbf{v} - \mathbf{v}_g) \cdot d\mathbf{a} = \int_V S_{\alpha_{\text{water}}} dV \quad (2.11)$$

where $\mathbf{v}$ is the absolute fluid velocity, $d\mathbf{a}$ is the differential surface area vector, and $\mathbf{v}_g$ is the local grid velocity associated with the Virtual Body's vertex projection. To maintain a sharp interface, *Simcenter STAR-CCM+* employs the H (HRIC) scheme (STAR-CCM+ 2506 User Guide [19]).

2.3.2 Flat Waves

The Flat VOF Wave model is applied in baseline simulations to evaluate flow development due solely to the motion of the platform. This model prescribes a constant free-surface elevation at the specified still-water level without introducing vertical wave motion.

2.3.3 Fifth-Order Stokes Waves

For simulations requiring realistic non-linear wave forcing, a Fifth-order VOF Wave model is employed, whose formulation enables expression of wave profile and phase velocity as non-linear expansions, capturing the asymmetry of steep ocean waves more accurately than linear wave theory (Fenton [7]). The formulation is strictly valid for Ursell numbers $U_r < 40$ (DNV-RP-C205 [4]), a criterion well-satisfied by the deep-water 15-MW VoltturnUS-S environment.

2.4 Floating Platform Kinematics

The rigid-body motions introduced in this section form the basis of the free-decay and full scale motion for wake is presented later in the thesis.

A freely floating body in a marine environment exhibits six motional DOF. To mathematically describe these motions, a body-fixed coordinate system $(\bar{x}, \bar{y}, \bar{z})$ is introduced, which translates and rotates relative to a global, earth-fixed inertial coordinate frame (x, y, z) . The motion in six degrees of freedom are defined by the displacement vector $\boldsymbol{\eta} = [\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6]^T$:

- **Translations:**
 - η_1 (Surge): Longitudinal translation along the $\bar{x}$ -axis (positive forward).
 - η_2 (Sway): Lateral translation along the $\bar{y}$ -axis (positive to starboard).
 - η_3 (Heave): Vertical translation along the $\bar{z}$ -axis (positive upwards).
- **Rotations:**
 - η_4 (Roll): Rotation about the $\bar{x}$ -axis.
 - η_5 (Pitch): Rotation about the $\bar{y}$ -axis.
 - η_6 (Yaw): Rotation about the $\bar{z}$ -axis.

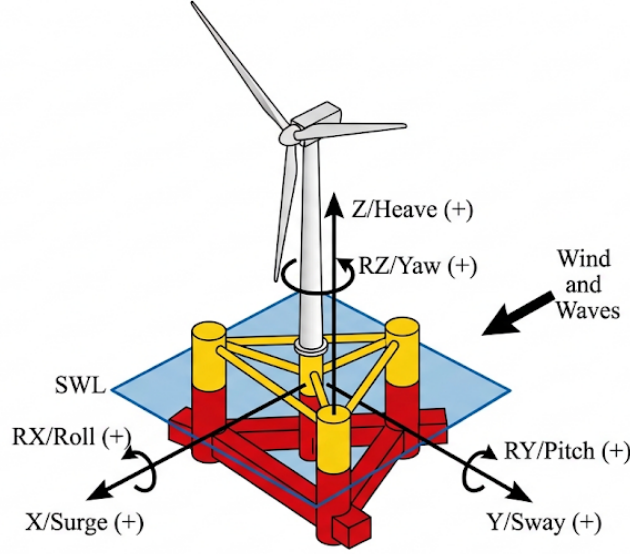


Figure 2.2: Illustration of the six DOF of a semi-submersible floating offshore wind turbine. Image generated using Google Gemini.

In traditional offshore engineering, the equilibrium of a floating platform is formulated using Newton’s second law. By equating the inertia of the platform to the sum of the environmental and reaction forces, the general coupled linearized equation of motion is expressed as:

$$(\mathbf{M} + \mathbf{A})\ddot{\boldsymbol{\eta}} + \mathbf{B}\dot{\boldsymbol{\eta}} + \mathbf{C}\boldsymbol{\eta} = \mathbf{F}_{exc} + \mathbf{F}_{moor} \quad (2.12)$$

where $\mathbf{M}$ is the 6×6 structural mass matrix, $\mathbf{A}$ is the added mass matrix representing the inertia of the surrounding fluid, $\mathbf{B}$ is the hydrodynamic damping matrix accounting for radiated waves and viscous skin friction, and $\mathbf{C}$ is the hydrostatic restoring matrix arising from changes in buoyancy. The terms $\mathbf{F}_{exc}$ and $\mathbf{F}_{moor}$ represent external wave/current excitation and mooring reaction forces, respectively. However, during the preliminary free-decay simulations used to validate the solver’s rigid-body kinematics in a calm water environment, the external excitation and mooring vectors are zero. Consequently, the rigid-body kinematics of the platform are governed by the unforced, linearized equation of motion:

$$(\mathbf{M} + \mathbf{A})\ddot{\boldsymbol{\eta}} + \mathbf{B}\dot{\boldsymbol{\eta}} + \mathbf{C}\boldsymbol{\eta} = \mathbf{0} \quad (2.13)$$

For the fully coupled high-fidelity wave simulations, the fluid loads are transferred directly to the rigid-body solver through the VBM solver. The instantaneous pressure and viscous shear stresses acting on the platform boundary are explicitly integrated at each computational timestep. These hydrodynamic loads are then supplied directly to the rigid-body equations of motion to determine the instantaneous translational and rotational accelerations ($\ddot{\eta}$) of the floating platform. A detailed description of this coupling procedure is provided in section 3.3.

2.5 Finite Volume Method

The nonlinear partial differential equations governing fluid dynamics generally lack analytical solutions. The Finite Volume Method (FVM) is utilized as the primary discretization framework because it intrinsically enforces the exact macroscopic conservation of mass and momentum across discrete control volumes. This conservation is a strict requirement for accurately tracking the sharp air-water interface in the VOF method, and for preserving momentum deficits in the far-wake region without artificial numerical loss.

2.5.1 Spatial Discretization

In the finite-volume framework, the governing equations are integrated over a set of discrete control volumes. Flow variables are stored at the centroids of these control volumes, as illustrated in Figure 2.3. Consequently, the values required at the cell faces for the convective and diffusive fluxes must be approximated through suitable interpolation schemes.

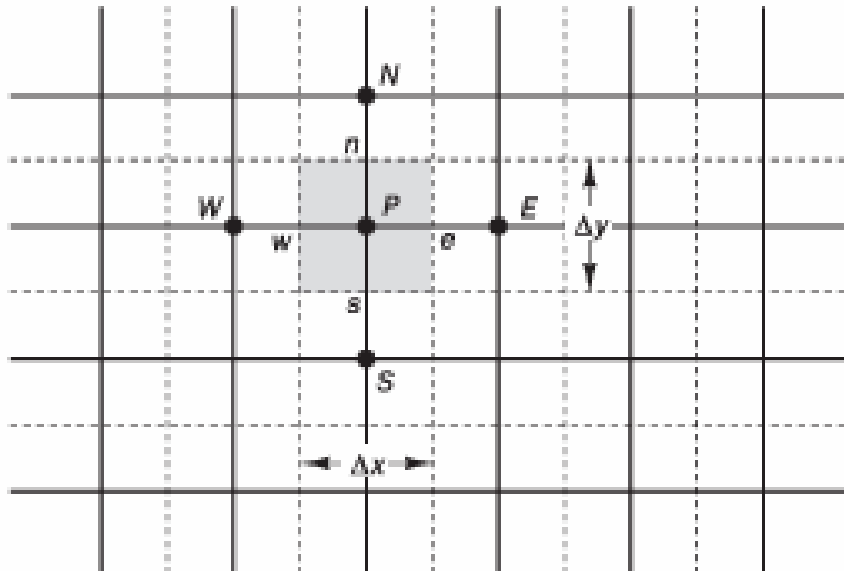


Figure 2.3: Control volume arrangement on a two-dimensional structured grid (Versteeg and Malalasekera [20]).

For the convective fluxes, the Bounded Central Differencing (BCD) scheme is used

(Versteeg and Malalasekera [20]). The BCD scheme acts as a dynamic hybrid approach: it applies second-order central differencing in smooth flow regions to reduce numerical dissipation and preserve the turbulent structures predicted by the turbulence model, while smoothly reverting to a stabilizing first-order upwind formulation in regions of high discontinuity, such as the VOF free surface.

2.5.2 Temporal Discretization

To accurately capture the highly transient flow physics of the turbulent wake and the dynamic platform motions, a second-order temporal discretization scheme is employed. While earlier implementations of the VBM were restricted to first-order time-stepping due to the dynamic projection of mesh vertices at the fluid-structure interface (STAR-CCM+ 2506 User Guide [19]), recent solver advancements allow the algorithm to satisfy the Space Conservation Law while utilizing second-order implicit time-stepping. This significantly reduces artificial numerical diffusion over long simulation durations, ensuring the preservation of fine-scale turbulent eddies in the far-wake region.

2.5.3 The SIMPLE Solver

The oceanic marine environment dictates a constant-density, incompressible flow regime. Under these conditions, the equations are solved sequentially using a Segregated Flow Solver driven by the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm (STAR-CCM+ 2506 User Guide [19]). The SIMPLE algorithm enforces mass conservation through a predictor-corrector sequence that iteratively updates the pressure and velocity fields until convergence is achieved. Furthermore, to prevent adjacent pressure nodes from decoupling on the collocated grid (artificial "checkerboarding"), the solver applies the Rhie-Chow momentum interpolation method (Versteeg and Malalasekera [20]).

2.5.4 Source Term Linearization and Matrix Stability

As established in Chapter 3, the IBM mathematically enforces the presence of the floating platform by introducing a localized volumetric body force density into the momentum equations. In the finite-volume discretization framework, source terms must be linearized into a constant component and a variable-dependent component, typically expressed as $S = S_u + S_p \phi_P$ (Versteeg and Malalasekera [20]).

To ensure stable convergence of the iterative solver, the discretized equations should satisfy the Scarborough criterion. In practice, this means that the coefficient matrix should be diagonally dominant. Diagonal dominance is naturally enhanced when the coefficient S_p is negative, as it adds directly to the magnitude of the central node coefficient, a_P .

However, the highly localized and dynamically updated nature of the IBM body force often acts primarily as an explicit source contribution (S_u). If the explicit

force magnitudes become excessively large, or if the structural motions trigger rapid force fluctuations, it severely degrades the diagonal dominance of the resulting matrix. This loss of diagonal dominance is a primary trigger for numerical instability, unbounded spatial oscillations, or complete solver divergence during the SIMPLE pressure-velocity coupling sequence. Consequently, mitigating this matrix instability necessitates the careful application of under-relaxation factors, strict adherence to Courant–Friedrichs–Lewy (CFL) time-step limits, and the inertial stabilization introduced via the DFBI scheme.

The governing physical and numerical concepts presented in this chapter provide the foundation for the immersed-boundary formulation employed in this work. The specific implementation of the Virtual Body Method and its coupling with the rigid-body solver are described in Chapter 3.

2.6 Wake Behind Platform

To evaluate the environmental impacts of a floating offshore wind turbine, it is essential to understand the physical mechanisms governing its wake. The evolution of the wake is characterized by the extraction of momentum, the generation of turbulence, and the recovery of the flow field. The principal mechanisms governing wake development behind a floating offshore wind turbine are illustrated in Figure 2.4.

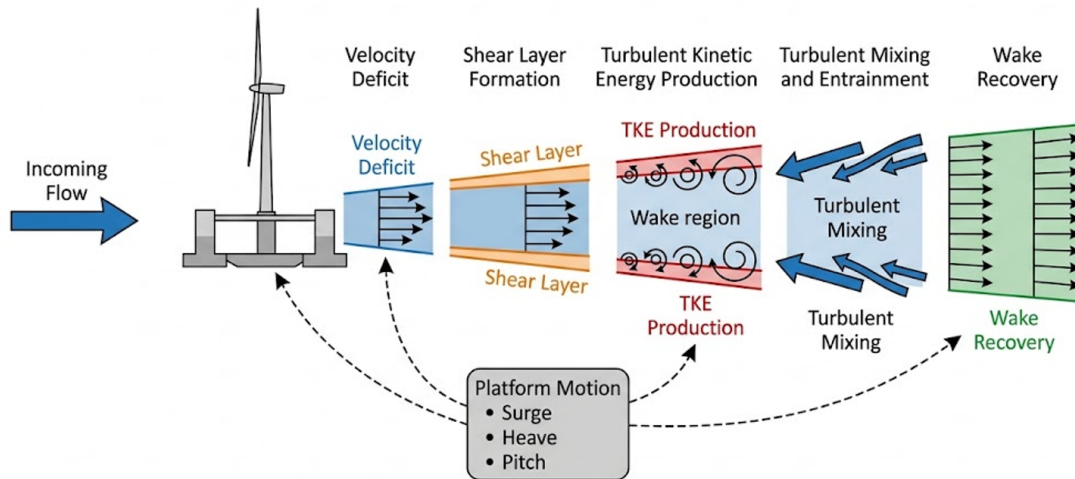


Figure 2.4: Conceptual illustration of wake development behind a floating offshore wind turbine platform. Platform motions may further modify turbulence generation and wake evolution.

As the fluid flows past the floating platform, momentum is extracted from the incoming flow through pressure and viscous forces acting on the structure. The resulting flow separation creates a downstream velocity deficit, commonly referred to

as the wake. At the periphery of this wake, a distinct boundary forms between the slow-moving fluid within the wake core and the undisturbed ambient flow. This transition zone is characterized by sharp velocity gradients that form strong shear layers. Because the production of TKE is driven by mean-flow shear, these high-velocity gradients act as the primary source for generating turbulent eddies along the wake edge (Dorrell et al. [5]).

The spatial extent and eventual dissipation of the wake are governed by the continuous production and transport of TKE. Turbulent mixing captures high-momentum fluid from the surrounding flow into the wake region, gradually redistributing momentum across the fluid domain. This process reduces the velocity deficit and drives the recovery of the wake as it propagates downstream (Dorrell et al. [5]).

Unlike fixed-bottom foundations, floating offshore wind turbines undergo continuous surge, heave, and pitch motions in response to wave loading. These motions modify the relative inflow conditions experienced by the platform and alter the pressure distribution surrounding the structure (Zhang et al. [23]). Consequently, wake development becomes inherently unsteady, affecting turbulence production, vortex shedding, and wake recovery. Understanding this coupling between platform motion and wake dynamics forms a central motivation for the present study.

3

Virtual Body Framework

Fully resolving the complex, large-scale motions of a floating platform using a traditional dynamic overset mesh is computationally expensive and can suffer from grid degradation [21]. To address this, the IBM is utilized to represent floating offshore wind turbine platforms without requiring body-fitted mesh deformation. The chapter introduces the fundamental mathematics of the IBM, outlines the physical challenges associated with FSI, and describes the specific realization of this approach. Finally, a numerical coupling scheme developed to stably evaluate the platform's rigid-body kinematics is presented.

3.1 The Immersed Boundary Method (IBM)

The fundamental principle of the IBM, originally pioneered by Peskin [15], is to simulate moving boundaries within a fluid domain on a simple, fixed Cartesian grid. Instead of deforming the mesh to conform to the structure's geometry, the virtual body is represented by a moving Lagrangian surface embedded within the fixed Eulerian grid.

The physical presence of the solid is mathematically enforced by introducing an externally imposed, localized body force density field, $\mathbf{f}$, into the continuous Navier-Stokes momentum equations (Goldstein, Handler, and Sirovich [9] and Fadlun et al. [6]):

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla \cdot (\rho\mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot (\mu\nabla\mathbf{u}) + \mathbf{f} \quad (3.1)$$

where $\mathbf{u}$ represents the fluid velocity in the fixed Eulerian frame.

The IBM couples fluid variables defined on a fixed Eulerian grid with boundary variables defined on a moving Lagrangian surface (Peskin [15] and Griffith and Patankar [10]). The local fluid velocity $\mathbf{u}(\mathbf{x}, t)$ is interpolated from the fixed Eulerian grid onto the Lagrangian boundary points $\mathbf{X}(s, t)$ to evaluate the instantaneous interface velocity $\mathbf{U}(s, t)$ using the Dirac delta function, δ :

$$\mathbf{U}(s, t) = \int_{\Omega} \mathbf{u}(\mathbf{x}, t) \delta(\mathbf{x} - \mathbf{X}(s, t)) d\mathbf{x} \quad (3.2)$$

where Ω represents the entire fluid domain.

Once the required Lagrangian boundary force $\mathbf{F}(s, t)$ is determined to satisfy the no-slip condition, it is projected back onto the surrounding fluid grid cells to act

as the volumetric body force $\mathbf{f}(\mathbf{x}, t)$ in Equation 3.1. This is also achieved via the Dirac delta function over the boundary surface Γ :

$$\mathbf{f}(\mathbf{x}, t) = \int_{\Gamma} \mathbf{F}(s, t) \delta(\mathbf{x} - \mathbf{X}(s, t)) ds \quad (3.3)$$

By utilizing a continuous feedback loop of velocity interpolation and force spreading, the local fluid velocity is driven toward the prescribed body velocity. This effectively enforces the no-slip condition on the moving interface without altering the underlying Eulerian grid [6].

3.2 Fully Coupled CFD Framework

Modeling floating offshore wind turbines introduces significant FSI challenges. The cylindrical columns of the VoltornUS-S platform generate complex, three-dimensional turbulent wake mixing and viscous drag damping. In conventional analyses, time-domain solvers rely on potential flow theory (Strip Theory) using pre-computed matrices for Added Mass ($\mathbf{A}$) and Radiation Damping ($\mathbf{B}$). However, potential flow assumes an inviscid fluid, making it insufficient for capturing the realistic hydrodynamic feedback required to accurately evaluate the hydrodynamic loading and wake development.

However, a known challenge in traditional IBM formulations is that the interface is treated as a massless virtual boundary. When dealing with massive floating structures, this massless assumption causes a critical phase lag in the explicit FSI (Kim and Peskin [11]). Because the numerical boundary lacks physical inertia, the solver fails to accurately capture the instantaneous hydrodynamic feedback. This misalignment leads to the well-documented artificial added-mass instability as documented in Causin, Gerbeau, and Nobile [3], which can cause the simulation to rapidly diverge if not properly treated.

To overcome the limitations of conventional potential flow tools and address the instability of the massless boundary, a fully coupled CFD framework is necessary. In this approach, hydrodynamic forces are not supplied as pre-computed matrices. Instead, they emerge naturally from the fluid-structure interaction and are resolved directly during the simulation. At each computational timestep, the instantaneous pressure and viscous shear stresses acting on the active virtual platform boundary are explicitly integrated. These locally resolved fluid loads are fed directly into the rigid-body equations of motion (defined previously in Chapter 2) to evaluate the instantaneous translational and rotational accelerations ($\ddot{\boldsymbol{\eta}}$). This direct coupling captures both radiation damping and viscous drag natively within the CFD environment, allowing hydrodynamic loading and wake development to be resolved within a single CFD framework.

3.3 The Virtual Body Method (VBM)

In STAR-CCM+, the IBM is implemented based on the Virtual Body Method. While classical IBMs impose the solid solely through the distributed forcing term $\mathbf{f}$ (as shown in Equation 3.1), the VBM actively modifies the computational control volumes intersected by the solid boundary. As the virtual body intersects the computational mesh, cells are dynamically classified as active or inactive depending on whether they lie outside or inside the solid geometry (STAR-CCM+ 2506 User Guide [19]). The resulting active and inactive cell treatment are illustrated in Figure 3.1. The governing transport equations are solved only within the active fluid cells, while the inactive cells are excluded from the solution process.

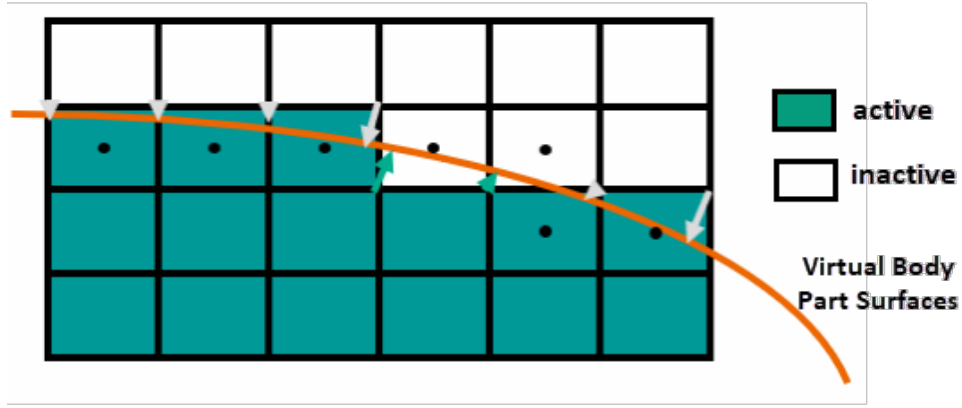


Figure 3.1: Dynamic classification of active and inactive cells, and vertex projection at the Virtual Body part surface.

The VBM projects the mesh vertices between the active and inactive cells directly onto the tessellated surface of the virtual body (see Figure 3.1). This cut-cell approach preserves the geometric representation of the moving structure, improving local conservation properties and enabling a more robust treatment of the interface in a multiphase VOF environment.

Because the vertex projection effectively moves the mesh locally at the fluid-structure interface, the shape and volume of the cut-cells vary with time. To prevent artificial mass generation, the solver explicitly enforces the Space Conservation Law (STAR-CCM+ 2506 User Guide [19]):

$$\frac{d}{dt} \int_V dV = \oint_A \mathbf{v}_g \cdot d\mathbf{a} \quad (3.4)$$

where $\mathbf{v}_g$ is the local grid velocity of the moving vertices. The convective mass flux across the cell faces, $\dot{m}_f$, is subsequently modified to account for this grid flux:

$$\dot{m}_f = \rho_f(\mathbf{v} \cdot \mathbf{a} - G_g) \quad (3.5)$$

To ensure numerical stability as the virtual body continuously alters cell volumes, the grid flux is evaluated as $G_g = \delta V_f^n / \Delta t$, representing the volume swept by the

face over the discrete time step.

3.4 Motion Coupling

In the present work, the rigid-body motion of the floating platform is solved using the native DFBI with VBM framework available in Simcenter STAR-CCM+. The solver provides a fully integrated fluid-structure interaction formulation that can be coupled directly with the Virtual Body Method (VBM) (STAR-CCM+ 2506 User Guide [19]). This allows the platform motion and surrounding flow field to be solved simultaneously within a single computational framework.

At each physical timestep, the hydrodynamic forces and moments acting on the platform are obtained by integrating the fluid pressure and viscous shear stresses over the active virtual body surface. The translational motion of the body is governed by Newton's second law:

$$m \frac{d\mathbf{v}}{dt} = \mathbf{f} \quad (3.6)$$

where m is the structural mass, $\mathbf{v}$ is the translational velocity of the centre of mass, and $\mathbf{f}$ is the resultant force vector. Rotational motion is evaluated in a body-fixed coordinate system according to Euler's equations:

$$\mathbf{I} \frac{d\boldsymbol{\omega}}{dt} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) = \mathbf{n} \quad (3.7)$$

where $\mathbf{I}$ is the inertia tensor, $\boldsymbol{\omega}$ is the angular velocity vector, and $\mathbf{n}$ is the resultant moment vector acting on the body (STAR-CCM+ 2506 User Guide [19]).

To advance the kinematics, the DFBI solver employs a fully coupled approach. The solver performs multiple internal iterations within each physical timestep to continuously update and converge the fluid forces and the resulting body kinematics. This iterative predictor-corrector coupling fundamentally mitigates the artificial added-mass instability that typically plagues loosely coupled (explicit) fluid-structure interaction schemes when applied to massive, dynamically responding offshore structures (Causin, Gerbeau, and Nobile [3]).

Following the convergence of the rigid-body kinematics within the DFBI solver, the updated position and orientation vectors are used to reposition the virtual boundary before advancing to the next physical timestep.

As the virtual platform moves, the solver dynamically re-evaluates the intersection of the body surface with the background Eulerian grid. The fluid cells are subsequently reclassified as active or inactive, and the cut-cell vertices are projected onto the updated body surface (STAR-CCM+ 2506 User Guide [19]). To prevent artificial mass generation caused by the slightly varying volumes of these cut-cells, the governing flow equations are solved on the modified computational domain while strictly satisfying the Space Conservation Law. The temporal change in cell volume is balanced by calculating the grid flux, G_g , swept by the moving faces over the

second-order discrete timestep (STAR-CCM+ 2506 User Guide [19]).

This procedure establishes a two-way coupling between the multiphase flow field and the platform motion. The hydrodynamic forces generated by the fluid dictate the rigid-body response of the platform, while the updated platform position instantaneously modifies the surrounding flow field. This enables the six-degree-of-freedom motion of the floating platform to be resolved simultaneously with the turbulent wake development.

4

Numerical Implementation

The governing physical equations and the mathematical formulation of the Virtual Body Method (VBM) have been established in Chapter 2 and Chapter 3, respectively. This chapter details the practical numerical implementation and simulation strategy used to evaluate the hydrodynamic response and wake development of floating offshore wind turbine platforms.

The methodology consisted of two validation exercises, a grid resolution assessment, and full-scale floating platform simulations. The validation cases were designed to verify the multiphase wave modelling capability of the Virtual Body Method and the rigid-body motion-update procedure before application to the full-scale simulations. The individual simulation stages employed different computational domains and numerical settings, as described in the following sections.



Figure 4.1: Overall methodology workflow adopted for the floating offshore wind turbine simulations.

Table 4.1: Summary of the numerical simulations performed in this study.

Case	Environment	Motion	Objective
Validation I	VOF waves	Free motion (surge, heave & pitch)	VBM validation
Validation II	Calm water	Free decay (heave & pitch)	Motion validation
Verification	Free stream	Fixed	Grid independence
Full-Scale	Uniform current	Fixed	Wake and mixing analysis

Note: Validation Case I employed a two-dimensional box geometry. Validation Case II, Verification, and the Full-Scale Simulations employed the three-dimensional VoltturnUS-S semi-submersible platform.

4.1 Validation Case I: 2D Free Box in VOF Waves

This stage assessed the capability of the VBM framework to reproduce wave-induced motions of a floating body in a multiphase environment. A simplified two-dimensional configuration was adopted as a preliminary validation of the fluid-structure interaction framework before applying the method to the full-scale platform simulations.

4.1.1 Transport equations

In this stage, the Volume of Fluid (VOF) multiphase model was utilized to capture the air-water interface. The flow was modeled as incompressible, solving the continuity and momentum equations via the Finite Volume Method (FVM). The Segregated Flow solver with the SIMPLE algorithm and Rhie-Chow momentum interpolation was employed. To prevent artificial numerical diffusion from smearing the distinct air-water interface over the computational grid, the High-Resolution Interface Capturing HRIC scheme was activated. The numerical settings were selected to maintain consistency with the VBM framework described in Chapter 3.

4.1.2 Computational domain and mesh

A 2D numerical wave tank with a length of 18 m and a water depth of 0.4 m was utilized. The floating box length and depth were 0.3 m and 0.2 m, respectively. The computational setup is shown in Figure 4.2.

The number of trimmed mesh for the numerical wave tank is 2,036,348. As shown in Figure 4.3, the mesh was refined at the free-surface elevation zone and around the virtual box boundary using cut-cells to accurately capture the free surface and the flow separation near the box.

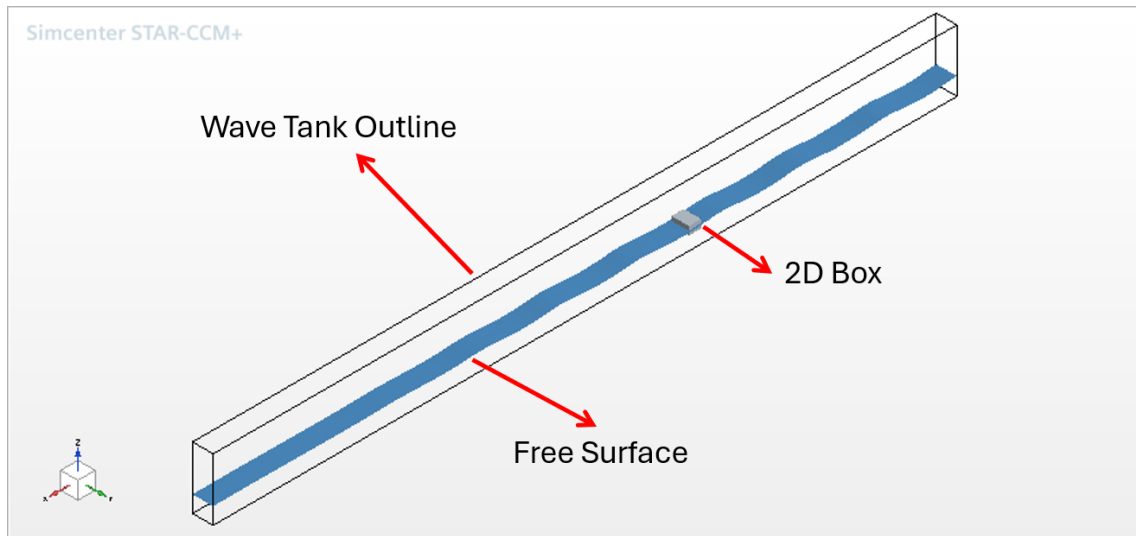


Figure 4.2: Setup and geometry for Validation Case I: 2D free box in VOF waves.

Simcenter STAR-CCM+

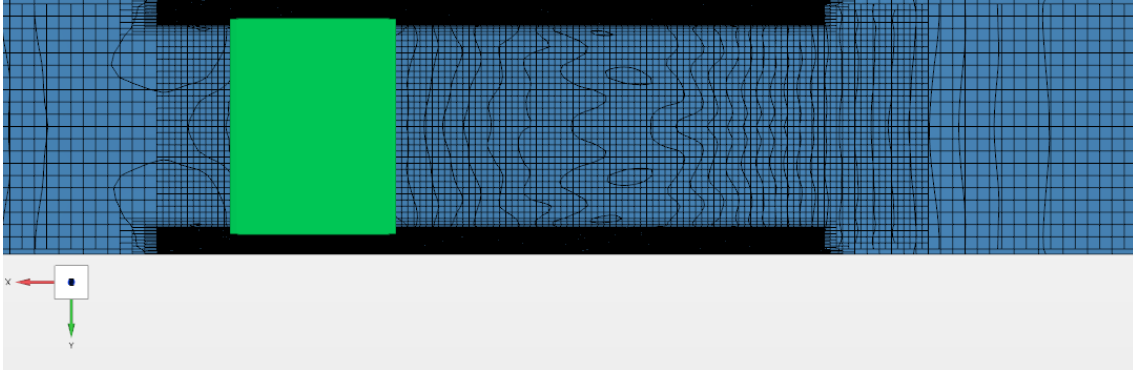


Figure 4.3: Mesh configuration with free surface and virtual boundary refinement.

4.1.3 Numerical setup

To evaluate the dynamic response, a fifth-order Stokes wave was prescribed at the inlet boundary with a wave height of 0.06 m and a wave period of 1.2 s. A wave-damping zone was applied at the outlet to prevent unphysical wave reflections back into the domain. For spatial discretization, a Bounded-Central Differencing (BCD) scheme was used. A fixed time step of 0.05 s was utilized to ensure a mean free-surface Courant-Friedrichs-Lewy (CFL) number of 8×10^{-3} .

The CFL condition dictates that the physical domain of dependence must be embedded within the numerical domain of dependence. Mathematically, the CFL number is a dimensionless parameter representing the ratio of the physical distance a fluid particle travels during a single time step to the local computational grid spacing. It is defined as:

$$\text{CFL} = \frac{U \Delta t}{\Delta x} \quad (4.1)$$

where U is the local flow velocity, Δt is the time step, and Δx is the characteristic cell dimension. Maintaining a CFL number significantly below 1.0 ensures that fluid perturbations do not cross more than one grid cell per time step, which is a strict requirement for temporal stability and for accurately capturing the sharp air-water interface within the VOF framework.

To govern the rigid-body kinematics within the native Dynamic Fluid-Body Interaction (DFBI) solver, the physical mass and inertial properties of the two-dimensional box were explicitly prescribed. The numerical setup adopted for Validation Case I is summarized in Table 4.2.

Within this implicit framework (STAR-CCM+ 2506 User Guide [19]), the hydrostatic restoring forces (buoyancy), as well as the hydrodynamic added-mass and radiation damping effects, are natively and dynamically resolved by the solver. At each internal iteration of the timestep, the solver integrates the instantaneous fluid pressure and viscous shear stresses directly over the active virtual body surface. This rigorous fluid-structure interaction ensures that the platform's response to the incident wave field is entirely driven by the resolved flow physics, eliminating the need for artificially prescribed stabilization parameters or idealized linear hydrostatic theory.

Table 4.2: Summary of the model and wave properties for Validation Case I: 2D free box in VOF waves.

Parameter	Value
Box Dimension , $L \times B \times H$	0.30 m $\times$ 0.42 m $\times$ 0.20 m
Box draft, T	0.10 m
Box mass, M	12.915 kg
Center of Gravity (KG)	0.10 m
Wave height	0.06 m
Wave period	1.2 s

4.1.4 Measured variables and locations

Time histories of surge, heave, and pitch motions were extracted and validated against the simulation using a DFBI implementation and experimental data, assessing the accuracy of the VBM multiphase coupling.

4.2 Validation Case II: 3D Free-decay Platform

This stage determined if the custom force-coupling algorithm accurately evaluates the platform's rigid-body mass, inertia, and hydrodynamic damping.

4.2.1 Transport equations

A single-phase, incompressible liquid domain was utilized for this free-decay test in calm water. The Navier-Stokes equations were solved using the segregated SIMPLE algorithm. The physical presence of the floating platform was enforced using the VBM, which dynamically deactivated cells lying inside the solid geometry and projected the vertices of the intersected cut-cells onto the body surface. The rigid-body kinematics were advanced using the implicit DFBI solver, which iteratively integrated the instantaneous hydrodynamic forces and moments directly into Newton's second law to determine the platform's dynamic response.

4.2.2 Computational domain and mesh

A 3D numerical calm-water tank domain spanning $9\text{m} \times 9\text{m}$ was generated, with the 4.1m water depth specified for the model-scale platform. The domain utilized a Cartesian background grid of 1×10^6 cells, with volumetric refinement focused entirely around the hull to preserve the geometric curvature of the pontoons and columns.

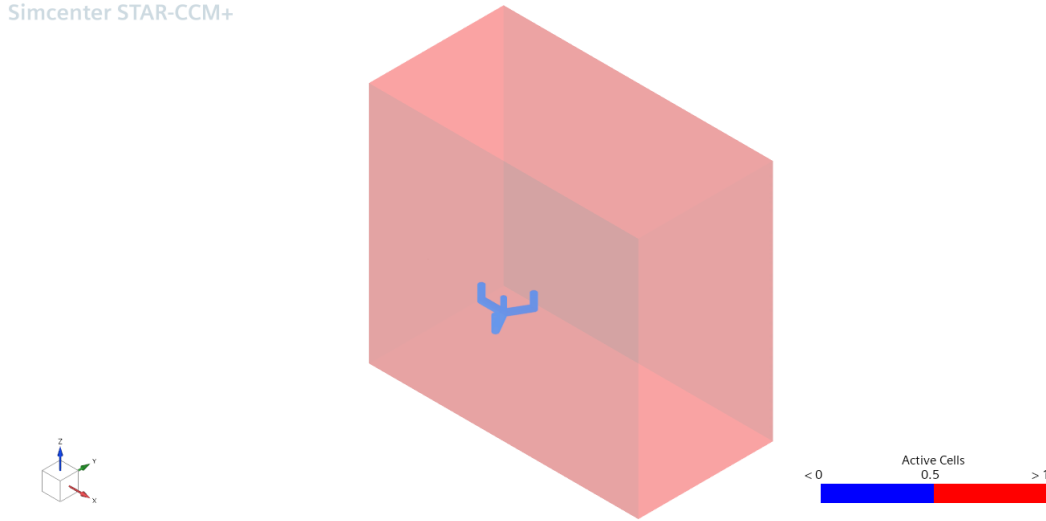


Figure 4.4: Setup and geometry for Validation Case II: Free-Decay of the 3D VoltturnUS-S platform.

4.2.3 Numerical setup

The 3D VoltturnUS-S platform was displaced from its equilibrium position in a specific DOF and released freely in calm water. To replicate the physical benchmark conditions of the 1st FOWTs comparative study (Ransley et al. [16]), the initial offsets for the individual decay tests were prescribed as a heave displacement of -0.1472m for the heave free-decay condition and a pitch angle of -9.798° for the pitch free-decay case. For spatial discretization, a Bounded-Central Differencing (BCD) scheme was used. The domain boundaries were given velocity inlet and side wall treated as symmetry walls to simulate the infinite expanse of the physical wave basin, coupled with a hydrostatic pressure outlet on top boundaries.

The numerical setup adopted for the free-decay validation is summarized in Table 4.3. The platform was released from prescribed initial heave and pitch offsets corresponding to the benchmark conditions of the 1st FOWT comparative study (Ransley et al. [16]). The numerical settings were selected to maintain consistency with the VBM framework described in Chapter 3. The values were determined using Froude-scaled properties of the 1:70 model and were applied throughout the simulations.

Table 4.3: Summary of model properties for Validation Case II: Free-decay of the 3D VoltturnUS-S platform.

Parameter	Value
Scaling ratio	1:70
Fluid density (Fresh water)	1000 kg/m ³
Platform mass, M	56.3 kg
Center of Gravity, Center of Gravity (CoG) (x, y, z) ^a	(−0.00477, 0.0, 0.26369) m
Pitch inertia, I_{yy}	26.68 kg m ²
Initial heave offset	−0.1472 m
Initial pitch offset	−9.798°

^a The CoG is given relative to the platform’s base at the centerline, which is the standard body-fixed coordinate system defined in the benchmark experiments (Ransley et al. [16]).

4.2.4 Measured variables and locations

The natural periods and damping ratios were obtained from the logarithmic decrement of the time-series decay responses in heave and pitch, respectively. Conceptually, the damping ratio (ζ) is a dimensionless parameter defined as the ratio of the system’s actual damping coefficient to its critical damping threshold, dictating how rapidly the free oscillations decay over time.

For an underdamped floating system, the damping ratio is practically evaluated from the free-decay time history using the logarithmic decrement (δ). The logarithmic decrement represents the natural logarithm of the ratio of two successive peak amplitudes, calculated over n cycles as:

$$\delta = \frac{1}{n} \ln \left(\frac{A_i}{A_{i+n}} \right) \quad (4.2)$$

where A_i is the amplitude of the i -th peak and A_{i+n} is the amplitude of the peak n cycles. The damping ratio is subsequently derived from the logarithmic decrement using the following relationship:

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} \approx \frac{\delta}{2\pi} \quad (4.3)$$

These derived quantities were then compared against the 1:70 scale physical wave-basin experiments reported by Ransley et al. [16].

4.3 Verification: Mesh Convergence

A mesh sensitivity study was conducted to ensure that the predicted wake characteristics were independent of the computational mesh. The objective was to quantify the influence of spatial resolution on the wake predictions and to identify a suitable grid for the subsequent full-scale simulations.

4.3.1 Transport Equations

The grid study was performed to isolate numerical discretization effects from multiphase wave interactions. The incompressible Navier–Stokes equations were solved using a RANS turbulence model. The RANS approach provides a computationally efficient representation of the mean turbulent flow field and was employed to evaluate the influence of mesh resolution on the predicted wake development.

4.3.2 Computational Domain and Mesh

The inlet boundary was positioned $10D$ upstream of the platform to allow the inflow to develop prior to interaction with the structure, while the outlet boundary was located $50D$ downstream to ensure complete capturing of the near- and far-wake regions. The lateral and vertical boundaries were placed sufficiently far from the wake to minimize blockage effects.

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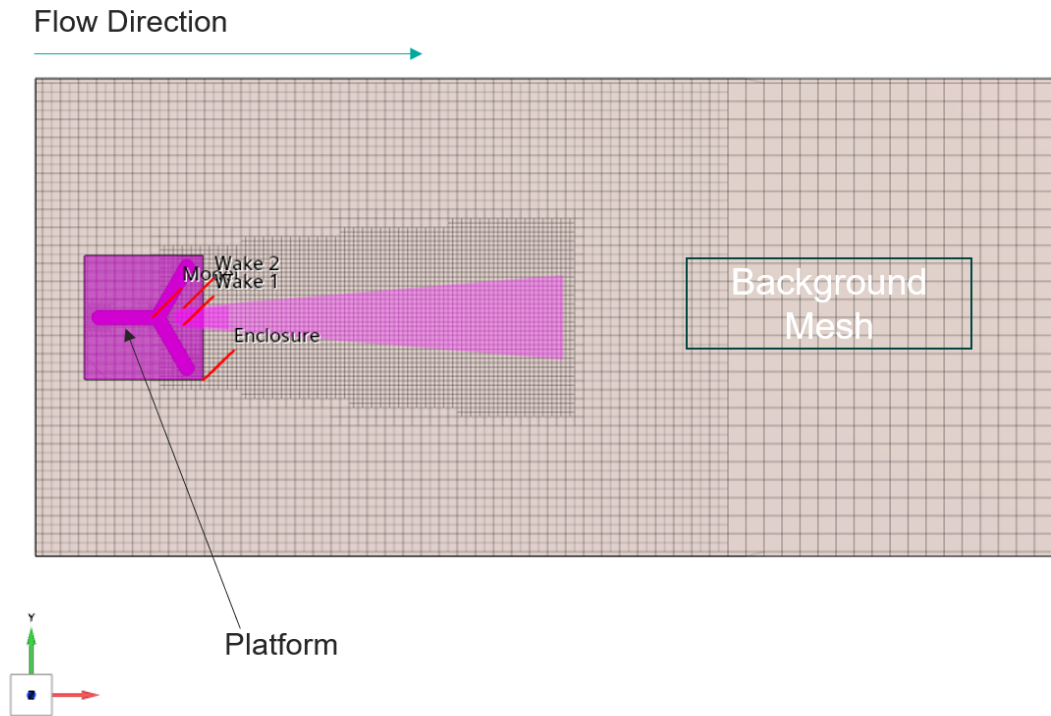


Figure 4.5: Computational grid and refinement used for the mesh sensitivity study.

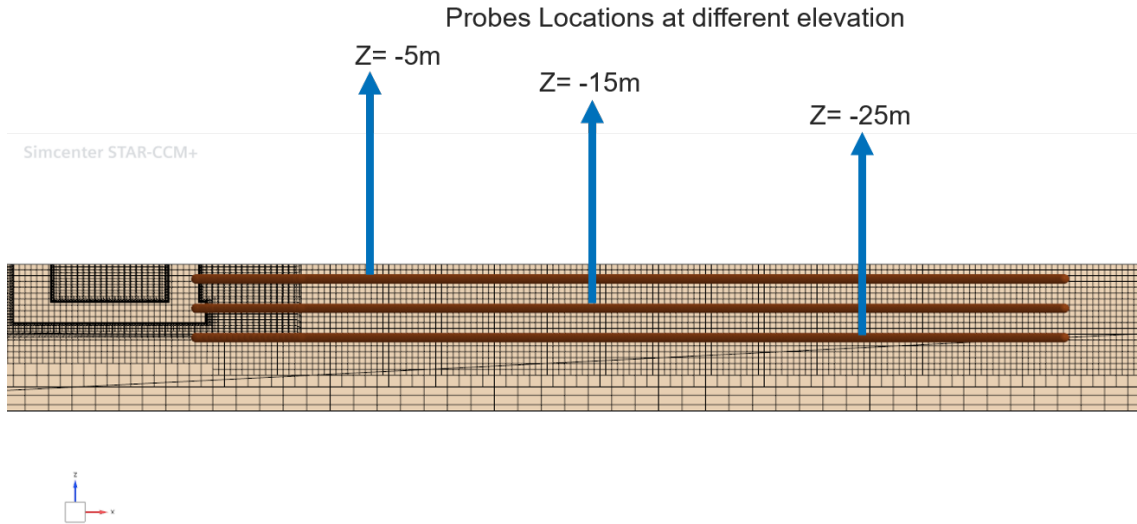
Three systematically refined Cartesian meshes, denoted as Coarse, Medium, and Fine, were generated using an identical mesh topology and refinement strategy. Local volumetric refinement was applied within the anticipated wake region to improve the prediction of wake development and recovery. Grid refinement was achieved by uniformly reducing the cell size while preserving the overall mesh distribution and refinement zones.

Table 4.4: Mesh resolutions.

Grid name	Platform[m]	Near-Wake[m]	Far-Wake[m]	Cell count
Coarse	2.00	1.00	1.50	1.41×10^6
Medium	1.25	0.50	1.00	3.67×10^6
Fine	1	0.25	0.75	29.35×10^6

4.3.3 Measured Variables and Locations

Wake statistics were extracted using horizontal line probes positioned along the wake centreline at the distances of $z = -5$ m, -15 m, and -25 m measured from the free surface, shown in Figure 4.6. Velocities were sampled at every time step and subsequently used to evaluate the spatial structure of the flow.


Figure 4.6: Locations of the vertical probe lines used for the mesh sensitivity study.

4.4 3D Full-Scale Platform Simulations

Building upon the validated grid and kinematic framework, this primary stage investigated the 3D turbulent wake induced by the dynamically responding VoltturnUS-S platform in a realistic, stratified ocean environment.

4.4.1 Transport equations

In this final stage, the VOF multiphase model, $k - \omega$ SST turbulence model, and energy equation were solved simultaneously. Fluid density and viscosity variations due to thermal stratification were dynamically calculated based on the IAPWS formulation.

4.4.2 Computational domain and mesh

The full-scale simulations employed the mesh identified through the grid resolution assessment. The computational domain had a width of 200 m and a total height of 75 m, including a water depth of 50 m as shown in Figure 4.7. The lateral boundaries were treated as symmetry planes, the upper boundary as a pressure outlet, and the seabed as a no-slip wall. All remaining boundary conditions were identical to those adopted in the mesh convergence study.

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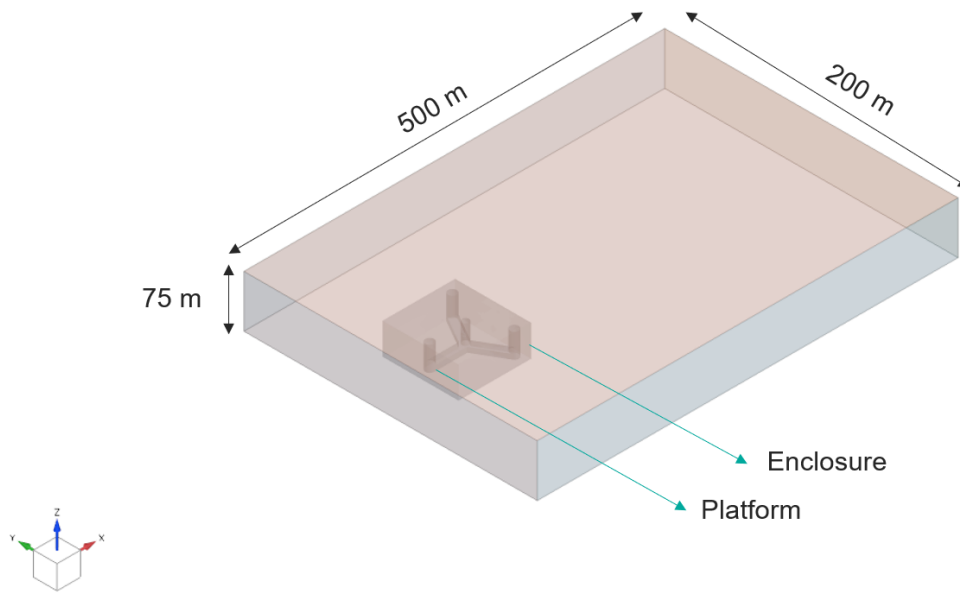


Figure 4.7: Computational Domain

Since Virtual Body boundaries do not inherently support prism-layer generation, a hybrid mesh strategy was adopted for the full-scale simulations. A moving enclosure surrounding the platform was defined as the Virtual Body region, while the platform geometry itself was discretized using prism layers to preserve near-wall resolution. During the simulation, cells located inside the Virtual Body are marked as inactive and excluded from the solution of the governing equations, while the surrounding fluid cells remain active. Cells that transition from inactive to active as the body moves are initialized using values extrapolated from neighboring active cells. The moving region was coupled to the background fluid domain through an interface and driven by the rigid-body motion solver. This approach enabled prism layers to be maintained throughout the simulation while retaining the geometric flexibility of the Virtual Body Method. A schematic representation of the adopted mesh arrangement is shown in Figure 4.8.

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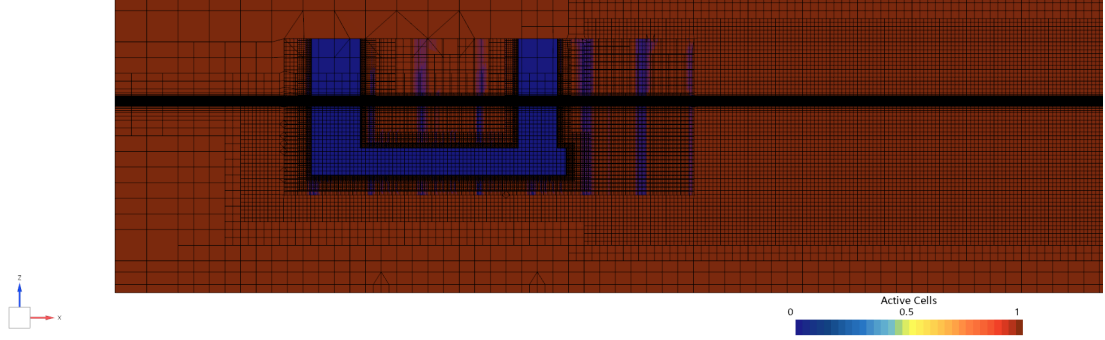


Figure 4.8: Active and inactive cells in the Virtual Body region surrounding the platform. The moving enclosure contains prism layers, while only the surrounding active cells participate in the flow solution.

4.4.3 Numerical setup

The prescribed environmental conditions consisted of a uniform current velocity of 0.5 m/s and a flat free surface. Temperature profiles were prescribed based on field data.

To ensure temporal stability, the time step (Δt) was dynamically controlled to enforce a maximum CFL limit of $C_{max} = 0.85$:

$$\text{CFL} = \frac{U \Delta t}{\Delta x} \leq 0.85 \implies \Delta t \leq 0.85 \frac{\Delta x}{U_{max}} \quad (4.4)$$

This resulted in a typical time step of 0.425 s. The total simulation duration (T_{total}) of 3500 s ensured the wash-out of numerical transients followed by sufficient statistical sampling.

4.4.4 Measured variables and locations

The flow-field analysis focused on the mean streamwise velocity $\langle U \rangle$, the Reynolds normal stresses $\langle w'^2 \rangle$, and the turbulent kinetic energy k . These quantities were used to characterize wake development, turbulence generation, and wake recovery downstream of the floating platform. Thermal effects were quantified using the mean temperature $\langle T \rangle$. In addition, temperature fluctuations, T' , were monitored to assess wake-induced mixing within the stratified water column. The wake velocity deficit was evaluated as

$$U_d = \frac{U_\infty - \langle U \rangle}{U_\infty}, \quad (4.5)$$

where U_∞ denotes the incoming current velocity and $\langle U \rangle$ is the mean streamwise velocity. The wake recovery was calculated according to

$$R(x) = \frac{\langle U(x) \rangle}{U_\infty}, \quad (4.6)$$

where $\langle U(x) \rangle$ is the mean streamwise velocity at the downstream location x . To assess turbulence generation within the wake, the turbulent kinetic energy production term, P_k , was also examined:

$$P_k = -\langle u'_i u'_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j}. \quad (4.7)$$

5

Results and Discussion

This chapter presents the results obtained from the numerical simulations. The analysis first focuses on the validation of the VBM and the custom force-coupling procedure. Following validation, the methodology is to investigate the hydrodynamic response of floating offshore wind turbine platforms and to establish confidence in the numerical framework prior to wake-flow analysis.

5.1 Validation Results

The numerical validation was conducted in two stages. The first stage evaluated the ability of the Virtual Body Method to reproduce wave-induced rigid-body motions using a simplified two-dimensional floating box. The second stage examined the free-decay response of the floating platform to verify that the motion-coupling framework correctly captures the system's restoring behaviour and hydrodynamic damping.

5.1.1 Validation Case I: 2D Free Box in VOF Waves

The dynamic response of the two-dimensional floating box was compared against simulations performed using the DFBI overset-mesh approach.

Figure 5.1 compares the heave displacement predicted by the VBM and the overset approach. The two solutions exhibit good agreement throughout the simulation period. Both methods reproduce the dominant oscillation frequency and comparable displacement amplitudes, demonstrating that the VBM accurately transfers hydrodynamic loads to the rigid-body solver while preserving the hydrostatic restoring characteristics of the floating body. To quantitatively evaluate the deviation between the two methods, the Root Mean Square Error (RMSE) was calculated as follows:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2} \quad (5.1)$$

where N is the total number of discrete time steps evaluated, y_i is the baseline overset solution, and $\hat{y}_i$ is the predicted VBM solution at the i -th time step.

The VBM predicts a peak-to-peak amplitude of 0.0623 m same as obtained using the DFBI solver. More importantly, the natural frequencies differs by only 0.65%,

with values of 1.233 s and 1.224 s obtained for the VBM and DFBI solutions, respectively. The phase shift remains limited to approximately 1.76° , indicating that the dominant wave period is reproduced accurately. The resulting RMSE between the two solutions is 0.0049 m. No evidence of numerical instability or artificial damping was observed during the simulation.

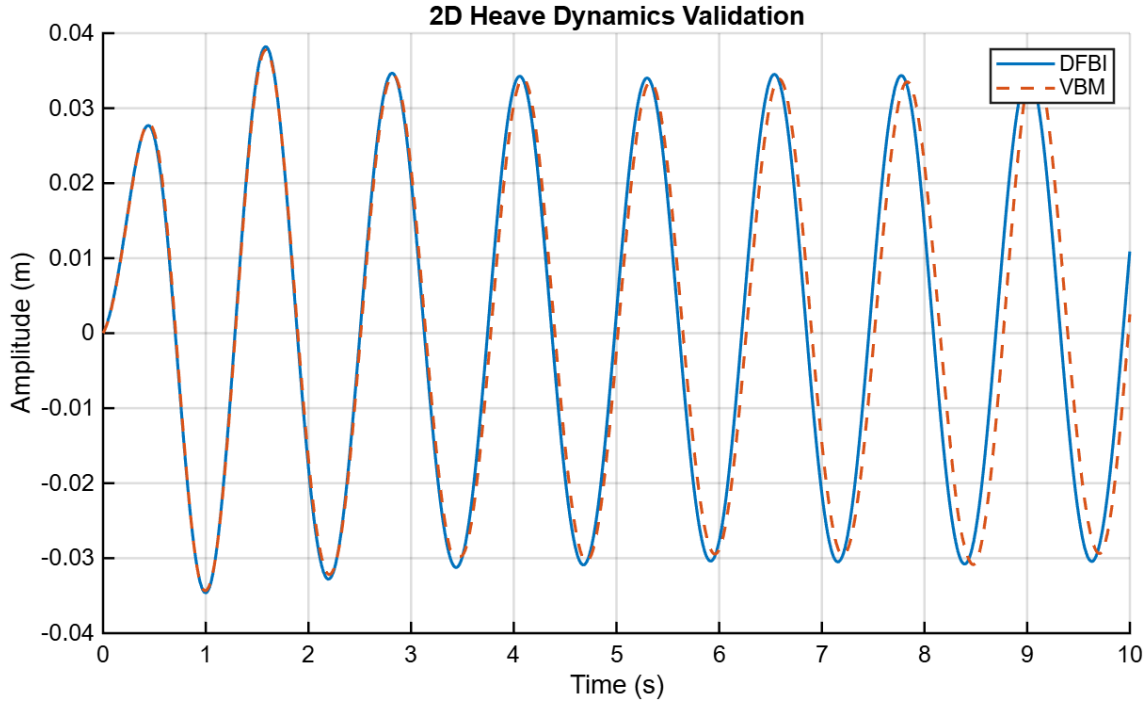


Figure 5.1: Comparison of heave displacement time histories obtained using the Virtual Body Method (VBM) and the DFBI overset-mesh approach.

The pitch response comparison is presented in Figure 5.2. Similar to the heave response, the VBM reproduces the dominant oscillatory behaviour and the associated motion amplitudes predicted by the DFBI reference solution. The agreement observed in the rotational degree of freedom demonstrates that the immersed-boundary framework correctly evaluates the hydrodynamic moments acting on the floating body. Since pitch motion is highly sensitive to the representation of mass distribution, hydrostatic restoring forces, and fluid loading, this result provides additional confidence in the robustness of the numerical implementation.

A quantitative evaluation of the pitch response shows that the peak-to-peak amplitude predicted by the VBM differs from the DFBI solution by approximately 14.82%, while the oscillation period differs by only 0.24%. The corresponding phase shift is approximately 0.58° . The resulting RMSE is 0.9715° .

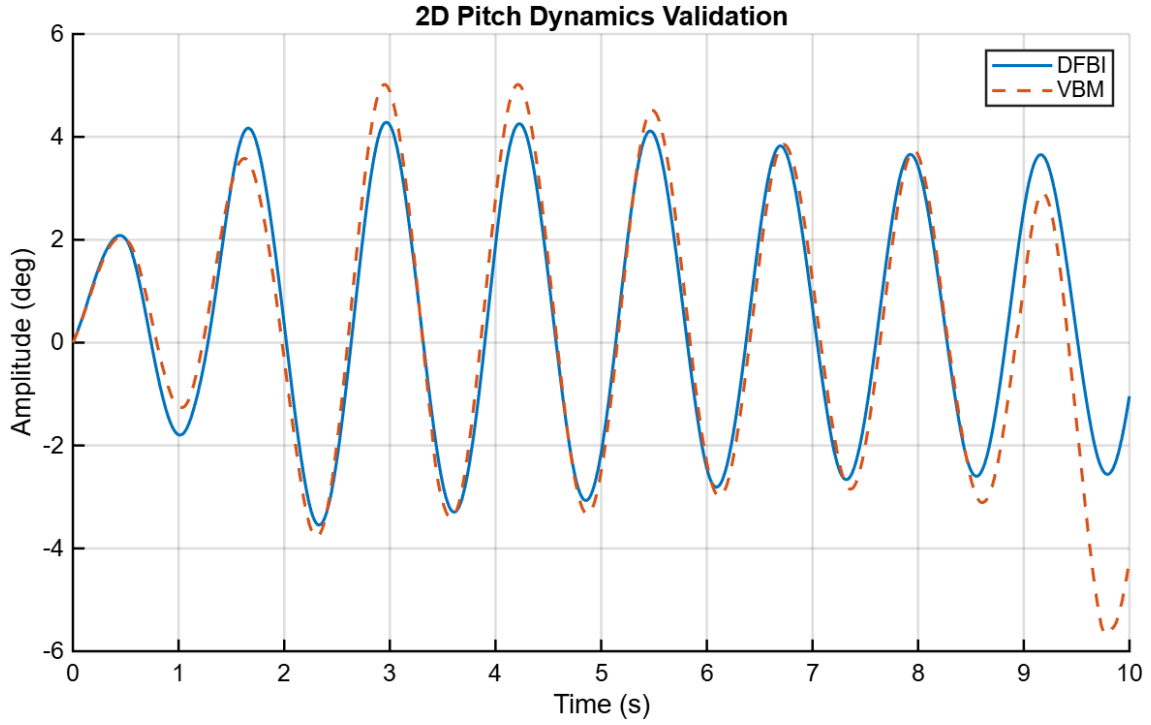


Figure 5.2: Comparison of pitch motion obtained using the Virtual Body Method (VBM) and the DFBI overset-mesh approach.

The quantitative validation metrics for the heave and pitch responses are summarized in Table 5.1. Overall, the results demonstrate that the Virtual Body Method reproduces the dominant wave-induced motions of the floating body while maintaining numerical stability throughout the simulation.

Table 5.1: Quantitative validation metrics for the two-dimensional floating box.

Metric	Heave	Pitch
Amplitude Error [%]	0	14.82
Natural Frequency Error [%]	0.65	0.24
Phase Shift [°]	1.76	0.58
DFBI Damping Ratio	-0.0050	-0.0128
VBM Damping Ratio	-0.0057	-0.0080
RMSE	0.0049m	0.9715°

Figure 5.3 presents the surge motion response compared against the reference overset DFBI solution. Overall, the VBM closely tracks the primary oscillation trends and frequency characteristics. While the two methods agree well during initial motion cycles, a gradual divergence emerges over physical time, reaching approximately 12% at $t = 10$ s. This discrepancy is primarily due to fixed-grid cut-cell vertex projection, where moving solid boundaries continuously re-classify fluid and solid cell volumes across time steps. Over the duration durations, these small temporal discretization errors accumulate as a minor phase drift in unconstrained horizontal

degrees of freedom. Additionally, variations in the fluid volume enclosed within the Virtual Body envelope slightly alter the effective structural inertia. Nevertheless, the VBM captures the fundamental hydrodynamic kinematics with sufficient accuracy for downstream wake-flow evaluations.

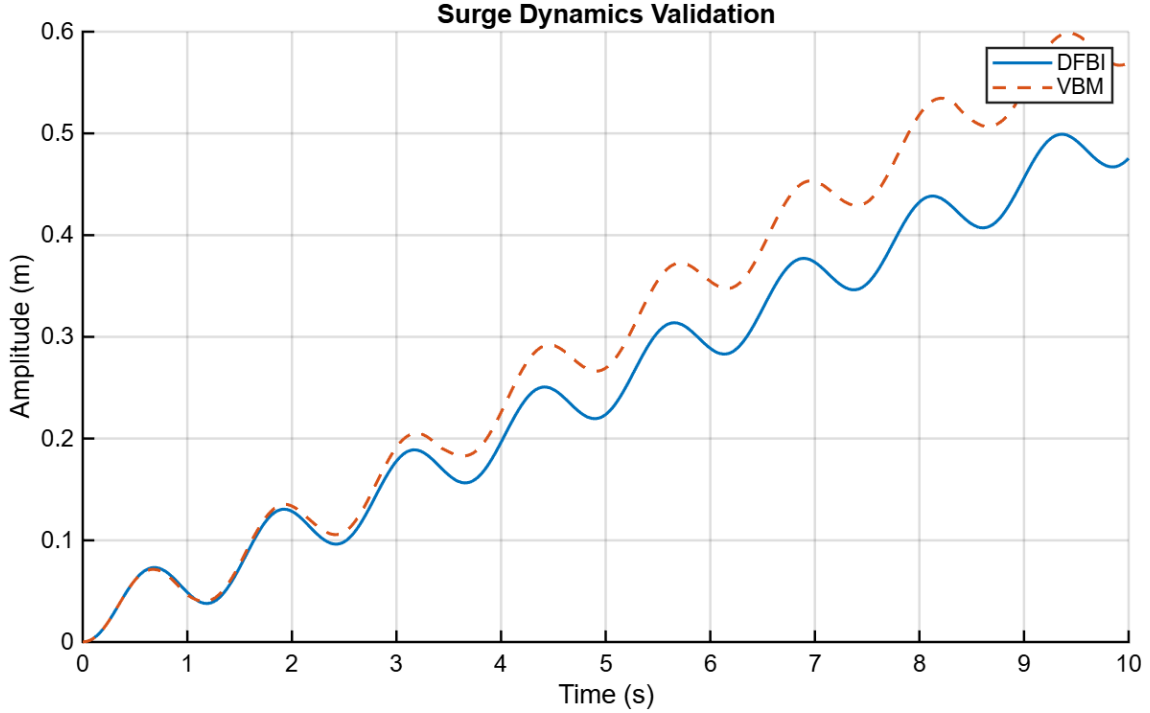


Figure 5.3: Comparison of surge displacement time histories obtained using the Virtual Body Method (VBM) and the DFBI overset-mesh approach.

5.1.2 Validation Case II: 3D Free-decay Platform

Following the wave-kinematic validation, free-decay simulations were performed to evaluate the ability of the proposed motion-coupling framework to predict the natural dynamic behaviour of the floating platform. The platform was displaced from its equilibrium position and subsequently released in calm water. The resulting free decay was monitored to assess the numerical representation of hydrostatic restoring forces, hydrodynamic damping, and rigid-body dynamics.

Three formulations were considered during the validation process: the Dynamic Fluid-Body Interaction (DFBI) overset-mesh approach, the VBM coupling framework developed in this work, and an implicit coupling formulation. The DFBI solution was used as the numerical reference for comparison.

Figure 5.4 presents the heave free-decay response of the floating platform. Following the initial displacement, the platform exhibits the expected damped oscillatory behaviour characteristic of a floating semi-submersible structure. The oscillation amplitude decreases progressively with time due to hydrodynamic damping mechanisms, including viscous dissipation and radiation effects. No signs of numerical

divergence or non-physical growth are observed for either coupling strategy, indicating stable numerical behaviour throughout the simulation.

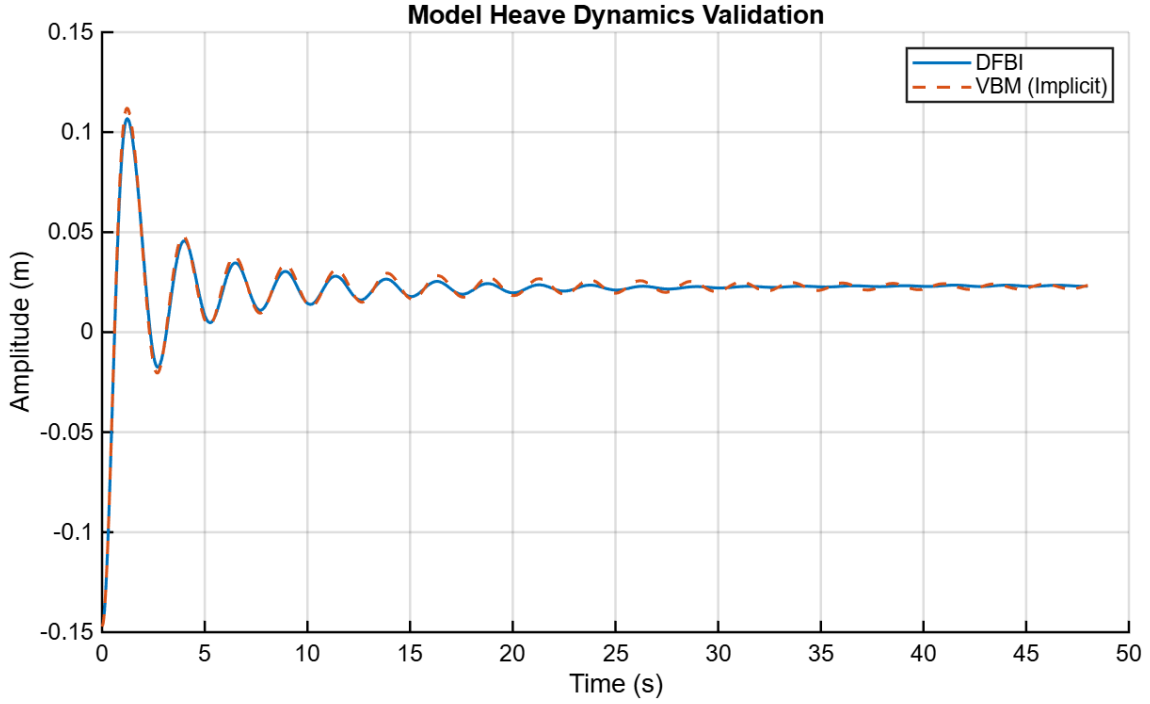


Figure 5.4: Heave free-decay response of the floating platform.

A comparison against the DFBI solution shows that the VBM reproduces the dominant heave dynamics with good accuracy. The predicted peak-to-peak amplitude is 0.1325 m compared with 0.1243 m obtained using DFBI. The natural oscillation period is reproduced within 0.7%, corresponding to periods of 2.734 s and 2.754 s for the VBM and DFBI solutions, respectively. The resulting phase shift is only 2.6°, while the RMSE is 0.0016 m. Furthermore, the predicted damping ratio is identical to the DFBI reference solution, indicating that the hydrodynamic damping characteristics of the platform are accurately captured. The results are summarised in Table 5.2.

Table 5.2: Comparisons for the free heave-decay simulations.

Metric	DFBI	VBM
Heave		
Amplitude [m]	0.1243	0.1325
Period [s]	2.754	2.734
Damping Ratio [-]	0.1339	0.1337
Phase Shift [°]	–	2.6
RMSE [m]	–	0.0016

Figure 5.5 presents the pitch free-decay response of the floating platform. The implicit VBM formulation shows close agreement with the DFBI reference solution.

The predicted peak-to-peak amplitude differs by approximately 2.9%, while the natural period is reproduced within 0.22%. The VBM predicts a natural period of 3.629 s compared with 3.621 s for the DFBI solution. The resulting phase shift is only 0.1° , and the RMSE is 0.199° . The damping ratio is also in reasonable agreement with the DFBI result, indicating that the dominant pitch dynamics are captured accurately.

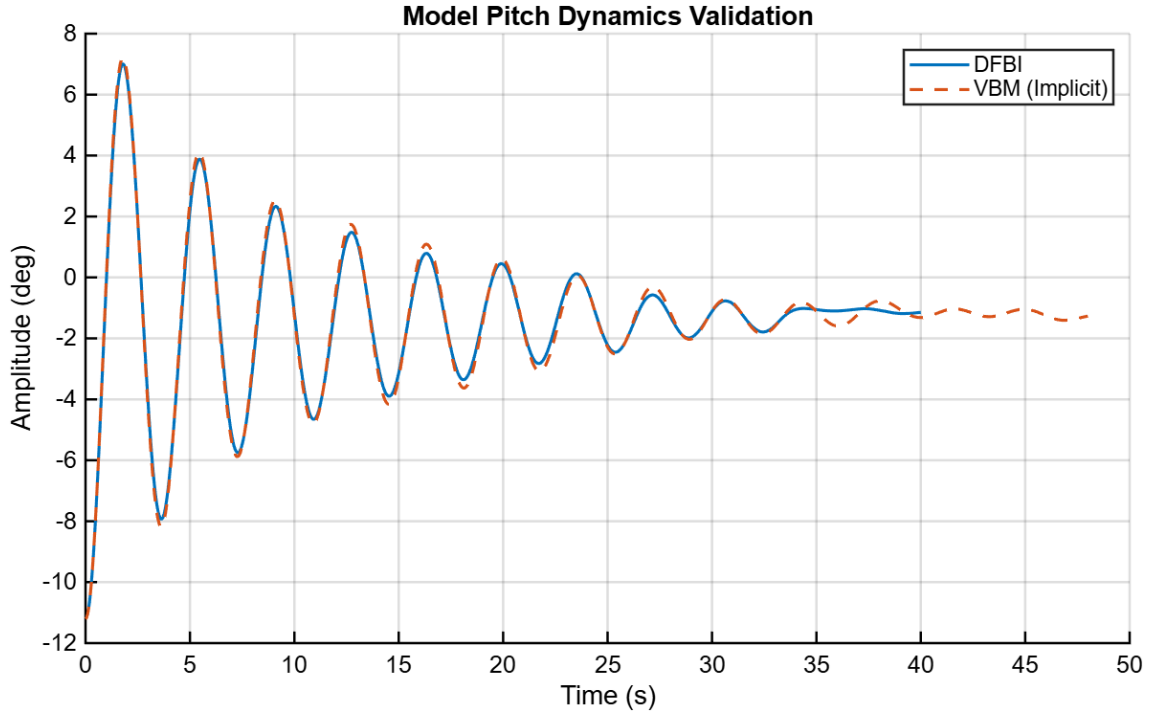


Figure 5.5: Pitch free-decay response of the floating platform.

Table 5.3: Comparisons for the free pitch-decay simulations.

Metric	DFBI	VBM
Pitch		
Amplitude [$^\circ$]	14.94	15.37
Period [s]	3.62	3.63
Damping Ratio [-]	0.107	0.127
Phase Shift [$^\circ$]	–	0.1
RMSE [$^\circ$]	–	0.1991

To justify the selection of the Virtual Body Method (VBM) over traditional dynamic overset mesh (DFBI) approaches, a quantitative assessment of computational efficiency was performed. Raw CPU and elapsed time data were extracted for both heave and pitch validation cases. To account for minor variations in grid sizing between the two methodologies, the computational cost was normalized as core-hours per million elements. Tables 5.4 and 5.5 present the absolute computational require-

ments for the heave and pitch simulations, respectively.

Table 5.4: Computational performance metrics for the heave free-decay validation.

Metric	DFBI (Overset)	VBM (IBM)
Mesh Size (Million Elements)	11.01	10.48
Average Core Count	190.8	128.1
Wall-Clock Time (h)	44.18	37.27
Total Core-Hours	8,429.08	4,774.10
Core-Hours / Million Elements	765.51	455.59

Table 5.5: Computational performance metrics for the pitch free-decay validation.

Metric	DFBI (Overset)	VBM (IBM)
Mesh Size (Million Elements)	6.06	5.86
Average Core Count	127.2	128.3
Wall-Clock Time (h)	40.69	24.18
Total Core-Hours	5,174.05	3,101.53
Core-Hours / Million Elements	854.09	529.36

The data demonstrates a substantial reduction in computational expense when employing the Virtual Body Method. The relative reductions in computational overhead achieved by adopting the VBM framework are summarized in Table 5.6. Normalized by mesh size, the VBM reduced the computational cost by 40.49% in the heave case and 38.02% in the pitch case. Fewer core-hours per million elements compared to the DFBI approach. This efficiency gain is primarily attributed to the elimination of the active overset mesh intersection algorithms, which require computationally intensive donor-receptor searches and hole-cutting procedures at every time step. Consequently, the VBM provides a robust and computationally viable alternative for long-duration hydrodynamic simulations of floating offshore structures.

Table 5.6: Savings in computational cost (VBM relative to DFBI).

Metric	Heave Savings (%)	Pitch Savings (%)
Wall-Clock Time	15.64	40.58
Total Core-Hours	43.36	40.06
Core-Hours / Million Elements	40.49	38.02

5.2 Mesh Convergence Study

A mesh convergence study was performed to evaluate the sensitivity of the predicted wake development to spatial resolution and to identify an appropriate mesh for the

subsequent full-scale simulations. Three systematically refined meshes were considered: a Coarse mesh (1.41×10^6 cells), a Medium mesh (3.67×10^6 cells), and a Fine mesh (29.35×10^6 cells). The Fine mesh was adopted as the reference solution for the comparative analysis.

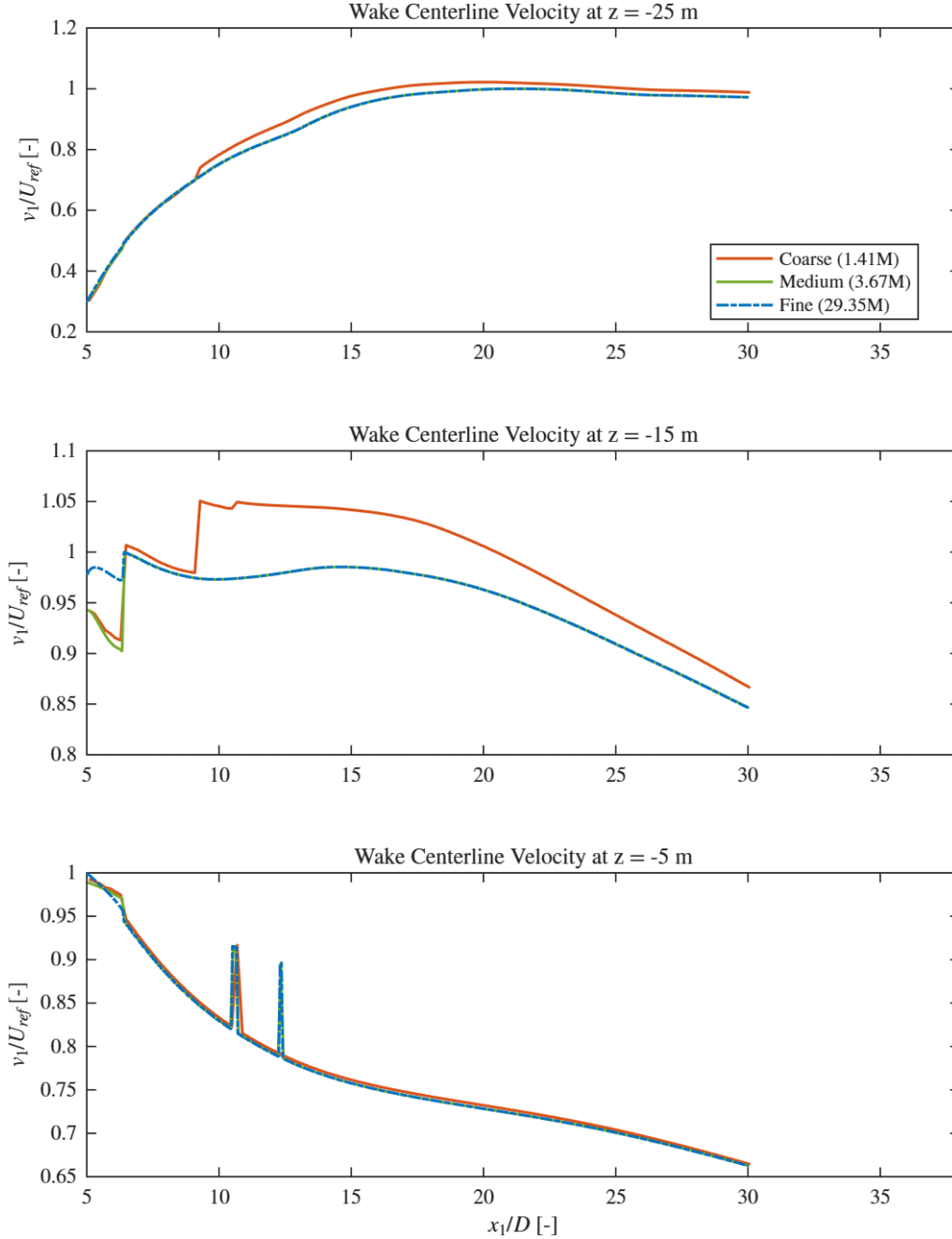


Figure 5.6: Normalized streamwise velocity profiles obtained using the Coarse, Medium, and Fine meshes at probe elevations of $z = -5$ m, $z = -15$ m, and $z = -25$ m.

The assessment was based on the mean streamwise velocity, normalized by the freestream velocity, U/U_∞ , extracted along horizontal line probes positioned at ele-

vations of $z = -5$ m, $z = -15$ m, and $z = -25$ m. Figure 5.6 compares the resulting wake recovery profiles obtained using the three mesh resolutions.

To quantify the spatial discretization error, the velocity profiles of the Coarse and Medium grids were compared directly against the Fine reference solution. Table 5.7 presents the corresponding relative differences.

Table 5.7: Relative difference for the Coarse and Medium meshes, utilizing the Fine mesh as the reference.

Probe Elevation	Coarse Rel. Diff. [%]	Medium Rel. Diff. [%]
$z = -5$ m	2.42	2.17
$z = -15$ m	4.69	1.64
$z = -25$ m	2.02	0.28

The largest discrepancies occur in the immediate wake region, where strong velocity gradients are present. The Coarse mesh exhibits numerical diffusion, which artificially reduces the magnitude of the velocity deficit and accelerates wake recovery. This behaviour is particularly evident at the $z = -15$ m elevation, where the Coarse mesh relative difference peaks at 4.69% and consistently predicts a weaker wake than the finer meshes. Refinement from the Coarse to the Medium mesh significantly reduces these discrepancies, producing velocity distributions that track the Fine-mesh solution throughout the majority of the computational domain. Although minor localized differences remain within the highly sheared near-wake transition, the overall agreement between the Medium and Fine meshes is robust. The relative differences for all probe elevations drop below 2.2%.

The velocity profiles demonstrate that the predicted wake development becomes progressively less sensitive to mesh refinement, indicating that numerical diffusion has a diminishing influence on the predicted wake recovery. While the Medium mesh captures the principal wake characteristics with good accuracy, the Fine mesh provides the highest spatial resolution necessary to maintain sharp near-wake gradients and minimize discretization uncertainty.

5.3 3D Full-Scale Platform Simulations

Following validation of the Virtual Body framework, the methodology was applied to the full-scale VoltturnUS-S platform to investigate the wake generated by the floating structure. The primary objective of this analysis was to examine the wake interactions and the influence on the thermocline of the floating platform the associated with the flow field.

5.3.1 Mean Velocity Deficit

The mean streamwise velocity field at a depth of 10 m is presented in Figure 5.7. A pronounced velocity deficit develops immediately downstream of the VoltturnUS-S

platform as momentum is extracted from the incoming flow by the platform columns and connecting pontoons. The strongest deficit occurs in the near wake, where flow separation produces a recirculation region characterized by low and locally negative streamwise velocities.

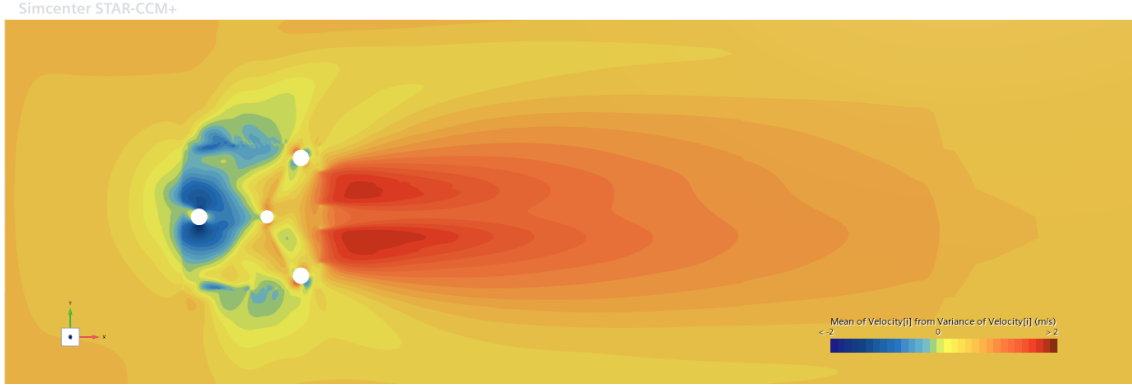


Figure 5.7: Contour of mean streamwise velocity at a depth of 10 m.

Unlike the wake behind a single monopile, the semi-submersible platform generates multiple interacting wakes. Each outer column produces a separate velocity deficit, while the central column and connecting pontoons modify the flow structure between them. These individual wake structures rapidly merge into a broader combined wake downstream of the platform. The interaction of the column wakes generates localized regions of enhanced shear and turbulence production, resulting in a complex and asymmetric velocity field.

A distinct recirculation zone is visible directly behind the upstream columns. Negative streamwise velocities indicate local flow reversal, which persists for several platform diameters downstream before gradually weakening. Further downstream, the velocity deficit becomes wider and more diffuse as turbulent mixing transfers momentum from the surrounding flow into the wake region.

5.3.2 Wake Recovery

The downstream evolution of the wake was examined using the normalized mean streamwise velocity, $\langle \bar{v}_1 \rangle / U_{ref}$, along the wake centreline at depths of 5 m, 15 m, and 25 m, as shown in Figure 5.8.

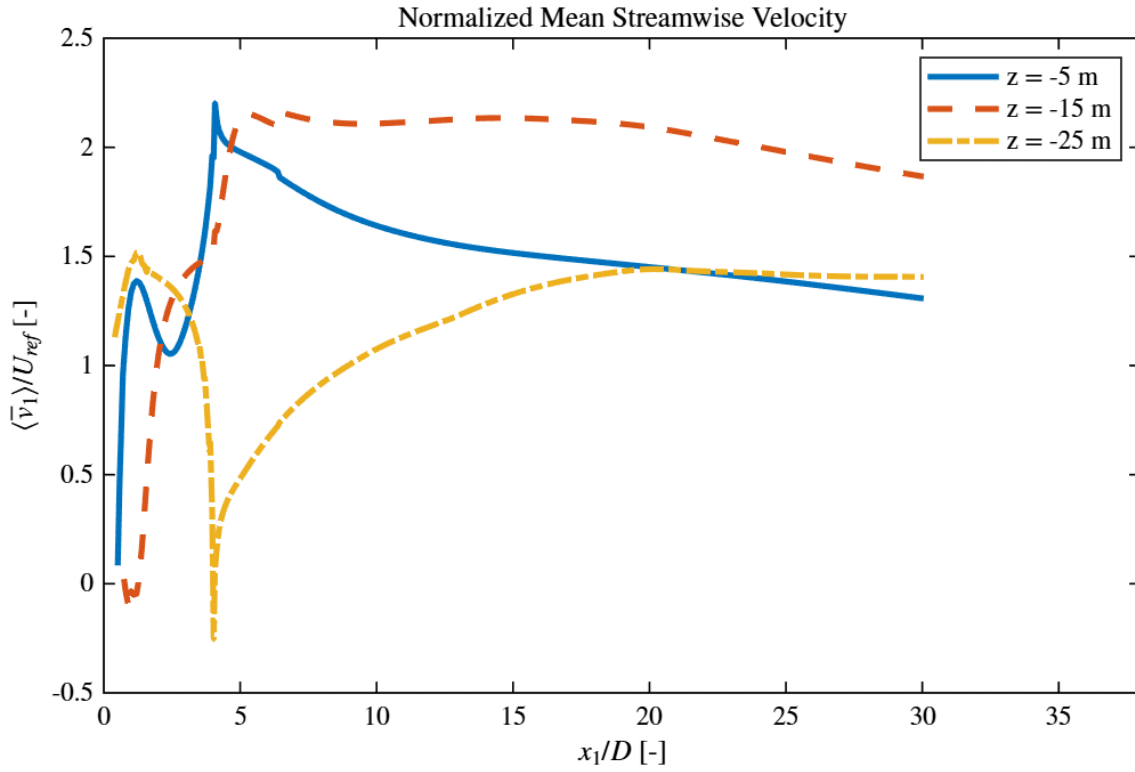


Figure 5.8: Normalized mean streamwise velocity $\langle \bar{v}_1 \rangle / U_{ref}$ along the wake centreline at depths of 5 m, 15 m, and 25 m.

The velocity profiles reveal that wake development varies considerably with depth. At 5 m depth, the flow experiences an initial reduction in velocity directly behind the platform, followed by a gradual recovery as momentum is entrained from the surrounding fluid. The normalized velocity decreases from a peak value of approximately 2.2 to around 1.3 at the furthest downstream location considered.

At 15 m depth, the flow accelerates around the platform and remains above the reference velocity over much of the downstream region. The velocity reaches values exceeding $2U_{ref}$ before gradually decreasing downstream. This behaviour indicates that the platform geometry redistributes momentum within the water column, creating localized acceleration regions in addition to the wake deficit.

At 25 m depth, a pronounced velocity deficit develops immediately behind the platform. The normalized velocity initially falls below zero, indicating local flow reversal associated with the recirculation region observed in Figure 5.7. Further downstream, the wake gradually recovers and approaches approximately $1.4U_{ref}$ as turbulent mixing transfers momentum into the deficit region. Although the blunt submerged pontoons at $z = -25$ m induce a sharp streamwise velocity deficit and localized flow reversal, the corresponding temperature profile remains stable. This occurs because stable density stratification generates negative forces in the lower water column.

Overall, the results demonstrate that wake recovery is strongly influenced by the multi-column geometry of the semi-submersible platform. The interaction of mul-

multiple wake structures, together with turbulent entrainment and localized flow acceleration around the structural members, produces a recovery process that varies significantly throughout the water column.

5.3.3 Temperature Distribution

The distribution of mean temperature in the vertical (z) direction within the wake is shown in Figure 5.9. The profiles illustrate how the thermal structure evolves as the flow moves downstream. Close to the platform, the temperature field remains relatively uniform, with only weak stratification near the free surface. Further downstream, however, the vertical temperature gradient becomes increasingly pronounced.

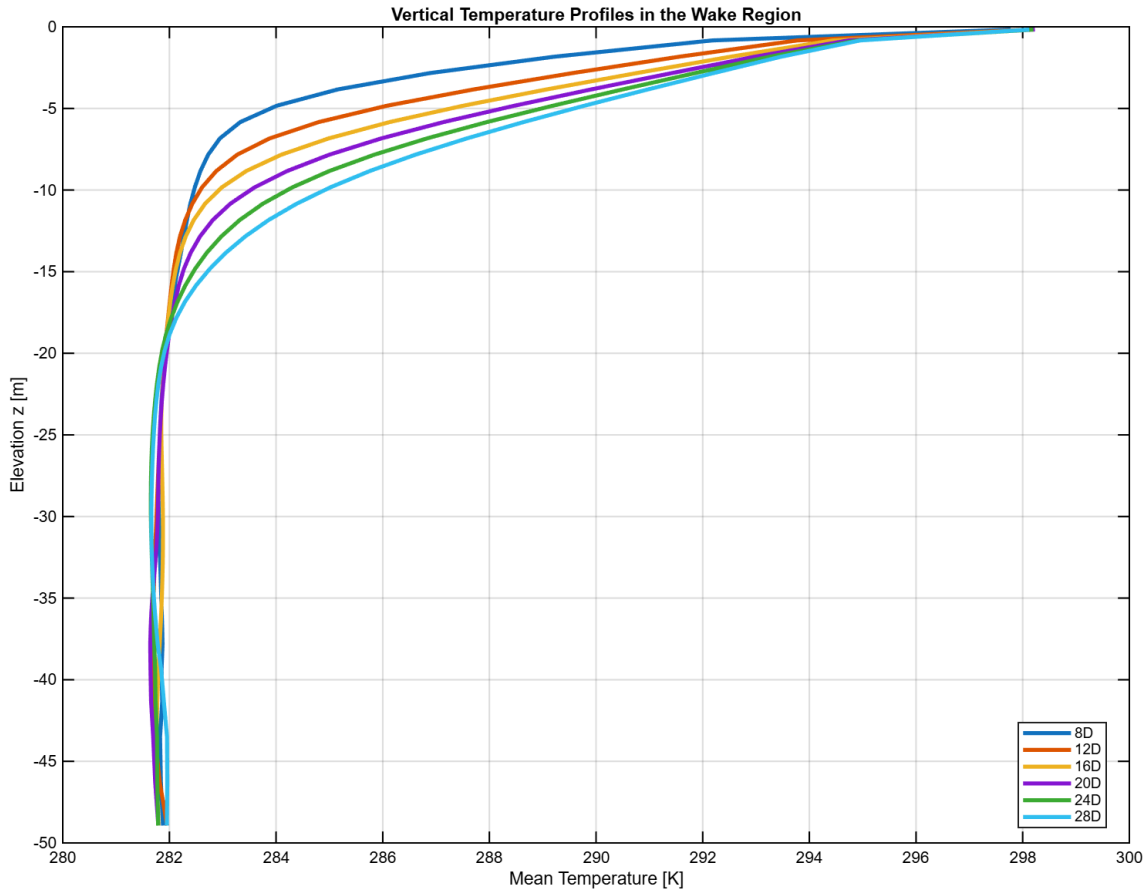


Figure 5.9: Mean temperature distribution in the wake at multiple downstream positions.

To provide a clearer view of the upper part of the water column, Figure 5.10 presents an enlarged view of the temperature profiles within the upper 5 m. The profiles gradually shift towards higher temperatures with increasing downstream distance, demonstrating that wake-induced mixing redistributes thermal energy within the stratified region.

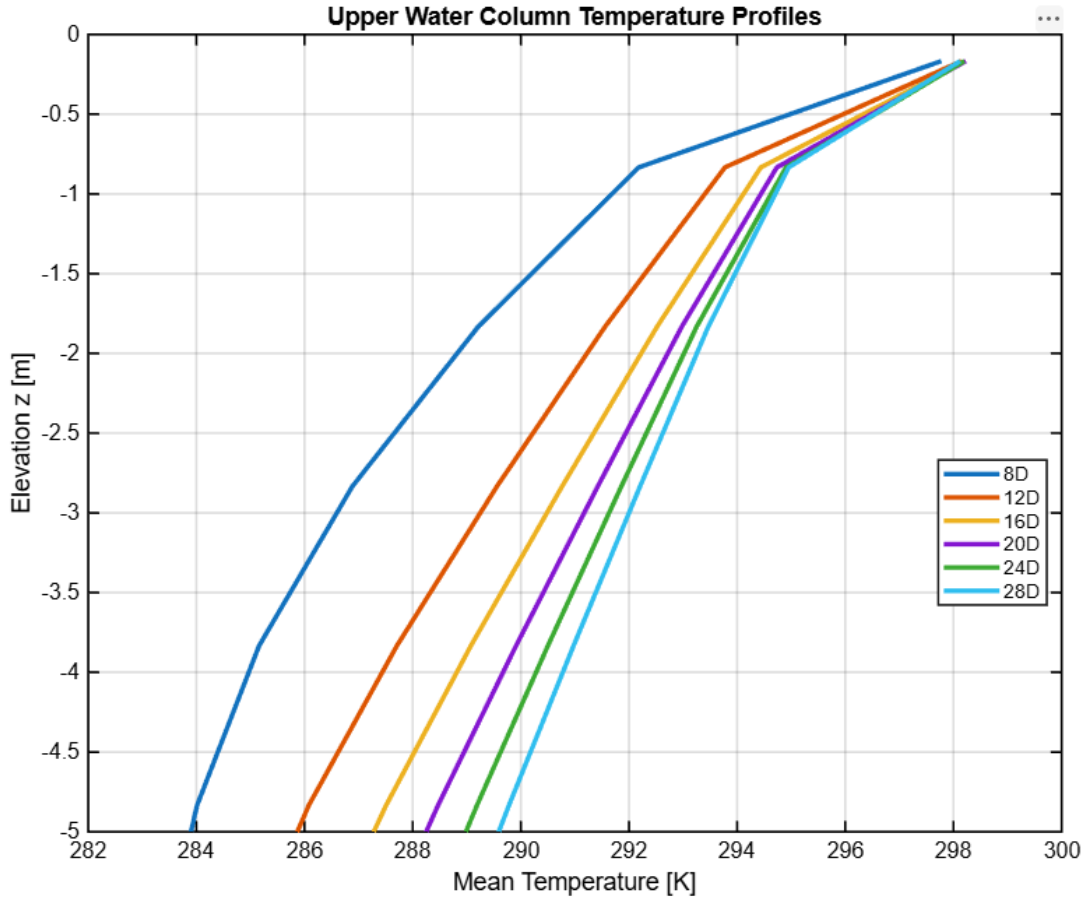


Figure 5.10: Expanded view of the upper water column showing the evolution of the temperature profiles between 8D and 28D downstream.

At 28D downstream, the surface mean temperature shows a clear increase relative to the near-wake reference at 8D. The surface temperature difference between these two locations reaches 0.35 K, indicating substantial warming of the upper water column as the wake develops. The maximum absolute temperature change at 28D ($\Delta\langle T \rangle = 5.82$ K) occurs very close to the free surface at a depth of $z = -3.83$ m. For the region below the draft, approximately $z < -20$ m, the temperature remains nearly constant across all downstream positions, demonstrating that the deeper water column remains unaffected by wake-driven mixing.

The temperature fluctuation, expressed through the variance $\langle T'^2 \rangle$, is shown in Figure 5.11. The three horizontal probe lines reveal how turbulent temperature deviations evolve along the downstream direction at different depths.

At the shallowest level ($z = -5$ m), the variance reaches its maximum value of 1.37 K^2 very close to the platform, at a downstream distance of 5.12 m. This indicates that the upper part of the water column responds strongly to the initial wake formation, where mixing and shear are most pronounced. At intermediate depth ($z = -15$ m), the largest fluctuation occurs at the furthest downstream position considered in the study, at $x_1 = 300.50$ m. The overall trend at this depth

remains relatively moderate, suggesting limited vertical exchange compared to the near-surface layer. At the deepest probe ($z = -25$ m), the variance remains low throughout the domain, with a maximum of 0.80 K^2 occurring at $x_1 = 4.00$ m. This behaviour reflects the stability of the deeper water column, where temperature gradients are weak and turbulent motions have limited ability to generate instantaneous temperature deviations.

Overall, the horizontal-probe results show that temperature fluctuations are strongest near the surface and decay with depth. Downstream evolution is modest except at the shallowest level, where wake-induced mixing persists over a longer distance.

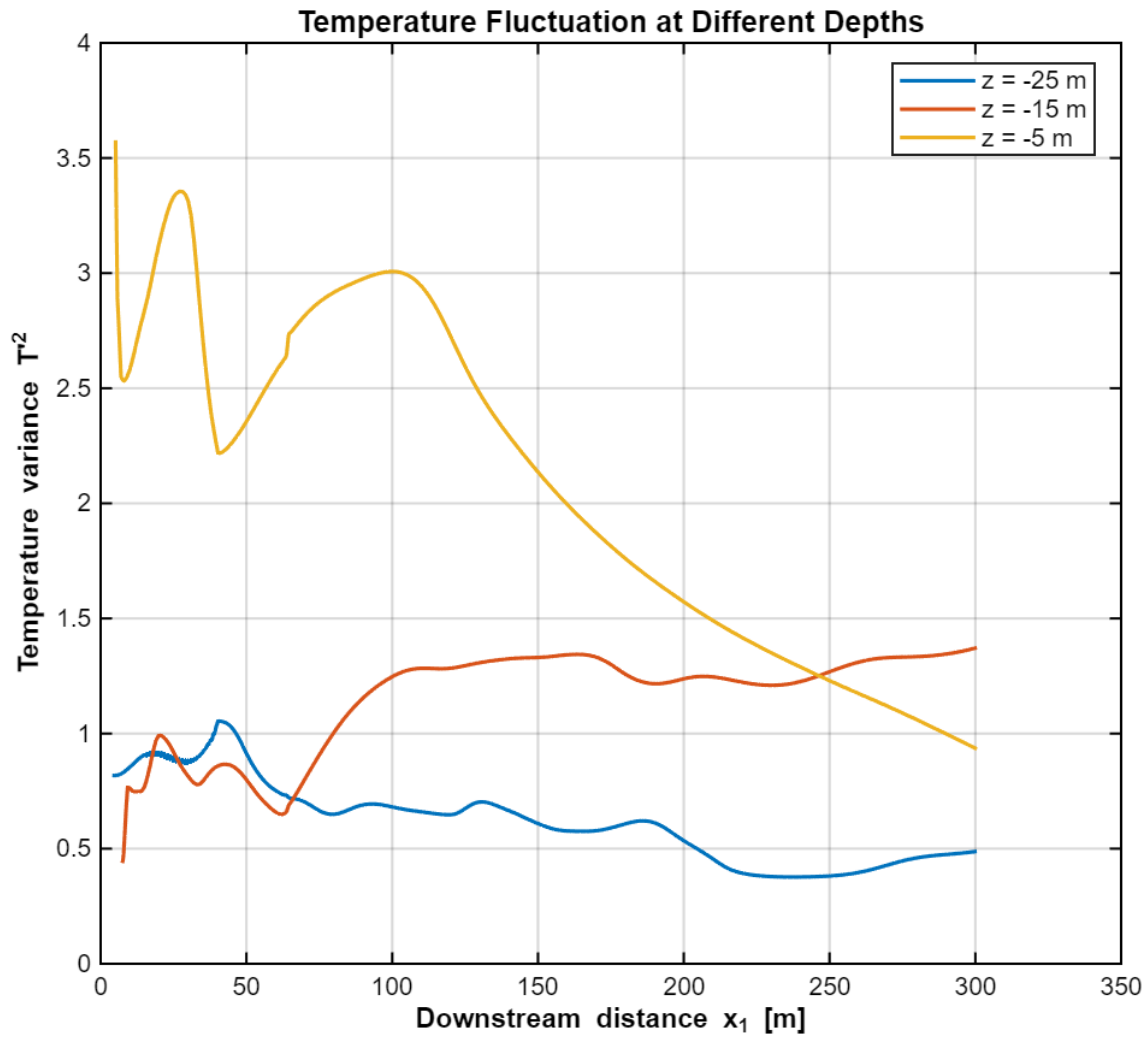


Figure 5.11: Temperature variance distribution at selected depths.

The instantaneous temperature field, shown in Figure 5.12, provides a qualitative view of the wake structure and stratification. The contour reveals a sharp thermocline separating the warm surface layer from the cold deeper water. Behind the platform, turbulent mixing erodes the stratification locally, creating a visible wake signature that extends several platform diameters downstream. The wake remains

largely confined to the upper water column, consistent with the probe measurements.

Simcenter STAR-CCM+

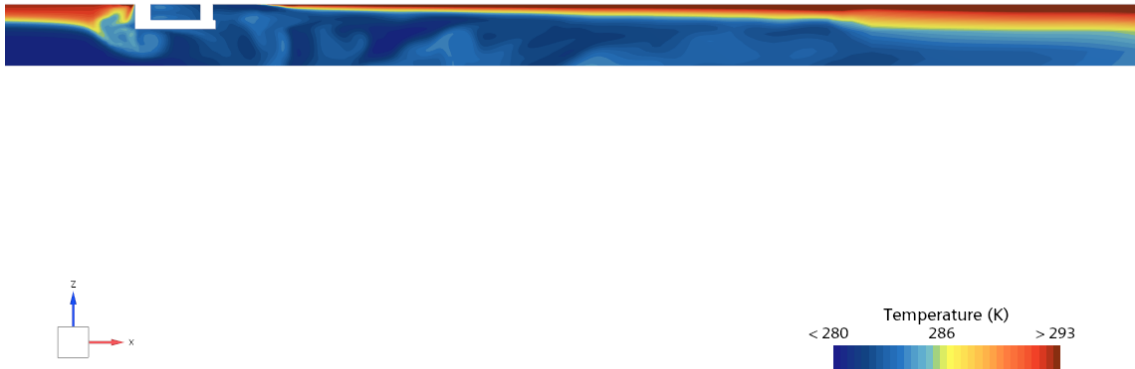


Figure 5.12: Instantaneous temperature contour illustrating stratification and wake development.

6

Conclusions

This thesis investigated the applicability of the IBM, implemented through the VBM within Simcenter STAR-CCM+, for the simulation of floating offshore wind turbine platforms. Building upon the numerical framework developed during Phase 1 of the project, the present work extended the methodology from fixed-bottom monopiles to multi-degree-of-freedom floating structures.

Validation of the numerical framework was performed in two stages. First, a two-dimensional floating box subjected to regular fifth-order Stokes waves was simulated and compared against a conventional DFBI overset-mesh solution. The VBM successfully reproduced the heave, surge, and pitch responses while maintaining numerical stability throughout the simulation period. The heave natural frequency differed by only 0.65%, the pitch by 0.24%. The surge response exhibited a moderate deviation of approximately 12% after extended simulation times. This discrepancy was primarily attributed to discretization error and minor trapped-fluid effects associated with the immersed-boundary representation.

Second, free-decay simulations of the UMaine VolturnUS-S semi-submersible platform were conducted to evaluate the motion-coupling procedure under calm-water conditions. The resulting damped oscillatory responses demonstrated realistic restoring behaviour and hydrodynamic damping characteristics. The results demonstrate that the Virtual Body Method provides a viable alternative to traditional body-fitted overset-mesh approaches for floating offshore wind turbine applications. The methodology significantly simplifies mesh generation while maintaining the ability to accurately reproduce rigid-body kinematics and hydrodynamic response. The implicit DFBI-VBM formulation closely matched the reference solution, with heave and pitch periods within 0.7% and 0.22%, respectively, and negligible phase shift.

A quantitative assessment of computational efficiency demonstrated that the VBM required approximately 38–40% fewer core-hours per million elements than the DFBI overset-mesh approach. This reduction was primarily attributed to the elimination of donor–receptor searches and hole-cutting operations required by overset mesh intersection algorithms at every time step.

The validated framework was applied to full-scale simulations of the VolturnUS-S platform in a thermally stratified current. The multi-column geometry generated a complex, three-dimensional wake with a persistent near-wake recirculation zone, pronounced velocity deficit, and delayed recovery. Thermal mixing was strongest

near the free surface, with a maximum mean temperature increase of 5.82 K at a depth of 3.83 m below the free surface. At depths below the platform draft (approximately $z < -20$ m), the temperature remained nearly constant across all downstream positions, demonstrating that the deeper water column was largely unaffected by wake-driven mixing. Temperature variance was highest near the surface and decayed with depth, confirming that wake-induced mixing is confined primarily to the upper water column.

In conclusion, the native DFBI-VBM framework was shown to be a robust, stable, and computationally efficient tool for simulating floating offshore wind turbine platforms. The successful validation of the rigid-body motion framework, combined with the substantial computational savings relative to overset meshing, establishes the methodology as a viable approach for long-duration CFD simulations of floating-platform wake dynamics and environmental impacts. The results provide a baseline for future investigations involving mooring coupling, fully resolved turbine aerodynamics, and multi-platform wind farm simulations.

7

Future Work

While the present study demonstrates the feasibility of employing the Virtual Body Method (VBM) to investigate the hydrodynamic response and wake characteristics of floating offshore wind turbine platforms, several opportunities remain for extending and improving the numerical framework.

Mooring System Integration The current simulations were performed without an explicit representation of the mooring system. Consequently, the platform motion response was governed solely by the hydrodynamic forces, hydrostatic restoring effects, and the custom motion-coupling framework. Future work should incorporate a fully coupled mooring line model to account for the additional restoring stiffness and damping introduced by the mooring system. This would enable a more realistic prediction of the platform dynamics under environmental loading and allow investigation of the interaction between platform motion, mooring tensions, and wake development.

Combined Wave-Current Metocean Conditions: Expanding from uniform current inflow to irregular wave spectra (e.g., JONSWAP / Pierson-Moskowitz) superimposed on sheared velocity profiles, evaluating motion-induced wake meandering under realistic metocean conditions.

Fully Coupled Turbine Representation The present work focusses on the platform. While this approach captures the dominant momentum extraction effects, future studies should consider a higher-fidelity turbine model with fully resolved rotor aerodynamics and structural flexibility. Coupling the VBM platform motion with a detailed turbine representation would enable investigation of aero-hydro-servo-elastic interactions and their influence on both power production and wake behaviour.

Wind Farm Simulations The current study focuses on a single floating offshore wind turbine platform. Future work should extend the methodology to multiple interacting turbines within a floating wind farm. Such simulations would facilitate the assessment of wake interactions, cumulative turbulence generation, and wake recovery between neighboring platforms. These effects are particularly important for farm layout optimization and the prediction of long-term energy production.

Bibliography

- [1] Christopher Allen et al. *Definition of the UMaine VoltturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine: IEA Wind TCP Task 37*. 2020. URL: <https://research-hub.nlr.gov/en/publications/definition-of-the-umaine-voltturnus-s-reference-platform-developed/>.
- [2] Alireza Arabgolarcheh, Amirhossein Rouhollahi, and Ernesto Benini. “Analysis of middle-to-far wake behind floating offshore wind turbines in the presence of multiple platform motions”. In: *Renewable Energy* 208 (2023), pp. 546–560.
- [3] P. Causin, J. F. Gerbeau, and Fabio Nobile. “Added-mass effect in the design of partitioned algorithms for fluid-structure problems”. In: *Computer Methods in Applied Mechanics and Engineering* 194.42-44 (Oct. 2005), pp. 4506–4527. ISSN: 00457825. DOI: 10.1016/j.cma.2004.12.005.
- [4] DNV-RP-C205. *Environmental conditions and environmental loads*. Tech. rep. Det Norske Veritas, 2017. URL: <https://www.dnv.com/energy/standards-guidelines/dnv-rp-c205-environmental-conditions-and-environmental-loads/>.
- [5] Robert M. Dorrell et al. “Anthropogenic Mixing in Seasonally Stratified Shelf Seas by Offshore Wind Farm Infrastructure”. In: *Frontiers in Marine Science* 9 (Mar. 2022), p. 830927. ISSN: 22967745. DOI: 10.3389/fmars.2022.830927. URL: <https://doi.org/10.3389/fmars.2022.830927>.
- [6] E. A. Fadlun et al. “Combined Immersed-Boundary Finite-Difference Methods for Three-Dimensional Complex Flow Simulations”. In: *Journal of Computational Physics* 161 (1 June 2000), pp. 35–60. ISSN: 00219991. DOI: 10.1006/jcph.2000.6484. URL: <https://doi.org/10.1006/jcph.2000.6484>.
- [7] John D Fenton. *A FIFTH-ORDER STOKES THEORY FOR STEADY WAVES*. Tech. rep. Journal of Waterway, Port, Coastal, and Ocean Engineering, 1985, pp. 216–234. DOI: [https://doi.org/10.1061/\(ASCE\)0733-950X\(1985\)111:2\(216\)](https://doi.org/10.1061/(ASCE)0733-950X(1985)111:2(216)).
- [8] Evan Gaertner et al. *Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine*. 2020. URL: <https://orbit.dtu.dk/en/publications/definition-of-the-iea-15-megawatt-offshore-reference-wind-turbine/>.
- [9] D. Goldstein, R. Handler, and L. Sirovich. “Modeling a No-Slip Flow Boundary with an External Force Field”. In: *Journal of Computational Physics* 105 (2 Apr. 1993), pp. 354–366. ISSN: 10902716. DOI: 10.1006/jcph.1993.1081. URL: <https://www.sciencedirect.com/science/article/pii/S0021999183710818>.

- [10] Boyce E. Griffith and Neelesh A. Patankar. “Immersed Methods for Fluid-Structure Interaction”. In: *Annual Review of Fluid Mechanics* 52 (Jan. 2020), pp. 421–448. ISSN: 00664189. DOI: 10.1146/annurev-fluid-010719-060228. URL: <https://doi.org/10.1146/annurev-fluid-010719-060228>.
- [11] Yongsam Kim and Charles S. Peskin. “Penalty immersed boundary method for an elastic boundary with mass”. In: *Physics of Fluids* 19.5 (2007). ISSN: 10706631. DOI: 10.1063/1.2734674.
- [12] Zhaobin Li, Guodan Dong, and Xiaolei Yang. “Onset of wake meandering for a floating offshore wind turbine under side-to-side motion”. In: *Journal of Fluid Mechanics* 934 (2022).
- [13] Sanjeev Malhotra. “Selection, Design and Construction of Offshore Wind Turbine Foundations”. In: *Wind Turbines*. Ed. by Ibrahim Al-Bahadly. London: IntechOpen, 2011. Chap. 10. DOI: 10.5772/15461. URL: <https://doi.org/10.5772/15461>.
- [14] Xiangchuan Meng et al. “Research Progress on Offshore Wind Turbine Foundation Structures and Installation Technologies”. In: *Marine Energy Research 2025, Vol. 2, Page 10006* 2 (2 Apr. 2025), p. 10006. ISSN: 3008-0932. DOI: 10.70322/mer.2025.10006. URL: <https://www.sciepublish.com/article/pii/508>.
- [15] Charles S. Peskin. “The immersed boundary method”. In: *Acta Numerica* 11 (Jan. 2002), pp. 479–517. ISSN: 14740508. DOI: 10.1017/S0962492902000077.
- [16] Edward Ransley et al. “Hydrodynamic response of a floating offshore wind turbine (1st FOWT Comparative Study Dataset)”. In: *University of Plymouth Research Repository* (2022). DOI: 10.24382/71j2-3385. URL: <https://doi.org/10.24382/71j2-3385>.
- [17] Abdolrahim Rezaeiha and Daniel Micallef. “Wake interactions of two tandem floating offshore wind turbines: CFD analysis using actuator disc model”. In: *Renewable Energy* 179 (2021), pp. 859–876.
- [18] Andhika Satria Pratama. *Prediction of Wake Flows Induced by Offshore Wind Turbine Foundations*. Tech. rep. Chalmers University of Technology, 2024.
- [19] STAR-CCM+ 2506 User Guide. *Siemens Digital Industries Software*. Tech. rep. Siemens Digital Industries Software, 2025.
- [20] H K Versteeg and W Malalasekera. *An Introduction to Computational Fluid Dynamics Second Edition*. Tech. rep. URL: www.pearsoned.co.uk/versteeg.
- [21] Roberto Verzicco. “Immersed Boundary Methods: Historical Perspective and Future Outlook”. In: *Annual Review of Fluid Mechanics* 55 (Jan. 2023), pp. 129–155. ISSN: 00664189. DOI: 10.1146/annurev-fluid-120720-022129. URL: <https://doi.org/10.1146/annurev-fluid-120720-022129>.
- [22] W. Wagner et al. “The IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam”. In: *Journal of Engineering for Gas Turbines and Power* 122.1 (Jan. 2000), pp. 150–184. ISSN: 0742-4795. DOI: 10.1115/1.483186. URL: <https://dx.doi.org/10.1115/1.483186>.
- [23] Wenzhe Zhang et al. “Computational Fluid Dynamics (CFD) applications in Floating Offshore Wind Turbine (FOWT) dynamics: A review”. In: *Applied Ocean Research* 150 (2 Sept. 2024), p. 104075. ISSN: 01411187. DOI: 10.1016/j.apor.2024.104075.

Declaration of Artificial Intelligence Use

Google Gemini Notebook was used during the preparation of this thesis for sourcing and organizing literature, supporting the drafting and revision of parts of the text, language correction, improvement of clarity and structure, troubleshooting and formatting of L^AT_EX code. All AI-assisted outputs were critically reviewed, edited, and, where applicable, verified against the original data and relevant computational fluid dynamics (CFD) literature. AI-assisted structural suggestions and code formatting were further validated by the author against the source material and compiler requirements. The CFD models, numerical setup, research methodology, selection of input data, interpretation of results, conclusions, and final content of the thesis remain the sole responsibility of the author.

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