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부유식 풍력터빈에 대한 연동해석

Coupled dynamic analysis of offshore floating wind turbines

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A thesis submitted to the faculty of KAIST in partial fulfillment of the requirements for the degree of Master of Science and Engineering in the Department of Mechanical Engineering, Division of Ocean Systems Engineering. The study was conducted in accordance with Code of Research Ethics[1]

2015. 12. 31

Approved by

Professor Lee, Phill-Seung

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of KAIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

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ABSTRACT

Renewable energy is attractive research issue. Especially, One of the most popular resource is wind energy because wind energy is relatively sustainable and nonpolluting. Recently, wind energy power increases dramatically in Europe, Japan, China and USA. Existing bottom fixed types have many limitation and problem such as the limitation of installation site, noise and so on. However, it is possible to solve these problem by using floating type wind turbines. To design optimal offshore floating wind turbine, Numerical analysis tools must be used. Also these analysis tools must predict loads and motion of wind turbines, considering complex environmental phenomenon. In this research, blade element momentum theory (BEMT) is used to calculate the aerodynamic loads and time domain potential theory is used to calculate the hydrodynamic response. Aerodynamic analysis module and hydrodynamic analysis module is developed individually at each department. Therefore, appropriate coupling method is used to calculate fully coupled aero-hydrodynamic response. In this research, partitioned coupling method is used, especially staggered solution procedure. Implementation procedure of analysis module will be explained and verification of analysis code is described.

Keywords: Hydrodynamics; Aerodynamics; Coupled dynamics; Coupling method; Partitioned approach; Offshore floating wind turbine; Renewable energy.

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Chapter 1. Introduction

1.1 Research background

Several resource such as oil, gas, coal and nuclear energy are the dominant source of energy in large parts of the world. However, These energy is harmful to the environment and limited resources. Therefore, there are many problems related to environment and society. Wind energy is one of most attractive renewable energy resource because it is nonpolluting, sustainable. Recently, wind energy power increases dramatically in Europe, Japan, China and USA. Especially, Denmark has a new world record for wind production by getting over 39% of its overall electricity from wind in 2014. Additionally, In 2013 wind power accounted for over 33% of Denmark's total electricity consumption. Other countries, China, Japan, Korea, USA, also continue to invest the wind energy (GWEC, 2014). [20]

Existing fixed type wind turbines have many problems such as limitation installation site, unsteady wind velocity, noise and so on. Recently offshore wind turbine unit increases because wind speed is steady and stronger in offshore area. Additionally, the problems of installation site that onshore fixed type wind turbines can be solved effectively. The development of bottom-fixed offshore wind turbines have been successful because the water depth of installation site is shallow water. However, offshore floating wind turbines have different mechanism because the support platforms are floating structure that can be installed in the deep water.

The offshore floating wind turbines have several difficulties. It is necessary to consider the motion of floater that affect the blade loading process and structure inertia loading. In this case, loading conditions that the blades experience are more complex than those of bottom-fixed offshore wind turbines when the floating body moves with 6-DOFs components. Therefore, these complicate interaction between the floating and wind turbine must be exactly considered. However, the offshore floating wind turbines still have many challenges to analysis, design, install, maintain. [10], [13], [20], [21]

It is important to predict the loads and dynamic responses of offshore floating wind turbine to design optimal floating wind turbines. The numerical analysis tools must consider complex physical phenomenon acting on offshore floating wind turbines.

As mentioned above, Analysis tool must be need to design the optimal offshore floating wind turbine. The analysis tools must calculate accurate loads and response of full systems. The fully coupled aero-hydro-elastic-servo dynamic analysis has been considered (Jonkman, 2009). The FAST code that calculates the aero-elastic response has been developed by NREL. Recently, HydroDyn module is added to FAST code to calculate coupled dynamic response of offshore floating wind turbine. Additionally, other analysis tools are also under the development, HAWC2, 3Dfloat, DeepC, Bladed and so on. [21]

In this research, fully coupled dynamic analysis code is developed and different analysis approach will be described to calculate coupled dynamic response of offshore floating wind turbines. Existing numerical analysis tools use monolithic coupling scheme to consider multi-physics system. However, present code that is developed in this research use partitioned coupling scheme because there are many disadvantage of monolithic approach.

Monolithic approach handle all the physical domain simultaneously. Therefore, each physical domain is mixed in formulation and analysis code dependently. When the analysis code is modified or upgraded, many complicate modifications of analysis code are necessary. Therefore, efficiency of analysis procedure decreases. However, partitioned approach handles each physical domain independently. Separate solvers are used for each physics domain. Therefore, modular solution approach is possible. It is each to maintain, modify or upgrade analysis code for offshore wind turbine and reuse of existing highly developed analysis code. [24], [25], [26], [27], [28], [29]

Multi-physics problems such as offshore floating wind turbine can be solved more effectively by using partitioned approach because offshore floating wind turbines must consider many physics domain such as wave, wind, mooring, current and so on. However, weakness of partitioned method is numerical solution stability. Therefore, solution stability and convergence study is needed for more stable and fast coupled dynamic analysis. [24]

In this research, a different coupling method of numerical analysis for offshore floating wind turbine is suggested. Existing numerical analysis tools [21] use monolithic method for multi-physics problems such as offshore floating wind turbine. However, analysis code developed in this research use partitioned method that can solve problems of monolithic method.

Chapter 2. Hydrodynamics

2.1 Overall description

2.1.1 Background theory

The interactions between wave and floating body are important to design of offshore floating structure systems. The calculation of loads and motion caused by these interaction is the main problem of marine hydrodynamics field. Under the linear assumption, the hydrodynamics can be split into two parts: radiation problem, diffraction problem. Additionally, hydrostatics also must be considered to calculate the buoyance of floating body and hydrostatic restoring force.

Navier-stokes equations is commonly used to solve the hydrodynamic problems. However, It is heavy computation cost to solve Navier-stokes equations. To be able to solve practical problems, hydrodynamic model is simplified based on assumption. These simplified hydrodynamic models are used for design procedure of offshore floating structures.

The choice of appropriate model is important. Appropriate hydrodynamic model depends on parameters such as wave length, wave height, and characteristic size of floating body. When the size of floating body is large compared to the wave length, wave radiation and diffraction is important. Wave diffraction force is influenced by how waves are scattered by floating structure. Wave radiation force dominate the damping mechanism. In the case of relatively small size structure, the effect of wave radiation and diffraction force deceases. As the wave height increases, viscous effects on the floating body also increases. Therefore, viscous drag force on the floating body dominates and the effects of wave radiation and diffraction force become small.

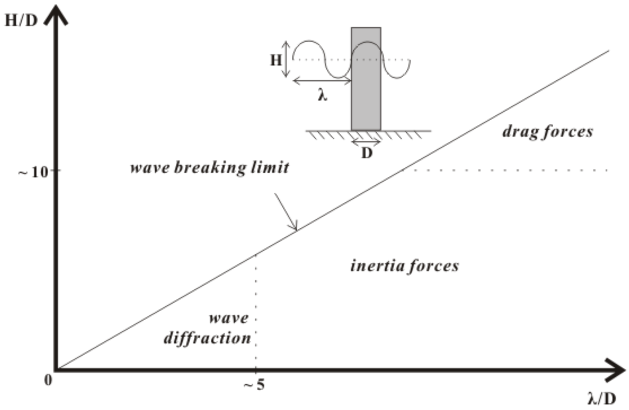

Figure 2.1. Classification of hydrodynamic models

Figure 2.1 shows what force is dominant in different condition. When Structure size is large, wave radiation and diffraction problem is dominant. Whereas structure size is smaller, wave radiation and diffraction problem is not significant. If incident wave height increase, drag force is dominant.

In this research, potential flow theory is used to solve offshore hydrodynamic problems. This potential flow is available under the some assumption, inviscid, incompressible, irrotational fluid. Potential flow theory is consider not viscous effect but wave radiation and diffraction problem. This method's limitation is that wave height is relatively smaller than dimension of floating structure.

When viscous effect is dominant, other hydrodynamic models are used. One of most commonly used model is Morison's equation. Morison's equation is a part of methods called strip theory. This hydrodynamic model can consider viscous drag as well as more flexibility with respect to wave modeling. However, Morison's equation has some limitation. This method can be applied to slender body ($\frac{D}{\lambda} < 0.1 \sim 0.2$). It means that wave scatter and reflection effect from the floating structure to incident wave is negligible. If wave length is relatively larger than dimension of floating structure, it is possible to simplify the diffraction effect and neglect wave radiation effect. [1], [3], [4]

2.1.2 Coordinate system

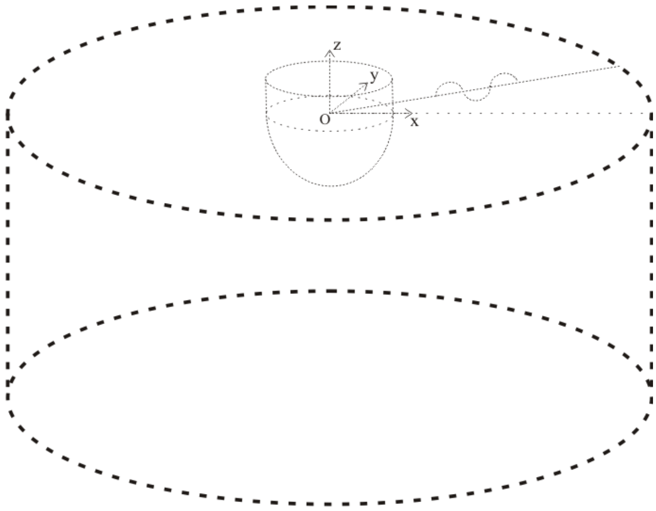

Figure 2.2. Coordinate system of floating body

Figure 2.2 shows coordinate system. In this research, Cartesian coordinate system is used to define platform motion. It is important to consider six rigid body modes of floating platform for analyzing offshore floating systems. Analysis descriptions are defined in global reference frame and body-fixed reference frame. The origin of body-fixed reference frame is at the SWL (Still Water Line) and the Z-axis directed upward opposite gravity force along the centerline of the undisplaced platform. Motion X, Y, Z represents platform translation motion, “surge”. “sway”, and “heave” respectively. Rotation with respect to the same axes are called “roll”, “pitch”, and “yaw”. In offshore hydrodynamic analysis, the body-fixed reference frame is used such that it coincides with the global coordinate system when the floating body is at rest in its mean position.

2.2 Numerical analysis

In this chapter, numerical hydrodynamic analysis procedure is explained. Chapter 2.2.1 explains the hydrodynamic analysis of frequency domain. Chapter 2.2.2 explains the hydrodynamic analysis of time domain. Frequency domain analysis is needed to obtain hydrodynamic coefficient of frequency domain used to implement time domain hydrodynamic coefficient. Therefore, frequency domain analysis is necessary procedure in time domain hydrodynamic analysis. After frequency domain hydrodynamic analysis is completed, time domain hydrodynamic analysis is implemented. Each analysis procedure is explained as follows. [4], [8]

2.2.1 Linear hydrodynamic model in frequency domain

2.2.1.1 Governing equation

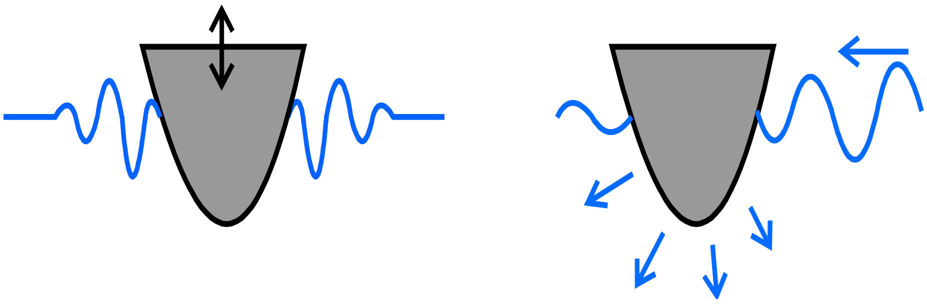

Figure 2.3. Hydrodynamic radiation and diffraction problem

Potential flow model cannot consider viscous effect e.g. viscous drag or flow separation. Fluid field is governed by the velocity potential $\phi(x, y, z, t)$ that satisfies Laplace equation and its boundary conditions in fluid domain. As mentioned above, there are two requirements that are important to the further derivation. First, the wave amplitude is relatively smaller than wave length and dimension of floating structure. Second, the motion amplitudes are assumed to be small, in the same order of magnitude as the wave amplitude. Under these assumption, Small wave amplitude satisfies the use of linear wave theory. Under the small wave amplitude and platform motion assumption, it is possible to divide hydrodynamic problem into 3 parts, hydrostatic, radiation, diffraction problems. In this chapter, important equations are derived as follows. [3], [6], [8], [9], [10]

The motion of fluid particles are governed by Newton's second law. The force is divided into 2 parts, body force and surface force.

$$\mathbf{m}a = \sum \mathbf{F} = \mathbf{F}_{Body} + \mathbf{F}_{Surf} \tag{2.1}$$

The Navier – Stokes' equation is given by.

$$\rho \frac{d\mathbf{v}}{dt} = \rho\mathbf{g} - \nabla\mathbf{P} + \mu\nabla^2\mathbf{v} \tag{2.2}$$

The right hand side of Equation 2.2 represents the forces. The first term explain the body force. The second and third terms describe the surface force representing pressure force and viscous force.

When the fluid is inviscid ($\mu = 0$), the Euler equation is derived as follows.

$$\rho \frac{d\mathbf{v}}{dt} = \rho\mathbf{g} - \nabla\mathbf{P} \tag{2.3}$$

If the fluid is irrotational ($\nabla \times \mathbf{V} = 0$), velocity components are described by velocity potential as follows.

$$\mathbf{V} = \nabla\phi \tag{2.4}$$

To calculate the fluid pressure, Bernoulli equation is derived by integrating the Euler equation.

$$\rho \frac{\partial \phi}{\partial t} + \mathbf{P} + \frac{1}{2}\rho |\nabla\phi|^2 + \rho\mathbf{g}z = C \tag{2.5}$$

In the Bernoulli equation, there are two unknown variables, pressure and velocity potential. Therefore, one more equation (continuity equation) is needed to obtain the solution. Laplace equation is derived by using continuity equation as follows. Continuity equation is given by.

$$\frac{\partial \rho}{\partial t} = \nabla \bullet \rho\mathbf{v} = 0 \tag{2.6}$$

When the fluid is incompressible, continuity equation is given by.

$$\nabla \bullet \mathbf{v} = 0 \tag{2.7}$$

When the fluid is irrotational, velocity potential can be represented. Laplace equation is derived from continuity equation as follows.

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{2.8}$$

Under incompressible, irrotational, inviscid flow assumption, Bernoulli equation and Laplace equation is derived by using continuity equation and equation of motion.

$$\text{Laplace equation : } \nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0$$

$$\text{Bernoulli equation : } \rho \frac{\partial \phi}{\partial t} + \mathbf{P} + \frac{1}{2}\rho |\nabla\phi|^2 + \rho\mathbf{g}z = C$$

Bernoulli equation and Laplace equation is the equation of motion for fluid particle. From this equation of motion, it is possible to calculate the pressure on the floating structure.

First of all, it is need to calculate the velocity potential from Laplace equation. Because Laplace equation is boundary value problem, the velocity potential satisfy with bottom boundary condition, free surface boundary condition, lateral boundary condition, and body boundary condition. Under linear assumption, hydrodynamic problems are divided into radiation and diffraction problem. Therefore total velocity potential is divided into incident wave velocity potential (Froude–krylov force), diffraction velocity potential, radiation velocity potential. [4], [6], [9], [10]

$$\phi_T = \phi_I + \phi_D + \phi_R \tag{2.9}$$

When total velocity potential is solved, pressure of a fluid particle is calculated by using Bernoulli equation. Total force acting on the floating body is obtained by integrating pressure. The force acting on floating structure is given by.

$$\mathbf{F} = \iint_{S_b} p\,\mathbf{n}\,ds \tag{2.10}$$

Moment acting on floating structure is given by.

$$\mathbf{M} = \iint_{S_b} P(\mathbf{r} \times \mathbf{n})\,dS \tag{2.11}$$

Under the linear assumption, Bernoulli equation can be linearized and rearranged as follows. As mentioned above, total velocity potential is divided into incident wave potential, radiation potential, diffraction potential.

$$\mathrm{P} = -\rho \frac{\partial \phi}{\partial t} - \rho \mathrm{g} z = -\rho \mathrm{g} z - \rho \left(\frac{\partial \phi_I}{\partial t} + \frac{\partial \phi_D}{\partial t} + \frac{\partial \phi_R}{\partial t} \right) \tag{2.12}$$

The term $-\rho \frac{\partial \phi}{\partial t}$ is dynamic pressure and $-\rho g z$ is static pressure. Dynamic pressure is divided into Froude-Krylov pressure, diffraction pressure and radiation pressure. .

$$\mathrm{P}_{static} + \mathrm{P}_{dynamic} = \mathrm{P}_{static} + \mathrm{P}_{F.K} + \mathrm{P}_D + \mathrm{P}_R \tag{2.13}$$

Total force acting on the floating body can be calculated by integrating the pressure on the wetted surface.

$$\mathrm{M}\ddot{\mathrm{q}} = \mathrm{F}_{gravity} + \mathrm{F}_{static} + \mathrm{F}_{F.K} + \mathrm{F}_D + \mathrm{F}_R \tag{2.14}$$

The term $\mathbf{F}_{gravity}$ and $\mathbf{F}_{static}$ are gravitational restoring force that can be affected by gravitational acceleration, center of mass, center of buoyancy and floating body's geometry. The term $\mathbf{F}_{F.K}$ and $\mathbf{F}_D$ are wave exciting force. The term $\mathbf{F}_R$ is radiation force that can be affected by acceleration and velocity components.

2.2.1.2 Boundary condition

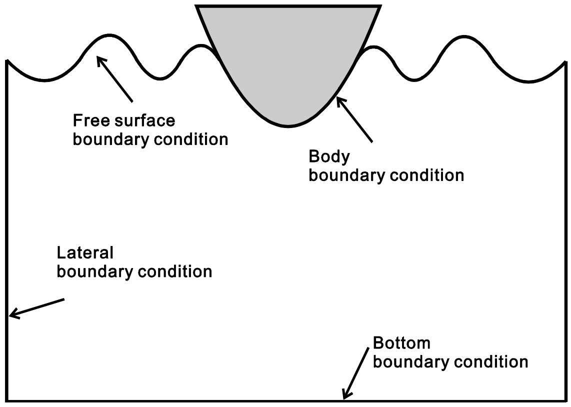

Figure 2.4. Boundary condition configuration

It is necessary to impose the boundary condition to solve the total velocity potential. In boundary value problem, fluid field is governed by Laplace equation. Therefore, velocity potential that satisfies the Laplace equation and boundary condition should be obtained. At sea bed, bottom boundary condition must be imposed. Fluid particle cannot pass through the bottom. Mathematical description is given by.[1], [4], [6], [8]

$$\frac{DF}{Dt} = \frac{\partial F}{\partial t} + \frac{\partial \phi}{\partial x}\frac{\partial F}{\partial x} + \frac{\partial \phi}{\partial y}\frac{\partial F}{\partial y} + \frac{\partial \phi}{\partial z}\frac{\partial F}{\partial z} = 0 \quad \text{at} \quad z = -h(x, y, t) \tag{2.15}$$

$$\text{with} \quad F(x, y, z, t) = z + h(x, y, t)$$

In this research, hydrodynamic problem is linearized. Therefore, linearized bottom boundary condition is given by.

$$\frac{\partial h}{\partial t} + \frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = -h(x, y, t) \tag{2.16}$$

If the bottom is plat, bottom boundary equation form can be simplified.

$$\frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = -h(x, y, t) \tag{2.17}$$

The free surface is material surface. Therefore, fluid particle must stay on free surface. Free surface boundary condition can be divided into kinematic free surface boundary condition and dynamic free surface boundary condition. Mathematical description of kinematic boundary condition is given by.

$$\frac{DF}{Dt} = \frac{\partial F}{\partial t} + \frac{\partial \phi}{\partial x}\frac{\partial F}{\partial x} + \frac{\partial \phi}{\partial y}\frac{\partial F}{\partial y} + \frac{\partial \phi}{\partial z}\frac{\partial F}{\partial z} = 0 \quad \text{at} \quad z = \eta(x, y, t) \tag{2.18}$$

$$\text{with} \quad F(x, y, z, t) = \eta(x, y, t) - z$$

$\eta(x, y, t)$ is the free surface wave elevation. Linearized boundary condition is given by.

$$\frac{DF}{Dt} = \frac{\partial \eta}{\partial t} + \frac{\partial \phi}{\partial z}\frac{\partial F}{\partial z} = 0 \quad \text{at} \quad z = 0 \tag{2.19}$$

then

$$\frac{\partial \eta}{\partial t} - \frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = 0 \tag{2.20}$$

Dynamic boundary condition is derived from Bernoulli equation.

$$\rho\frac{\partial \phi}{\partial t} + \mathbf{P}_{atm} + \frac{1}{2}\rho\left|\nabla\phi\right|^2 + \rho\mathbf{g}\eta = \mathbf{P}_{atm} \quad \text{at} \quad z = \eta(x, y, t) \tag{2.21}$$

Linearized form is given by.

$$\frac{\partial \phi}{\partial t} + \mathbf{g}\eta = 0 \quad \text{at} \quad z = 0 \tag{2.22}$$

Combined free surface boundary condition form is given by.

$$\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = 0 \tag{2.23}$$

At the wetted surface of floating body, the velocity of a fluid particle is the same as velocity of floating body moving in the normal direction of the wetted surface of floating body. Mathematical description of body boundary condition is given by.

$$v_n = \frac{\partial \phi}{\partial n} = u_n = \mathbf{u}\cdot\mathbf{n} \quad \text{at wetted surface} \tag{2.24}$$

n is normal vector of wetted surface and *u* is velocity of floating body.

Lateral boundary condition presents radiation condition. It is given by.

$$\sqrt{R}\,(\frac{\partial}{\partial R} + i\,k)(\phi - \phi_I) = 0 \text{ on } \quad S_\infty \tag{2.25}$$

2.2.1.3 Equation of motion

As mentioned above, hydrodynamic force is obtain from velocity potential that satisfy the Laplace equation and boundary condition. The hydrodynamic coefficients obtained from radiation and diffraction problem are added mass coefficient, damping coefficient, hydrostatic stiffness coefficient and coefficient corresponding to wave exiting force in frequency domain. Equation of motion for frequency domain is given by.

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{F}_{radiation} + \mathbf{F}_{diffraction} + \mathbf{F}_{static} + \mathbf{F}_{line} \tag{2.26}$$

then

$$(\mathbf{M} + \mathbf{A}(\omega))\ddot{\mathbf{q}} + ((\mathbf{B}(\omega) + \mathbf{B}_{ext})\dot{\mathbf{q}} + (\mathbf{C} + \mathbf{C}_{ext})\mathbf{q} = \mathbf{F}_{wave}(\omega) \tag{2.27}$$

In this system, $\mathbf{q}$ is displacement of floating body and is assumed to be harmonic response $\mathbf{q} = \mathrm{Re}\{\mathbf{q}e^{i\omega t}\}$. $\mathbf{M}$ is total inertia mass matrix of floating body and $\mathbf{B}_{ext}$, $\mathbf{C}_{ext}$ is external damping coefficient and external hydrostatic coefficient caused by additional offshore equipment such as mooring system. Although Hydro-dynamic coefficients calculated from frequency domain cannot be used to solve transient analysis of floating wind turbine, where nonlinear effects, transient analysis, irregular wave are considered, the coefficients cal-culated in frequency domain are used to derive hydrodynamic coefficient for time domain analysis.

2.2.2 Linear hydrodynamic model in time domain

In this section, time domain hydrodynamic analysis is discussed. Total external loads on floating platform are described except loads from wind turbine itself. Hydrodynamic analysis in frequency domain is commonly used in offshore industry. However, there are several application that violate this linear assumption such as forces and moment caused by wind, mooring, current, ice, viscous damping, irregular wave. Therefore, time domain hydrodynamic is used to exactly consider other external loads. The time domain hydrodynamic analysis can be described using the classic formulation by Cummins. Equation of motion for floating platform is as follows.[3], [7], [8], [9], [10]

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{F}_{hydro} \tag{2.28}$$

The force components are divided into 3 parts: wave exciting force, hydrostatic force, radiation force. The force acting on the floating structure in time domain is given by.

$$\mathbf{F}_{hydro} = \mathbf{F}_{wave} + \rho g V_0 \delta_{i3} - \mathbf{C}_{hydro}\mathbf{q} - \int_0^t \mathbf{K}(t-\tau)\,\dot{\mathbf{q}}(\tau)\,d\tau \tag{2.29}$$

The equation of motion for time domain hydrodynamic model is given by.

$$(\mathbf{M}+\mathbf{A})\ddot{\mathbf{q}}(t) + \int_{-\infty}^{t} \mathbf{K}(t-\tau)\dot{\mathbf{q}}(\tau)d\tau + \mathbf{B}_{ext}\,\dot{\mathbf{q}}(t) + (\mathbf{C}_{hydro} + \mathbf{C}_{ext})\,\mathbf{q}(t) = \mathbf{F}_{wave}(t) \tag{2.30}$$

$\mathbf{M}$ is mass matrix of floating structure. $\mathbf{B}_{ext}$ and $\mathbf{C}_{ext}$ is external damping coefficient and external hydrostatic stiffness matrix. $\mathbf{C}_{hydro}$ is hydrostatic matrix. These components are independent to frequency under the linear assumption. The terms of this equation of motion in Equation (2.31) is described separately at following section.

2.2.2.1 Radiation problem

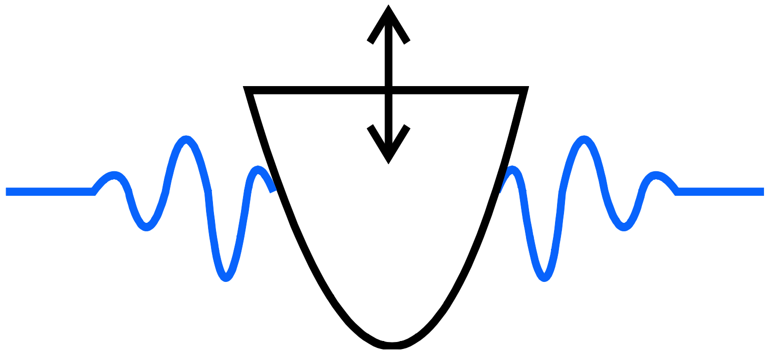

Figure 2.5. Hydrodynamic radiation problem

A floating structure that moves in fluid experiences added mass and damping force. When floating body moves, This motion generates wave radiation from itself and contribute to added mass and wave radiation damping. This radiation wave leads to a memory effect and outgoing energy flux that damps the motion of floating body. The term $\int_0^t \mathbf{K}(t-\tau)\,\dot{\mathbf{q}}(\tau)d\tau$ is related to radiation problem. This term describes load contribution from radiation wave damping and additional contribution from added mass effect that is not consider in added mass coefficient in time domain **A**. when the motion of floating body generates a wave, free surface experience memory effect, wave radiation loads depend on the history of motion for floating body. To calculate the wave radiation loads, superposition of generated radiation waves that are contribution to previous wave radiation load must be considered. This can be able to describe the appropriate time lag effect. This procedure can be implemented using convolution integral in which the function **K** is called impulse response function or radiation-retardation kernel. The memory effect can be captured by using numerical convolution integral in time domain. The meaning of radiation-retardation kernel is found by considering a unit impulse in velocity of floating body. Radiation-retardation kernel is calculated using frequency domain hydrodynamic coefficient.

$$\mathbf{K}(\tau) = -\frac{2}{\pi}\int_0^\infty \omega[a(\omega) - a(\infty)]\,\sin(\omega\tau)d\omega \tag{2.31}$$

ω is frequency and $\mathbf{a}(\omega)$ is added mass coefficient in frequency domain. The other form of radiation-retardation kernel is given by.

$$\mathbf{K}(\tau) = \frac{2}{\pi}\int_0^\infty \mathbf{b}(\omega)\,\cos(\omega\tau)d\omega \tag{2.32}$$

$\mathbf{b}(\omega)$ is radiation damping coefficient in frequency domain. This form is more commonly used because it is easier to calculate numerically. Impulsive hydrodynamic added mass coefficient is given by.

$$\mathbf{A} = \mathbf{a}(\omega) + \frac{1}{\omega}\int_0^\infty \mathbf{K}(\tau)\sin(\omega\tau)d\tau \tag{2.33}$$

This impulsive added mass is acceleration dependent. $\mathbf{a}(\omega)$ is added mass coefficient in frequency domain. However, Infinite added mass matrix is commonly used because its form is simpler.

$$\mathbf{A} = \mathbf{a}(\infty) \tag{2.34}$$

2.2.2.2 Diffraction problem

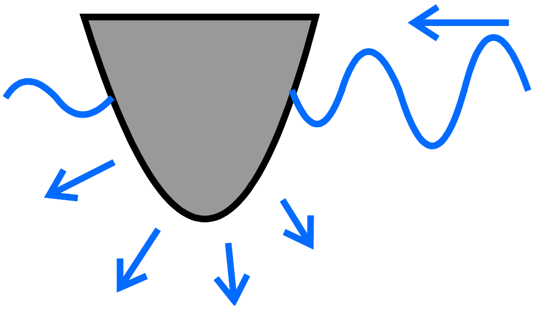

Figure 2.6. Hydrodynamic diffraction problem

The term $\mathbf{F}_{wave}$ represents the total wave exciting force acting on the floating body. As mentioned above, airy wave theory describes the kinematics of regular wave. This airy wave theory describes how the velocity and acceleration of fluid particle decay exponentially with depth. Wave exciting force is related to incident wave and scattered wave. Magnitude of wave exciting force is directly proportional to the wave amplitude. The wave exciting force from the irregular wave is the same as the sum of exciting force caused by each individual regular wave. Mathematical description is given by.

$$\mathbf{F}_{wave}(t) = \int_{-\infty}^{\infty} \mathbf{H}(t-\tau)\zeta(\tau)d\tau \tag{2.35}$$

ζ is wave amplitude and $\mathbf{H}$ is impulse response function corresponding to wave exciting force**.** Impulse response function corresponding to wave exciting force is derived as follows.

$$\mathbf{X}(\omega,\beta) = \int_{-\infty}^{\infty} \mathbf{H}(t)\, e^{-i\omega t}\, dt \tag{2.36}$$

$\mathbf{X}$ is wave exciting force calculated in frequency domain. ω is incident wave frequency and β is angle of incident wave. The complex Fourier transforms are as follows.

$$2\pi \cdot \mathbf{K}(t) = \int_{-\infty}^{\infty} \mathbf{X}(\omega,\beta)\, e^{i\omega t}\, d\omega \tag{2.37}$$

then

$$\mathbf{K}(t) = \frac{1}{\pi}\int_{0}^{\infty} [\mathrm{Re}(\mathbf{X}(\omega))\cos\omega t - \mathrm{Im}(\mathbf{X}(\omega))\sin\omega t]\, d\omega \tag{2.38}$$

2.2.2.3 Hydrostatic problem

The hydrostatic force and moments keep a floating body stable position. Buoyancy force, gravitational force and change of wetted portion of floating body contribute to the static stability. The total hydrostatic force is obtain from integral of hydrostatic pressure over the wetted surface of floating body. [3], [10]

$$F_i = (\rho V_0 - m) g \delta_{i3} - (m y_G - \rho V_0 y_B) g \delta_{i4} + (m x_G - \rho V_0 x_B) g \delta_{i5} - \sum_{j=1}^{6} c_{ij} \zeta_j \tag{2.39}$$

The first three terms are the effect of buoyance and gravity that keep the floating body its mean position (SWL). The terms (x_G, y_G, z_G) and (x_B, y_B, z_B) are the position of center of gravity and center of buoyancy when offshore floating wind turbine is in the mean position (SWL). V_0 is displaced volume of floating body. In the last term, c_{ij} is the components of hydrostatic stiffness matrix as soon as the floating body moves and displacements ζ_j are no longer 0. Hydrostatic stiffness matrix is as follows. In hydrostatic stiffness matrix, A_0 is the water plane area of undisplaced body.

$$c = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_0 & \rho g \iint_{A_0} y d A_0 & -\rho g \iint_{A_0} x d A_0 & 0 \\ 0 & 0 & \rho g \iint_{A_0} y d A_0 & \rho g \iint_{A_0} y^2 d A_0 + \rho g V_0 z_B - m g z_G & 0 & -\rho g A_0 x_B + m g x_G \\ 0 & 0 & -\rho g \iint_{A_0} x d A_0 & 0 & \rho g \iint_{A_0} x^2 d A_0 + \rho g V_0 z_B - m g z_G & -\rho g A_0 y_B + m g y_G \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.40}$$

In this research, linearized hydrostatic force is used that cannot consider wave elevation and motion of floating body. Linearized hydrostatic force is calculated just in still water condition and no motion of body.

2.3 Verification

In this section, numerical verification of hydrodynamic analysis. The solution from hydrodynamic analysis code is numerically approximated. Therefore, analysis code verification must be implemented. To verify the numerical solution, appropriate numerical model is chosen and numerical solution calculated in present code is compared with commercial software WAMIT. [10]

2.3.1 Numerical model

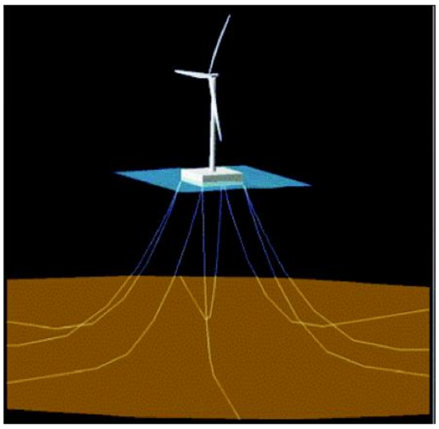

Figure 2.7. ITI Energy barge model

In this research, NERL offshore 5 MW baseline wind turbine is used to verify the analysis code. The barge type support platform is used to support NREL 5MW wind turbine system. Barge concept is chosen because of its simplicity geometry. NREL 5 MW baseline wind turbine is mount on the barge type floating platform. ITI Energy barge model is used in this research.

ITI energy barge model is developed by Universities of Glasgow and Strathclyde with ITI Energy. This platform is ballasted with seawater to obtain the reasonable draft. Barge platform is moored by eight catenary mooring lines to restrain its drifting. As mentioned chapter 2.1.2, the coordinate of these properties is floating body fixed frame.

Table 2.1. Overall properties of NREL 5 MW baseline wind turbine

Rating	5 MW
Rotor orientation, configuration	Upwind, three blades
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple-stage gearbox
Rotor, hub diameter	126 m, 3 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, Rated rotor speed	6.9 rpm, 12.1 rpm
Rated tip speed	80 m/s
Overhang, shaft tilt, precone	5 m, 5 deg, 2.5 deg
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg
Coordinate location of overall CM	(-0.2 m, 0.0 m, 64 m)

Table 2.2. Summary of properties for ITI Energy barge model

Size(W, B, H)	40 m, 40m, 10m
Moon pool(W, B, H)	10m, 10m, 10m
Draft, freeboard	4 m, 6 m
Water displacement	6,000 m^3
Mass, including ballast	5,452,000 kg
CM location below SWL	0.281768 m
Roll inertia about CM	726,900,000 $kg \cdot m^2$
Pitch inertia about CM	726,900,000 $kg \cdot m^2$
Yaw inertia about CM	1,453,900,000 $kg \cdot m^2$
Anchor depth	150 m
Separation between opposing anchors	773.8 m
Unstretched line length	473.3 m
Neutral line length on sea bed	250 m
Line diameter	0.0809 m
Line mass density	130.4 kg/m
Line extensional stiffness	589,000,000 N

2.3.2 Numerical result

Numerical solution calculated in present code is compared with WAMIT. WAMIT is hydrodynamic analysis program that is widely used commercial software in offshore hydrodynamic industry. To verify the hydrodynamic analysis module in present code, radiation-retardation kernel is compared with WAMIT results. Numerical results are as follows. [9], [11], [12]

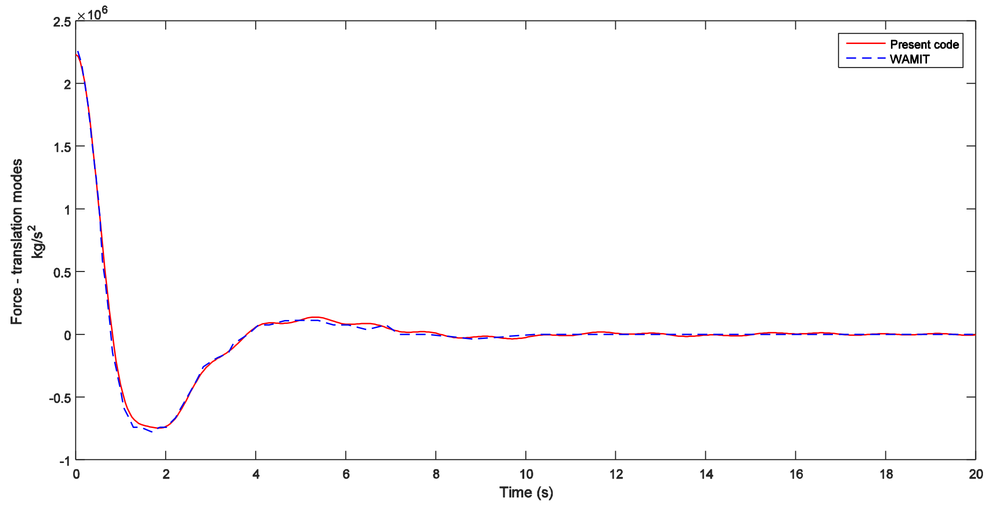

Figure 2.8. Retardation kernel function curves of force-translation modes (K22)

Figure 2.8 shows the numerical result of radiation-retardation kernel corresponding to K22 component. The result calculated from present code is almost same as WAMIT. Additionally, other components of radiation-retardation kernel is compared with WAMIT as follows.

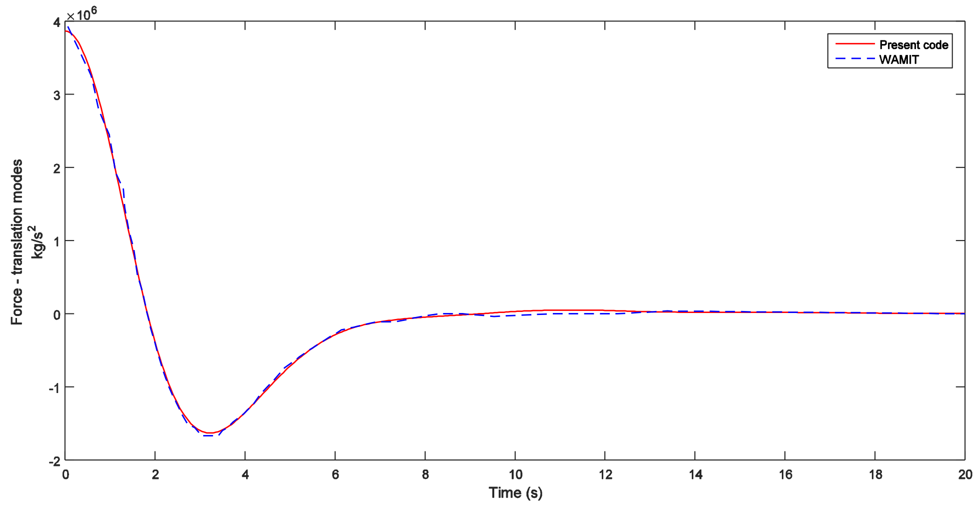

Figure 2.9. Retardation kernel function curves of force-translation modes (K33)

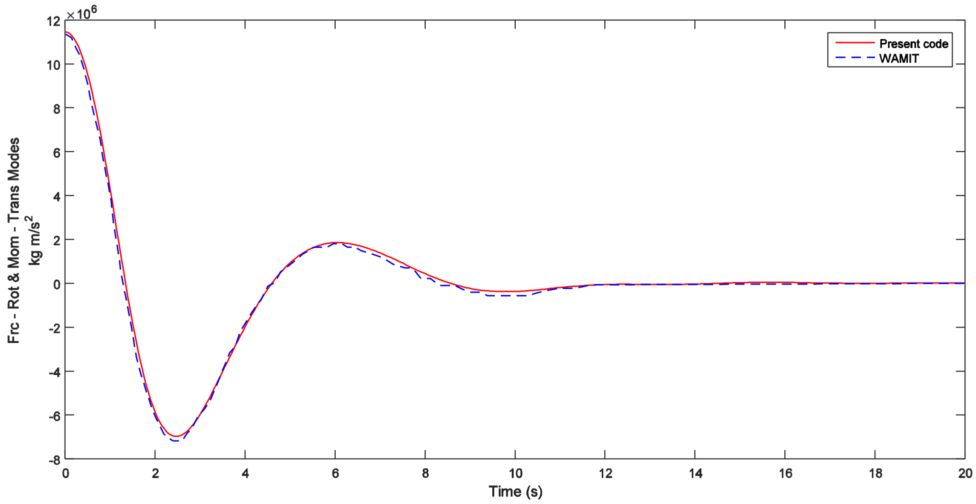

Figure 2.10. Retardation kernel function curves of frc-rot & mom-trans modes (K15)

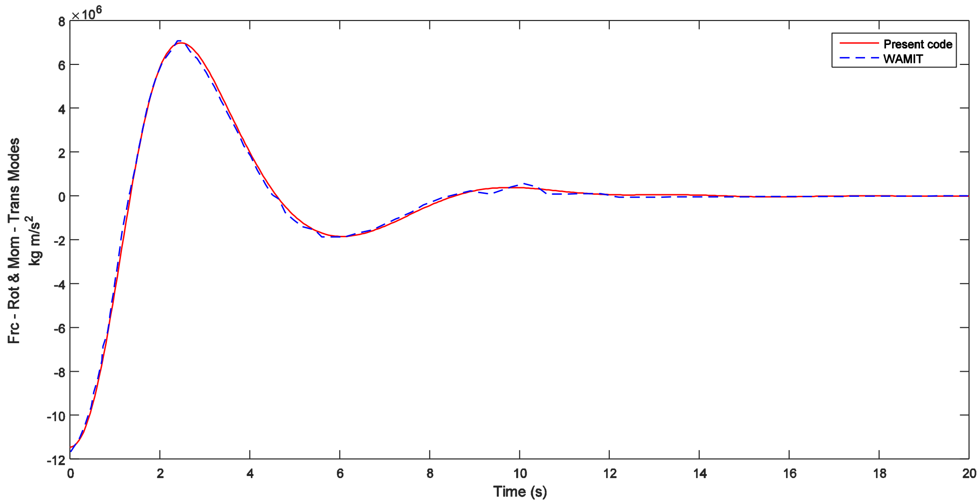

Figure 2.11. Retardation kernel function curves of frc-rot & mom-trans modes (K24)

As shown in **Figure 2.8, Figure 2.9, Figure 2.10, Figure 2.11,** radiation-retardation kernels calculated from present code are almost same as WAMIT results.

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Chapter 3. Aerodynamics

3.1 Blade element momentum theory

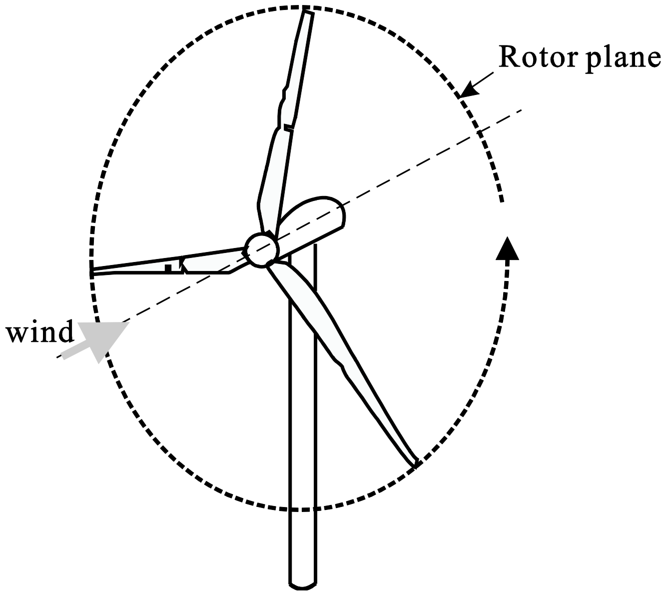

Figure 3.1. Configuration of wind turbine

Aerodynamics are described by two aerodynamic model, BEMT (Blade Element Momentum Theory), GDWT (Generalized Dynamic Wake theory). Aerodynamic analysis module used in present code is blade element moment theory. In this section, blade element momentum theory is explained.

Blade element momentum theory is commonly used to design wind turbine because of cost efficiency. In this research, blade and tower are considered as rigid body. Aerodynamic analysis module in present code calculates forces and moments acting on blades. Blade element momentum theory is divided into two different theory that is blade element theory and blade momentum theory. Blade element theory assume that the blade can be divided into several small elements that don't affect other elements aerodynamically. Aerodynamic force calculated at each element can be obtain from two-dimensional airfoils. Total forces and moments acting on blades can be calculated from integral of each elemental force and moment along the blades. The other theory is blade momentum theory. Blade momentum theory assumes that the loss of pressure or momentum in the blade plane is caused by the work done by airflow passing through the rotor plane on the blade elements. Induced velocity can be calculated by using this blade momentum theory in the axial and tangential directions. This calculated induced velocity affect the inflow on rotor plane. Therefore, induced velocity affect the forces and moments calculated by blade element theory. To calculate aerodynamic loads and induced velocity, these two theory is combined and has iterative solution procedure. [14]

However, blade element momentum theory has limitations. This theory cannot consider tip and hub vortex effect and also cannot describe skewed inflow completely. To make up these limitation, various corrections are suggested. Although BEMT has these limitation, it is widely used aerodynamic model because it is possible to calculate aerodynamic load at each elements modeled as a two-dimensional airfoil. More detail solution procedure is explained in this chapter.

3.1.1 Blade momentum theory

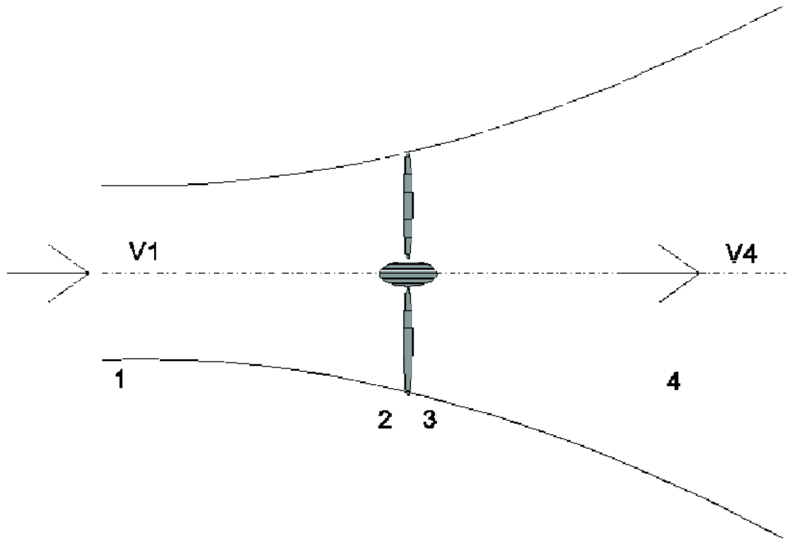

Figure 3.2. Axial stream tube

Induced velocity about axial and tangential direction is calculated by using momentum theory. This theory is to use a momentum balance at a rotating annular stream tube passing through a turbine. Blade element momentum theory has some assumption as follows. [14] , [15]

- Incompressible air
- Frictional drag force is negligible
- The number of blades is infinite
- The inflow is steady
- Thrust loading and velocity are uniform over the disk
- The wake rotation is negligible

Bernoulli's equation can be applied because the inflow is frictionless.

$$p_2 - p_3 = \frac{1}{2}\rho(v_1^2 - v_4^2) \tag{3.1}$$

Force is obtain by considering the area.

$$dF_x = (p_2 - p_3)dA \tag{3.2}$$

then

$$dF_x = \frac{1}{2}\rho(v_1^2 - v_4^2)dA \tag{3.3}$$

In this section, induction factor is defined by.

$$a = \frac{v_1 - v_2}{v_1} \tag{3.4}$$

The Final form of axial force is given by.

$$dF_x = \frac{1}{2}\rho V_1^2[4a(1-a)]2\pi r dr \tag{3.5}$$

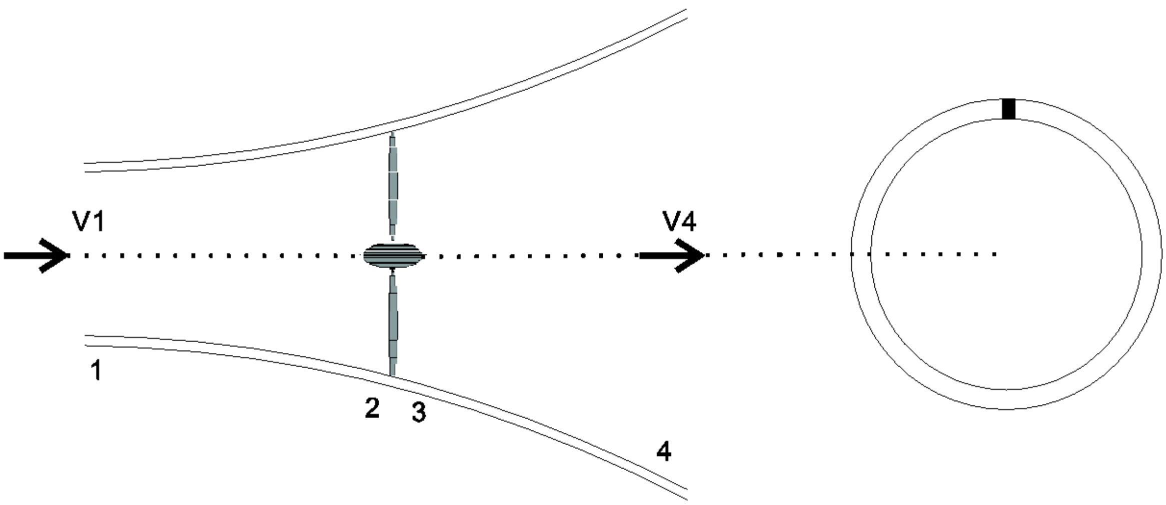

Figure 3.3. Annular stream tube

Figure 3.3 show that annular stream tube. There are 4 regions. 1 is upstream area, 2 is just before the blades, 3 is just after the blades and 4 is downstream of the blades. Conservation of angular momentum is applied to the annular stream tube.

Moment of inertia : $I = mr^2$

Angular momentum : $L = I\omega$

Torque : $T = \frac{dL}{dt}$

then

$$T = \frac{dI\omega}{dt} = \frac{d(mr^2\omega)}{dt} = \frac{dm}{dt} r^2 \omega \tag{3.6}$$

where ω is angular velocity of blade wake and Ω is angular velocity of blade rotation. The torque corresponding to each element is given by.

$$dT = d\dot{m} \cdot \omega r^2 \tag{3.7}$$

then

$$dT = \rho 2\pi r dr V_2 \omega r^2 \tag{3.8}$$

where

$$d\dot{m} = \rho A V_2 = \rho 2\pi r dr V_2 \tag{3.9}$$

Angular induction factor a' is defined as follows.

$$a' = \frac{\omega}{2\Omega} \tag{3.10}$$

Then final tangential force is derived.

$$dT = 4a'(1-a)\rho V_1 \Omega r^3 \pi dr \tag{3.11}$$

where

$$V_2 = V_1(1-a) \tag{3.12}$$

Axial force and tangential force is obtained by using momentum theory.

3.1.2 Blade element theory

In this section, blade element theory is mainly explained. Blade element theory has some assumption. First, there is no interaction effect between each blade element and the force on a blade element is calculated by only lift and drag coefficients. [14], [15]

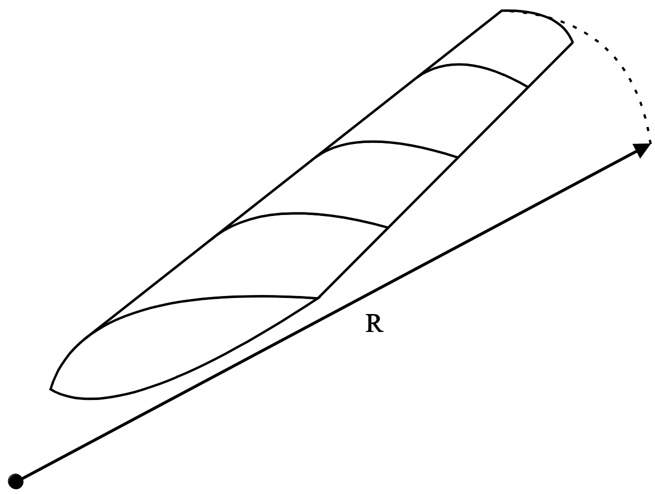

Figure 3.4. Configuration of blade elements

Figure 3.4 show the divided blade into N elements. Each blade element will experience different inflow because the blade elements have a different rotational speed (Ωr), different chord length (c) and twist angle (γ).

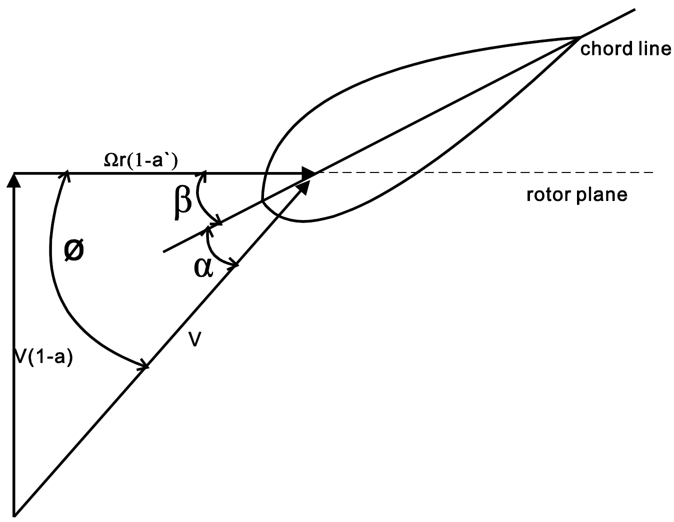

Figure 3.5. Local element velocity components

Figure 3.5 shows the velocity components of local element. Lift and drag coefficient data is obtain by wind tunnel test. Relative flow that is relation between moving airfoil and the flow must be considered because most wind tunnel test is done with stationary condition. The average tangential velocity that blades experience is given by.

$$\Omega r + \frac{\omega r}{2} = \Omega r(1 + a') \tag{3.13}$$

then

$$\tan\beta = \frac{\lambda_r (1 + a')}{(1 - a)} \tag{3.14}$$

where λ_r is local tip speed ratio.

$$\lambda_r = \frac{\Omega r}{V} \tag{3.15}$$

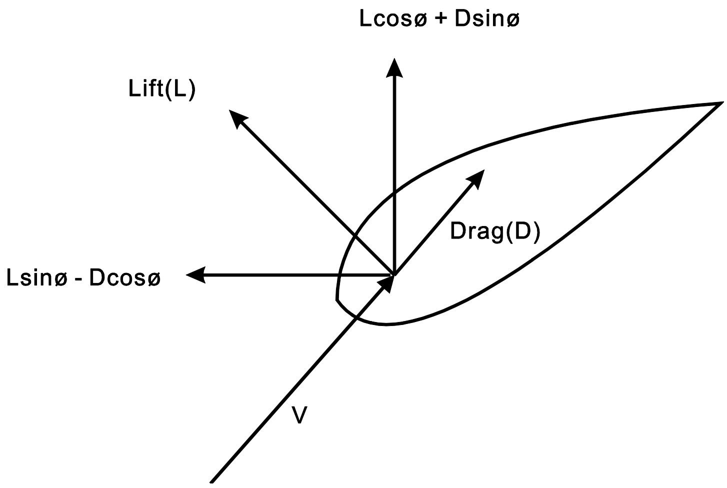

Figure 3.6. Local element force components

Figure 3.6 shows the forces acting on the local blade element. The lift and drag force is perpendicular and parallel to the local inflow. Local axial and tangential force components are given by.

$$dF_x = B \cdot (dL\cos\phi + dD\sin\phi) \tag{3.16}$$

$$dT = B \cdot (dL\sin\phi - dD\cos\phi) \tag{3.17}$$

where *dL* and *dD* are local lift and drag force.

$$dL = C_L \frac{1}{2} \rho V^2 c\, dr \tag{3.18}$$

$$dD = C_D \frac{1}{2} \rho V^2 c\, dr \tag{3.19}$$

Therefore, final form of force components is derived.

$$dF_x = B \cdot \frac{1}{2} \rho V^2 (C_L \cos\phi + C_D \sin\phi) \cdot c \cdot dr \tag{3.20}$$

$$dT = B \cdot \frac{1}{2} \rho V^2 (C_L \sin\phi - C_D \cos\phi) \cdot c\, dr \tag{3.21}$$

$$dQ = B \cdot \frac{1}{2} \rho V^2 (C_L \sin\phi - C_D \cos\phi) \cdot c \cdot r dr \tag{3.22}$$

dF_x is normal force, dQ is tangential force, dT is torque(moment) and c is chord length.

3.1.3 Blade element momentum solution procedure

The equation from blade element theory and blade momentum theory is obtain. The blade momentum theory describes the axial and tangential force in terms of induction factor. [14], [15]

$$dF_X = \frac{1}{2}\rho V_1^2 [4a(1-a)] 2\pi r \, dr \tag{3.23}$$

$$dT = 4a'(1-a)\rho V_1 \Omega r^3 \pi \, dr \tag{3.24}$$

The blade element theory describes the loads acting on the blades in terms of the lift and drag coefficient of airfoil.

$$dF_X = B \cdot \frac{1}{2}\rho V^2 (C_L \cos\phi + C_D \sin\phi) \cdot c \cdot dr \tag{3.25}$$

$$dT = B \cdot \frac{1}{2}\rho V^2 (C_L \sin\phi - C_D \cos\phi) \cdot c \, dr \tag{3.26}$$

$$dQ = B \cdot \frac{1}{2}\rho V^2 (C_L \sin\phi - C_D \cos\phi) \cdot c \cdot r dr \tag{3.27}$$

From these equation derived by different theory, the important relation can be obtained.

$$\frac{a}{1-a} = \frac{\Gamma \cdot [C_L \sin\phi + C_D \cos\phi]}{4Q \cos^2\phi} \tag{3.28}$$

$$\frac{a'}{1-a} = \frac{\Gamma \cdot [C_L \cos\phi - C_D \sin\phi]}{4Q\lambda_r \cos^2\phi} \tag{3.29}$$

where

$$\Gamma = \frac{Bc}{2\pi r}, \quad \lambda_r = \frac{\Omega r}{V_1} \tag{3.30}$$

The solution cannot be obtained directly from these equation. To find the solution, iterative solution procedure must be required. The solution procedure of BEMT is explained as follows.

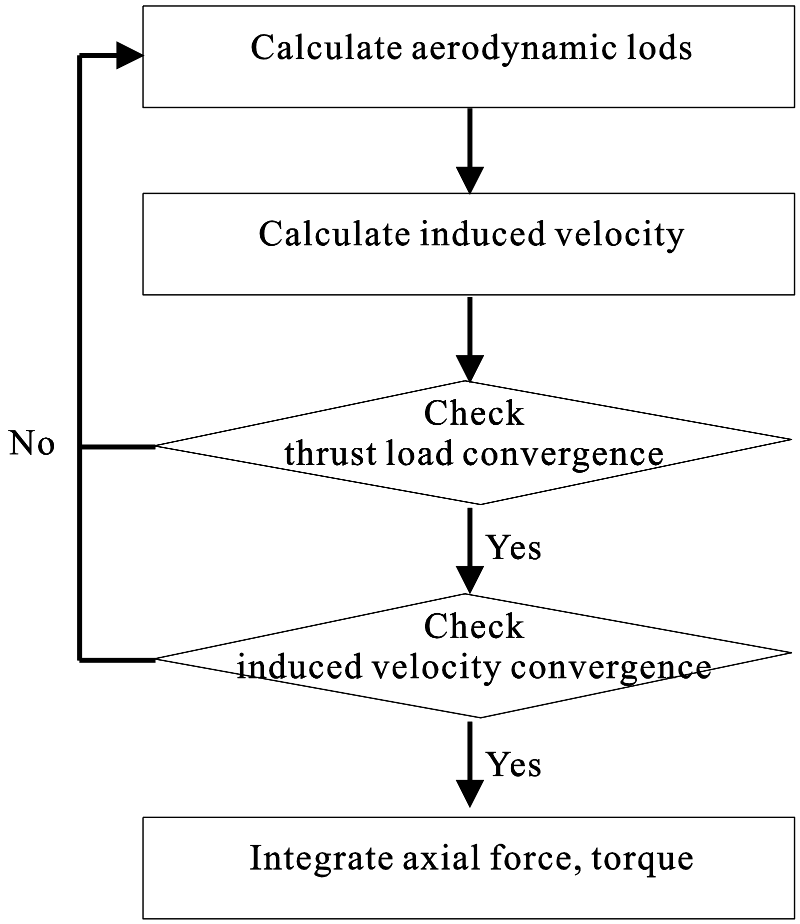

Figure 3.7. Iterative solution procedure for BEMT

Figure 3.7 show the solution procedure of BEMT. First, thrust load and induced velocity acting on the blades are calculated. If the thrust load and induced velocity satisfy the convergence criteria, aerodynamic load components at each blade element are integrated along the blade. Then total aerodynamic force components are obtained.

3.2 Gyro effect

Gyro effect is that the rotating body which moves with high angular velocity maintains the rotating axis. Gyro effect has a damping effect of floating body motion in waves due to revolving disk. Reduction of floater motion due to gyro effect of disk rotation is observed. When the wind turbine operates, rotor angular velocity will induce the rotor angular momentum. Rotor angular momentum is given by.

$$\mathbf{L}_r = \mathbf{I}_r \cdot \boldsymbol{\omega}_r \cdot \mathbf{i}_r \tag{3.31}$$

$\mathbf{I}_r$ is the vector of moment of inertia at rotor. $\boldsymbol{\omega}_r$ is the vector of rotor angular velocity and $\mathbf{i}_r$ is the unit vector in the rotational direction. The floater motion induces the change of angular momentum. Therefore, gyro moment at rotor fixed coordinate is described as follows.

$$\mathbf{M}_{Gyro}^{Rot} = \frac{d\,\mathbf{L}_r}{dt} = \boldsymbol{\omega}_p^{Rot} \times \mathbf{L}_r \tag{3.32}$$

$\boldsymbol{\omega}_p^{Rot}$ is the motion of floating body at rotor reference frame. In general, offshore floating wind turbine experiences a gyro moment about y-, z-axis in rotor fixed coordinate when the floater moves with rotational motions about y-, z-axis. In this case, the rotor spins with constant angular velocity about the x-axis in rotor fixed coordinate. Therefore, rotational direction vector is given by,

$$\mathbf{i}_r = (-1, 0, 0) \tag{3.33}$$

Gyro moment at rotor axis coordinate is as follows.

$$\mathbf{M}_{Gyro}^{Rot} = \frac{d\,\mathbf{L}_r}{dt} = \boldsymbol{\omega}_p^{Rot} \times \mathbf{L}_r = \mathbf{I}_r\, \boldsymbol{\omega}_r\, [0, -\dot{q}_6, \dot{q}_5] \tag{3.34}$$

This damping effect by gyro moment is proportional to rotor angular velocity $\boldsymbol{\omega}_r$, moment of inertia $\mathbf{I}_r$ and floater motion $\boldsymbol{\omega}_p^{Rot}$. [20], [21], [22]

3.3 Numerical results

In this section, aerodynamic loads verification will be described. As mentioned above, aerodynamic analysis procedure is explained. Aerodynamic load can be obtain in present aerodynamic analysis code. However, the code verification is needed because the solution is numerically calculated. The numerical model is NREL 5 MW baseline wind turbine model. The results calculated from present code is compared with FAST results.

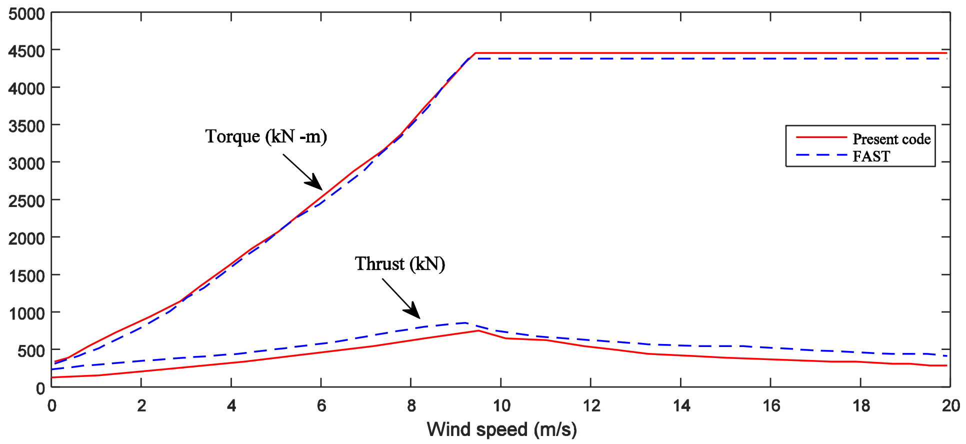

Figure 3.8. Thrust and torque curves at bottom fixed condition

Figure 3.8 shows the thrust and torque calculated from present code and FAST code in bottom fixed condition. The solution calculated from present code is compared with the solution calculated from FAST code at various wind velocity. When the wind speed is stronger than 11.4 m/s, Pitch control is working. Therefore, torque acting on the blades is steady in pitch control condition as shown in **Figure 3.8.**

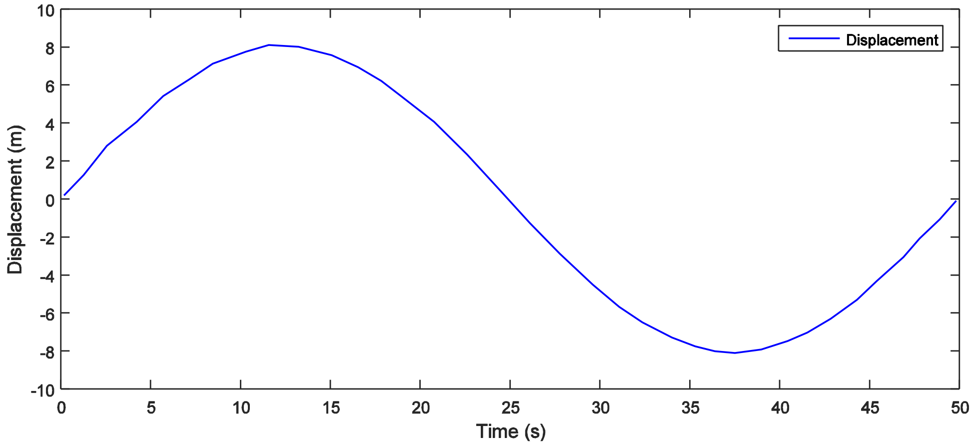

Figure 3.9. Harmonic surge motion of wind turbine

Figure 3.9 shows the harmonic surge motion of offshore floating wind turbine. In this case, when the harmonic motion is induced at floating platform, thrust coefficient is calculated with harmonic 6-DOFs motion.

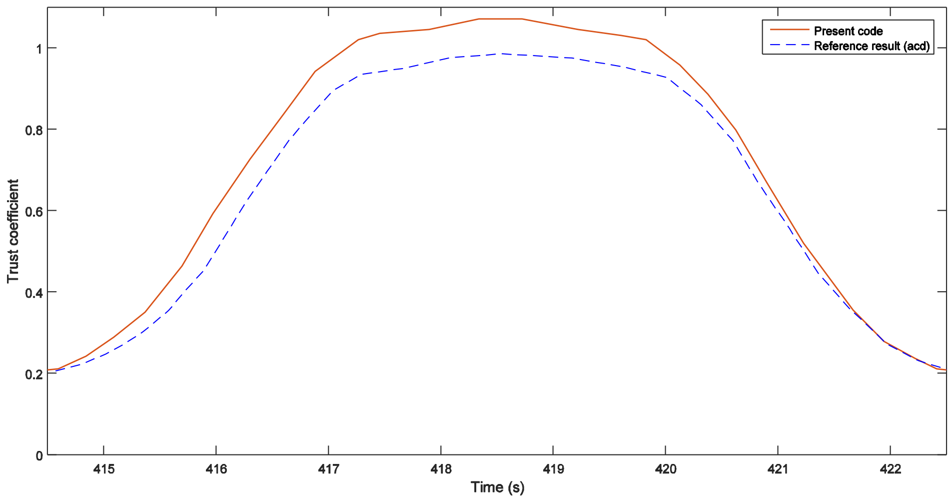

Figure 3.10. Thrust coefficient with harmonic surge motion of wind turbine

Figure 3.10 shows the thrust coefficient calculated in present code and reference result [23]. When the wind turbine move with 6-DOFs harmonic motion, the trust coefficient at rotor can be calculated in present code.

Chapter 4. Aero-Hydro coupled dynamic analysis

4.1 Formulation

As mentioned above, hydrodynamic and aerodynamic analysis module is developed individually. To analysis fully coupled dynamic analysis, It is necessary to interact between analysis modules. Equation of motion for coupled dynamic analysis is given by.

$$(\mathbf{M}+\mathbf{A})\ddot{\mathbf{q}}(t)+\int_{-\infty}^{t}\mathbf{K}(t-\tau)\dot{\mathbf{q}}(\tau)d\tau+\mathbf{B}_{ext}\,\dot{\mathbf{q}}(t)+(\mathbf{C}_{hydro}+\mathbf{C}_{ext})\,\mathbf{q}(t)=\mathbf{F}_{wave}(t)+\mathbf{F}_{aero}(t) \quad (4.1)$$

Aerodynamic load term is added to external term of existing time domain hydrodynamic formulation. Because aerodynamic analysis is done at rotor axis reference frame, components of aerodynamic load is needed to transform the coordinate to floating body fixed frame.

To obtain numerical coupled dynamic response, mathematical formulation for coupled dynamic analysis is transformed to incremental formulation.

$$(\mathbf{M}+\mathbf{A})^{t+\Delta t}\ddot{\mathbf{q}}+\frac{\Delta t}{2}\mathbf{K}(0)^{t+\Delta t}\dot{\mathbf{q}}+\mathbf{C}^{t+\Delta t}\mathbf{q}={}^{t+\Delta t}\mathbf{F}_{wave}+{}^{t+\Delta t}\mathbf{F}_{aero}-\int_{0}^{t}\mathbf{K}(t+\Delta t-\tau)\,\dot{\mathbf{q}}(\tau)d\tau-\frac{\Delta t}{2}\mathbf{K}(\Delta t)^{t}\,\dot{\mathbf{q}} \quad (4.2)$$

Incremental formulation can be solved numerically. Δt is time step that is used in numerical solution procedure. In this research, Newmark - β method is used to solve incremental formulation. [2]

$${}^{t+\Delta t}\dot{\mathbf{q}}={}^{t}\dot{\mathbf{q}}+[(1-\delta)^{t}\,\ddot{\mathbf{q}}+\delta^{t+\Delta t}\ddot{\mathbf{q}}]\cdot\Delta t \quad (4.3)$$

$${}^{t+\Delta t}\mathbf{q}={}^{t}\mathbf{q}+{}^{t}\dot{\mathbf{q}}\cdot\Delta t+[(\frac{1}{2}-\alpha)^{t}\,\ddot{\mathbf{q}}+\alpha^{t+\Delta t}\ddot{\mathbf{q}}]\cdot\Delta t^{2} \quad (4.4)$$

First, effective stiffness matrix and load vector must be constructed to use Newmark - β method

$$\hat{\mathbf{K}}=(\mathbf{M}+\mathbf{A})\cdot\frac{1}{\Delta t^{2}\alpha}+\frac{\delta}{\alpha}\cdot\frac{\Delta t}{2}\cdot\mathbf{K}(0)+\mathbf{C} \quad (4.5)$$

$${}^{t+\Delta t}\hat{\mathbf{R}}={}^{t+\Delta t}\mathbf{F}_{aero}+{}^{t+\Delta t}\mathbf{F}_{wave}+{}^{t+\Delta t}\mathbf{F}_{1}+{}^{t+\Delta t}\mathbf{F}_{2}-{}^{t+\Delta t}\mathbf{F}_{3} \quad (4.6)$$

where

$${}^{t+\Delta t}\mathbf{F}_{1}=(\mathbf{M}+\mathbf{A})\cdot(\frac{1}{\alpha\cdot\Delta t^{2}}{}^{t}\mathbf{q}+\frac{1}{\alpha\cdot\Delta t}{}^{t}\dot{\mathbf{q}}+(\frac{1}{2\alpha}-1)^{t}\,\ddot{\mathbf{q}}) \quad (4.7)$$

$$ {}^{t+\Delta t}\mathbf{F}_2 = (\frac{\Delta t}{2}\mathbf{K}(0)) \cdot (\frac{\delta}{\alpha \cdot \Delta t}{}^{t}\mathbf{q} + (\frac{\delta}{\alpha} - 1){}^{t}\dot{\mathbf{q}} + \frac{\Delta t}{2}(\frac{\delta}{\alpha} - 2){}^{t}\ddot{\mathbf{q}}) \tag{4.8} $$

$$ {}^{t+\Delta t}\mathbf{F}_3 = \int_0^t \mathbf{K}(t + \Delta t - \tau)\dot{\mathbf{q}}(\tau)d\tau + \frac{\Delta t}{2}\mathbf{K}(\Delta t){}^{t}\dot{\mathbf{q}} \tag{4.9} $$

$\hat{\mathbf{K}}$ is effective stiffness matrix and $\hat{\mathbf{R}}$ is effective load vector. Last term of effective load vector is memory effect term that is corresponding to radiation force caused by radiation wave generated by motion of floating body.

4.2 Numerical coupling scheme

As mentioned above, hydrodynamic and aerodynamic analysis module is developed individually. To analysis fully coupled dynamic analysis, It is necessary to interact between analysis modules. Equation of motion for coupled dynamic analysis is described in **chapter 4.1.** There are two coupling method to solve the multi–Physics problems: monolithic method and partitioned method. These coupling method have difference in terms of coupling approach. [24], [25], [26], [27], [28], [29]

Monolithic method is call as direct method. This method treats all the domains simultaneously. Therefore, a single set of algebraic equation is constructed involving degree of freedom corresponding to all domains. All the domains are constructed in a single code structure, so it is relatively difficult to modify and maintain the analysis code.

In the 1970s, multi-physics coupled analysis within a single analysis code was a challenge problem. In this coupled analysis procedure, these analysis code becomes the spaghetti code that is difficult to handle. Partitioned method is suggested to solve these difficulties. Partitioned method is called as iterative method. This method treat the domain one at a time. Therefore, several sets of unknowns are treated iteratively rather than by solving the full algebraic system. Each domain is separated and solved by individual solvers. Each sub-domain is separately solved and exchange the data. Partitioned approach allows the use of well-established analysis code and solution procedure for each sub-domain. Therefore, It is convenient to reuse of existing and highly developed analysis code. Additionally, it is easy to maintain and modify the analysis code. In this research, partitioned coupling method is used to consider interaction between aerodynamics and hydrodynamics. Especially, staggered solution procedure is used.

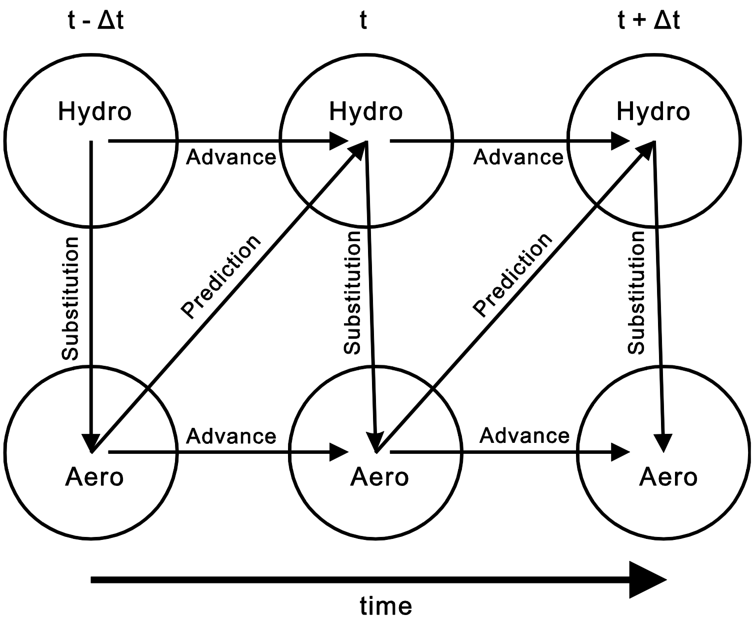

Figure 4.1. Staggered solution procedure

Figure 4.1 shows the staggered solution procedure used to solve the coupled problems. Staggered solution procedure is the simple and commonly used partitioned method. In solution procedure, Previous step's aerodynamic loads are predictor. From the aerodynamic load predictor, the motion of floating body is calculated in hydrodynamic analysis code. Then aerodynamic load is calculated by using the motion of floating body calculated in hydrodynamic analysis code. This solution procedure is repeated at every time step until the motion of floater satisfy the convergence criteria. However, this partitioned method has some weakness. Partitioned method must consider iterative solution procedure. Therefore, solution stability and converge is not guaranteed. In this research, solution converge and stability is reasonable. At each time step, convergence criteria of aerodynamic load and motion of floater is satisfied within relative error 1.0E-5.

4.3 Numerical result

This chapter will explain the results of fully coupled dynamic analysis. As mention above, hydrodynamic analysis, aerodynamic analysis and gyro effect is considered to solve the loads and motions of offshore floating wind turbine. In this chapter, the solution of fully coupled dynamic analysis is presented and verified with FAST code. The code verification is done by free decay test, regular wave test and regular wave-uniform wind test. Each verification results will be shown as follows.

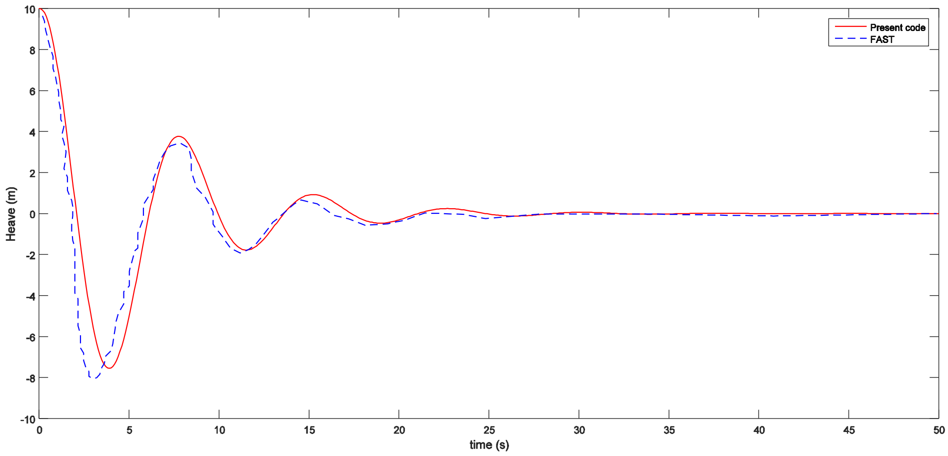

Figure 4.2. Heave free decay curve

Figure 4.2 shows that heave free decay test curve. Initial heave position is 10 m. The result calculated from present code is compared with FAST code. This result show that present code and FAST code calculate almost same response.

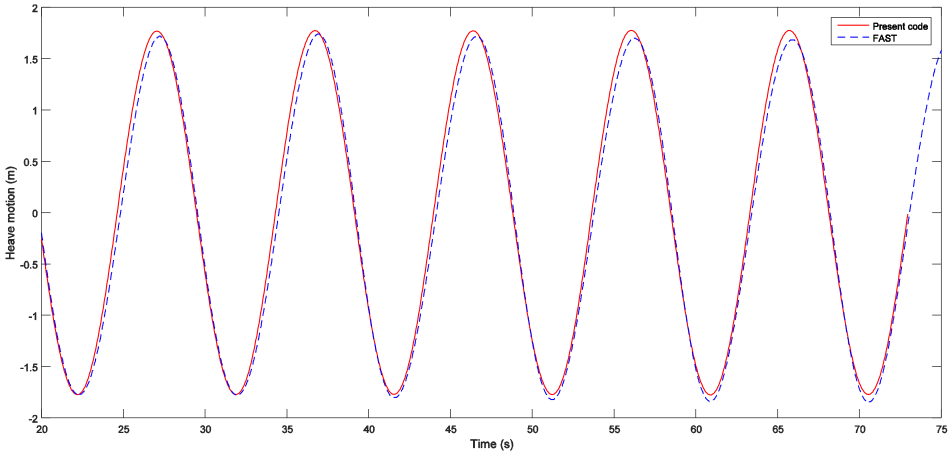

Figure 4.3. Heave curves of regular wave test

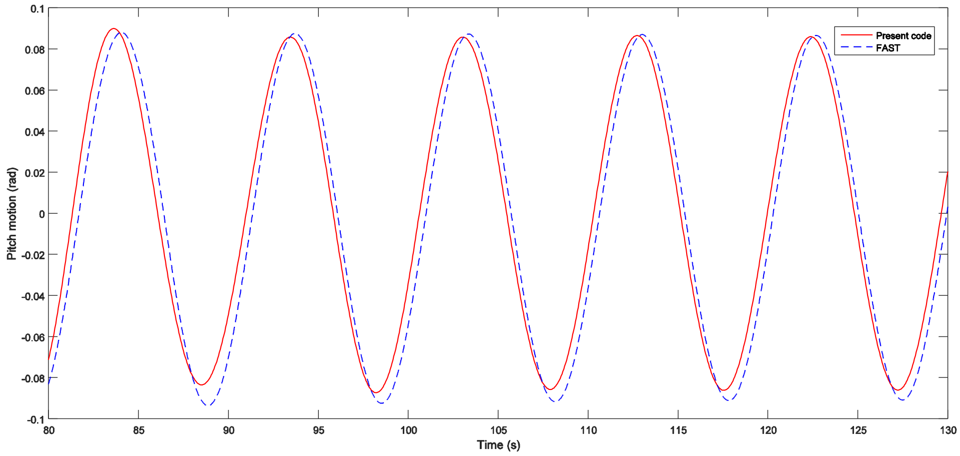

Figure 4.4. Pitch curves of regular wave test

Figure 4.3 shows only regular wave test results of heave motion. Analysis condition is uniform wind velocity is 0 m/s, wave height is 3.66 m and wave period is 9.7 s. When a regular wave is coming, the motion of the floating body calculated in present code is compared to FAST code. The heave and pitch motion is compared with FAST code results because the dominant modes of 6-DOFs are heave and pitch motion for offshore floating wind turbine. **Figure 4.4** shows only regular wave test results of pitch motion. **Figure 4.3, Figure 4.4** shows the dynamic response of steady state response because incident wave frequency and magnitude is same between each analysis code. In this section, the response of magnitude and frequency is compared between each analysis code except transient area.

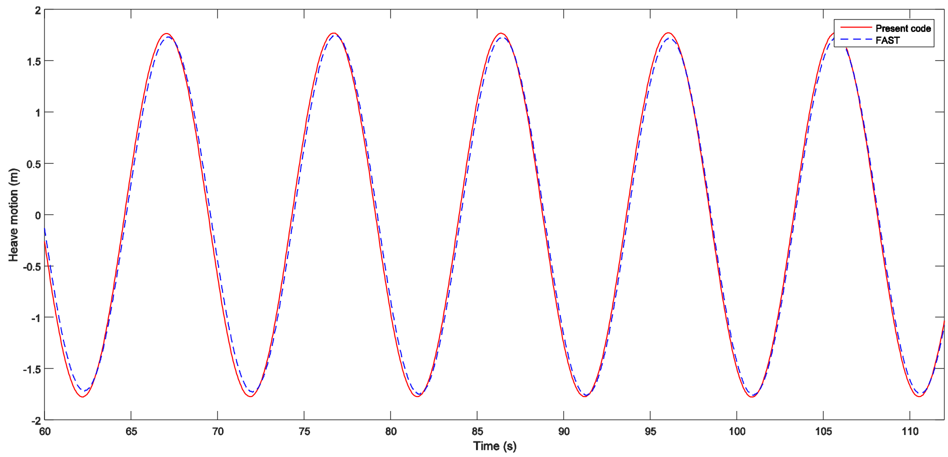

Figure 4.5. Heave curves of uniform wind & regular wave test

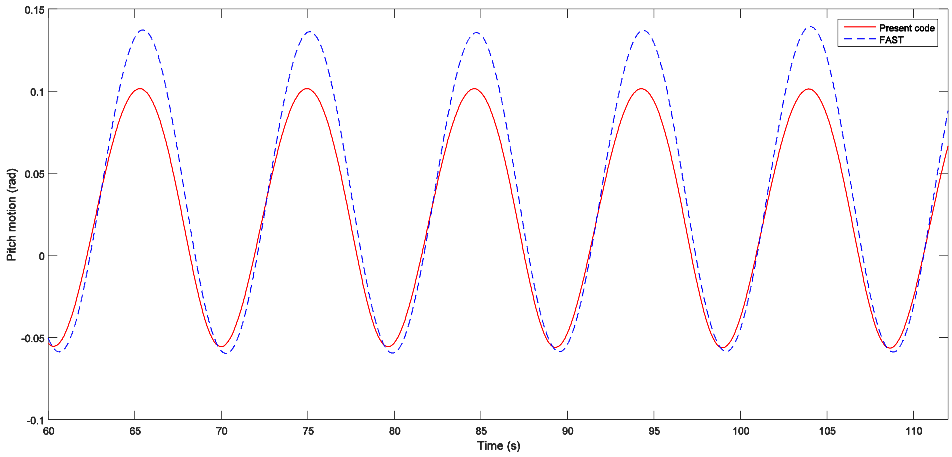

Figure 4.6. Pitch curves of uniform wind & regular wave test

Figure 4.5 shows uniform wind & regular wave test results of heave motion. Analysis condition is uniform wind speed is 10 m/s and wave height is 3.66 m and wave period is 9.6 s. The results calculated in present code is compared to FAST code. **Figure 4.6** shows the pitch motion calculated from present code and FAST code. The result of heave motion is almost same at each analysis code. However, The platform pitch motion of each analysis code is slightly different as shown **Figure 4.6.** Therefore, It is need to do experimental study to verify the numerical analysis results calculate from each analysis code.

Chapter 5. Conclusions

5.1 Conclusions and future works

This thesis focused on a new approach for numerical analysis of offshore floating wind turbines. The proposed method is partitioned coupling method that has different approach from monolithic approach. When multi-physics problem such as offshore floating wind turbine is considered, monolithic method that is used in existing offshore floating wind turbine analysis tools has some difficulties.

The method suggested in this research can solve these difficulties effectively because partitioned method offer modular analysis. Additionally, each analysis module can be developed and modified individually. Therefore, each analysis module can be solved by optimal each solver. Analysis tools to calculate dynamic response of offshore floating wind turbine must consider various physics phenomenon. Therefore, Partitioned method is more suitable for offshore floating wind turbine problems than monolithic method in terms of analysis efficiency and code development. In this research, reasonable results is obtained by using partitioned method. Therefore, It is possible to use partitioned method to solve coupled dynamic response of offshore floating wind turbines.

However, partitioned method has some weakness. Because partitioned method offer modular analysis, iterative solution procedure must be considered. Solution convergence and stability is less stable than monolithic method. Therefore, solution convergence check must be considered each time step. It is need to develop numerical procedure of partitioned approach to calculate more stable solution of dynamic response for offshore floating wind turbines.

References

[1] J.N. Newman. (1977). *Marine Hydrodynamics*, The MIT press.

[2] Bathe KJ. (1996). Finite element procedures. Prentice Hall.

[3] Lee C.H., & J.N. Newman. (2006). *WAMIT User Manual*, Version 6.3, Chestnut Hill, MA: WAMIT.

[4] J.M.J. Journee and W.W. Massie. (2001). OFFSHORE HYDRODYNAMICS, First Edition, Delft University of Technology.

[5] Yoon JS, Cho SP, Jiwinangun RG, Lee PS. Hydroelastic analysis of floating plates with multiple hinge connections in regular waves. Marine Structures 2001;36:65-87.

[6] Kim KT, Lee PS, Park KC. A direct coupling method for 3D hydroelastic analysis of floating structures. International Journal for Numerical Methods in Engineering 2013;96(13):842-866.

[7] S.M. Chase. An algorithm for filon quadrature. Communication of the ACM 1969.

[8] C.H. Lee, J.N Newman. Computation of wave effects using the panel method. Numerical Models in Fluid-Structure Interaction 2004.

[9] L. Roald, J. Jonkman, A. Robertson. The Effect of Second-Order Hydrodynamics on a Floating Offshore Wind Turbine. National Renewable Energy Laboratory Technical Report 2014.

[10] Jason M. Jonkman. Dynamics of Offshore Floating Wind Turbines-Model Development and Verification. WIND ENERGY 2009;12:459-492.

[11] A. Robertson, J. Jonkman, M. Masciola, H. Song, A. Goupee, A. Coulling, C. Luan. Definition of the Semisubmersible Floating System for Phase II of OC4. National Renewable Energy Laboratory 2014.

[12] J. Jonkman. Definition of the Floating System for Phase IV of OC3. National Renewable Energy Laboratory 2010.

[13] E. N. Wayman and P.D. Sclavounos. Coupled Dynamic Modeling of Floating Wind Turbine Systems. National Renewable Energy Laboratory 2006.

[14] P.J. Moriarty, A.C. Hansen. AeroDyn Theory Manual. National Renewable Energy Laboratory 2005.

[15] Grant Ingram. Wiud Turbine Blade Analysis using the Balde Element Momentum Method. Durham University 2011.

[16] J. B. de Vaal, M. O. L. Hansen, T. Moan. Effect of wind turbine surge motion on rotor thrust and induced velocity. Wind Energy 2014;17:105-121.

[17] Thomas Solberg. Dynamic Response Analysis of a Spar Type Floating Wind turbine. Norwegian University of Science and Technology. Master’s thesis 2011.

[18] Hideo Fujiwara, Takashi Tsubogo, Tasunori Nihei. Gyro Effect of Rotating Blades on the Floating Wind Turbine Platform in Waves. Twenty-first International Offshore and Polar Engineering Conference 2011.

[19] Md. Nur-E-Mostafa. A STUDY ON DYNAMIC REPONSE OF SPAR-type FLOATING WIND TURBINE IN WAVES USING 3-D GREEN FUNCTION METHOD CONSIDERING ROTATING OF WINDMILL BLADES. Yokohama National University. Doctoral dissertation 2012.

[20] Denis Matha, Jason Jonkman. Model Development and Loads Analysis of an Offshore Wind Turbine on a Tension Leg Platform, with a Comparison to Other Floating Turbine Concepts. National Renewable Energy Laboratory 2009.

[21] A. Robertson, J. Jonkman, W. Musial, F. Vorpahl, W. Popko. Offshore Code Comparison Collaboration, Continuation: Phase II Results of a Floating Semisubmersible Wind System. National Renewable Energy Laboratory 2013.

[22] GLOBAL WIND REPORT 2014. GLOBAL WIND EVERGY COUNCIL.

[23] Thanh-Toan Tran, Dong-Hyun Kim. The platform pitching motion of floating offshore wind turbine: A preliminary unsteady aerodynamic analysis. Journal of Wind Engineering and Industrial Aerodynamics 2015;142:65-81.

[24] C.A. Felippa, K.C. Park, C. Farhat. Partitioned analysis of coupled mechanical systems. Comput. Methods Appl. Mech. Engrg 2001;190:3247-3270.

[25] A. H. Barbat, N. Molinares, R. Codina. EFFECTIVE OF BLOCK ITERATIVE SCHEMES IN COMPUTATING THE SEISMIC RESPONSE OF BUILDINGS WITH NONLINEAR BASE ISOLATION. Computers & Structures 1996;58:133-141.

[26] Hermann G. Matthies, Jan Steindorf. Partitioned but strongly coupled iteration schemes for nonlinear fluid-structure interaction. Computers & Structures 2002;80:1991-1999.

[27] K. C. Park, Carlos A. Felippa. Staggered Procedures Revisited – Initial Fondest Hopes, Ensuing, Applications, and Future Prospects. 5th European Congress on Computational Methods in Applied Sciences and Engineering 2008.

[28] Hermann G. Matthies, Jan Steindorf. Partitioned strong coupling algorithms for fluid-structure interaction. Computers & Structures 2003;81:805-812.

[29] Andrew Yeckel, Lisa Lun, Jeffrey J. Derby. An approximate block Newton method for coupled iterations of nonlinear solvers: Theory and conjugate heat transfer applications. Journal of Computational Physics 2009;228:8566-8588.

Summary

Coupled dynamic analysis of offshore floating wind turbines

최근 전세계적으로 친환경 기술에 대한 관심과 함께 부유식 해상 풍력발전기에 대한 관심과 규모가 유럽, 미국, 일본, 중국을 중심으로 급증하고 있는 추세이다. 기존의 육상이나 수심이 낮은 해안에 설치하는 고정식 풍력발전기의 문제점인 설치장소에 대한 제약이나 소음 등 여러 문제사항들을 수심이 깊은 해상에 설치가 가능한 부유식 풍력발전기를 통해 해결할 수 있다. 설치장소에 대한 제약사항에 대한 문제가 해결되면서 대규모 풍력발전단지가 조성되고 해상으로 설치장소가 이동함에 따라 양질의 바람자원을 지속적으로 얻을 수 있기 때문에 대체 에너지원으로 상당한 잠재력을 가지고 있다.

부유식 풍력발전시스템을 설계하기 위해서는 풍력발전기에 작용하는 하중과 동적 거동을 정확하게 예측할 수 있는 수치해석 툴이 필요하다. 부유식 풍력발전기를 해석하기 위한 수치해석 툴은 파도, 조류, 바람, 계류시스템과 같이 풍력발전기에 작용하는 여러 물리현상들을 동시에 고려해야 한다. 기존의 풍력발전기 해석 툴들의 경우 고정식 풍력발전기를 해석하기 위한 해석 툴이다. 그러나 최근 부유식 풍력발전기 해석 툴을 개발하기 위해 유럽과 미국을 중심으로 연구가 활발하게 진행 중이다.

본 연구에서는 부유식 풍력발전기의 동적 거동 및 하중을 예측할 수 있는 해석 툴을 개발하였다. 기존의 풍력발전기 해석 툴의 연동해석 방법인 Monolithic method 와는 다른 Partitioned method 를 사용하여, 기존의 풍력발전기 해석 툴들의 개발 및 해석 진행과정에서 겪는 어려움과 불편함을 다소 개선할 수 있는 방법을 제시하였다. 또한 개발된 코드와 기존의 잘 알려진 해석 툴과 비교를 통해 해석의 정확도를 비교하였다.

본 연구에서 제시하는 방법으로, 기존의 풍력발전기 해석 툴에서 사용하는 연동해석 방법과 다른 방법론을 통한 효율적인 해석 및 개발 방식을 제안하였다. 그러나 Partitioned method 의 경우 해의 수렴성과 안정성 부분에서 상대적으로 취약한 단점을 지니고 있다. 따라서 해석과정에서 해의 수렴과 안정성을 확인하는 과정을 거쳤고 향후 연구과정에서 이 부분을 보완할 필요가 있다.

핵심어: 유체동역학; 공기역학; 연동해석; 부유식 해상 풍력발전기