Proceedings of the ASME 2023
International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE2023
August 20-23, 2023, Boston, Massachusetts

DETC2023-117954

MULTI-BODY MODELING FOR CONCEPTUAL DESIGN OF CO-LOCATED OCEAN RENEWABLE ENERGY AND AQUACULTURE SYSTEMS

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ABSTRACT

This study presents a multi-body dynamic modeling approach for exploring and optimizing the novel co-location design of ocean-based renewable energy systems and aquaculture fishery systems. As both systems expand offshore to meet global energy and food demands, competition for limited oceanic space has become a growing concern. The co-location of these two distinctive systems offers a solution to this challenge by combining them in overlapping geographical locations while addressing their respective objectives and constraints. The study introduces a conceptual design configuration that integrates floating offshore wind turbines with a fish production aquaculture system, effectively maximizing the use of available space. A multidisciplinary design optimization technique is employed to simultaneously solve hydrostatic and hydrodynamic properties, wave forcing terms, multi-body dynamic system equations, and the optimization problem. The study primarily aims to provide a comprehensive approach that offers a problem solution framework, valuable insights from the design solutions, and guidance for future development of various architectures and configurations of co-located ocean renewable energy and aquaculture systems. By addressing the challenges of co-location at the conceptual design stage with a systematic optimization framework, the study hopes to contribute to the optimal use of the ocean environment. Furthermore, the methodology presented in this study will inspire the application of multi-body dynamics for integrating heterogeneous systems across other disciplinary domains.

Keywords: Co-Location, Ocean Renewable Energy, Floating Offshore Wind Turbines, Aquaculture, Multi-Body Dynamics

1. INTRODUCTION

Ocean-based renewable energy systems, encompassing floating offshore wind turbines, wave energy converters, and tidal current turbines, as well as aquaculture production systems, are crucial for ensuring sustainable energy and food supplies for the future. As the development of both types of systems continues to expand into offshore locations, competition for space may become inevitable [1–3]. Consequently, exploring co-location opportunities is becoming a proactive approach to address this challenge [4, 5].

While co-location of ocean-based renewable energy systems and aquaculture production systems could be a solution to address spatial competition, it is important to consider that each system has its own objectives and constraints. For instance, metocean conditions, such as wave and ocean current, may positively affect one system's performance [6] while simultaneously hindering the other [2]. Therefore, co-location design must take into account various factors, including optimal site selection, architectures of integrated multi-functional systems, and multidisciplinary design couplings.

This study introduces the application of a multi-body dynamic modeling technique for floating structures to represent and optimize a conceptual and multi-functional co-located ocean energy and aquaculture system. The proposed approach considers the competing objectives and constraints of these two distinct subsystems, enabling a balanced integration of their respective requirements. A multidisciplinary design optimization technique is employed to simultaneously solve hydrostatic and hydrodynamic properties, wave forcing terms, multi-body dynamic system equations, and the optimization problem. This approach aims to maximize the system performance within the physical constraints of the combined subsystems.

2. PROBLEM DEFINITION

Existing co-location studies and practices have primarily focused on either using one system for both purposes [7] or placing both systems in close proximity to share utilities, such as powering the aquaculture system with ocean wave energy converters

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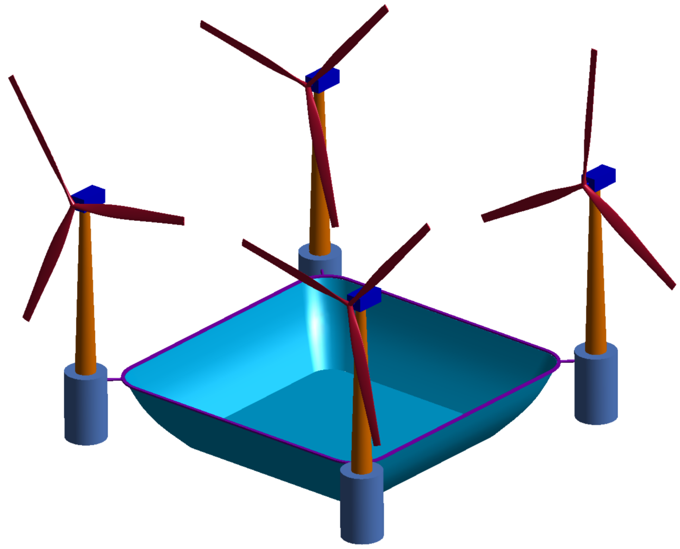

FIGURE 1: A CONCEPTUAL CO-LOCATION SCHEMATIC FOR THE INTEGRATED WIND FARM AND AQUACULTURE FISHERY

[8]. However, the synergies of co-location can be maximized if both systems are designed together during the conceptual design exploration stage. This study proposes multi-body modeling strategies for the conceptual design of co-located systems, enabling efficient exploration of design potentials.

A conceptual design configuration illustrating the co-location of floating offshore wind turbines and a fish production aquaculture farm is presented in Fig. 1. This integrated layout demonstrates how these two systems can be strategically combined in an offshore environment, optimizing the use of available space while addressing their respective objectives and constraints.

As an initial design effort, we consider a reduced-dimension multi-body dynamic problem involving multiple floating objects connected via link and joint mechanisms. Hydrodynamic forcing terms are applied to each floating object, while the kinematics and kinetics of the connected bodies are solved to satisfy mechanical constraints. A monolithic multidisciplinary design optimization problem is formulated, which simultaneously solves associated disciplinary domain models, such as hydrostatic, linear potential flow wave, and mechanical dynamic models, along with the constrained optimization problem. The optimization problem aims to identify the optimal co-location design configuration that maximizes cost-efficiency in generating energy and aquacultural products, while maintaining feasibility to dynamic constraints.

3. MODELING METHODS

The co-location of ocean renewable energy and aquaculture systems requires modeling of coupled floating objects. A hydrodynamic modeling technique for floating objects can be applied to each subsystem or each individual component of the overall integrated multi-body system. Hydrodynamic coefficients required for solving the multi-body dynamic problem are obtained through the solutions to three distinct problems: hydrostatics, hydrodynamic radiation, and wave-diffraction. The hydrostatic problem is geometrically defined and integrated over the boundary panel meshes. The other two problems, hydrodynamic radiation and wave-diffraction, are formulated using linear potential flow wave theory in the frequency domain, discretized and solved using the boundary element method (BEM) over the boundary panel meshes.

3.1 A Floating Object

A partially or fully-submerged floating body with single or multiple degrees of freedom (DOFs) and connected to a mooring system experiences a total external force, given as:

$$F_i^{\mathrm{EX}} = F_i^{\mathrm{AM}} + F_i^{\mathrm{RA}} + F_i^{\mathrm{DF}} + F_i^{\mathrm{HS}} + F_i^{\mathrm{VD}} + F_i^{\mathrm{MD}}, \quad (1)$$

where F_i^{EX} is total external force exerted to the floating body, F_i^{AM} is force due to impulsive added mass, F_i^{RA} is wave radiation force, F_i^{DF} is diffraction force due to incident surface wave, F_i^{HS} is hydrostatic force, F_i^{VD} is viscous drag force, and F_i^{MD} is force induced by the mooring system. The force due to impulsive added mass is given as:

$$F_i^{\mathrm{AM}} = -A_{ij}^{\mathrm{imp}} \ddot{q}_j, \quad (2)$$

where A_{ij}^{imp} is the impulsive hydrodynamic added mass tensor and $\ddot{q}_j$ is the floating body acceleration vector. This equation represents the virtual inertia contribution (commonly referred to as added mass) to the system due to acceleration of the immersed body. The added mass tensor for the hydrodynamic radiation problem is a function of frequency, given as:

$$A_{ij}(\omega) = A_{ij}^{\mathrm{imp}} - \frac{1}{\omega}\int_0^\infty K_{ij}(t)\sin(\omega t)\,dt, \quad (3)$$

where K_{ij} is the convolution kernel that represents the retardation of wave-radiation, given as:

$$K_{ij} = \frac{2}{\pi}\int_0^\infty B_{ij}(\omega)\cos(\omega t)\,d\omega, \quad (4)$$

B_{ij} is the frequency domain solution to the *radiation* (body in motion) problem, and ω is angular frequency. However, the instantaneous response to acceleration is given by the infinite frequency hydrodynamic added mass. Since the convolution kernel representing the retardation of wave-radiation, $K_{ij}(t)$, is assumed to be of finite energy, the impulsive hydrodynamic added mass is equivalent to the infinite frequency added mass, given as:

$$A_{ij}^{\mathrm{imp}} = \lim_{\omega\to\infty} A_{ij}(\omega) \equiv A_{ij}. \quad (5)$$

The wave radiation force is given as:

$$F_i^{\mathrm{RA}} = -\int_0^t K_{ij}(t-\tau)\,\dot{q}_j\,d\tau, \quad (6)$$

where $\dot{q}_j$ is the floating body velocity vector. The diffraction force is the solution to the *diffraction* (wave excitation) problem, given as:

$$F_i^{\mathrm{DF}} = F_i^{\mathrm{FK}} + F_i^{\mathrm{SC}}, \quad (7)$$

where F_i^{FK} and F_i^{SC} are Froude-Krylov (incident wave) and wave scattering (diffracted wave) forces, respectively. Time domain wave excitation force reflects stochastic sea states determined by JONSWAP spectrum [9]. The hydrostatic force is given as:

$$F_i^{\mathrm{HS}} = -C_{ij} q_j, \quad (8)$$

where C_{ij} is the hydrostatic stiffness tensor and q_j is the floating body displacement in all DOFs. Readers are referred to Ogilvie [10] and Newman [11] for detailed theories of hydrodynamic modeling.

3.2 Multi-Body Dynamics

Components of the co-located system consisting of multiple floating bodies, connected by joints or slack lines, exhibit constrained motions in response to various external forces. Inevitably, these mechanical constraints add significant complexities to the equation of motion for the floating objects. The external forces given in Eq. (1) applies to the center of mass for each floating body component. However, solving motions in all DOFs for all individual floating bodies do not satisfy motion constraints defined by the link and joint connections. Thus, the multi-body system DOFs are redefined in term of the relative kinematics between all connected bodies. The external force given in Eq. (1) is translated in the form of energy using Lagrange's equation, given as:

$$\frac{d}{dt}\left(\frac{\partial \mathscr{L}}{\partial \dot{q}_j}\right) - \frac{\partial \mathscr{L}}{\partial q_j} = \sum_i F_i \frac{\partial x_i}{\partial q_j}, \tag{9}$$

where $\mathscr{L}$ is Lagrangian, defined by:

$$\mathscr{L} = \mathscr{T} - \mathscr{V}, \tag{10}$$

$\mathscr{T}$ is kinetic energy, and $\mathscr{V}$ is potential energy.

3.3 Optimization Problem

The optimization formulation is given as:

$$\begin{aligned} \min \quad & J = \frac{\sum_k \text{CapEx}_k + \sum_k \text{OpEx}_k}{(\$/\text{Wh})\ \text{AEP} + (\$/\text{tonne})\ \text{AAP}} \\ \text{s.t.} \quad & \ddot{q}_j^2 \le \ddot{q}_{j,\max}^2 \\ & q_j \le q_{j,\max} \\ & T_j^{\text{link}} \le T_{j,\max}^{\text{link}} \\ \text{where} \quad & k \in \{\text{ORE}, \text{AQ}\}\,. \end{aligned} \tag{11}$$

The objective function J is formulated to minimize the system's expense ratio, given as the ratio of the overall cost to overall revenue. CapEx represents capital expenses, and OpEx represents operational expenses. The subscript k denotes the corresponding subsystem, which is either ocean renewable energy (ORE) or aquaculture (AQ). Generally, in the levelized cost of energy (LCOE) formulation, annual energy production (AEP) in watt-hours (Wh) is used as the denominator in the objective function. However, the raw production values of these two subsystems are incomparable. Therefore, in this study, we convert the annual productions of both subsystems into monetary revenue units by multiplying (\$/Wh) and (\$/tonne) to the AEP and annual aquacultural production (AAP), respectively. This approach allows for a fair cost to production calculation when optimizing the co-location design. Constraint functions are formulated to limit the maximum amplitude of accelerations, maximum translational and angular displacements, and maximum linkage tension for each body in motion.

4. DISCUSSIONS AND CONCLUSION

In the final version of this study, we aim to present the following research tasks: (1) the resulting equations of motion formulated to define the full n-body dynamic problem of co-located ocean renewable energy and aquaculture systems, (2) an analysis of the design exploration results, including the couplings between design parameters and physical behaviors, (3) the optimal co-location configuration accompanied by an overall cost-to-revenue analysis, and (4) a generalized design methodology for exploring various architectures and configurations that may yield higher synergies through co-location. This comprehensive approach will provide valuable insights and guidance for future development in co-located ocean renewable energy and aquaculture systems. Furthermore, the outcome of this research may inspire the use of multi-body dynamics in integrating heterogeneous systems for synergies in other disciplinary domains, paving the way for innovative solutions across various industries.

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