Effect of a rotational damper on a moored and articulated multibody offshore system in waves

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Abstract. Wave-induced motions and loads on a moored and articulated multibody offshore structure are investigated through numerical analysis. A coupled mooring-joint-viscous flow solver is employed to account for mooring dynamics, joint restrictions, nonlinear rigid body motions, and viscous flow effects. The study focuses on two modular floating structures (MFSs) connected by a flexible joint, with and without a rotational damper, and positioned using four symmetrical mooring lines. The analyzed responses encompass multibody motions and the associated forces acting in the hinged joints and the mooring lines. The results reveal that the influence of the damper on heave motions is less significant. Notably, the presence of the rotational damper has a noticeable impact on pitch motions between the two hinged MFSs. Introducing a rotational damper on the flexible joint effectively dampens the highly dynamic pitch motions while not imposing additional loads on the flexible joints.

1. Introduction

As the global population continues to grow, the availability of natural resources and land space is increasingly constrained. To address this challenge, the concept of very large floating structures (VLFS) has been developed to alleviate land space limitations. VLFSs have the potential to serve a wide range of purposes, including the development of marine resources, oil and gas exploration, offshore tourism, and fish farming. Additionally, VLFSs can contribute to expanding land space for airports and offer opportunities for future generations. The prototype for VLFSs can be traced back to the "sea station" concept proposed by Edward R. Armstrong [1]. Various concepts and applications of VLFSs for coastal and offshore use have been reviewed and summarized by Lamas-Pardo et al. [2]. Jiang et al. [3] provide a comprehensive overview of the state-of-the-art advancements in modeling hydrodynamics and hydroelasticity for VLFSs.

Due to their substantial size, VLFSs often experience significant bending moments and shear forces. Consequently, it is crucial to carefully evaluate their hydroelastic behavior in waves during the design process [4]. In contrast to traditional VLFSs, the concept of modular floating structures (MFSs) has emerged. MFSs are constructed from multiple interconnected modules, offering advantages such as reduced fabrication, transportation, and installation costs [5]. MFSs have even been developed as fundamental building blocks for artificial islands within the Space@See project [6]. For modularized VLFSs, one of the pivotal technologies is the connection design, which can employ various articulation techniques, including hinged, prismatic, cylindrical, and screw joints. Additionally, these techniques can be categorized into rigid and flexible joints. A novel design presented by [7] introduces the flexible-base hinged connector (FBHC), comprising a hinged joint and two flexible bases, to reduce connection loads in VLFSs. Figure 1 provides examples of common applications of hinged joints in offshore floating bodies.

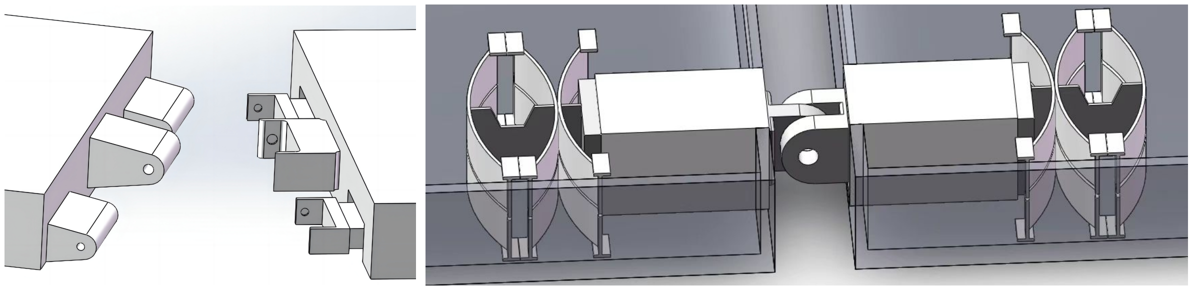


Figure 1. Typical articulated connectors for VLFSs [3]. (reproduced with permission from Elsevier).

Based on our review of research on MFSs, it becomes evident that the potential flow theory approach has been widely utilized. In these studies, connections are typically treated as independent linear springs with six degrees of freedom [8]. For instance, Jiang et al. [9] assessed the potential flow theory solver's ability to simulate moored and articulated multibody offshore structures. Their findings indicated that reasonable agreement between numerical predictions and experimental measurements was achieved for the floating modules, particularly under wave frequencies that significantly differ from the modules' natural frequencies. However, deviations were observed when dealing with wave frequencies close to the natural frequencies of the modules. This inaccuracy is attributed to the limited consideration of flow viscosity or strong nonlinear free surface flows within the potential flow theory. To enhance accuracy in such scenarios, potential flow theory solvers often require the introduction of additional damping mechanisms.

In previous work, we developed and validated a mooring-viscous flow solver for nonlinear wave-structure interaction, mooring dynamics, and associated viscous flow effects, focusing on a single body [10]. Subsequently, we extended our investigation to include two different connections, namely rigid joints and flexible joints, between two modular floating structures to study wave-induced motions and loads on a moored and articulated multibody offshore structure [11, 12]. In this paper, we introduce a novel aspect by presenting an analysis of a rotational damper integrated into a moored and articulated multibody offshore system subjected to waves. Our study primarily examines the influence of the rotational damper on the wave-induced motions and loads experienced by the MFSs. The comprehensive analysis encompasses various aspects, including the characterization of multibody motions, the evaluation of forces within the mooring lines, and the assessment of forces and moments acting on the connection joints. Ultimately, we present our results and derive conclusions based on our findings.

2. Theoretical background

This section gives a brief overview of used numerical methods, including the Navier-Stokes equations governing fluid dynamics, a lumped-mass model addressing mooring line dynamics, and a forward algorithm simulating the nonlinear rigid body motions of the MFSs. For a more comprehensive description, refer to Jiang [13]; Jiang and el Moctar [11].

2.1. Fluid dynamics

The flow in the present study is assumed to be incompressible, viscous and Newtonian, where the governing continuity and momentum conservation equations are written as follows:

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot [(\mathbf{v} - \mathbf{v}_m)\,\mathbf{v}] = \nu_e \nabla^2 \mathbf{v} - \frac{1}{\rho_e} \nabla p_d \tag{2}$$

$$p_d = p - \rho_e\,(\mathbf{g} \cdot \mathbf{r}) \tag{3}$$

where $\mathbf{v}$ is the velocity vector, ∇ is the gradient operator; $\mathbf{v}_m$ is the velocity vector of relative grid motion, ν_e and ρ_e are the effective kinematic viscosity and the effective density; p_d is the dynamic part of pressure p. Here, $\mathbf{g}$ is the gravity vector and $\mathbf{r}$ is the position vector.

For free surface hydrodynamic applications, the effective density and kinematic viscosity are expressed in terms of the volume fraction α via the Volume-Of-Fluid (VOF) method [14]:

$$\rho_e = \alpha \rho_w + \rho_a\,(1 - \alpha) \tag{4}$$

$$\nu_e = \alpha \nu_w + \nu_a\,(1 - \alpha) \tag{5}$$

where subscripts w and a represent the two immiscible fluids, water and air, respectively. At each time step, the existing velocity field converts phase fractions, then the distribution and the development of the free surface is estimated using the extended VOF formulation [15]:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\mathbf{v}\alpha) + \nabla \cdot [\mathbf{v}_r \alpha\,(1 - \alpha)] = 0 \tag{6}$$

where $\mathbf{v}_r$ is a velocity field normal to the interface, standing for the artificial compression on the free surface, with its magnitude being proportional to the instantaneous velocity.

2.2. Multibody dynamics

The behavior of multibody dynamic without joints is a extension of the nonlinear formulation of rigid body motions [16]:

$$\mathbf{H}\,(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}\,(\mathbf{q}, \dot{\mathbf{q}})\,\dot{\mathbf{q}} = \tau \tag{7}$$

where $\mathbf{H}$ is the mass matrix, $\mathbf{C}$ is the body force matrix, and τ is the external force vector. Provided that kinematic constraints are applied, the equation of motion becomes as following:

$$\mathbf{H}\,(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}\,(\mathbf{q}, \dot{\mathbf{q}})\,\dot{\mathbf{q}} = \tau + \tau_c \tag{8}$$

Here, τ_c is the constraint force. This force is unknown, but it has the important property that allows us to either calculate its value, or to eliminate it from the equation [17].

2.3. Mooring dynamics

The mooring dynamics are approached by a lumped-mass model [18]. This method involves lumping effects of mass, external forces, and inertial reactions at a finite number of nodes along a mooring line. The equation of motion for each node i is written as follows:

$$(\mathbf{m}_i + \mathbf{a}_i)\,\ddot{\mathbf{r}}_i = \mathbf{T}_i + \mathbf{C}_i + \mathbf{W}_i + \mathbf{B}_i + \mathbf{D}_i \tag{9}$$

where $\mathbf{m}_i$ is the mass matrix of node i; $\mathbf{a}_i$, the corresponding added mass; $\mathbf{T}_i$, tensile force; $\mathbf{C}_i$, a numerical internal damping force; $\mathbf{W}_i$, the net buoyancy; $\mathbf{B}_i$, the interaction with sea bed; $\mathbf{D}_i$, the hydrodynamic drag force. The second-order system of ordinary differential equation is reduced to a first-order differential equation system, then it could be solved by using second-order Runge-Kutta integration scheme with a constant time step.

2.4. Coupling approach

The coupling approach comprises a mooring model which used to consider the mooring dynamics, and a mechanical model which used to represent a articulated multibody system. The multi-module coupling technique is achieved by coupling each solver module with the module of rigid body motions. Mooring induced forces and joint-induced kinematic constraints directly affect the equations of rigid body motions, while flow dynamics is coupled with rigid body motions in an iterative manner. In the inertial coordinate system, the forces and moments acting on rigid bodies are given as:

$$\mathbf{F} = \mathbf{F}_p + \mathbf{F}_v + \mathbf{F}_c + \mathbf{F}_m + m\mathbf{g} \tag{10}$$

$$\mathbf{M} = \mathbf{M}_p + \mathbf{M}_v + \mathbf{M}_c + \mathbf{M}_m \tag{11}$$

where subscripts p and ν are the pressure and viscous components, respectively. Subscripts c and m are the constraint and mooring components, respectively. Pressure and viscous fluid forces and moments are obtained from the aforementioned Navier-Stokes equations Eqs. (1) to (3).

The forces and moments induced by the constraint are calculated using the equations of motion given in Sect. 2.2. Based on the fact that constraint forces deliver zero power along every direction of velocity freedom that is compatible with the motion constraints:

$$\begin{bmatrix} \mathbf{F}_c \\ \mathbf{M}_c \end{bmatrix} \cdot \dot{\mathbf{q}} = 0 \tag{12}$$

The mooring-induced forces and moments are computed via the lumped-mass model introduced in Sect. 2.3. The mooring solver (Π) uses the boundary values of rigid body solver (Ω) from the previous time step or iteration to compute its values for the next time step or iteration:

$$\mathbf{X}_{\Pi}^{n+1,\, i+1} = \Pi\left(\mathbf{X}_{\Omega}^{n+1,\, i}\right) \tag{13}$$

where $\mathbf{X}$ is the vector space containing boundary values, n stands for time steps and i for iterations. The updated $\mathbf{X}_{\Pi}$ is then used to calculate $\mathbf{X}_{\Omega}$ for the next time step or iteration:

$$\mathbf{X}_{\Omega}^{n+1,\, i+1} = \Omega\left(\mathbf{X}_{\Pi}^{n+1,\, i+1}\right) \tag{14}$$

For further details of the coupling between fluid dynamics, nonlinear rigid body motions and mooring dynamics, see [10, 11, 13, 16].

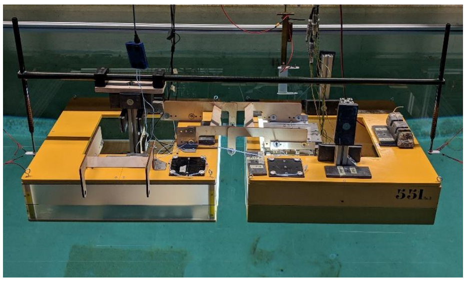
3. Test case description

To study the effects of the rotational damper on connection joints of wave-induced motions and loads for a moored and articulated multibody system, the present test cases consist of two boxes representing the floating modules articulated by flexible connection joints. Table 1 lists particulars of the floating box, including the location of its CoG above keel. For additional details, see the model test report [19].

Table 1. Particulars of the floating module

Length	Breadth	Depth	Draft	CoG	K_{xx}	K_{yy}	K_{zz}
0.643 m	0.643 m	0.2143 m	0.1286 m	0.1246 m	0.24 m	0.24 m	0.2625 m

In our previous study [11], discrepancies were observed between the computed and measured pitch motions. Specifically, the computed pitch motions of both floating bodies were larger than the measurements. This discrepancy can be attributed to several factors. Firstly, the hinged



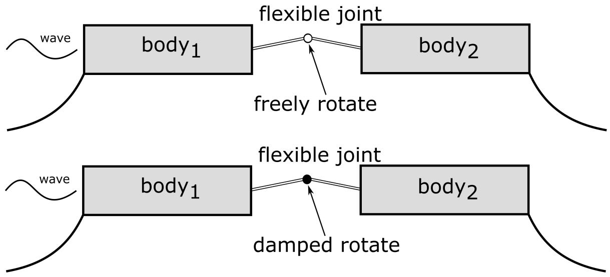


Figure 2. An overview of the experimental setup within Space@Sea project [19], along with a perspective view of the current configuration.

joint used during the experiment is more complex than the numerical representation. In the experimental setup, the joint had to incorporate load cells, as shown in Fig. 2, which affected its actual position during the physical experiment. This difference in joint configuration between the experiment and our simulations contributed to the discrepancies. Secondly, the designed joint within the experimental model test was found to be relatively inflexible. The rotational hinge damping present in the experiments was not considered in our previous simulations. As an extension, this study focuses on evaluating the effect of a rotational damper on wave-induced motions and loads in a flexibly connected multibody offshore system. By incorporating this damper into our simulations, we aim to address its hydrodynamic effects.

4. Results and discussion

To assess the impact of a rotational damper, this section analyzes multibody motions and the corresponding loads on the joints. Figure 3 illustrates the comparison of heave motions between two bodies connected using a flexible joint, without and with a rotational damper. We consider a head wave with an amplitude of $\zeta = 0.021$ m and a wave period of $T = 1.81$ s. The floating body closer to the wave maker is denoted as the front body (Body 1, $B1$), while the one farther away from the wave maker is labeled as the rear body (Body 2, $B2$). The subscript d indicates results obtained from the flexible joint integrated with a damper ($B1_d$ and $B2_d$). It is evident that heave motions are hardly affected by the added damper. When a floating structure is moored with a soft mooring system, heave motions are generally dominated by its hydrostatic stiffness and inertia [20].

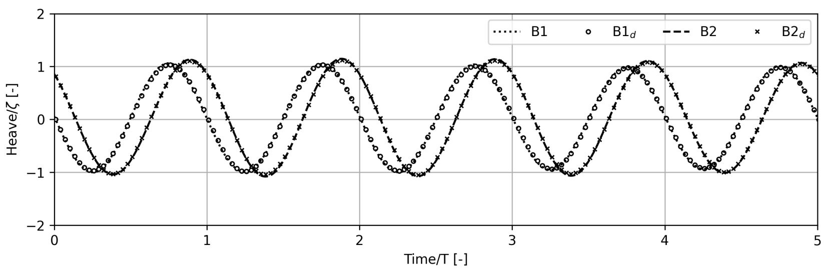


Figure 3. Comparative heave responses of the front body (B1) and the rear body (B2), where ζ is the wave amplitude and T is wave period.

However, significant discrepancies are evidenced in the pitch motions between the flexible joint without rotational damping and the one with rotational damping, as illustrated in Fig. 4.

Specifically, the pitch motions of both $B1$ and $B2$ without rotational joint damping are greater than those obtained from the flexible joint with rotational damping.

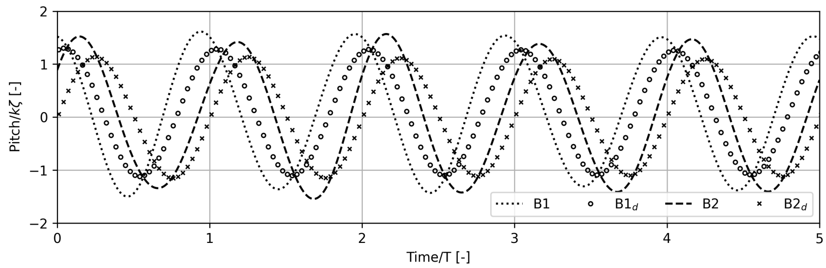


Figure 4. Comparative pitch responses of the front body (B1) and the rear body (B2), where ζ is the wave amplitude, T is wave period, and k is the wave number.

Figure 5 illustrates the corresponding longitudinal forces F_x and vertical forces F_z acting on the flexible joint without and with a rotational damper, respectively. Remarkably, the longitudinal and vertical hinge forces of the flexible joint without any rotational damping closely match those obtained from the flexible joint with rotational damping. This is primarily due to the forces acting on the hinge joint being dominated by surge and heave motions, which are more or less the same for the two considered flexible joints. Furthermore, strong nonlinearities are evident in the vertical joint forces for both cases.

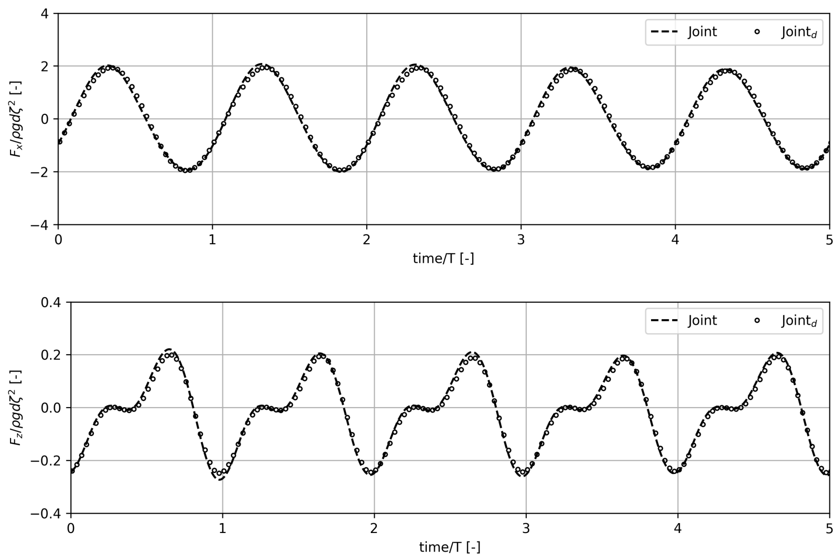


Figure 5. Comparative horizontal (top) and vertical (bottom) forces acting in the flexible joints, where ρ is water density, g is the acceleration of gravity, d is the length of body, and ζ is the wave amplitude.

5. Conclusions

This paper investigates the hydrodynamic performance of a rotational damper integrated into a moored and articulated multibody floating offshore system. Two types of flexible joints, a rotational freely flexible joint, and a rotational damped flexible joint, were employed to connect two floating modules. The system was positioned using four symmetric mooring lines. A coupled mooring-joint-viscous flow solver was utilized to predict the motion and load responses of the configured concepts, considering fluid dynamics, mooring line dynamics, and nonlinear rigid body motions. The primary focus was on the influence of the damper-based hinge joint on wave-induced motions and loads.

The results indicate that a rotational damper integrated into the flexible joint had a minimal impact on the translational motions of the system. However, notable differences were observed in pitch motions, where the pitch motions of a rotational damped flexible joint were smaller than those of the rotational freely flexible connected joint for both front and rear bodies. Overall, the hinge forces of the two types of flexible joints were comparable. This finding provides clear evidence to MFSs designers that a rotational damper can be installed to improve the stability of moored and articulated multibody offshore systems without significantly altering the forces and moments acting on the system compared to those without a rotational damper.

To draw more generalized conclusions, additional sea states, such as irregular waves, would need to be considered. However, simulating irregular waves can be computationally expensive. As these approaches model highly resolved spatial flow features with nonlinear and coupled equations in the time domain, making it challenging to perform a large number of long-time irregular wave simulations. To address this challenge, various frameworks for efficient irregular wave simulations have been developed [21–24], and this will be the focus of our future work.

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