Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 3194–3199

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Coupling effects on the dynamic response of moored floating platforms for offshore wind energy plants

Alessandro Giusti[a,*], Giovanni Stabile[b], Enzo Marino[a], Claudio Borri[a]

[a]*Department of Civil and Environmental Engineering, University of Florence, via di Santa Marta 3, 50139 - Florence, Italy*
[b]*SISSA MathLab, International School for Advanced Studies, via Bonomea 265, I-34136 - Trieste, Italy*

Abstract

The increasing importance of offshore deep-water wind energy together with the complexity of the wind-wave-structure interaction problem makes the dynamic analysis of floating platforms a case of considerable interest. In this work, the dynamics of moored floating platforms for deep-water wind energy purposes is analysed in regular waves in order to discuss the effects on the motion due to the coupling of different degrees of freedom, usually associated with the operation of the mooring system and the hydrodynamic action, and the role of the main parameters affecting the motion. The platform is modelled as a rigid body and the associated differential dynamic problem is solved by using a suitable Lie group time integrator. The loads associated with mooring lines and waves are respectively assessed through a quasi-static model and a linear hydrodynamic model. The coupling of different degrees of freedom is usually related to loads with higher-frequency components and non-zero mean value that could bring the system into a mean dynamic configuration rather different from the static equilibrium configuration. Moreover, very interesting to limit the oscillations of the body is the effect of the location of the center of mass, the lower the center the lower the amplitude of pitch and roll response.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: moored floating platforms; coupled dynamic response; offshore wind energy

1. Introduction

The reduction of greenhouse gas emissions is undoubtedly one of the most important challenges of the twenty-first century. In order to reduce the emissions associated with the traditional sources of energy, i.e. fossil fuels, the exploitation of renewable energy resources gained over the years a primary role and focused the research towards the development of reliable and more cost effective technologies. Wind energy is one of the most promising renewable resources. In the last fifteen years it had a significant growth becoming the third energy resource in terms of produced power and the first renewable energy resource [1]. In particular, offshore wind energy is becoming more and more important due to wider available sites and better wind conditions, in terms of higher mean wind speed and less turbulent wind field.

* Corresponding author.
E-mail address: alessandro.giusti@dicea.unifi.it

1877-7058
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.527

For certain water depths, the use of floating platforms with mooring lines is considered the most economical support concept [2]. The possibility that such kind of structures can undergo large displacements [3], especially during severe sea-states, makes the design and optimization of offshore wind turbines a very complex problem of wind-wave-structure interaction, which requires the use of advanced numerical tools, as accurate as computationally efficient [4]. It has been recently shown the crucial role that more accurate simulation models play in the prediction of structural dynamics and associated loads for fixed-bottom wind turbines [5–7]. By contrast, for floating technologies there are still several aspects that need a deeper understanding. In this context, the coupled dynamic response of floating barge platforms is analysed in the present paper for a series of regular waves in order to better understand the role of some of the main parameters affecting the motion and the effects due to the coupling of different degrees of freedom.

2. Dynamic model

The floating platform is modelled as a rigid body free to move in the Euclidean space and subjected to the action of the waves and the mooring lines. The dynamic differential problem is formulated by using a mixed representation of the velocities [8]. Let us consider an inertial reference frame $I = \{O; x, y, z\}$ defined by the orthonormal basis $\mathcal{S} = \{\mathbf{e}_i^I\}$ and a body-attached (non-inertial) reference frame $B = \{G; x', y', z'\}$ defined by the orthonormal basis $\mathcal{M} = \{\mathbf{e}_i^B\}$. The notation $(\bullet)^{(\diamond),(\circ)}$ indicates a physical quantity $(\bullet)$ observed in the frame $(\diamond)$ and expressed with respect to the basis $(\circ)$, with $(\diamond) = I, B$ and $(\circ) = \mathcal{S}, \mathcal{M}$. Alternatively, if the indication of the reference frame is not significant (for instance for forces and torques), the superscript is limited to the information about the basis, i.e. $(\bullet)^{(\circ)}$. Let us introduce the vector $\hat{\mathbf{q}} = [\mathbf{x}_G^{I,\mathcal{S}}; \boldsymbol{\psi}]$ collecting the position vector $\mathbf{x}_G^{I,\mathcal{S}}$ of the center of mass and the rotational vector $\boldsymbol{\psi}$ (φ_i are the corresponding Tait-Bryan angles), and the vector $\hat{\mathbf{v}} = [\mathbf{v}_G^{I,\mathcal{S}}; \boldsymbol{\omega}^{\mathcal{M}}]$ collecting the velocity vector $\mathbf{v}_G^{I,\mathcal{S}}$ of the center of mass and the angular velocity $\boldsymbol{\omega}^{\mathcal{M}}$ of the body.

2.1. Time integrator

The dynamic problem is solved with a suitable Lie group time integrator developed in [9,10]. The algorithm, based on the geometric method, can solve the set of differential equations that describe the dynamics of rigid bodies without the necessity of introducing a parametrization to handle the kinematic compatibility. Such method permits to maintain a minimum number of equations without increasing the non-linearities and avoids the singularities associated with some parametrizations of the rotation, for instance Euler angles.

2.2. Hydrodynamic and mooring line loads

Hydrodynamic loads are modelled in the framework of the linear theory that implies the superimposition of three different sub-problems: diffraction (Froude-Kriloff and scattering loads), radiation and hydrostatics [2,11]. Loads can therefore be computed by means of the Cummins approach [12]. However, for the study of the steady response of the system under the action of a regular wave, it is also possible to use a simpler model, referred in this work as the steady regular model. Such model is the time domain representation of the frequency domain problem and requires that the system oscillates at the same frequency of the incident wave [2].

Mooring lines are modelled with the quasi-static theory developed in [2]. The model considers each line in static equilibrium at any time instant. The forces acting at the fairleads, and then on the platform, can be computed on the basis of the current configuration of the body. Possibility of incorporating geometrically exact flexible elements [13] consistent with the platform kinematic model is left for future developments.

3. Coupled response

Hydrodynamic loads are directly included in the analysis as external loads (wave excitation) and linear transformations of the state variables (hydrostatic and radiation forces). On the contrary, since mooring line loads depend nonlinearly on the configuration of the floating body, they could be included in the analysis by means of an iterative procedure so that at each time step the dynamic equilibrium is verified. For the most cases, even a weak coupling,

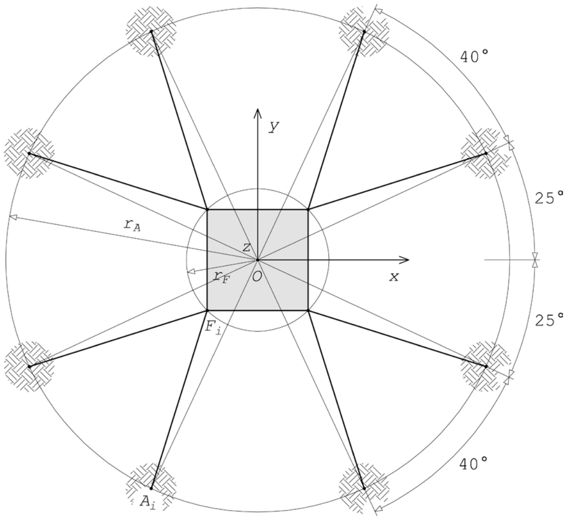

Fig. 1. Layout of the mooring system in the static equilibrium configuration.

i.e. mooring loads computed with respect to the configuration at the previous time step, is usually accurate enough. The system consists of a parallelepiped platform 40×40×10 m ($a \times b \times c$, where c is the height) of mass $m = 5\,998.538$ t, if otherwise specified, anchored to a seabed 150.0 m deep with a system of eight mooring lines arranged all around the platform as depicted in Fig. 1, with radius to the fairleads $r_F = 28.28$ m and radius to the anchors $r_A = 423.4$ m. The lines have a diameter $D_c = 0.1454$ m, an unstretched length $l = 460$ m, if otherwise specified, a mass density per unit length $\mu_c = 130.4$ kg/m and an extensional stiffness $EA = 589 \cdot 10^6$ N. The moored platform is very similar to the one reported in [2].

3.1. Coupling of different degrees of freedom

Mooring systems with slack lines usually imply the coupling of different degrees of freedom. Fig. 2 (left panels) shows the non-zero components of the mooring loads acting on the platform when the body translates along the x-axis without rotating. For the sake of completeness, both the quasi-static model of Jonkman [2] and that one of Faltinsen [11] are considered. Very interesting is the consequent trend of the vertical force. Independently from the sign of the displacement, the load has a symmetric trend with respect to the undisplaced configuration. In the case of sinusoidal displacements along the x-axis, such a trend is associated with vertical forces with a dominant double frequency and a mean value different from the one corresponding to the static equilibrium configuration. Similar considerations can be drawn considering other degrees of freedom.

Also the combination of the rotational motion with a follower or non-follower interpretation of loads can cause the coupling of different degrees of freedom. Fig. 2 (right panels) shows the components of a sinusoidal follower load with respect to the basis $\mathcal{S}$ of an inertial frame when the system oscillates about the y-axis with the same frequency of the force. In particular, the vertical component of the load has a non-zero mean value and a dominant double frequency. The mean value and the distortion of the sinusoid (higher frequencies) depend, among others, on the out-of-phase between the load and the rotation. For three dimensional rotational motions, such a coupling is much more complex.

3.2. Role of the main parameters

The moored floating platform is analysed for a series of regular waves directed along the x-axis in order to better understand the role of some of the main parameters affecting the motion over different wave periods. In particular the effects of the wave amplitude, length of the lines, mass of the platform, and mass distribution are analysed. Fig. 3 shows the variation of the response amplitude operator (RAO) of the pitch angle. The response is linear with respect to the amplitude ζ of the incident wave (according to the linearity of the loading model), whereas the length of the lines does not significantly affect the response provided that the moorings remain slack. An increase of the mass of the

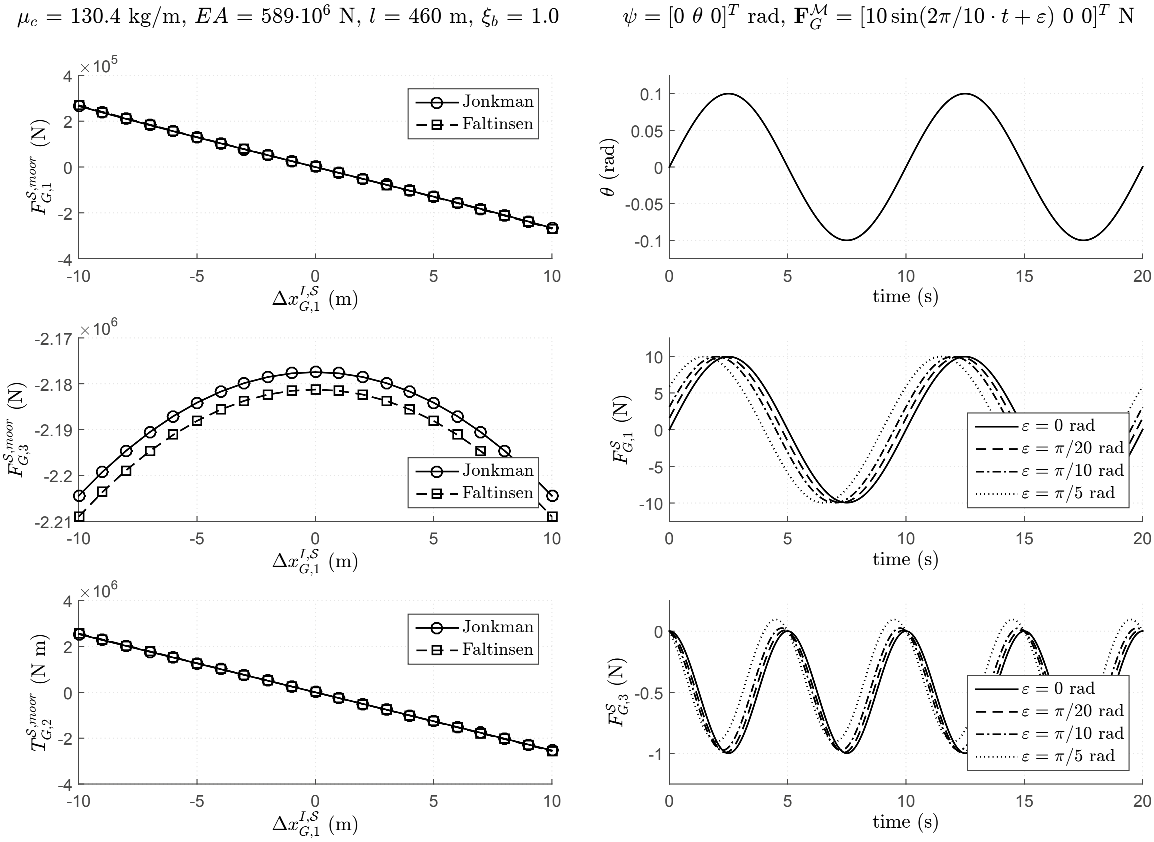

Fig. 2. (left) effect of the translation of the center of mass along the *x*-axis on the loads of the mooring system; (right) non-zero components of a sinusoidal follower force with respect to the basis of the inertial frame in the case of sinusoidal pitch motions with the same frequency of the load and for different out-of-phases of the force.

platform without changing the geometry shifts the natural frequency of the system towards the low frequencies and also implies an increase of the maximum amplitude of the rotation related to the increase of the submerged portion of the body and thus of the hydrodynamic action. Very interesting is the effect of the distribution of the mass. Lowering the centre of mass (see Fig. 3 bottom-right panel, where: case 1, 60% of the mass placed in the lower third of the body; case 2, homogeneous body; case 3, 60% of the mass placed in the upper third) it is possible to limit the amplitude of the rotation without significantly modifying the natural frequency of the system. Fig. 3 highlights also an important issue of such large floating platforms due to the pitch (and roll) natural frequency falling in a typical range of a real sea spectrum. For this reason other technical solutions were introduced over the years to limit pitch oscillations, as the construction of the so called moon pool in the middle of the platform [2].

3.3. Directional waves

If the floating platform is subjected to an incident wave misaligned with respect to a principal direction of the system, the dynamic response is much more complex because the system oscillates about a variable axis and also the coupling effects due to the mooring system and the hydrodynamic action become very complex, especially when the rotational oscillations become large. Fig. 4 shows the steady time history of the configuration of the body obtained in the case of an incident wave directed 22.5 degrees with respect to the *x*-axis for a wave period of 6.5 s, very close to a natural frequency of the system, and a period of 7.0 s. The system oscillates about a mean configuration that can be rather different with respect to the static equilibrium configuration, especially for surge and sway motions.

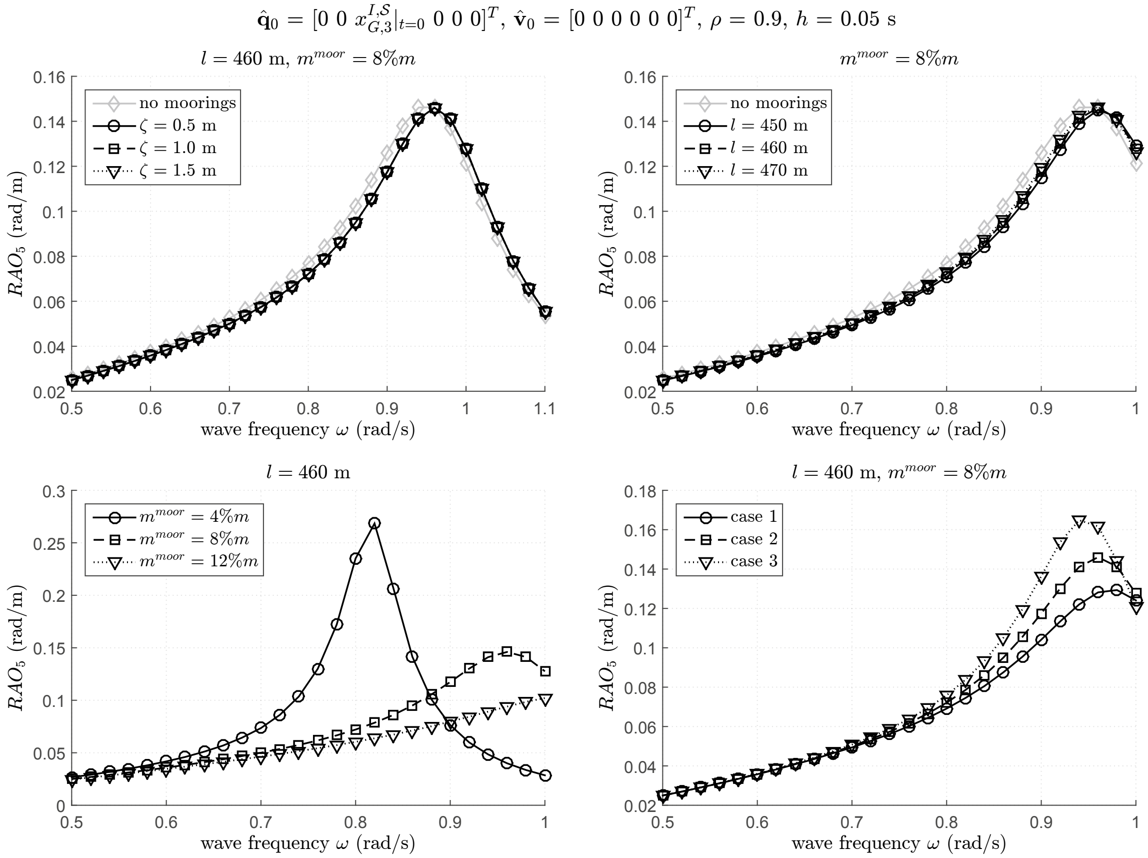

Fig. 3. Effect of different parameters (wave amplitude, length of the lines, mass of the platform, distribution of the mass) on the steady pitch response of a floating platform under the action of regular waves directed along the x-axis.

4. Conclusions

The dynamic response of a moored floating platform was discussed in the framework of the linear hydrodynamic theory in the case of regular waves. Mooring lines were modelled with a quasi-static theory and the coupled dynamic problem was solved with an efficient Lie group time integrator.

The rotational motion (pitch and roll) of the so called buoyancy stabilized platforms is slightly influenced by the presence of slack mooring lines, which, however, are necessary to provide the constraints against surge, sway, and yaw motions. For these reasons, given the linear hydrodynamic model, the pitch response of the platform under different wave amplitudes is linear and the length of the lines does not significantly affect the response. The mass of the platform together with the extension of the cut water-plane area has a key role in the dynamics of the moored platform and should be designed to shift the natural frequencies of the system as far as possible from the typical range of frequencies of the sea state considered. In any case, in order to limit the pitch (and roll) response, the center of mass should be placed as low as possible.

In the case of waves misaligned with respect to a principal axis of the system, the response becomes very complex and the coupling of different degrees of freedom, associated with the rotation about a variable axis, the hydrodynamic action, and the operation of the mooring system, could become very relevant so that the system can oscillate about a mean dynamic configuration rather different from the static equilibrium configuration. This phenomenon is particularly significant in the neighbourhood of the natural frequency of the system involving the pitch (or roll) motion. However, since in this case the system does not undergo small oscillations, as required by the linear hydrodynamic theory, the phenomenon needs to be further investigated.

$$\hat{\mathbf{q}}_0 = [0\ 0\ \text{-}0.13532\ 0\ 0\ 0]^T,\ \hat{\mathbf{v}}_0 = [0\ 0\ 0\ 0\ 0\ 0]^T,\ \zeta = 1.0\ \text{m},\ \rho = 0.9,\ h = 0.05\ \text{s}$$

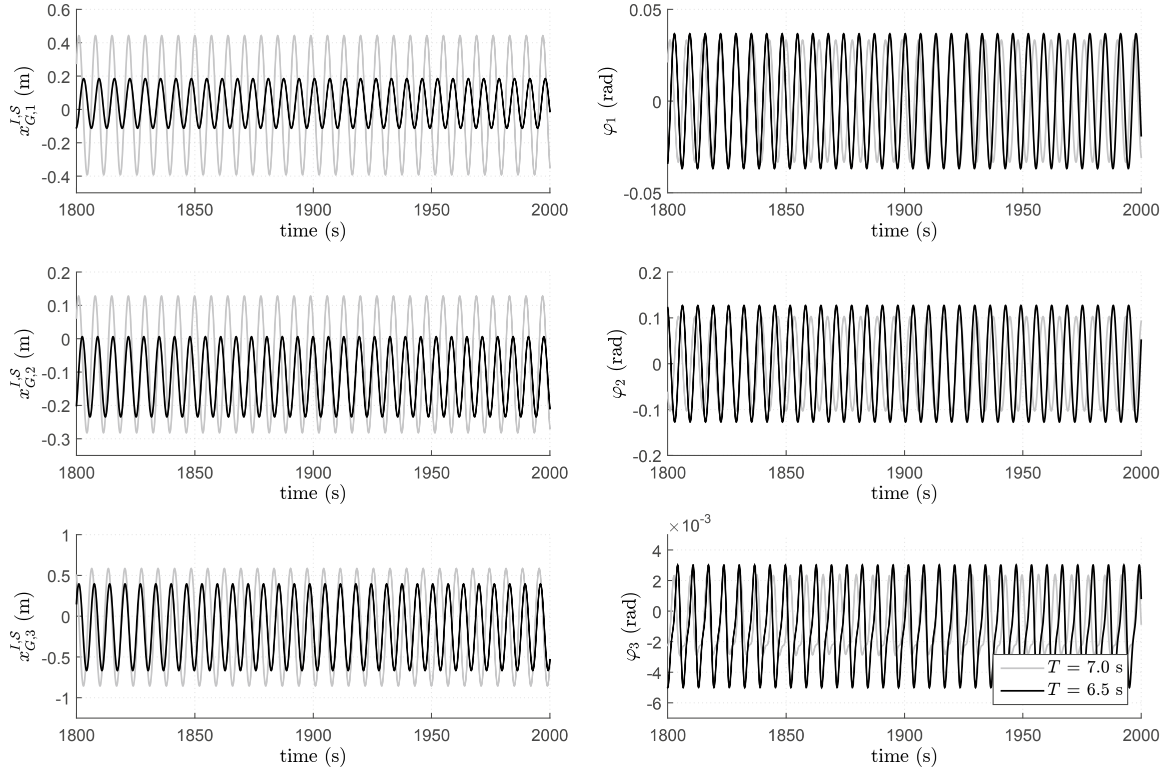

Fig. 4. Time histories of the trajectory of the center of mass and the Tait-Bryan angles in the case of an incident regular wave (steady regular model) directed 22.5 degrees with respect to the *x*-axis.

References

[1] EWEA, Wind in power, 2015 European statistics, Report, The European Wind Energy Association, 2016.
[2] J. M. Jonkman, Dynamics of offshore floating wind turbines - model development and verification, Wind Energy 12 (2009) 459–492.
[3] M. Philippe, A. Babarit, P. Ferrant, Modes of response of an offshore wind turbine with directional wind and waves, Renewable Energy 49 (2013) 151–155.
[4] A. Cordle, State-of-the-art in design tools for floating offshore wind turbines, Deliverable report UpWind_WP4_D4.3.5_Floating design tools, 2010.
[5] E. Marino, C. Lugni, C. Borri, The role of the nonlinear wave kinematics on the global responses of an OWT in parked and operating conditions, Journal of Wind Engineering and Industrial Aerodynamics 123 (2013) 363–376.
[6] E. Marino, H. Nguyen, C. Lugni, L. Manuel, C. Borri, Irregular nonlinear wave simulation and associated loads on offshore wind turbines, Journal of Offshore Mechanics and Arctic Engineering 137 (2015) 021901.
[7] E. Marino, A. Giusti, L. Manuel, Offshore wind turbine fatigue loads: The influence of alternative wave modeling for different turbulent and mean winds, Renewable Energy 102 (2017) 157–169.
[8] A. Müller, Z. Terze, Geometric methods and formulations in computational multibody system dynamics, Acta Mechanica 227 (2016) 3327–3350.
[9] O. Brüls, A. Cardona, On the use of Lie group time integrators in multibody dynamics, Journal of Computational and Nonlinear Dynamics 5 (2010) 031002.
[10] O. Brüls, A. Cardona, M. Arnold, Lie group generalized-α time integration of constrained flexible multibody systems, Mechanism and Machine Theory 48 (2012) 121–137.
[11] O. M. Faltinsen, Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.
[12] W. E. Cummins, The impulse response function on ship motions, Schiffstechnik 9 (1962) 101–109.
[13] E. Marino, Isogeometric collocation for three-dimensional geometrically exact shear-deformable beams, Computer Methods in Applied Mechanics and Engineering 307 (2016) 383–410.