X-SEA VERIFICATION REPORT 5

Dynamics of Offshore Wind Sub-structures

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Summary:

This document reports the verification of X-SEA software dynamic analysis. In order to validate the performance of the X-SEA program and verify its capability in dynamic modelling and analysing complex offshore wind turbine support structures, three case studies of a monopile structure, a jacket structure and a tripod structure, all supporting a 5MW offshore wind turbine, are considered. The case studies been performed in X-SEA and FAST v8 programs.

The monopile structure has 30 meters height and a fixed pile support at the bottom. The time histories of the lateral reaction forces in X and Y directions, vertical reaction forces, and reaction moments about X, Y and Z directions calculated in X-SEA match with those calculated in FAST.

The jacket locates on the seabed with a fixed boundary condition, has 70.15 m height driven into 50 m water depth and extends 20.15 m above the mean sea level. The mean wind speed is 14 m/s. Wave kinematics of 8 m significant wave height and 10 sec period are considered. The time-histories of the dynamic lateral reaction forces in the x- and y-directions, vertical reaction force, and reaction moments about x-, y- and z-directions resulted from X-SEA are in good agreement with those from FAST v8.

The tripod support structure on the seabed with a fixed boundary condition of 55 m long driven into 45 m water depth, and extends 10 m above the mean sea level. The significant wave height is 8 m, the wave period is 10 seconds and steady wind velocity is 8 m/sec at reference height 90 m above the mean sea level. The time-histories of the top-tower dynamic lateral forces in the x- and y-directions, vertical reaction force, and moments about x-, y- and z-directions calculated in X-SEA are also in good agreement with those calculated from FAST v8. The transient responses due to structural damping and initialised hydrodynamic and aerodynamic loads are in the first 30 seconds and damped out quickly.

It can therefore be concluded that the dynamic analysis in X-SEA program performs normally.

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1 Offshore Monopile Structure

1.1 Introduction

For the verification of X-SEA software, the dynamic analysis of an offshore monopile structure is carried out using X-SEA and original FAST programs. The monopile structure has 30 meters height and a fixed pile support at the bottom.

In order to compare the X-SEA results with those of FAST, the lateral forces in X and Y directions, vertical forces, moments about X, Y and Z directions were calculated. All the node positions calculated from the X-SEA are illustrated in Figure 1. There are total 31 nodes and 30 elements in each model.

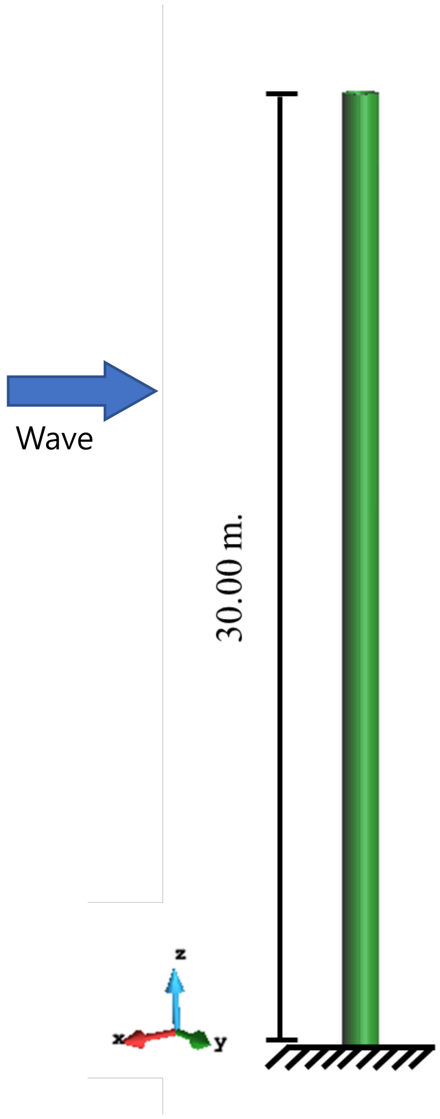


Figure 1. Model of the offshore monopile substructure in X-SEA

1.2 Geometric and Material Properties of Offshore Monopile Structure

The monopile height is 30 m and in circular hollow section illustrated in **Figure 2** with outer diameter of 1.129 m and thickness of 0.030m.

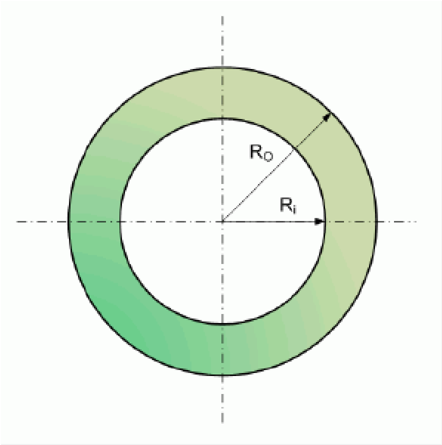


Figure 2. Circular hollow section

The material properties of steel for the tripod top, legs and bracings to be used in the analysis are elastic modulus E = 2.0x10^{11} N/m2; Poisson's ratio (ν) = 0.30 and mass density = 7850 kg/m3.

1.3 Analysis Results of X-SEA and FAST

The resulted dynamic lateral reaction forces in the x- and y-directions and the vertical reaction force in the z-direction are compared in **Figure 3**, **Figure 4**, and **Figure 5**, respectively. **Figure 6**, **Figure 7**, and **Figure 8** compare the resulted dynamic reaction moments on the jacket support structure about x-, y- and z-directions, respectively. The reaction forces and moments resulted from X-SEA are in good agreement with those resulted from FAST v8.

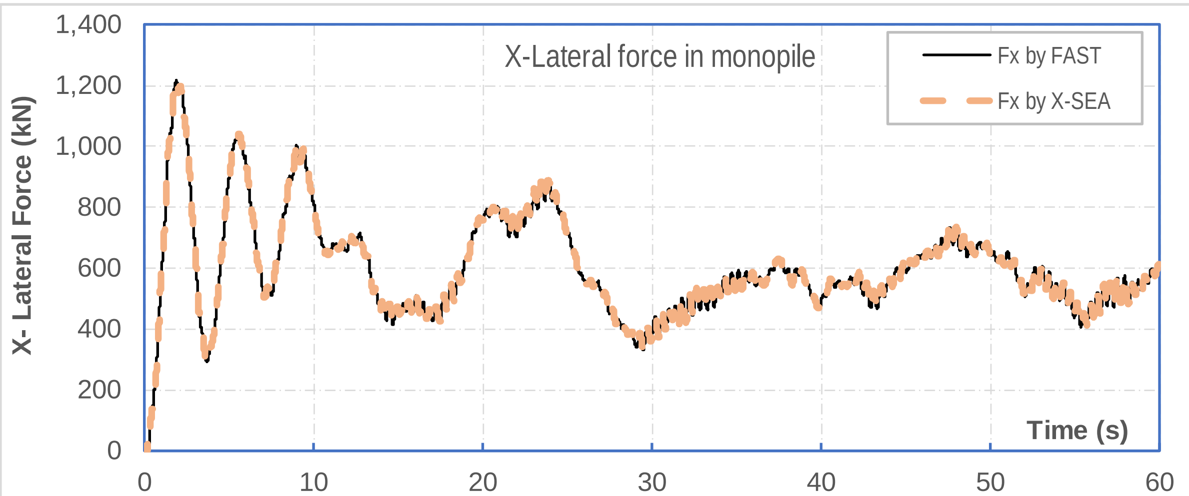


Figure 3. Comparison of lateral forces in X-direction of the offshore monopile structure models resulted from X-SEA and FAST programs.

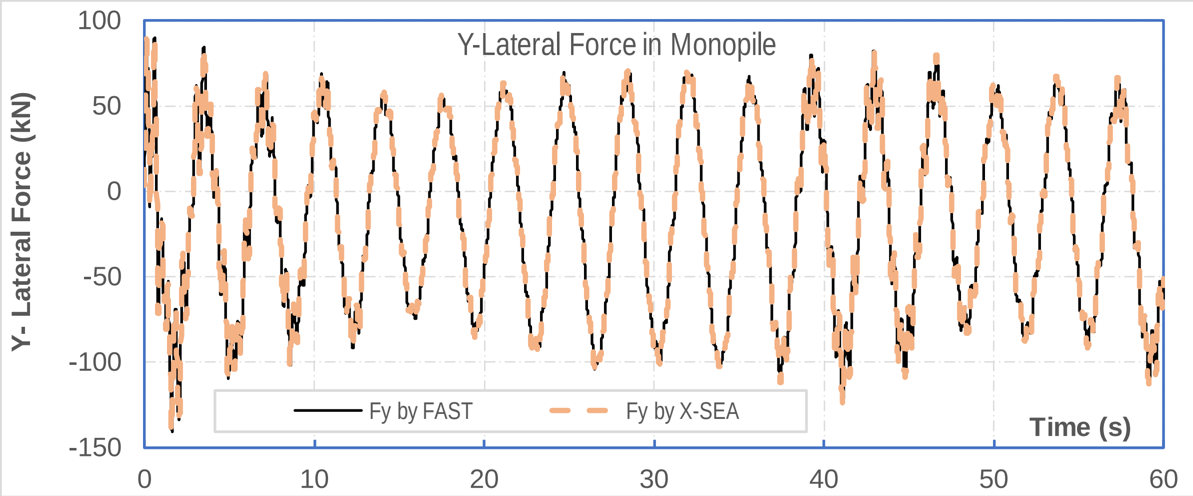


Figure 4. Comparison of lateral forces in Y-direction of the offshore monopile structure models resulted from X-SEA and FAST programs.

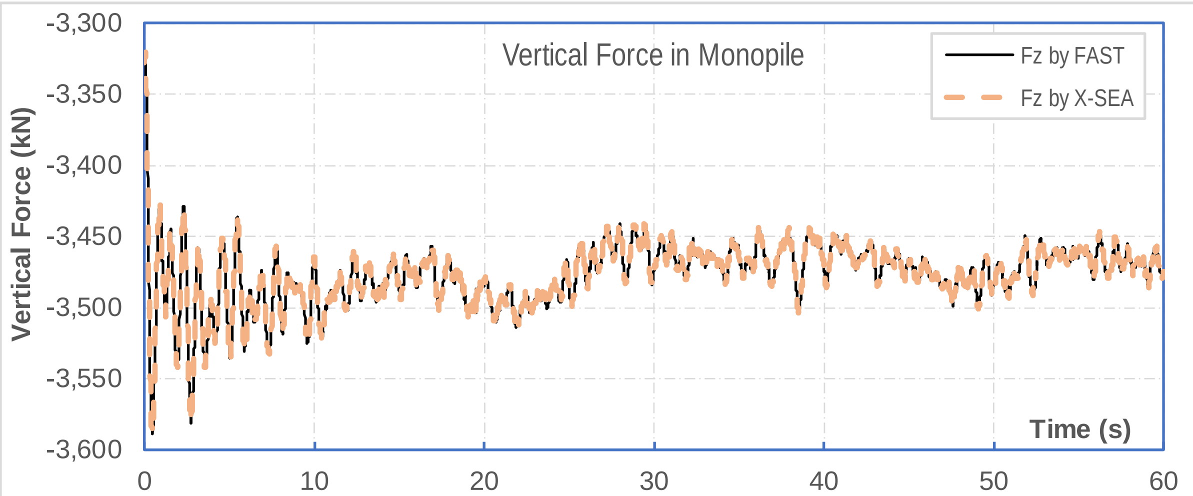


Figure 5. Comparison of vertical forces of the offshore monopile structure models resulted from X-SEA and FAST programs.

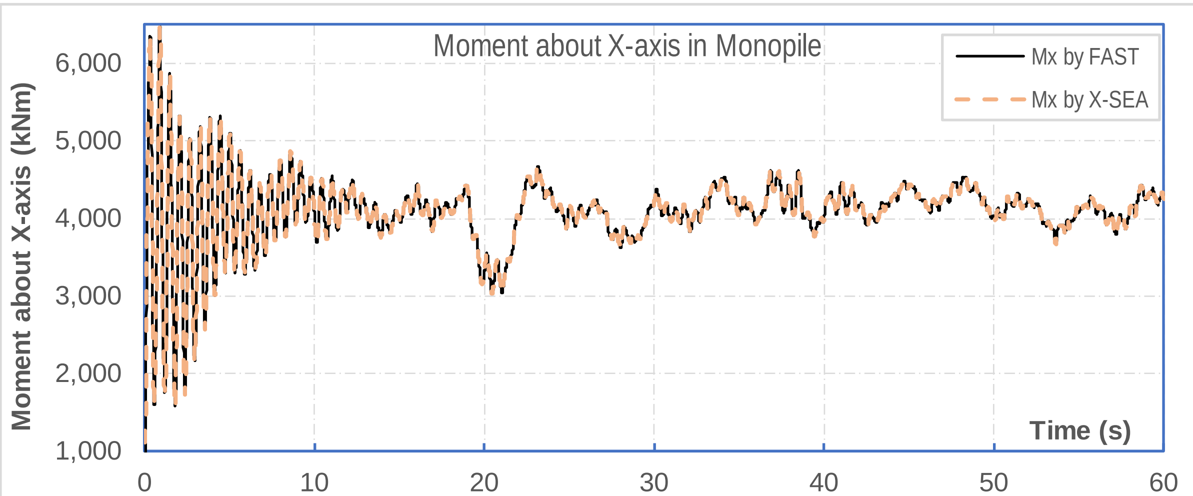


Figure 6. Comparison of bending moment about X-axis of the offshore monopile structure models resulted from X-SEA and FAST programs.

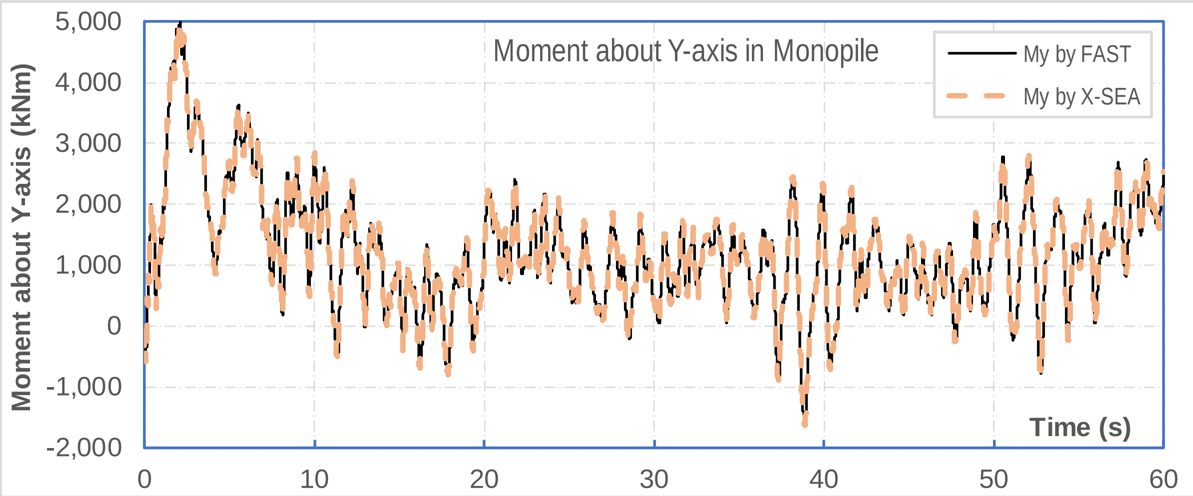


Figure 7. Comparison of bending moment about Y-axis of the offshore monopile structure models resulted from X-SEA and FAST programs.

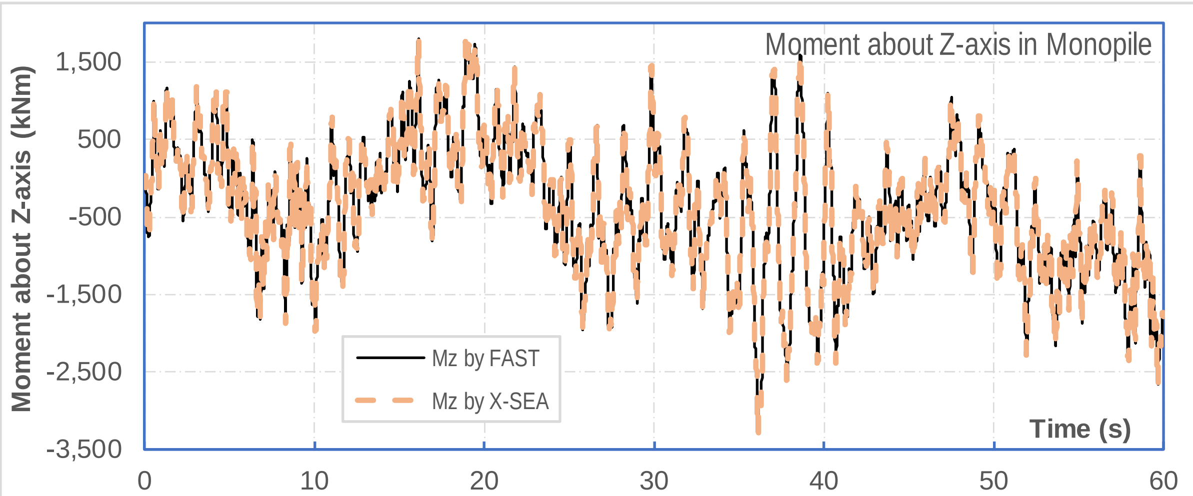
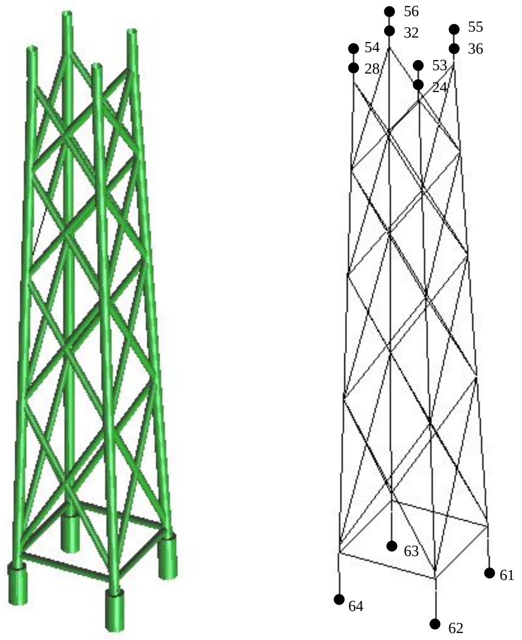


Figure 8. Comparison of bending moment about Z-axis of the offshore monopile structure models resulted from X-SEA and FAST programs.

2 Jacket Support Structure for NREL 5MW Offshore Wind Turbine

2.1 Introduction

The jacket support structure of the OWT, which was studied in the US National Renewable Energy Laboratory (NREL), was located on the seabed with a fixed boundary condition, had 70.15 m height driven into 50 m water depth and extended 20.15 m above the mean sea level. The mean wind speed was 14 m/s. The support structure corresponded to periodic wave kinematics of 8 m significant wave height and 10 sec period of wave, where the water density was 1025 kg/m3. The jacket structure model is illustrated in **Figure 9**. Thar model has 12 joints and 112 elements. The joint numbers 61–64 were the fixed boundary conditions located on the seabed. The joint numbers 24, 28, 32, 36, 54, 55 and 56 were the transition pieces or interface joints to transfer the loads and motions within the X-SEA program. The geometry and material properties of the jacket structure are given in **Table 1**.



(a) With Rendering (b) Without Rendering

Figure 9. Model of jacket support structure for NREL 5MW offshore wind turbine.

Table 1. Geometry and material properties of the jacket support structure.

Parameter	Value
Outer diameter of a leg [m]	1.200
Wall thickness of a leg [m]	0.045
Outer diameter of a diagonal [m]	0.800
Wall thickness of a diagonal [m]	0.035
Young's modulus [N/m^2]	2.1×10^{11}
Density [kg/m^3]	7850

2.2 Analysis Results of the Jacket Structure by X-SEA and FAST

The same wave forces produced by Airy wave theory were applied to both X-SEA and FAST v8 substructure models (Jonkman, 2018). The resulted dynamic lateral reaction forces in the x- and y-directions and the vertical reaction force in the z-direction are compared in Figure 10, Figure 11, and Figure 12, respectively. Figure 13, Figure 14, and Figure 15 compare the resulted dynamic reaction moments on the jacket support structure about x-, y- and z-directions, respectively. These reaction forces and moments resulted from X-SEA and FAST v8 substructure models in good agreement.

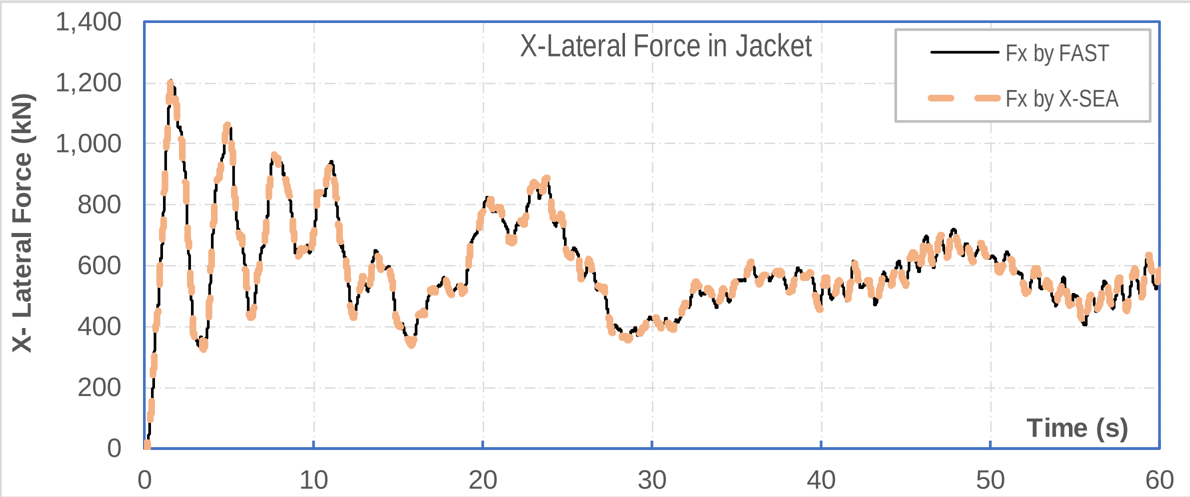


Figure 10. Comparison of dynamic reaction lateral forces in X-direction of the offshore jacket structure models resulted from X-SEA and FAST programs.

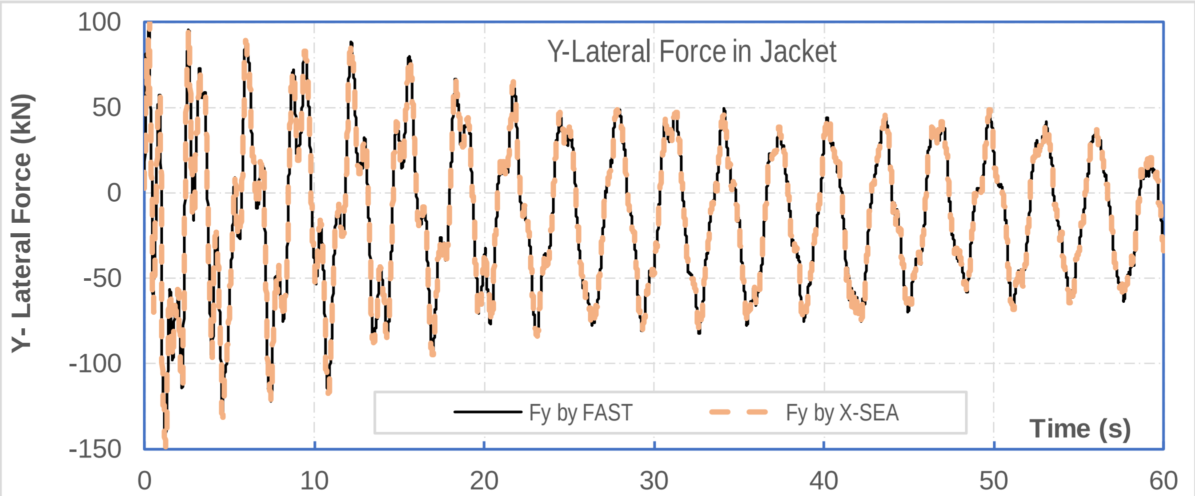


Figure 11. Comparison of dynamic reaction lateral forces in Y-direction of the offshore jacket structure models resulted from X-SEA and FAST programs.

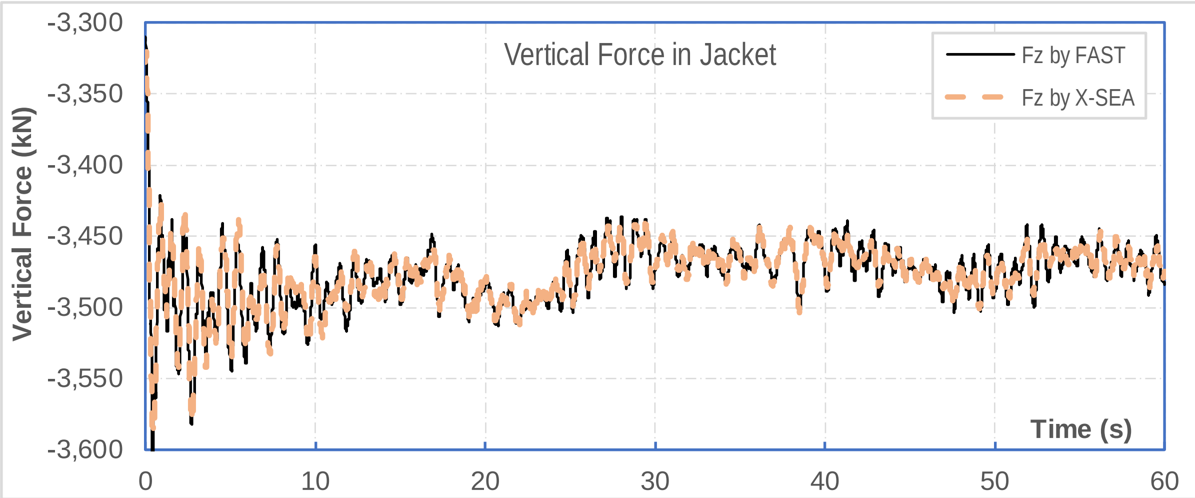


Figure 12. Comparison of dynamic reaction vertical forces of the offshore jacket structure models resulted from X-SEA and FAST programs.

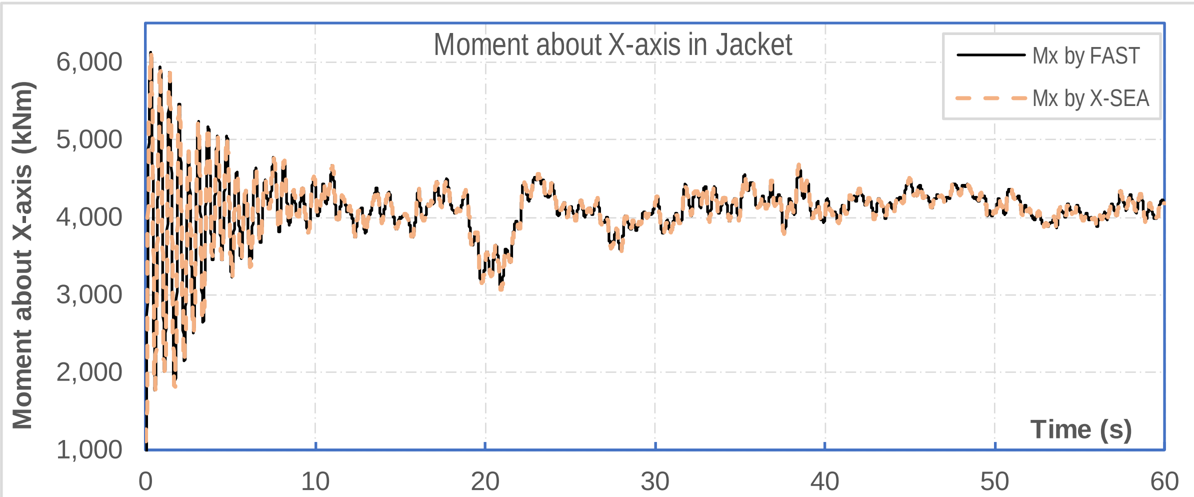


Figure 13. Comparison of dynamic reaction moments about X-direction of the offshore jacket structure models resulted from X-SEA and FAST programs.

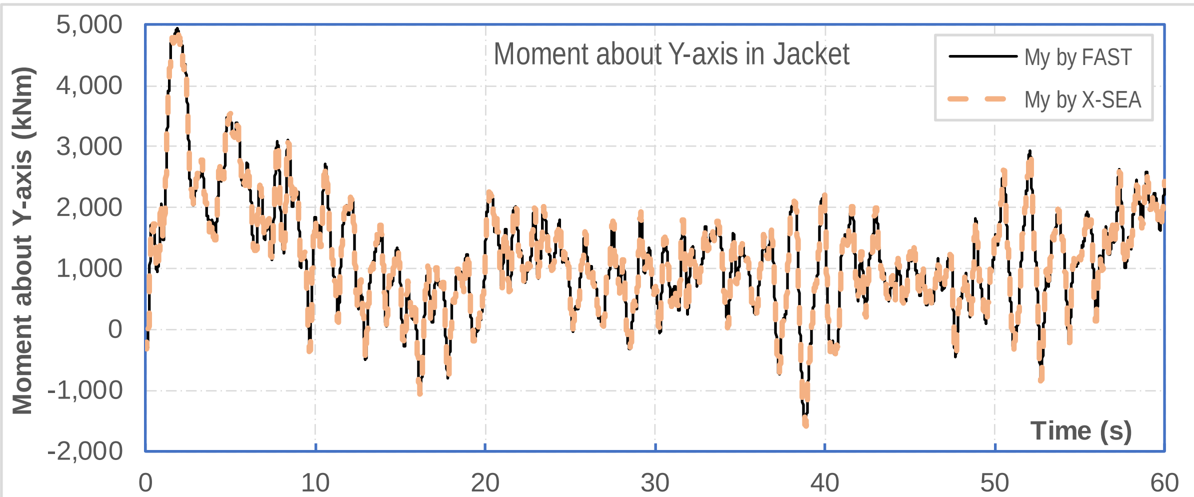


Figure 14. Comparison of dynamic reaction moments about Y-direction of the offshore jacket structure models resulted from X-SEA and FAST programs.

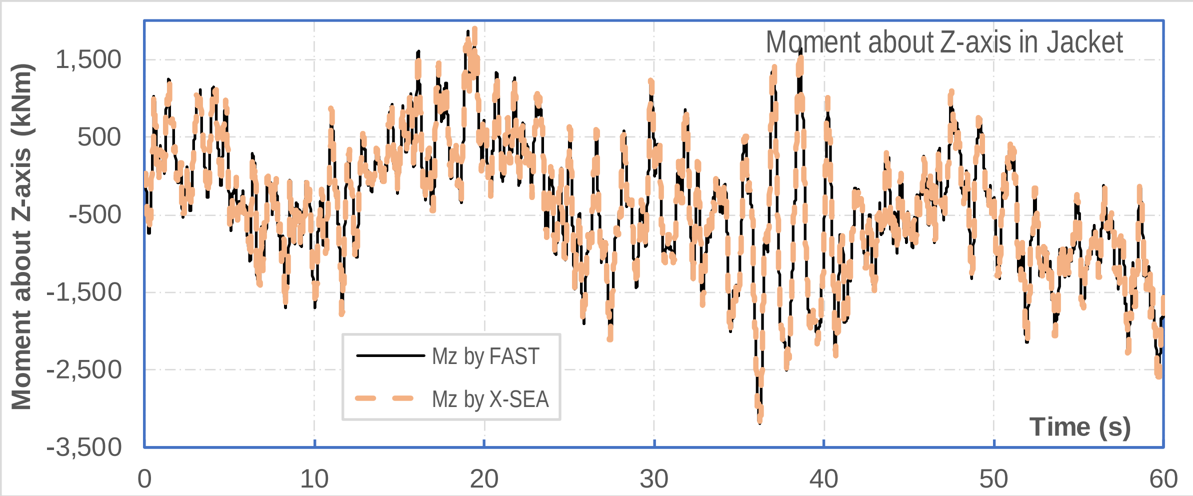


Figure 15. Comparison of dynamic reaction moments about Z-direction of the offshore jacket structure models resulted from X-SEA and FAST programs.

2.3 Concluding Remarks

In order to validate the performance of the X-SEA program on its capability in dynamic modelling and analysing complex offshore wind turbine jacket structures, a case study of a jacket structure supporting a 5MW offshore wind turbine, which was studied in the US National Renewable Energy Laboratory, has been performed in X-SEA and FAST v8 programs. The jacket was located on the seabed with a fixed boundary condition, had 70.15 m height driven into 50 m water depth and extended 20.15 m above the mean sea level. The mean wind speed was 14 m/s. The support structure corresponded to periodic wave kinematics of 8 m significant wave height and 10 sec period of wave.

The time-histories of the dynamic lateral reaction forces in the x- and y-directions, vertical reaction force, and the dynamic reaction moments about x-, y- and z-directions have been calculated. The reaction forces and moments resulted from X-SEA are in good agreement with those resulted from FAST v8.

3 Tripod Structure Supported NREL 5MW Offshore Wind Turbine

3.1 Introduction

The tripod support structure of a wind turbine, which was researched in NREL, was sitting on the seabed with a fixed boundary condition of 55 m long driven into 45 m water depth, and extended 10 m above the mean sea level. This structure was modelled in X-SEA program with external forces acquired from the hydrodynamic module in FAST program. The water density is 1027 kg/m^3, the significant wave height is 8 m, the wave period is 10 seconds and steady wind velocity is 8 m/sec at reference height 90 m above the mean sea level. Based on the longest natural periods the structure and the wave period, the analysis period is selected as the first 60 seconds, which should correspond to the start-up to power production and consist of both transient and steady behaviour. The support structure was modelled by using 158 nodes and 163 elements as illustrated in Figure 16**.** The geometry and material properties of the tripod structure are given in **Table 2**.

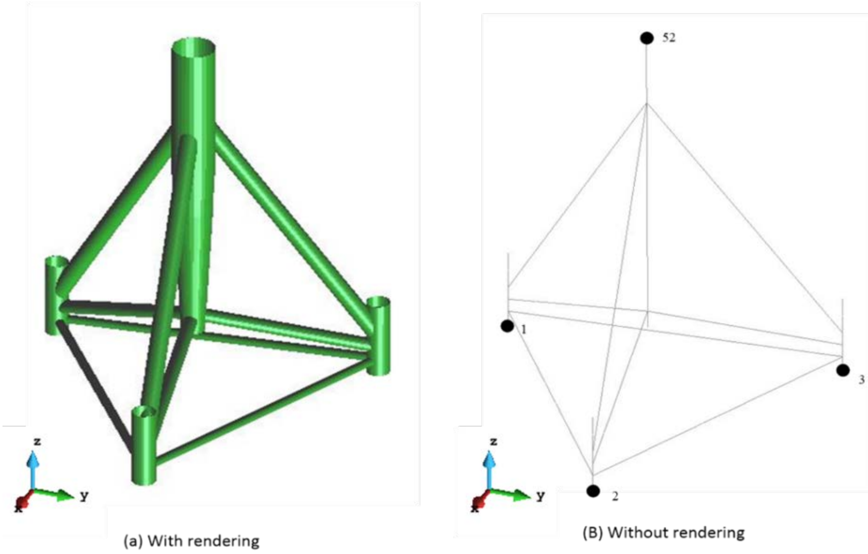


Figure 16. Model of tripod support structure for NREL 5MW offshore wind turbine.

Table 2. Geometry and material properties of the tripod support structure.

Outer diameter of diagonal brace [m]	2.475-1.200
Wall thickness of diagonal brace [m]	0.035-0.025
Outer diameter of main tubular [m]	5.412-1.875
Wall thickness of main tubular [m]	0.05-0.035
Young's Modulus [N/m^2]	2.1×10^{11}
Density [kg/m^3]	7850

3.2 Analysis Results of the Tripod Structure by X-SEA and FAST

The verification example focused on comparing six components of dynamic top-tower forces and moments resulted from FAST and from X-SEA coupled with FAST program. That comparison aims at assuring that the X-SEA program could produce correct results as FAST.

The resulted top-tower dynamic lateral forces in the x- and y-directions and vertical force in the z-direction are compared in Figure 17, Figure 18 and Figure 19, respectively. Figure 20, Figure 21, and Figure 22 compare the resulted top-tower dynamic moments on the tripod support structure about x-, y- and z-directions, respectively. These forces and moments resulted from X-SEA and FAST v8 substructure models in good agreement.

The marginal differences between X-SEA and FAST results in Figure 17 (top-tower X-lateral force) and Figure 20 (top-tower moment about X-axis) can be attributed to the fact that the ratio of X-SEA/FAST obtained from the natural frequency of the six mode shapes are 0.9994, 0.9994, 0.9995, 0.9996, respectively.

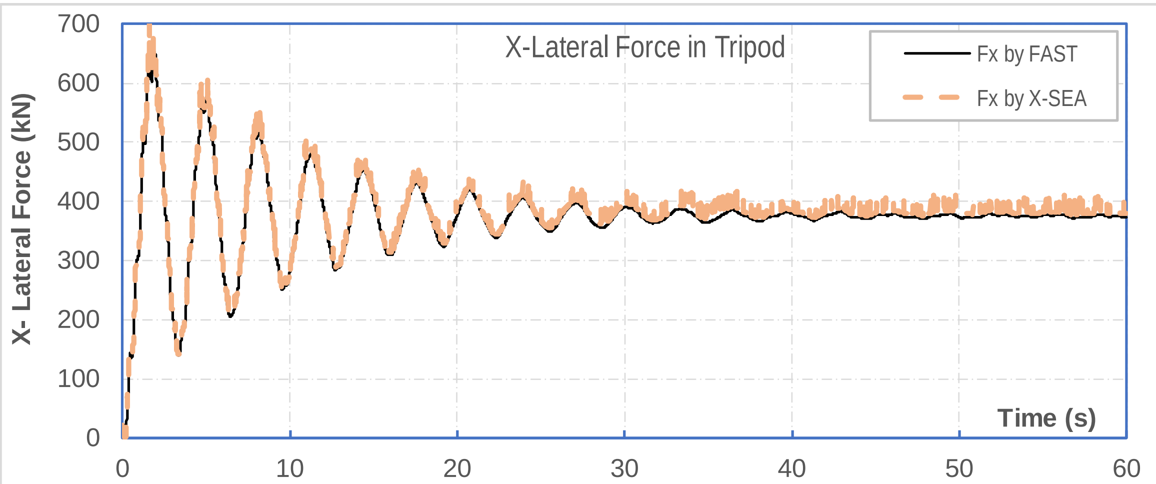


Figure 17. Comparison of top-tower dynamic lateral forces in X-direction of the offshore tripod structure models resulted from X-SEA and FAST programs.

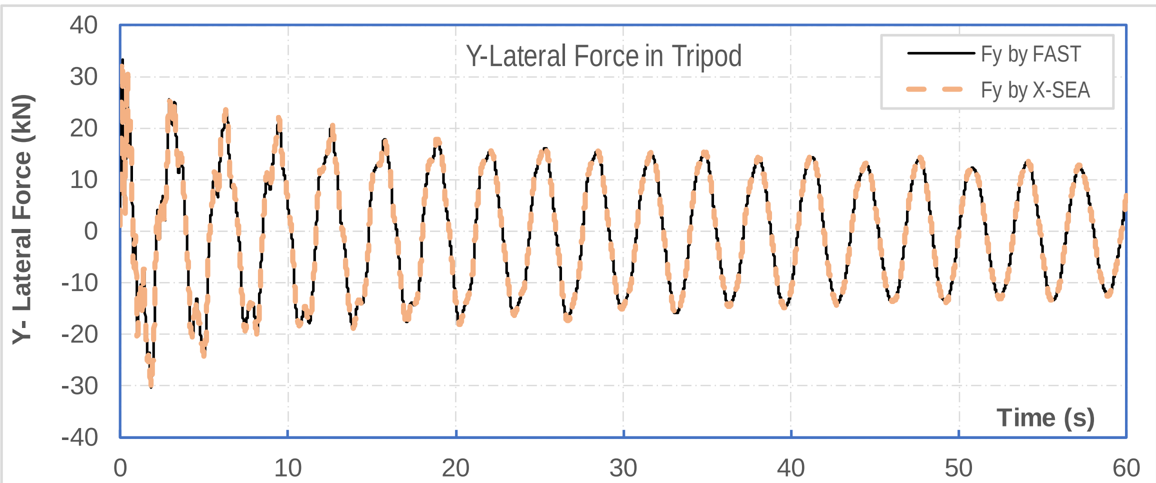


Figure 18. Comparison of top-tower dynamic lateral forces in Y-direction of the offshore tripod structure models resulted from X-SEA and FAST programs.

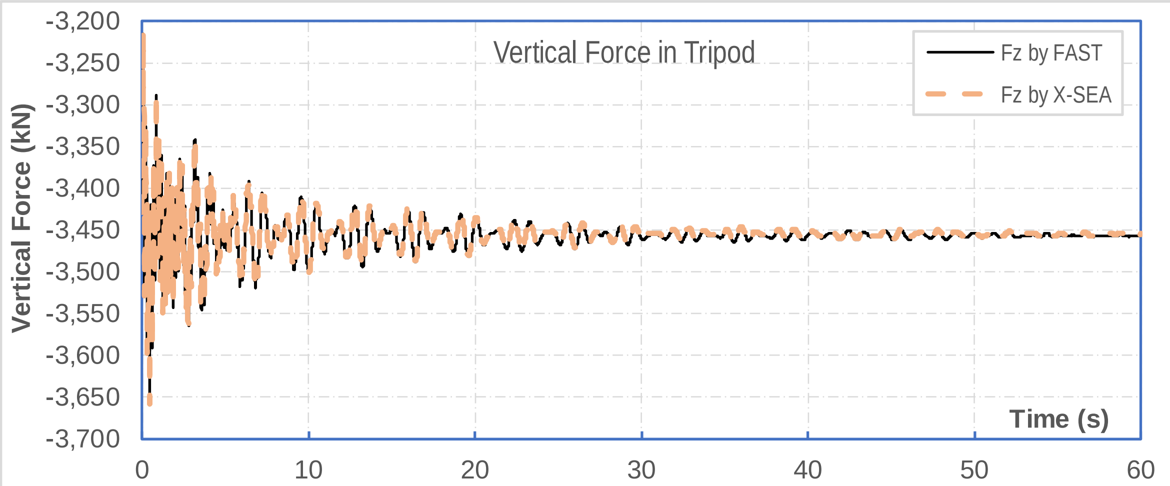


Figure 19. Comparison of top-tower dynamic vertical forces of the offshore tripod structure models resulted from X-SEA and FAST programs.

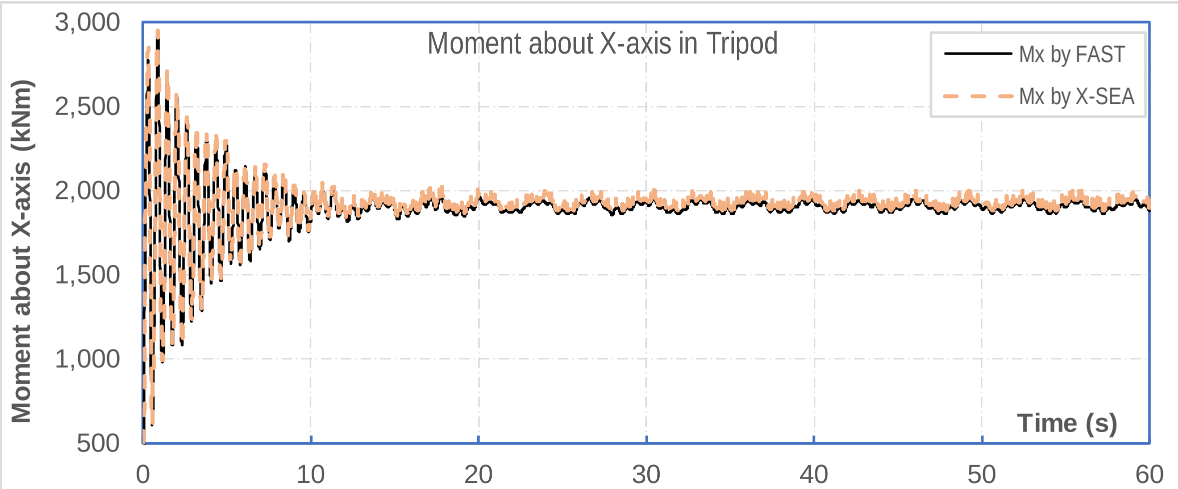


Figure 20. Comparison of top-tower dynamic moment about X-axis of the offshore tripod structure models resulted from X-SEA and FAST programs.

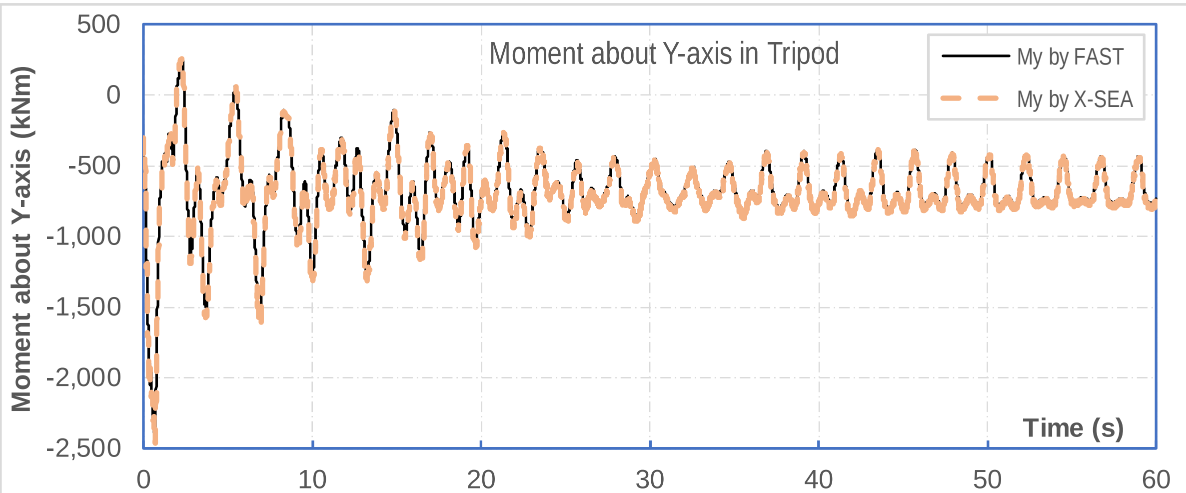


Figure 21. Comparison of top-tower dynamic moment about Y-axis of the offshore tripod structure models resulted from X-SEA and FAST programs.

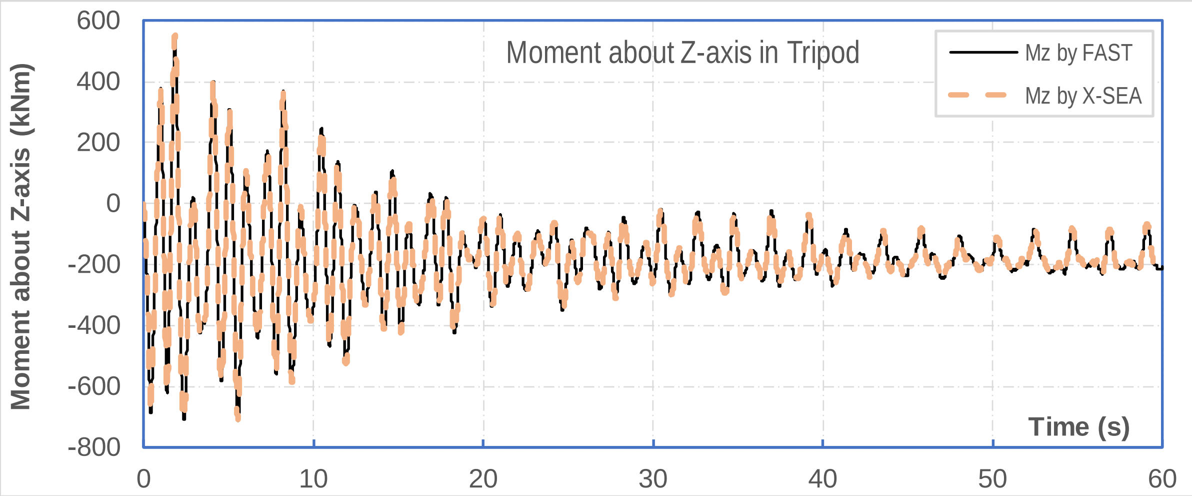


Figure 22. Comparison of top-tower dynamic moment about Z-axis of the offshore tripod structure models resulted from X-SEA and FAST programs.

3.3 Concluding Remarks

The performance of the X-SEA program on its capability in dynamic modelling and analysing complex offshore wind turbine tripod structures has been performed by using a case study of a tripod structure supporting a NREL 5MW offshore wind turbine and comparing the results with FAST v8 program. The tripod support structure was sitting on the seabed with a fixed boundary condition of 55 m long driven into 45 m water depth, and extended 10 m above the mean sea level. This structure was modelled in X-SEA program with external forces acquired from the hydrodynamic module in FAST program. The significant wave height is 8 m, the wave period is 10 seconds and steady wind velocity is 8 m/sec at reference height 90 m above the mean sea level.

The time-histories of the top-tower dynamic lateral forces in the x- and y-directions, vertical reaction force, and moments about x-, y- and z-directions have been calculated. These forces and moments resulted from X-SEA and FAST v8 are in good agreement.

These responses, except for the lateral forces in Y-direction, are seen to be transient and significantly attenuated in the first 30 seconds and then undergoing steady. Such initial transient behaviour is due to the small amount of damping in the structure and the method by which the hydrodynamic load and aerodynamic loading are initialized at the start of the simulation. Therefore, the transient responses are damped out quickly.

The marginal differences between X-SEA and FAST results (the top-tower X-lateral force and the moment about X-axis) can be attributed to the approximate ratio of X-SEA/FAST obtained from the natural frequency of the first six mode shapes. It can therefore be concluded that the present study program performs normally.