Ocean Engineering 159 (2018) 348–357

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Simplified load estimation and sizing of suction anchors for spar buoy type floating offshore wind turbines

Laszlo Arany[a], S. Bhattacharya[b,*]

[a] Atkins, UK
[b] University of Surrey, UK

ARTICLE INFO

Keywords:
Floating wind turbines
Anchor lines
ULS loads
Hywind wind farm

ABSTRACT

Floating offshore wind turbines are complex dynamic structures, and detailed analysis of their loads require coupled aero-servo-hydro-elasto-dynamic simulations. However, time domain approach used for such analysis is slow, computationally expensive and requires detailed data about the wind turbine. Therefore, simplified approaches are necessary for feasibility studies, front-end engineering design (FEED) and the early phases of detailed design. This paper aims to provide a methodology with which the designer of the anchors can easily and quickly assess the expected ultimate loads on the foundations. For this purpose, a combination of a quasi-static wind load analysis and Morison's equation for wave load estimation using Airy waves is employed. Dynamic amplification is also considered and design load cases are established for ultimate limit state (ULS) design. A simple procedure is also presented for sizing suction caisson anchors. All steps are demonstrated through an example problem and the Hywind case study is considered for such purpose.

1. Introduction

Offshore wind turbines are becoming significant contributors to the energy mix of many European countries, including the UK, the Netherlands, Germany and Belgium. However, the vast majority of the currently installed capacity worldwide is in shallow waters, particularly the North Sea, Irish Sea and Baltic Sea. The water depth for most currently operational wind farms is below 30–35 m. Commercial wind turbines are almost exclusively bottom fixed structures, with the majority of them installed on monopile foundations.

Most of the wind resource worldwide, however, is found in deeper waters, including significant portions of the coasts of the US, Japan, China, Norway and the Mediterranean (Henderson et al., 2002; European Wind Energy Association, 2013; Ho et al., 2016). Floating offshore wind turbines (FOWTs) are considered the best solution for harvesting wind energy from deep water sites where bottom fixed turbines are uneconomical (Myhr et al., 2014). Analysis of loads and motions of FOWTs is a challenging task, and typically requires a coupled aero-servo-hydro-dynamic analysis. Furthermore, anchor design requires incorporating soil-structure interaction (SSI) in the analysis.

It is important to have a simplified methodology for estimating the loads on the anchors in order to generate conceptual anchor designs for feasibility studies and the early phases of design. This paper aims to provide a simplified approach for finding an upper bound limit for the expected loads on the floating offshore wind turbine structure. These loads may be transferred to the anchor through different load paths for different mooring and anchor types (Randolph and Gourvenec, 2011). The load estimation methodology presented in the paper is applicable for most combinations of mooring systems and anchors, however, the anchor sizing example presented considers catenary moorings and suction caisson anchors.

As opposed to offshore oil and gas structures where vertical and horizontal loads dominate the loading, the dominant load for bottom fixed offshore wind turbines is the overturning moment. These moments usually form the design basis for both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) requirements. However, in the case of floating wind turbines, the righting moment which acts against the overturning moment is provided by the floating platform (e.g. a ballast system for a spar supported wind turbine). Therefore, designing against the overturning moment is the task of the naval architect (the designer of the floating platform) and is of little concern to the designer of the foundation (anchor).

The main loads transferred to the anchoring system are the horizontal and vertical forces, see Fig. 1. The horizontal force is caused by the

* Corresponding author.
E-mail addresses: S.Bhattacharya@surrey.ac.uk, Subhamoy.Bhattacharya@gmail.com (S. Bhattacharya).

https://doi.org/10.1016/j.oceaneng.2018.04.013
Received 6 November 2017; Received in revised form 22 January 2018; Accepted 7 April 2018

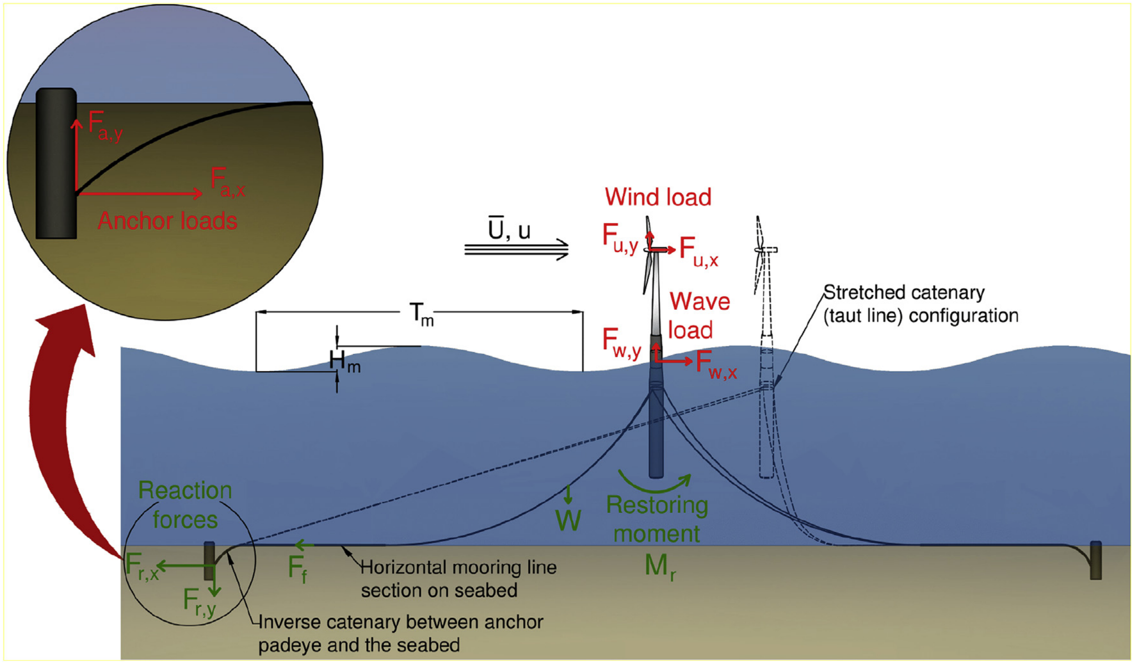

Fig. 1. Normal operating conditions and stretched mooring line configurations with loads and reaction forces. Also shown are anchor loads (vertical and horizontal), mooring segments on the seabed, and inverse catenary at anchor.

combination of

- thrust force on the rotor due to wind - F_u,
- drag force on the wind turbine tower and the platform sections above mean sea level - F_{DT},
- wave load on the spar buoy - F_w,
- current load on the spar buoy - F_C,
- rotational frequency loads such as mass and aerodynamic imbalance loads (1P loads) - F_{1P},
- blade passage frequency loads (3P loads) - F_{3P}.

It has been shown by Arany et al. (2015, 2017) that the wind load on the rotor and the wave load on the support structure dominates the magnitude of loading on the foundation. Furthermore, the 1P, 3P, current and tower drag loads are less significant. It should be noted, however, that current loads are significant for estimating the motions of the platform. Simplified calculation methods are derived below to obtain the ultimate load on the anchor of a spar supported floating offshore wind turbine. An example of an offshore wind turbine supported on a floating spar is then considered based on the Hywind floating platform, currently being built in Scotland (Statoil, 2015). Finally, a simplified anchor sizing procedure is presented, which is demonstrated to produce conservative upper bound estimates for the required suction caisson with similar values to those found in the environmental statement of the Hywind floating wind park (Statoil, 2015).

2. Methodology

In order to analyse the Ultimate Limit State (ULS) load on the Floating Offshore Wind Turbine (FOWT) anchor, the following ultimate load scenarios are defined, using the terminology of DNVGL-ST-0437 (DNVGL, 2017):

(E-1) the combination of the 50-year extreme wind speed (with the turbine shut down) and the maximum wave load due to the 50-year extreme wave height, or

(E-2) the combination of the maximum wind load due to Extreme Operating Gust (EOG) at rated wind speed and the 1-year extreme wave height.

It is not necessary to consider the scenario with the maximum wave height (due to the 50-year extreme wave height) and the maximum wave load (due to EOG at rated wind speed) together as the probability of both occurring together is negligible for the intended design life of 25 years. This is because the maximum wind load occurs when the wind speed is around the rated wind speed and the turbine is operational, while the maximum wave load occurs in a 50-year storm when the turbine is shut down due to the high wind speed. The thrust load on the shutdown turbine is significantly reduced compared to the peak thrust force around the rated wind speed (an example thrust curve is shown in Fig. 2.)

A further complication in the load calculation of FOWTs compared to bottom-fixed structures is the range of allowed motions of the floater itself. Motions in six degrees of freedom (surge (x), sway (y), heave (z) displacements and the pitch (y), roll (x) and yaw (z) rotations) have to be considered for floating structures. An important difference between bottom fixed and floating structures is the allowed roll or pitch angle (typically called tilt for bottom fixed structures). DNV-JS-101 (DNV, 2014) suggests 0.5° total allowed tilt for bottom fixed structures including accumulated rotation, while DNV-JS-103 (DNV, 2013) permits 7° of pitch motion for FOWTs. The pitch motion of the structure introduces a relative velocity component in the wind speed experienced by the rotor, and therefore special control algorithms are required to avoid positive feedback of the motion (Nielsen et al., 2006; Jonkman, 2007).

The maximum load is assumed to be the sum of the wind load F_u, the drag F_D and inertia F_I components of the wave load F_w, the wind drag on the superstructure (structural components above still water level) F_{DT}, and the current load on the floating platform F_C.

$$F_{total} = F_u + F_I + F_D + F_{DT} + F_C \tag{1a}$$

The loads shown here are calculated as loads at the floater padeye where the mooring lines are connected to the floater. This load is transferred through the mooring line to the anchor. Based on the mooring