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CFD simulations of wind loads on a container ship: Validation and impact of geometrical simplifications

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ABSTRACT

Due to the increasing windage area of container ships, wind loads are playing a more important role in navigating the ship at open sea and especially through harbor areas. This paper presents 3D steady RANS CFD simulations of wind loads on a container ship, validation with wind-tunnel measurements and an analysis of the impact of geometrical simplifications. For the validation, CFD simulations are performed in a narrow computational domain resembling the cross-section of the wind tunnel. Blockage effects caused by the domain boundaries are studied by comparing CFD results in the wind tunnel domain and a larger domain. The average absolute difference in numerically simulated and measured total wind load on the ship ranges from 37.9% for a simple box-shaped representation of the ship to only 5.9% for the most detailed model. Modeling the spaces in-between containers on the deck shows a 10.4% average decrease in total wind load on the ship. Modeling a more slender ship hull while keeping the projected front and side area of the ship similar, yields an average decrease in total wind load of 5.9%. Blockage correction following the approach of the Engineering Sciences Date Unit underestimates the maximum lateral wind load up to 17.5%.

1. Introduction

Due to the trend of increasing ship sizes, the wind loads on a ship are playing a more important role in navigating the ship under high winds at open sea and especially in the harbor where the ship is being maneuvered in confined spaces. In the harbor, accurate knowledge of the wind loads is also important to determine berth requirements such as safe working loads of bollards and characteristics of fenders. Wind coefficients used in practice for a ship at open sea are often taken from literature, i.e. OCIMF (1994) and SIGTTO (2007), empirical methods (Haddara and Guedes Soares, 1999), or obtained from wind tunnel tests. Many wind tunnel studies are not a public open resource, although exceptions are for instance the wind tunnel database by Blendermann (1996) and a study of wind loads on a 9000+TEU container ship by Andersen (2013). Also numerical simulation by Computational Fluid Dynamics (CFD) can be used for the assessment of the wind loads.

The use of CFD in wind engineering, also referred to as Computational Wind Engineering, has seen a rapid growth in the past 50 years (Murakami, 1997; Stathopoulos, 1997; Baker, 2007; Solari, 2007; Meroney and Derickson, 2014; Blocken, 2014, 2015; Meroney, 2016; Tominaga and Stathopoulos, 2016). Indeed, also concerning wind loads on ships, several CFD studies have been published, several of which include a comparison between CFD simulations and wind tunnel measurements. Wnęk and Guedes Soares (2015) focused on the wind load on an LNG carrier with a very specific geometrical shape. Koop et al. (2012) compared wind tunnel measurements and CFD simulations for five different ship types: (1) a Moss type LNG carrier; (2) a membrane type LNG carrier; (3) a shuttle tanker at 10 m draft; (4) a shuttle tanker at 22 m draft; and (5) an FPSO (Floating, Production, Storage and Offloading vessel). Both Wnęk and Guedes Soares (2015) and Koop et al. (2012) show good results when comparing the force coefficients C_X, C_Y and C_N obtained from CFD simulations with wind tunnel data. However, the results of the comparison were provided in graphical form but not in an overall percentage difference between wind tunnel and CFD data. None of these studies however provided a detailed analysis of the impact of geometrical simplifications on the predicted wind loads.

This paper presents wind load simulations on a container ship at open sea. The Port of Rotterdam is interested in wind force coefficients for a wide range of ships, which can be provided using CFD simulations. However the results of these CFD simulations require solution

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verification and validation. The current study focuses both on the validation and on the impact of geometrical simplifications of the ship's hull and on-deck container stacks on the obtained wind load. The validation is performed by comparison with wind tunnel data of force coefficients from Andersen (2013). The outline of the paper is as follows. First, the definition of forces and coefficients is provided in Section 2. Next, the wind tunnel measurement setup (Section 3) and the CFD simulations (Section 4) are described. Since the blockage ratio of the ship in the wind tunnel is high, measured and simulated force coefficient values are corrected for blockage in Section 5. In Section 6, the corrected force and moment coefficients of the simple to detailed container ship geometries are compared to the measurement results. In addition, the impact of geometrical simplifications on the total ship wind load is discussed. Next, the ship is placed in a larger domain to study the impact of wind flow blockage caused by the domain wall boundaries. These CFD results are also described in this section. The paper concludes with discussion, future work, and conclusions.

2. Definition of loads and coefficients

The coordinate system of the ship is different from the coordinate system of the wind tunnel/CFD domain used in this paper. The ship coordinate system, shown in Fig. 1, has its origin on the ship centreline, halfway the length between perpendiculars ($L_{pp}/2$), here based on the hull at the waterline. The axes are defined as follows:

– The x-axis is positive forward
– The y-axis is positive to starboard
– The z-axis is positive downward.

The forces studied in this paper are shown in Fig. 1, they are:

– The longitudinal force X (N)
– The lateral force Y (N)
– The moment about the z-axis N (Nm); positive when the ship bow moves to starboard.

The longitudinal force X, the lateral force Y, and the moment around the z-axis N are made non-dimensional as follows:

$$C_X = \frac{X}{\frac{1}{2}\cdot\rho\cdot U^2\cdot A_f}$$
$$C_Y = \frac{Y}{\frac{1}{2}\cdot\rho\cdot U^2\cdot A_s}$$
$$C_N = \frac{N}{\frac{1}{2}\cdot\rho\cdot U^2\cdot A_s\cdot L_{oa}} \qquad (1)$$

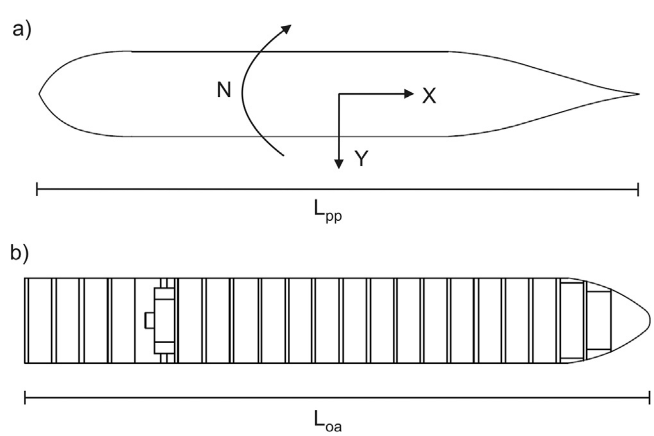

Fig. 1. a) Definition of forces X and Y, and moment N. The origin is located halfway the length between perpendiculars (L_{pp}) here based on the hull at the waterline b) Top view of the ship, showing the length over all (L_{oa}).

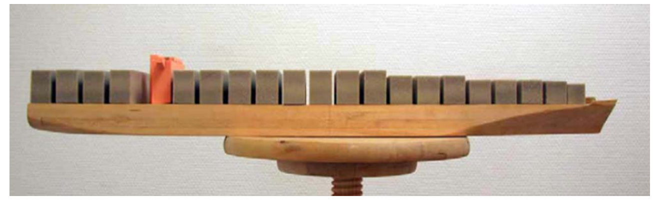

Fig. 2. Wind tunnel model of the container ship (© Elsevier, reproduced with permission; source: Andersen (2013)).

where
ρ=the density of air (=1.225 kg/m^3 at 15 °C).
U=the wind flow velocity experienced by the ship (m/s)
A_f=projected front area of the ship (m^2)
A_s=projected side area of the ship (m^2)
L_{oa}=length over all of the ship (see Fig. 1b)

3. Wind tunnel measurement setup

3.1. Test section and model geometry

A wind tunnel study on wind loads on a post-Panamax container ship was performed by Andersen (2013). A 9000+TEU container ship at scale 1/450 (see Fig. 2) was tested in a closed-loop low-speed boundary layer wind tunnel at FORCE Technology in Kongens, Lyngby, Denmark. The wind tunnel test section has dimensions L×W×H=2.6×1.0×0.7 m^3, with chamfered corners of 0.11 m, as shown in Fig. 3. The container ship was placed in the middle of a turntable with the center point located at 0.79 m from the inlet of the measurement section. For the current study Andersen agreed to share the drawings of the wooden ship model since the CAD drawings are confidential. Roughly the fully loaded ship model size is L×W×H=0.750×0.101×0.077 m^3, where the height originates from the distance between the water line to the top of the highest container stacks (7 high) that cover more than half the ship. The bridge of the ship, depicted in orange in Fig. 2, is located higher, up to about 0.10 m at reduced scale. In full scale this container ship is approximately 340 m long, 45 m wide and 35 m high. The projected front area of the reduced-scale model is A_f=0.0096 m^2 and the projected side area is A_s=0.05 m^2. The length over all L_{oa} is 0.75 m (full scale 340 m) and the length between perpendiculars L_{pp} is 0.71 m (full scale 320 m). In the wind tunnel study by Andersen, more configurations were studied but these are not taken into consideration for the current study since the ship with full load will have the largest wind load. Wind tunnel tests were performed for 19 different wind angles at 10° intervals. The ship is symmetrical with respect to its longitudinal centerline, therefore measurements for the other 17 wind directions were not performed.

3.2. Experimental conditions

Vertical mean wind speed and streamwise turbulence intensity profiles were measured at the center of both turntables in the wind tunnel, located at 0.79 m and 1.94 m downstream from the inlet of the measurement section, with the ship model absent. Note that measuring these profiles at the location of the turntable (=incident profiles) is better than measuring them at the inlet of the test section (=approach-flow profiles), as the incident profiles are those that are representative of the results obtained with the model at that position. Earlier research has shown that approach-flow profiles and incident profiles can differ markedly (Blocken et al., 2008). The fact that vertical profiles measured at different locations in the wind tunnel can differ substantially was also demonstrated by Andersen (2013). Fig. 4a shows the vertical mean wind speed profiles measured at both turntables. Above 0.04 m from the wind tunnel floor, the mean wind velocity is larger when measured