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WIND LOADS ON THE TOPSIDE OF A FLNG VESSEL: WIND TUNNEL MODEL TESTS

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Abstract. *Evaluation of wind loads on offshore structures is crucial in the design and can be decisive in the design of novel structures or innovative designs, such as the large FLNG vessels analyzed in this work, with 450 m length, 81 m draught and a height of 38 m. The tests were carried out in a wind tunnel with a 1:200 scale model attached to a six freedom force and torque sensor subjected to an ocean far from shore atmospheric boundary layer with potential coefficient of 0.10. Two situations were tested: the vessel alone under two different drafts: 17.08 m (fully loaded) and 10.64 m (ballast) in the prototype scale. The same model was tested with the presence of a shuttle vessel, in both tandem and side-by-side configurations. The shuttle is a MossPherical type LNG carrier with 300 m length, 52 m draught and a height of 28 m. The results show that the shuttle vessel has little influence on the FLNG mean wind load in both side-by-side and tandem configuration. The maximum load coefficient observed for the FLNG were: surge coefficient 0.4 , sway coefficient 1.5, roll coefficient 0.3 and yaw coefficient 0.3. On the other hand the FLNG has a large influence on the shuttle vessel, reducing the wind load, according to the relative position. When in tandem configuration, the reduction is of the order of 50% on the drag coefficient and 75% on the yaw moment coefficient since the shuttle vessel was in the wake of the FNLG.*

Keywords: *FLNG vessel, shuttle, wind tunnel, wind load*

1. INTRODUCTION

Evaluation of wind loads on offshore structures is crucial in the design stage of a number of subsystems, such as mooring or dynamic positioning systems, as well as for operations. This can be decisive in the design of novel structures or innovative designs, such as Floating Liquefied Natural Gas (FLNG) vessels analyzed in this work which has dimensions: 450 m in length, 81 m in draught, height of 38m and full draft 17.08m.

Wind tunnel tests of scale models are used to obtain the wind load action on the topside of a vessel (Simiu & Scanlan, 1996; OCIMF, 2008). Numerical modeling with Computer Fluid Dynamics (CFD) software is used with the same purpose (Yuck, Hong, & Choi, 2005; Fujiwara, Yukawa, Sato, & Kato, 2012; Faltinsen, 1990). The experimental approach is normally more costly than the numerical one, mainly because any geometric change requires the construction of a new model and the repetition of all tests. An experimental analysis is, however, still recommended.

The comparison between experimental and numerical approaches using CFD is of great concern as both techniques have their limitations (Silva, Pagot, Nader & Jabardo, 2010). CFD limitations reside mostly on turbulence modeling or computational costs for more advanced models such as LES. On the other hand, scale models are used in wind tunnel tests, so scale effects may appear when passing the results to prototype scale.

In this paper the experimental analysis of a FLNG and shuttle vessel using wind tunnel tests is presented. The numerical analysis was left for future publication.

2. METHODOLOGY

The measurements were performed at the Boundary Layer Wind Tunnel of the Instituto de Pesquisas Tecnológicas de São Paulo – Brazil (IPT), shown in Fig. 1. This wind tunnel is 40 m long and has a test section 3 m wide and 2 m high. The model was positioned on a turntable which makes possible to analyze different wind headings.

Figure 1. Boundary Layer Wind Tunnel at IPT

Two situations were tested taking into account the measurements on the FLNG. The first considered the 1:200 scale model of the FLNG vessel stand-alone (Fig. 2a) while the second considered the FLNG and the shuttle vessel (MossPherical type LNG carrier) in side-by-side configuration (Fig. 2b).

Two situations were also considered when the measurements were performed on the shuttle vessel. It was measured alone and in tandem configuration with the FLNG.

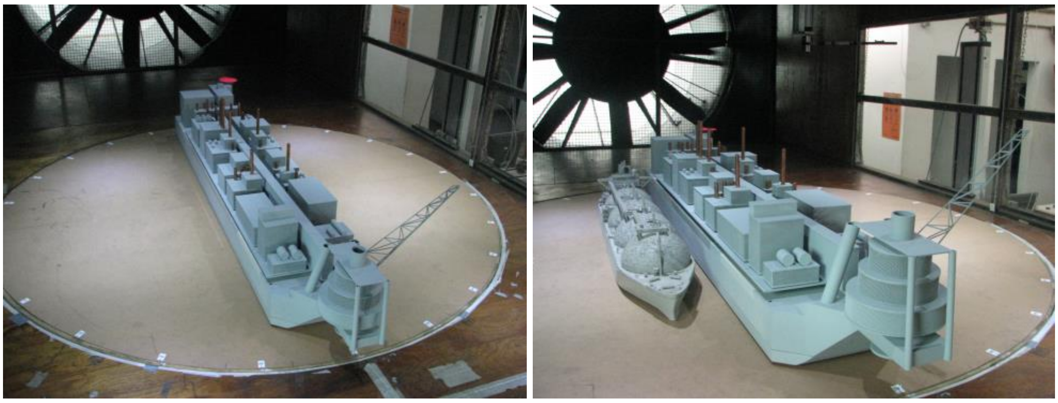


Figure 2. (a) The FLNG and (b) side-by-side with MossPherical scale model inside the IPT's BLWT

2.1 Boundary layer simulated in wind tunnel

In order to obtain all the loads due to wind action in both FLNG and shuttle topsides, the atmospheric boundary layer had to be properly modeled. Therefore, the boundary layer over the ocean was modeled in the wind tunnel. The velocity profile is shown on the left side of Fig. 3. It should be noted that the reference velocity (v_{ref}), used to obtain dimensionless values of the velocity, was taken at a reference height (z_{ref}) of 50 mm, which corresponds to 10 m at prototype scale. This profile can be modeled according to the power law (Equation 1). The right side of the Fig. 3 shows the turbulence intensity profile.

$$\frac{v}{v_{ref}} = \left(\frac{z}{z_{ref}}\right)^{p} \tag{1}$$

The power law exponent for the boundary layer modeled was p = 0.10 (Simiu & Scanlan, 1996).

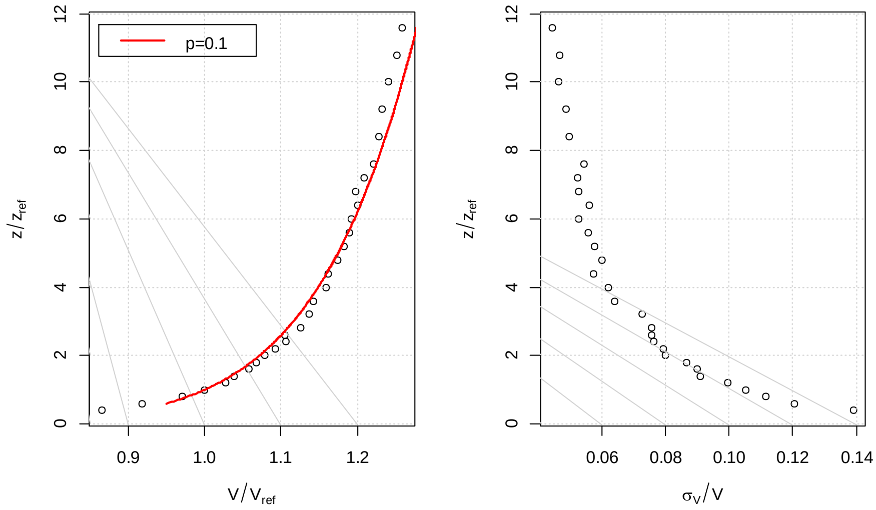


Figure 3. Velocity and turbulence intensity profiles simulated in BLWT

2.2 Force and moment measurements

The measurements were performed by a six degree-of-freedom load cell RUAG 196 which is capable of measuring all three components of force and three components of moment. The coordinate system is shown in the Fig. 4. The results of this paper consider the coordinate system moving with the model, as the load cell is fixed to it. Roll, pitch and yaw moments about x, y and z axes respectively were obtained using the right-hand rule.

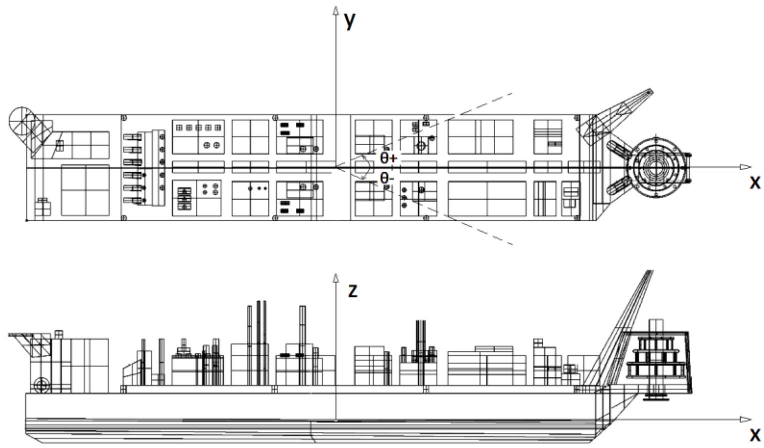


Figure 4. Coordinate system to determine forces and torque

The force coefficients CFi and the moment coefficients CMi expressions are given by:

$$CFi = \frac{F_i}{q.A} \quad (2)$$

$$CMi = \frac{M_i}{q.A.L} \quad (3)$$

where F_i e M_i are the forces and moments measured. The index i correspond to the directions x, y and z; A is the reference surface area adopted for each vessel; L is the reference length adopted for each vessel and q is the dynamic pressure given by:

$$q = \frac{1}{2}\rho.v^2 \quad (4)$$

where ρ is the air density and v its velocity. The dynamic pressure was obtained using the velocity at reference height (50 mm at model's scale), measured with a Pitot tube.

2.3 FLNG vessel alone

The 1:200 FLNG scale model shown in the Fig. 2a was built considering all relevant geometric characteristics. All basic dimensions are presented in Table 1.

Table 1. FLNG prototype and model dimensions

	Length overall	Moulded breadth	Moulded depth	Draft fully loaded	Draft ballast
Prototype	450 m	81 m	38 m	17.1	10.6
Model	2.25 m	0.40 m	0.19 m	0.09	0.05

The wind loads were measured with wind heading varying from 0º up to 360º with 15º steps (Fig. 5) under two different drafts, FLNG fully loaded and ballast, as shown in Tab. 1.

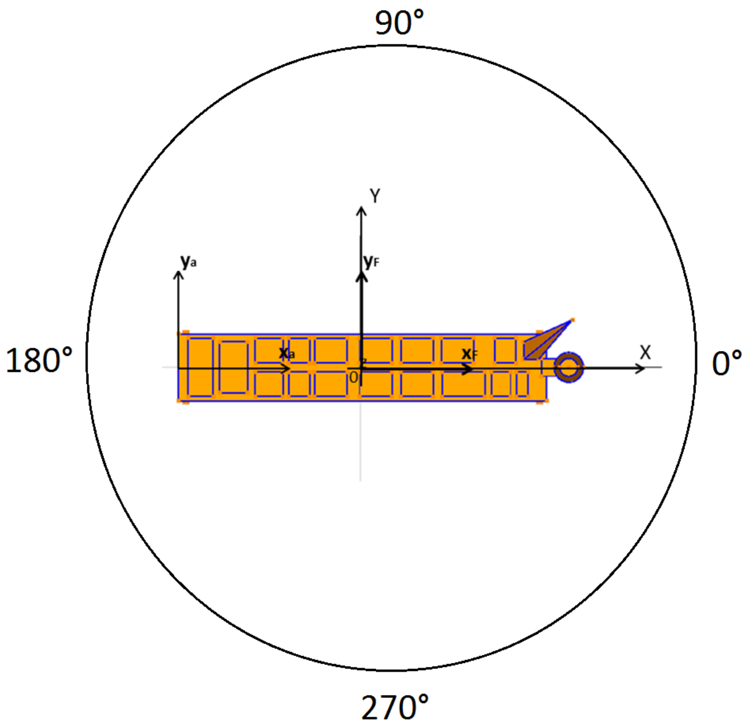


Figure 5. Wind orientation

2.4 Shuttle MossPherical isolated

The 1:200 scale model of the shuttle MossPherical type LNG carrier with basic dimensions exposed in Tab.2 was also built to verify how the wind load acting on the FLNG topside is changed by the presence of the shuttle and vice versa. As was done for the FLNG, the shuttle was previously tested on its own with wind heading varying from 0° to 360° with 15° steps.

Table 2. MossPherical prototype and model dimensions

	Length overall	Moulded breadth	Moulded depth	Draft fully loaded	Draft ballast
Prototype	330 m	52 m	28 m	17.1	10.6
Model	1.65 m	0.26 m	0.14 m	0.06	0.05

2.5 Shuttle MossPherical isolated

For the side-by-side tests two spacing distances were considered. The first one was 4 m at prototype's scale (Fig. 6), which corresponds to 0.02 m at model's scale, and the second was 10 m at prototype's scale, which corresponds to 0.05 m at model's scale. Both FLNG and shuttle MossPherical were tested with two different drafts (fully loaded and ballast), according to Tables 1 and 2. For these tests two different combinations of drafts were considered: when the FLNG was fully loaded, the shuttle was ballast and when the FLNG was ballast the shuttle was fully loaded. These were taken to be the typical worst case situations with respect to mean wind loads.

Forces and moments were measured just on the FLNG for the wind headings of +15°, 0° and -15°.

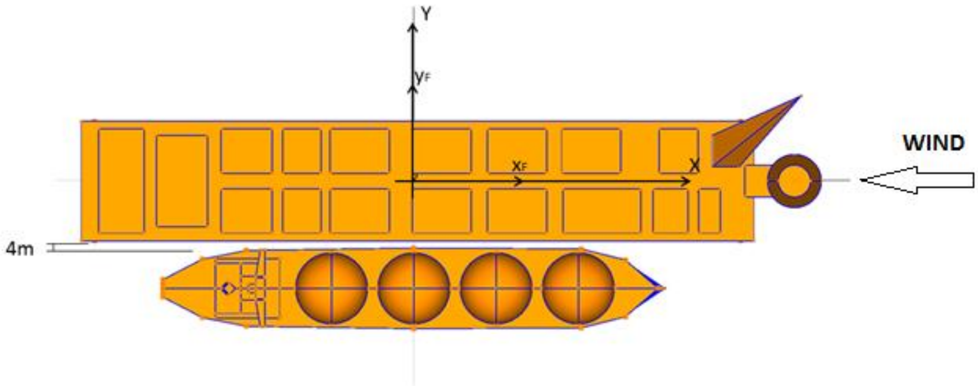


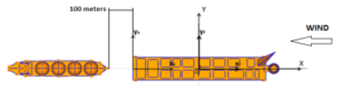
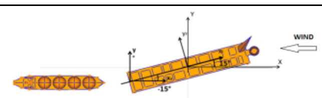
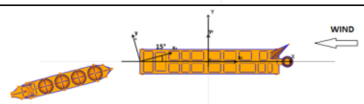
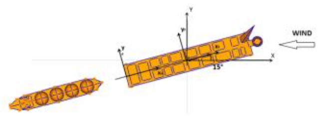
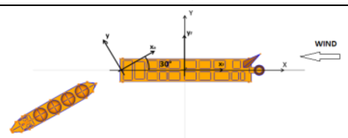
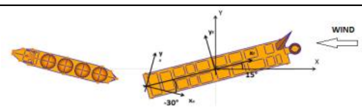
Figure 6. FLNG and MossPherical in side-by-side configuration.

2.6 FLNG and MossPherical in tandem configuration

For the tandem configuration, the shuttle MossPherical was always positioned 0.5 m away (model scale) from the FLNG and downstream. Its influence over the wind load on the FLNG topside was negligible as expected. For this reason, just the forces and moments on the shuttle were measured.

Different heading angles were considered for both vessels as illustrated in Table 3.

Table 3. Heading angle combinations for the FLNG and the shuttle MossPherical considering the tandem tests.

	FLNG 0º	FLNG +15º
MossPherical 0º		
MossPherical +15º		
MossPherical +30º		
MossPherical -15º		

3. RESULTS

The results presented in this section use the notation below.

flngC0 - FLNG on its own and ballast;
flngC1 - FLNG on its own and fully loaded;
SS04C0 - FLNG ballast with MossPherical fully loaded at its side, 4 m away;

SS04C1 - FLNG fully loaded with MossPherical ballast at its side, 4 m away;
SS10C0 - FLNG ballast with MossPherical fully loaded at its side, 10 m away;
SS10C1 - FLNG fully loaded with MossPherical ballast at its side, 10 m away;
mosC0 - MossPherical on its own and ballast;
TmosA00 - FLNG fully loaded at 0º and MossPherical ballast - tandem configuration, forces measured on MossPherical;
TmosA15 - FLNG fully loaded at 15º and MossPherical ballast - tandem configuration, forces measured on MossPherical;

3.1 FLNG on its own and with MossPherical by its side

In this case a comparison was made between the wind load on the FLNG on its own and on the FLNG with the MossPherical at its side. The reference area adopted for the FLNG scale model was A = 1 m^2, while the reference length was L = 1 m.

Figure 7 presents the results of force coefficients along x axis (CFx - surge) according to Fig. 4. The CFx for the FLNG alone was reduced about 10% when the draft of fully loaded was changed to the draft of ballast, as the frontal area was smaller. When the shuttle was positioned in side-by-side configuration, no wind load variation was observed for the headings of 0° and -15°, but a reduction of the absolute value of CFx can be seen for +15°. The reduction was about 15% and is related to the fact that for this wind heading the shuttle is positioned upstream of the FLNG vessel.

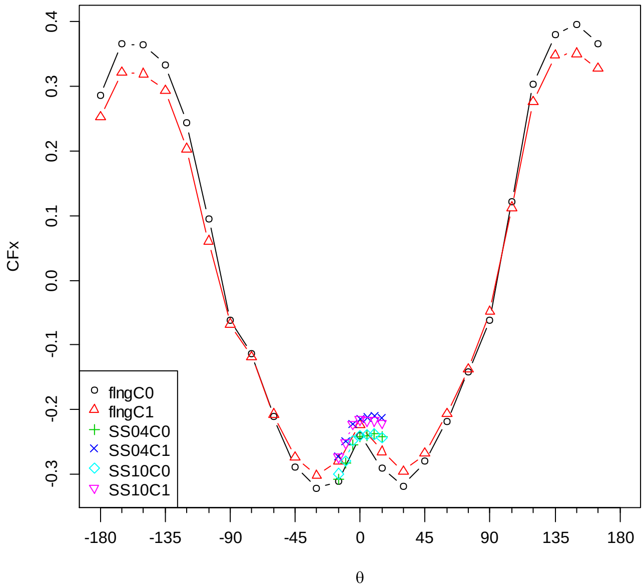


Figure 7. CFx: FLNG alone and side by side with MossPherical

Figure 8 presents the results of force coefficients along y axis (CFy - sway), according to Fig. 4. The value of CFy, considering the FLNG alone, was also reduced about 10% when the draft was changed from fully loaded to ballast at the wind headings of -90° and +90°. The presence of the shuttle in side-by-side configuration did not affect significantly the wind load on FLNG for the headings tested (between -15° and +15°), considering the y axis. Moreover, the change of the spacing distance did not produce any meaningful difference. This denotes that the Venturi effect can be neglected.

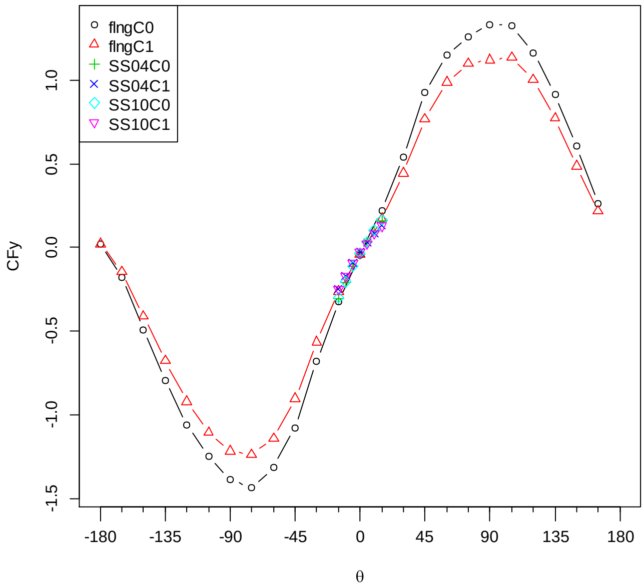


Figure 8. CFy: FLNG alone and side by side MossPherical

In Figs. 9 and 10 the results of moment coefficients of roll and yaw are shown. For the case of CMx (roll) (Fig. 9) the draft change was the only reason for a reduction in wind load. No meaningful differences were observed, for the wind headings tested, when the shuttle was positioned on FLNG's side. The yaw moment coefficient CMz (Fig. 10), however, increased with the presence of the shuttle due to its wake.

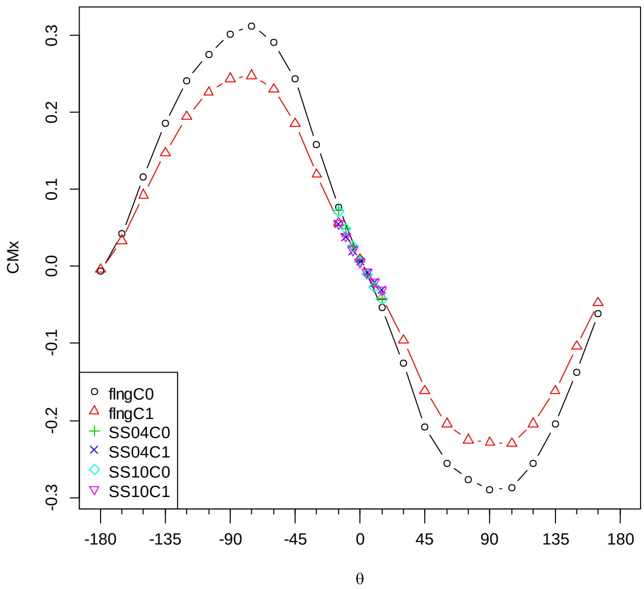


Figure 9. CMx: FLNG alone and side by side MossPherical

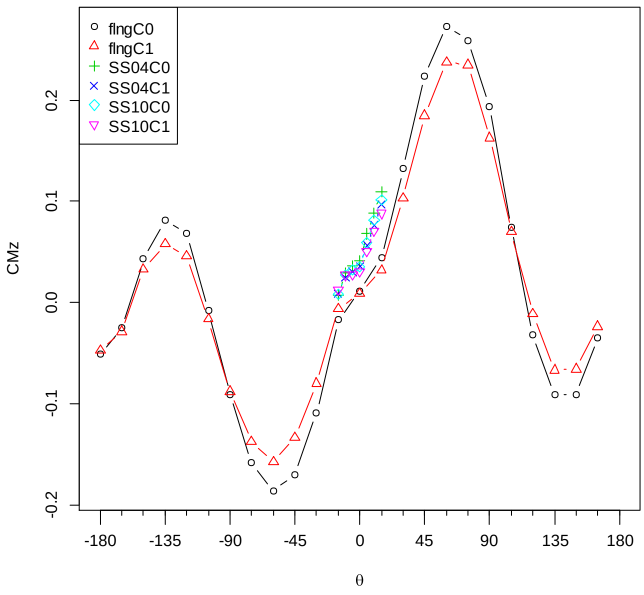


Figure 10. CMz: FLNG alone and side by side MossPherical

The results show that no meaningful difference was produced by increasing the spacing distance between the vessels from 0.02 m to 0.05 m (4 m and 10 m on prototype's scale, respectively). Side-by-side configuration produced meaningful changes only on CFx and CMz.

3.2 MossPherical isolated and in tandem with FLNG

This section presents the results for the FLNG influence on the wind loads acting on the shuttle MossPherical, when the former is positioned upstream in different tandem configurations (see Tab.4). The shuttle was firstly tested alone as stated before. For the shuttle vessel the reference area was $A = 0.5\ m^2$ and the reference length was $L = 0.5$ m.

In the Figs. 11 and 12 the force coefficients measured on the MossPherical for x and y directions are presented. It is clear that the force coefficient respect to x axis (CFx) is drastically reduced when the wind heading is in the vicinity of 0° for both vessels. When both vessels are aligned and the wind heading is 0° the reduction is greater than 50% in comparison to the shuttle alone. This result is expected as the shuttle is much smaller than the FLNG. Once the former is located downstream, the wake of the FLNG has great influence over the wind load on MossPherical's topside. For CFy no meaningful differences between the shuttle alone and with the presence of the other vessel were observed.

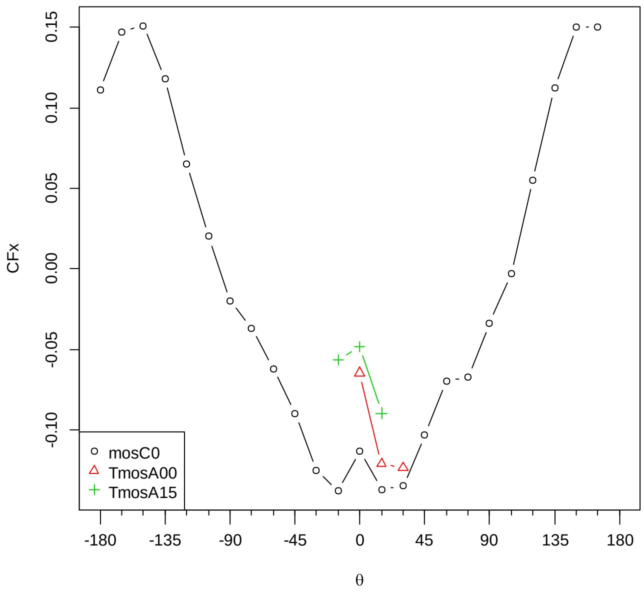


Figure 11. CFx: MossPherical alone and in tandem configuration with the FLNG

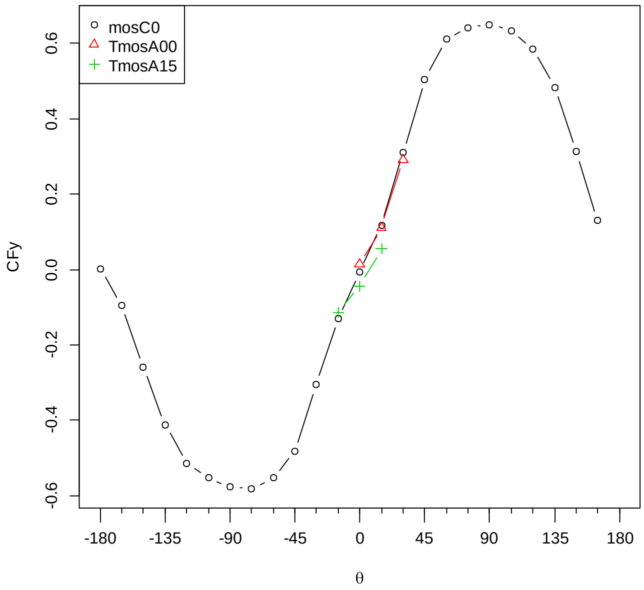


Figure 12. CFy: MossPherical alone and in tandem configuration with the FLNG

Figures 13 and 14 show the results for roll (CMx) and yaw (CMz) coefficients respectively.

All the moment coefficients measured in tandem configurations were pretty much the same of those measured for the shuttle alone. The only exception was for the FLNG positioned upstream at a heading of 15°. For this situation the CMz was reduced.

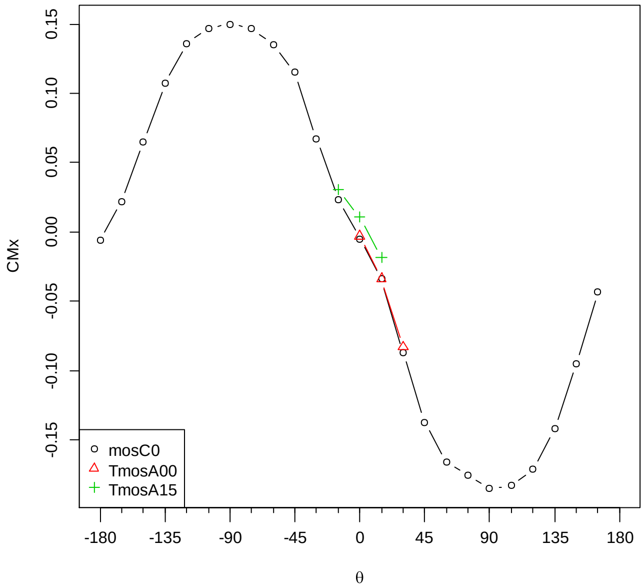


Figure 13. CMx: MossPherical alone and in tandem with FLNG

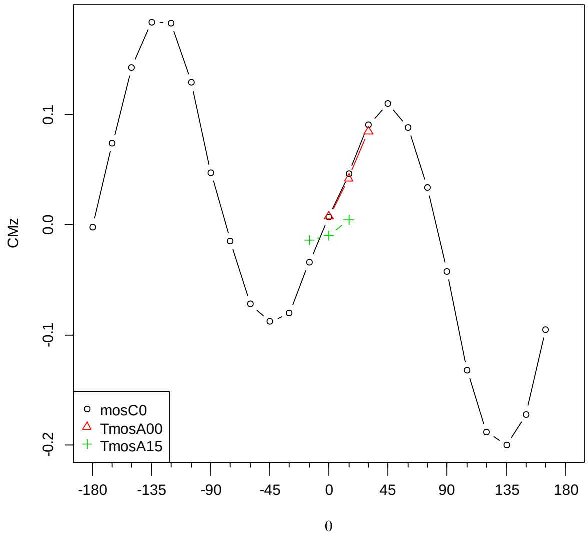


Figure 14. CMz: MossPherical alone and in tandem with FLNG

4. CONCLUSIONS

The analysis of the FLNG alone pointed out that the maximum wind load variation (force and moment coefficients) due to the change in draft was around 10%. In comparison to the side-by-side configuration with the shuttle MossPherical, the absolute value of the CFx (surge) was reduced for the wind heading of +15°. On the other hand, the yaw coefficient CMz (yaw) increased as an effect of the wake of the shuttle. The other force and moment coefficients did not suffer meaningful changes for the situations tested. The spacing distance between the vessels does not exert any influence on FLNG's wind load at all.

The wind load was also measured on the MossPherical topside. It was observed that all the loads due to wind action are reduced when the shuttle is moving downstream of the FLNG.

5. ACKNOWLEDGEMENTS

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