Wind-Tunnel Investigation of Wind Loads on a Post-Panamax Container Ship as a Function of the Container Configuration on Deck

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Wind-Tunnel Investigation of Wind Loads on a Post-Panamax Container Ship as a Function of the Container Configuration on Deck

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ABSTRACT

An investigation of the wind forces acting on a 9,000+ TEU container ship has been carried out through a series of wind tunnel tests. It was investigated how the wind forces depend on the container configuration on the deck using a 1:450 scale model and a series of appropriate container configurations. The wind tunnel tests were carried out in the naturally existing boundary layer of the wind tunnel. The longitudinal and transverse forces and the yaw moment were measured and the measurements were corrected for the effects of the boundary layer and blockage in the wind tunnel. The results are presented as non-dimensional coefficients. It is concluded, that the measured forces and moment depend on the container configuration on deck, and the results may provide a general idea of how the magnitude of the wind forces is affected by a given container stacking configuration on a similar container ship.

KEY WORDS

Wind loads, container ship, container stacking, wind resistance, wind tunnel tests.

INTRODUCTION

The fuel efficiency and performance of container vessels is of great concern for shipowners due to economic and environmental considerations. Much effort is put into measures that can improve ships' fuel efficiency by even a few per cent. All ships experience air and wind resistance while under way, and they may experience adverse effects of wind while manoeuvring in harbours and confined waterways.

The wind resistance is proportional to the relative wind speed squared and direction and the projected windage area of the ship. Unlike most other ship types a container ship has a windage area that varies significantly with the loading condition i.e. the configuration of containers on deck, and apparently little is done to minimise the wind resistance on board most container ships.

Wind tunnel investigations of the container configuration's influence on the wind forces were carried out by Andersson (1978) using a model of a 211 m container ship with 19 different deck configurations. Blendermann (1997) did wind tunnel tests of ten container configurations resembling random configurations on two ships with overall lengths, L_{oa}, of 198 m and 294 m. Other investigations have been carried out for more general ship types, e.g. Berlekom (1981) and Aage (1968).

Today the size of container ships has increased and it is considered relevant to investigate how forces and moments depend on the container configuration on the deck of a 9,000+ TEU container ship. Even more importantly the service speed of container ships has increased in recent years, which results in relative wind directions closer to head wind and higher relative wind speeds. The aim of the present study is, through a purely experimental approach, to provide directly applicable results for container ship operators.

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METHODS

Coordinate system

The Cartesian right handed coordinate system (Figure 1) is fixed to the ship. The axes originate from the intersection between the centerline and the baseline in $L_{pp}/2$ and the axes are defined as follows (cf. ITTC (1993)):

- The *x*-axis is positive forward.
- The *y*-axis is positive to starboard.
- The *z*-axis is positive downwards.

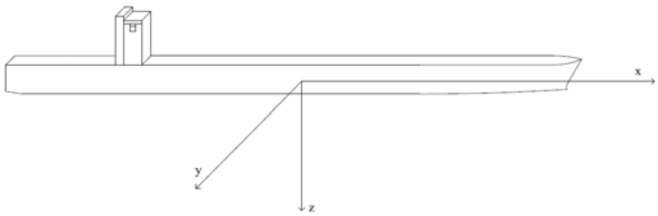

Figure 1 – Definition of coordinate system.

In the wind tunnel two forces and one moment were measured (see Figure 2):

- Longitudinal force, positive in the direction of *x*. Here designated *X*.
- Transverse force, positive in the direction of *y*. Here designated *Y*.
- Vertical force, positive in the direction of *z*. Here designated *Z*.

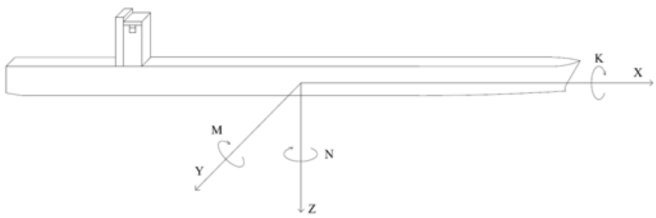

Figure 2 - Definition of forces and moments.

Wind Forces on Ships

The wind forces on a ship generally influence the ship by increasing the propulsion resistance. The longitudinal force generally constitutes the largest part of the total wind induced resistance.

The transverse force causes yaw, drift and deviation from the course, which can cause added resistance in two ways: The ship's heading is not aligned with the steered course, which alone gives greater resistance. The drift must be compensated for, which means that the rudder angle must be increased. Increased rudder angle will also cause increased resistance. Its magnitude compared to the longitudinal force is discussed by Andersson (1978) and Berlekom (1981). According to Andersson (1978) the induced resistance from the increased rudder angle plays an insignificant role, while according to Berlekom (1981) it can be of the same magnitude as the longitudinal force for stronger winds.

Generally the longitudinal force is of greatest importance for the propulsion resistance. Its share in the total resistance is discussed by Berlekom (1981) and Aage (1968). According to Berlekom (1981) the wave and wind resistance are of the same magnitude. However, Aage (1968) states that the wind resistance rarely makes up more than 10% of the total resistance. There is general agreement that under normal operational circumstances the wave resistance constitutes the largest contribution of the two to the total resistance.

Relative Wind

When the air flows over the ocean surface a natural boundary layer is formed. The local wind field caused by the movement of the ship does not have a boundary layer and is homogenous as illustrated in Figure 3.

Figure 3 - Local wind field caused by ship and the natural wind gradient at sea.

The wind field encountered by the part of the ship above the sea surface is thus a combination of the wind field with a boundary layer and the homogenous wind field caused by the ship's forward speed. The relative wind direction φ is found by vector addition of the ship's wind field and the relative wind (Figure 4), where $\varphi = 0°$ is head wind.

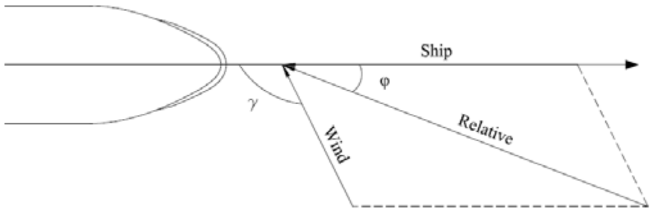

Figure 4 - Relative wind direction φ.

Non-dimensional Coefficients

The measured forces and moments are post-processed into non-dimensional coefficients to make the results independent of wind velocity and ship size. The results are normalised using the flow velocity in the middle of the wind tunnel, U_{free}, the density of the air, ρ, and the ship's length between the perpendiculars (L_{pp}) in a suitable exponent. (Equations [1] to [3]):

$$X' = \frac{X}{½ \cdot \rho \cdot U^2 \cdot L_{pp}^2} \quad [1]$$

$$Y' = \frac{Y}{½ \cdot \rho \cdot U^2 \cdot L_{pp}^2} \quad [2]$$

$$N' = \frac{N}{½ \cdot \rho \cdot U^2 \cdot L_{pp}^3} \quad [3]$$

The described coefficients are convenient if different configurations of the same ship are to be compared because they are normalised using the constant L_{pp}. If the measurement results are to be used for a ship which is not geometrically similar to the tested ship, the results can be non-dimensionalised using the ship's projected areas A_s and A_f as done in Andersen (2011). The latter form is most suitable when comparing ships, which are not geometrically identical.

Earlier Investigations

It is concluded in Blendermann (1997) that the container configuration influences the wind forces. Uneven bay height increases the wind resistance. According to Blendermann (1997) a ship with randomly stacked containers on deck compared with a fully stacked ship experience:

- Significantly higher longitudinal force.
- Smaller transverse force.
- Smaller roll moment.

- Smaller yaw moment.

Additionally, a ship with random configuration on the fore deck (forward of the superstructure) and a full container stacking on the aft deck has a significantly reduced yaw moment for relative wind directions between 0° and 50°. In Andersson (1978) the individual configurations are more thoroughly described and the following conclusions are drawn:

- Changes in the configuration on the aft deck have little influence on the magnitude of the longitudinal force. Thus there is little difference between the empty ship and a ship, which only carries containers on the aft deck.
- Changes in the configuration on the fore deck are of great importance for the magnitude of the longitudinal force.
- Random container configuration can increase the longitudinal force significantly. Large irregularities such as many empty bays can increase the longitudinal force by 70-100% compared to the fully stacked reference ship for relative wind from ahead.
- Streamlining of the container configuration on the front deck has little influence on the longitudinal force.
- The influence of the configuration on the yaw moment is remarkable. A configuration with containers on the front deck but without containers on the aft deck is disadvantageous (the yaw moment becomes large) for relative wind from ahead.
- The influence of the side area of the ship on the transverse force and the roll moment is large.
- A configuration with full load on the fore deck and streamlining of the aft deck is the most favourable of the 19 tested configurations.

Model

The model is of scale 1:450. Only the part of the ship above the waterline is modelled. For practical reasons the model only has one draught which is the design draught of 13 meters. The ship has the following approximate main dimensions:

L_{oa}: 340 m
L_{pp}: 320 m
Beam: 45 m

The maximum length of the model is limited by the width of the wind tunnel. The model must be able to be turned 180° in the wind tunnel, which limits the length of the model to about 75 cm and a model scale of 1:450.

The model is very simple, but the small degree of detail of the model is considered acceptable. The effect on the model test results of a high degree of detail would be larger than in full scale, because the relative effect of all the small details would be larger in the model tests.

The model has 20 container bays numbered from aft as seen in Figure 5 and the model is seen in Figure 6. The container blocks were cut out in hard foam and were fixed to the model with strong double adhesive tape in order to make them interchangeable.

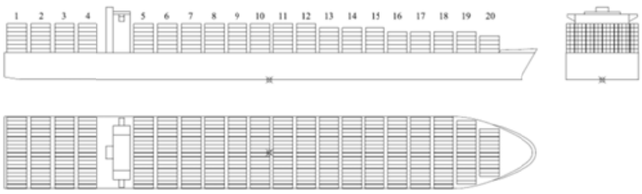

Figure 5 - Reference condition (01-01-02) with full container stacking and numbered bays.

Figure 6 - Wind tunnel model with fully stacked deck.

Wind tunnel Equipment

The wind tunnel is a closed low-speed tunnel with a maximum speed of 80 m/s. An outline of the wind tunnel is seen in Figure A1 in Appendix A. The model and the strain gauge are mounted through holes in the floor of the wind tunnel. The wind tunnel can be seen in Figure A2 in Appendix A.

Boundary Layer

The described combined wind field is difficult to create in any wind tunnel and impossible to create in the particular wind tunnel used in this series of tests. Instead the boundary layer was measured prior to the tests in two different locations in the wind tunnel in order to locate the most suitable position of the model in the wind tunnel and to enable correction for the effect of the boundary layer on the measurements. The boundary layer was measured with a hotwire instrument. The natural velocity profile of the wind flowing across the ocean can be described as:

$$\frac{U(H)}{U(H_{10})} = \left(\frac{H}{H_{10}}\right)^{\propto}, \quad [4]$$

where H is the height above the sea surface in meters, H_{10} is a reference height which traditionally is 10 meters. α is the exponent representing the velocity profile. For velocity profiles over the ocean α is usually between 0.11 and 0.14, which is then the exponent which should be approximated when wind tunnel tests of ocean structures are carried out (Norwegian Maritime Directory (1997)).

The average flow speed, U_{mean} is plotted as a function of the height above the floor of the wind tunnel, z, in Figure 7. In the same plot the α = 0.11 velocity profile scaled to the model scale is plotted for comparison. For the boundary layer 0.79 m downstream α = 0.139 and 1.94 m downstream α = 0.155. Consequently, it was decided to perform the wind tunnel tests in the location 0.79 m downstream of the beginning of the test section, because the boundary layer there is the closest approximation to the 0.11 profile.

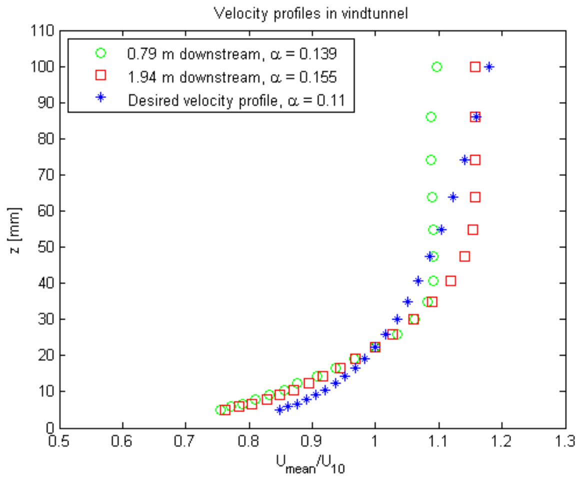

Figure 7 - Hot wire measurements of mean velocity in wind tunnel. The reference height of 10 m corresponds to 22.2 mm in the model scale.

From Figure 7 it is seen that the velocity becomes constant in z = 41 mm, which thus is the thickness of the boundary layer in the chosen position.

Reynolds number

Prior to the tests it was investigated how the measured coefficients depended on the Reynolds number, *Re,* determined by the flow velocity U in the middle of the wind tunnel, the characteristic length L which was taken as L_{pp} of the model and the kinematic viscosity of air, ν, which was considered constant $\nu = 1.5 \cdot 10^{-5}$ m²/s.

Re is of great importance for model tests, and generally *Re* in model scale should correspond to the full scale *Re*. However, the required flow speed is not possible to obtain in the wind tunnel in question. Nevertheless it is considered possible to conduct model tests, even if the *Re* is not matched, if the model is sufficiently "sharp-edged" and the flow separation corresponds to full scale.

To confirm the independence of the flow velocity a test of the *Re* dependency was conducted. The measurements were carried out for $\varphi = 0°$, 45° and 90° with a minimum flow velocity of 5 m/s and maximum 60 m/s. The measured coefficients *X’ Y’* and *N’* are plotted as function of *Re* in Figure 8.

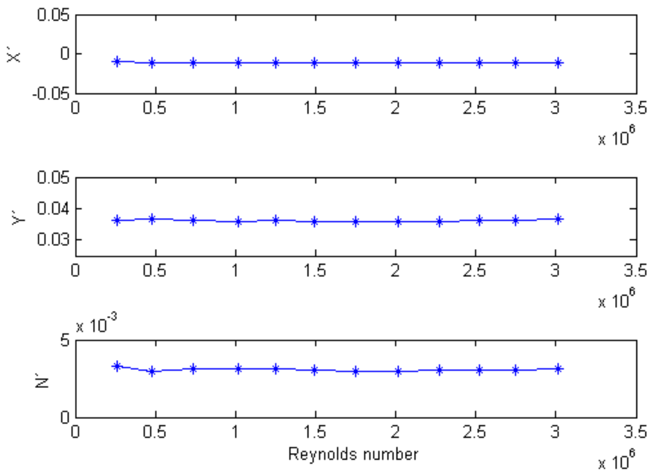

Figure 8 - Reynolds number test for $\varphi = 45°$.

As can be seen from Figure 8 the coefficients became constant, and thereby independent of the flow velocity, for $Re > 1.5 \cdot 10^6$. It was thus decided to carry out the tests at a flow velocity of about 45 m/s, which corresponds to $Re = 2.2 \cdot 10^6$.

Correction for Boundary Layer

The free flow velocity U_{free} was measured in a position in the middle of the wind tunnel (340 mm above the wind tunnel floor) using a pitot tube. However, the velocity used for making the measurement results non-dimensional, cf. Eqs. [1-3] is the velocity experienced by the model at a given reference height. The model is located within the boundary layer and thus the flow velocity experienced by the model is lower than the free flow velocity.

From the measurements of the boundary layer in Figure 7 it was observed that U became constant at $z = 41$ mm. Thus $H = 41$ mm was used for the correction (41 mm corresponds to 18.45 m in full scale). The measured free flow velocity was thus corrected to the height of 10 m, which corresponds to 22.2 m in the model scale, using Equation [4] and the exponent $\alpha = 0.139$ previously found.

Correction for Blockage

In the wind tunnel the model partly blocked the flow and thus affected the flow, so a further correction had to be applied. The blockage was max 7.4% for the fully stacked model and for the empty model the blockage was 1.18%. All measurement results were corrected for blockage using a standard procedure for wind tunnel tests; cf. Engineering Sciences Data Unit (1980).

Container Configurations

Many considerations are taken into account when loading containers on board a ship. Some are:

- Reefer containers must be placed where the power supply for the refrigeration is located. Hazardous goods containers have designated locations.
- Containers are loaded for unloading in the right order at different ports of call.
- Heel, trim and stability are taken into consideration when loading the ship.

- The weight of the individual containers dictates the maximum allowable height of a stack to avoid destructive forces on the containers in a seaway.
- The line of sight from the bridge must be 500 meters or two ship lengths whichever is the smaller, i.e. it must be possible to see the sea surface from the bridge 500 m in front of the ship, which dictates how high the containers in front of the bridge can be stacked (SOLAS 2001).

Thus, it is far from coincidental how the containers on deck are stacked, but the result may very well look coincidental. The influence of container configuration on the wind forces rarely seems to be taken into account.

For the model tests it was convenient to vary the height of an entire bay in contrast to varying the individual stacks. Thus, in most cases a container bay has the same height across the width of the ship. The configurations are described in the following together with the expected outcome of the tests. Illustrations of the configurations are found in the Results section.

<u>Even deck load</u>
Configurations with an even load of one, three and five containers on deck were tested.

<u>Streamlined</u>
The effect of streamlining the container configurations was investigated to see whether there is a difference between streamlining the configuration fore and aft of the bridge. It is expected, as stated by Andersson (1978) that streamlining aft has the largest reducing effect on the longitudinal forces when the ship is encountering relative wind from fore.

<u>Empty bays</u>
Some bays can be completely empty and it is concluded by Andersson (1978) that these "holes" in the configuration have a large influence on the longitudinal force, which is expected to increase with increased number of empty bays. The expected worst case scenario is when every second bay is empty.

<u>Random load</u>
Most container configurations appear more or less random. Obviously there are different degrees of "randomness" or "unevenness" in container configurations, examples of which have been exemplified in the selected configurations. The degree of unevenness is considered to depend on the difference between the highest and lowest container stacks. The bigger the height difference the larger the longitudinal force is expected to be. By Andersson (1978) it is suggested that full load on the aft deck and random load on the fore deck can influence the yaw moment significantly and this effect was investigated.

<u>Reduced stack height in the outermost bays</u>
Maersk Line and other ship owners reduce the maximum stack height in the outermost bays to reduce the risk of losing containers overboard. It is expected that this primarily will reduce the transverse force and only have limited effect on the longitudinal force.

RESULTS

The measured forces were made non-dimensional using the measured dynamic pressure for each test run. Thereafter the coefficients were corrected for boundary layer and blockage as previously described. The coefficients were plotted as a function of the relative wind direction φ.

Uncertainties and Irregularities

Several uncertainties could have influenced the test results and some additional tests were carried out to shed light on the reproducibility of the measurement results:

- Difference in measurement results for the same container configuration if the model is completely dismantled from the strain gauge and removed from the wind tunnel between two otherwise identical measurement runs.
- Difference in measurement results for two subsequent measurement runs without removing the model.
- Difference in tests runs clockwise and anti-clockwise.

The first item was investigated with two different configurations and a slight difference could be observed. The largest discrepancy was 6.7%. Generally, the model was not removed from the wind tunnel between tests, since it was possible to change the container models with model mounted in the strain gauge. It was not possible to observe any difference in measurement results in two immediately subsequent and identical measurement runs.

All tests were performed by turning the model clockwise in the wind tunnel assuming the flow in the tunnel was symmetrical. However, by turning the model anti-clockwise it was observed that the measurements were not exactly mirrored, which means that the flow in the wind tunnel is not perfectly symmetrical.

The velocity profile in the wind tunnel can cause discrepancies when transferring the measured forces to full scale since it is not possible the create a boundary layer in the wind tunnel which fully represents the real boundary layer combined by the natural wind boundary layer and the constant velocity profile from the ship's forward speed. When scaling to full scale Aage (1968) claims that the result can be errors up to 40%.

Scaling inaccuracies may also influence the results. Most details are omitted on the model which means that the coefficients are too small compared to full scale. To precisely assess this uncertainty one will have to conduct full scale tests.

Results

The results are presented in the following. It was apparent, as expected, that the measured forces and moments did indeed depend on the container configuration on deck. Of greatest interest for steaming ships is the behaviour of the forces for relative wind directions between 0-50° (head winds). The fully stacked condition is used as the reference condition (see Figure 5).

Uniform configurations

In general the forces on the ship were expected to increase with increasing number of containers in the stacks on deck. The greatest effect of increased stacking height was on the transverse force as seen in Figure 9. The longitudinal force was also influenced - more so for following relative wind directions. The yaw moment was also influenced significantly for relative wind between 0° and 40° The configuration with an even layer of one (Figure 9), three (Figure 10) and five (Figure 11) containers on deck are compared with the fully stacked configuration (Figure 5) in Figure 12.

Figure 9 - Configuration 01-01-04 with one layer of containers on deck. 15.8% of full deck stacking.

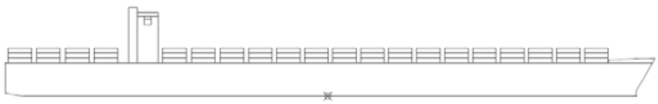

Figure 10 - Configuration 01-01-03 with three layers of containers on deck. 47.3% of full deck stacking.

Figure 11 - Configuration 01-01-05 with five layers of containers on deck. 78.25% of full deck stacking.

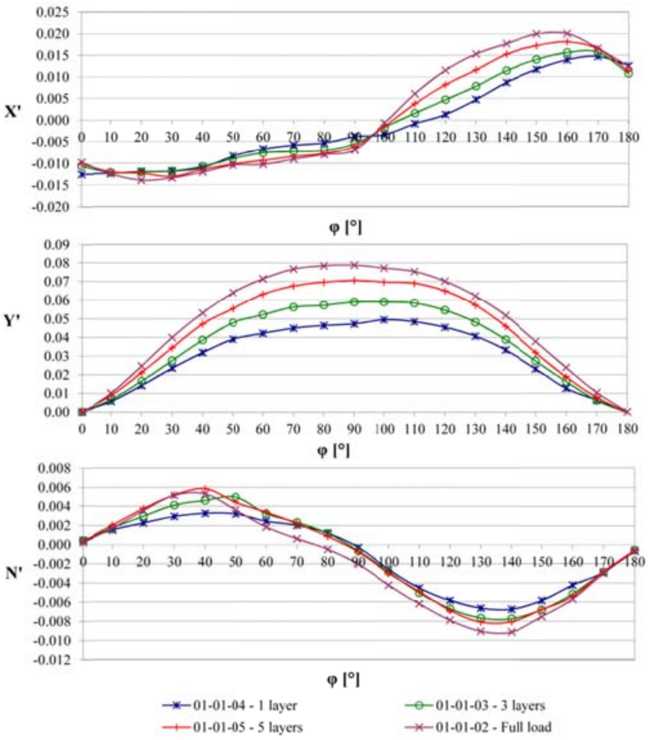

Figure 12 - Configurations with one, three and five layers of containers on deck compared to the fully stacked condition.

<u>Streamlined configurations</u>

The smallest longitudinal force was found for the configuration streamlined both fore and aft (Figure 14) as seen in Figure 16. Compared to the fully loaded configuration the reduction in longitudinal force was significant, and for a relative wind direction of 50° the difference was 43%. The difference was almost as large for the configuration that was streamlined aft only (Figure 13). Contrary to what is stated by Andersson (1978) it was in this case not the configuration streamlined aft which has the smallest longitudinal coefficient for head wind.

For the yaw moment there was a distinct difference. The configuration streamlined on the fore deck (Figure 15) had a clearly smaller yaw moment than the other configurations for head winds, and the configuration streamlined aft had the largest yaw moment for head winds. For following winds the opposite scenario was the case.

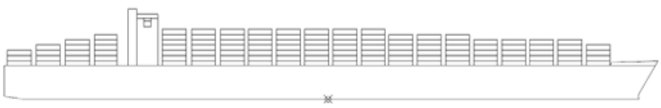

Figure 13 - Configuration 01-04-01 streamlined aft. 91.9% of full deck stacking.

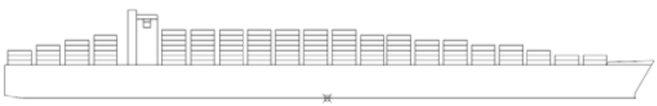

Figure 14 - Configuration 01-04-02 streamlined fore and aft. 83.1% of full deck stacking.

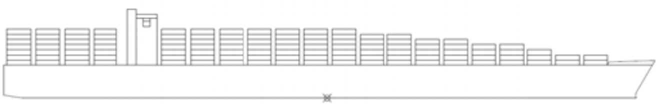

Figure 15 - Configuration 01-04-03 streamlined fore. 91.1% of full deck stacking.

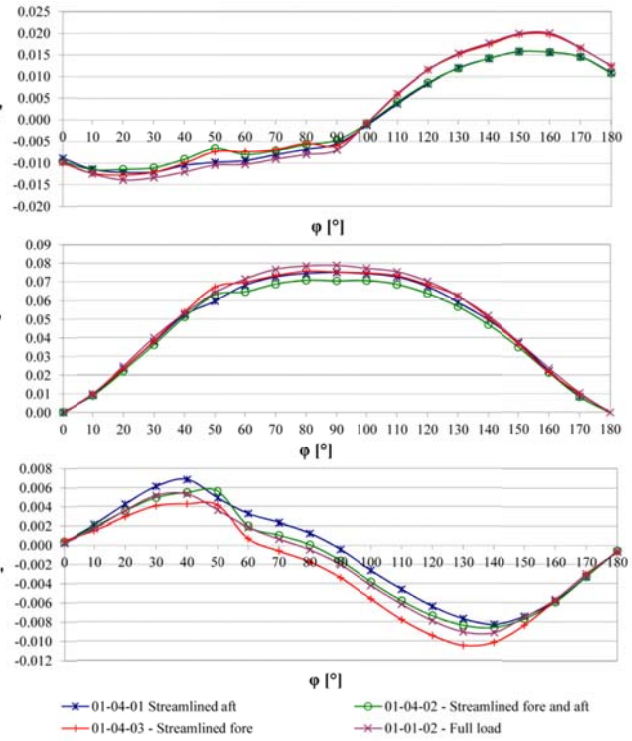

Figure 16 - Streamlined configurations compared to the full load condition.

<u>Empty bays</u>

The configuration with every second bay empty (Figure 17) was the most extreme case in this group of configurations. For head winds the longitudinal force was significantly larger than for any other configuration, which can be seen in Figure 18. In fact, the measured longitudinal force for relative wind from 30° was more than twice the magnitude than the fully stacked reference condition.

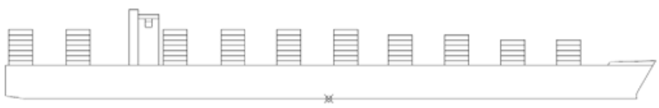

Figure 17 - Configuration 01-02-01 every second bay empty. 51.1% of full deck stacking.

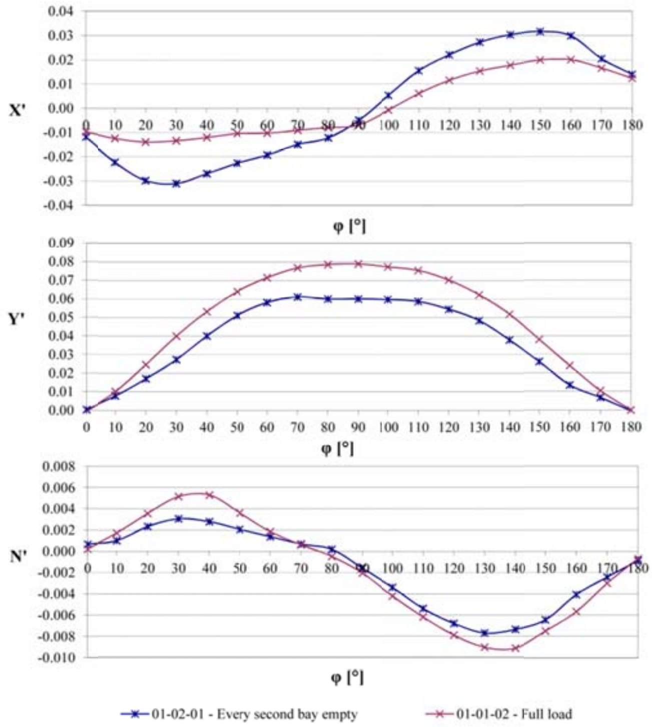

Figure 18 - Configuration with every second bay empty compared to the fully stacked condition.

Random stacking of containers

A configuration with random stacking on the entire deck (Figure 19) was compared with a configuration with random stacking on the front deck and full stacking on the aft deck (Figure 20) and the fully stacked reference condition. The comparison is illustrated in Figure 21. The longitudinal force turns out to be significantly larger for the two conditions for relative head winds. The difference for relative wind from 30° is 54%. The tendency for following winds is the same though less pronounced. As suggested by Blendermann (1997) the configuration with random stacking on the fore deck and full stacking on the aft deck could experience a reduced yaw moment compared to the totally random configuration for head winds. This proved to be the case here as well.

Figure 19 - Configuration 01-05-01. Random load over all. Highest stacking height seven containers. 68.9% of full deck stacking.

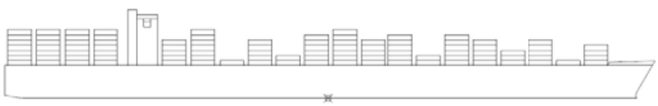

Figure 20 - Configuration 01-05-02. Random load fore, full load aft. Highest stacking height seven containers. 77.8% of full deck stacking.

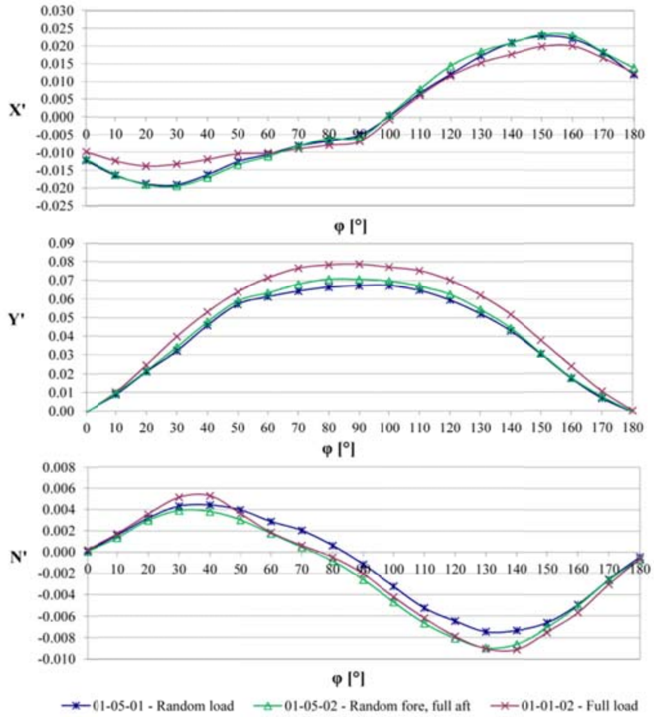

Figure 21 - One configuration with random stacking overall and one with random stacking on fore deck and full stacking aft compared to the fully stacked condition.

Random stacking over all of maximum stack height of seven (Figure 19) and five containers (Figure 22) respectively were also investigated and are compared in Figure 23. As expected the longitudinal force was smaller for the lower stack heights. Compared to the reference condition the difference for relative wind from 30° the difference is 30% and 46% respectively.

Figure 22 - Configuration 01-05-03. Random stacking over all. Highest stacking height five containers. 46.6% of full deck stacking.

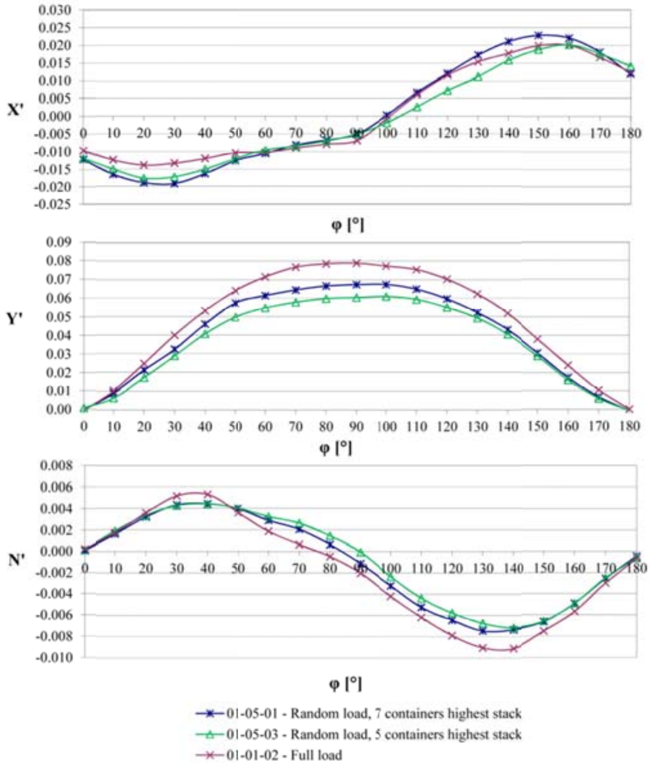

Figure 23 - Random stacking with highest stacking height of seven containers, compared to the random configuration with highest stacking height of five containers compared to the full load configuration.

Two different configurations with the same maximum stacking height of five containers but different degree of unevenness were compared. The more uneven configuration (Figure 22) had a larger difference in stacking height in the bays. The two are compared to the completely even configuration of five containers high (Figure 11) in Figure 25. For relative winds from fore there is a clear difference in the longitudinal force. The most even of the configurations (Figure 24) is close to the completely even configuration. For relative wind from 20° the difference is 50% between the more uneven and the even and 17% between the less uneven and the even configuration.

Figure 24 - Configuration 01-05-06. Random load overall. Highest stacking height five containers, but more even profile than configuration 01-05-03. 58.7% of full deck stacking.

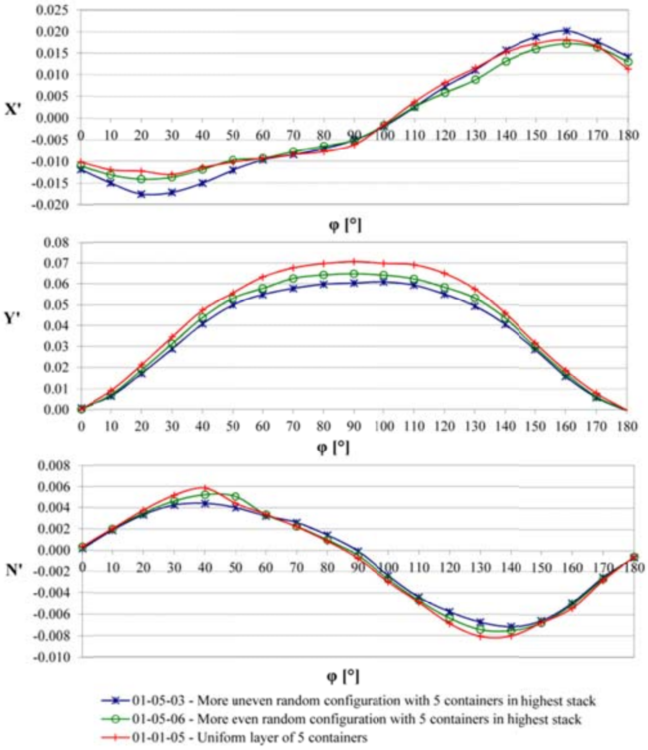

Figure 25 - Two random configurations with highest stacking height of five containers and different degree of unevenness compared to the configuration with a uniform layer of five containers.

Three almost identical configurations were compared. They were both randomly stacked and the only difference in the stacking height was in bay 10 where the stacking height was zero (Figure 27), five (Figure 22) and seven containers (Figure 26) for the three configurations respectively. The comparison is seen in Figure 28. The configuration with the highest stacking height in bay 10 has the highest longitudinal force of the three, while there was little difference between the configuration with five and zero containers in bay 10. It thus appears that the influence on the longitudinal force is larger from a high bay than from a "hole" in the configuration of similar magnitude.

Figure 26 - Configuration 01-05-04. Random load overall. Highest stacking height seven containers in bay 10. 48.25% of full deck stacking.

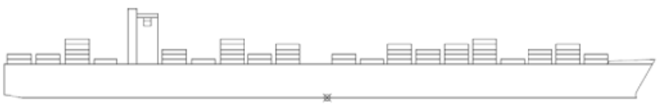

Figure 27 - Configuration 01-05-05. Random load overall. Highest stacking height five containers. Bay 10 empty. 42.6% of full deck stacking.

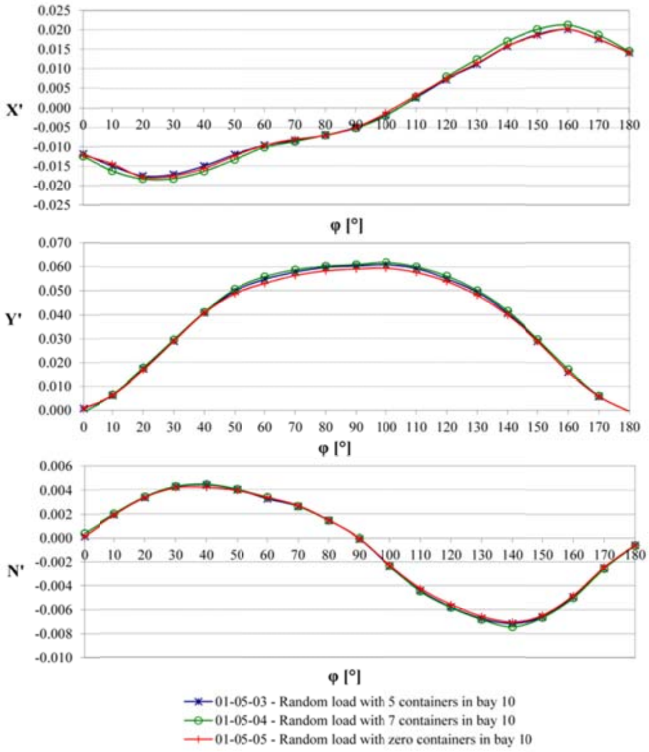

Figure 28 - Three almost identical random configurations. Only difference is in bay 10.

Pyramid-shape

Three more or less pyramid-shaped configuration were compared. The first had full load except for one container in the outermost stack in all bays (Figure 29). The second had full load except two containers in the outermost stack and one in the next stack (Figure 30). The third had six containers less in each bay on each side (Figure 31).

Figure 29 - Configuration 02-01-01. One container less in each bay on each side. 98.2% of full deck stacking.

Figure 30 - Configuration 02-01-02. Three containers less in each bay on each side. 94.6% of full deck stacking.

Figure 31 - Configuration 02-01-03. Six containers less in each bay on each side. 89.3% of full deck stacking.

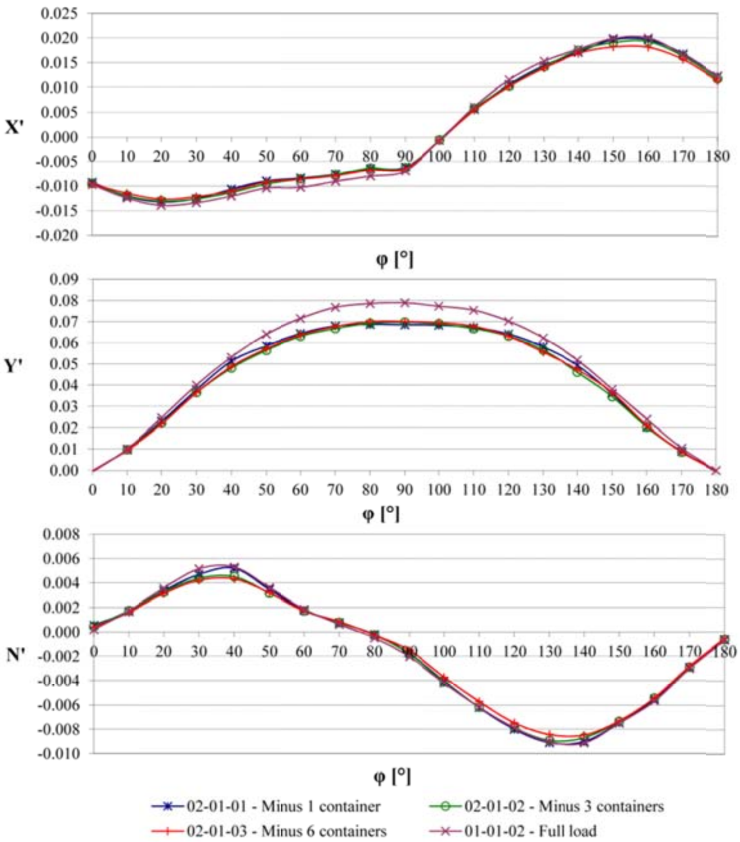

Figure 32 - Three more or less pyramid shaped configurations compared to the fully stacked condition.

As seen in Figure 32 the longitudinal force was smaller for all three configurations than for the full load reference condition, but the difference between the three pyramid-shaped configurations was small. The biggest difference was expectedly on the transverse force, which was reduced for all three, but again there was not much difference between the three configurations. The difference in transverse force for relative wind from 90° between the pyramid configurations and the full load reference condition was 13%. For any difference in the yaw moment the full load reference condition was consistently higher.

DISCUSSION

The small degree of detail probably means that caution must be exercised when scaling up to full size forces. The measurements carried out here serve the purpose of indicating the influence, trends and tendencies of different stacking configurations used in practice.

The measurements showed a clear relationship between the container configuration and the wind forces acting on the ship model.

Container ships in operation will most frequently encounter relative winds in the range of 0-50° which makes this interval the most relevant. From a global resistance point-of-view it is of greatest interest to reduce the longitudinal force and the yaw moment.

In general, the longitudinal force increased with increasing unevenness of the container configuration. The degree of unevenness is hard to define, but it appears that the difference in height between the individual bays plays the major role for the force. If the difference in height between individual bays was pronounced and if there were high bays exceeding the height of the other bays on the deck, it increased the longitudinal force.

The longitudinal force for head winds did not seem to depend on the projected front area of the model, but more on the container configuration along the full length of the model.

The transverse force appeared to be the easiest to predict being more or less directly proportional to the projected side area of the ship. This was the case for all investigated configurations except the three pyramid shaped configurations. However, the degree of extent to which the configurations approximated to a pyramid did not seem to influence the transverse force much.

The factor primarily influencing the yaw moment was the side area of the model and more importantly how the area was distributed over the ship's length i.e. the ratio between the projected area of the front and aft deck. For configurations with relatively more containers on the aft deck a clear reduction in the yaw moment was observed for relative head winds. Thus the yaw moment seemed to depend on the size and centre of gravity of the side area of the ship. The more aft the centre of gravity was located, the smaller was the yaw moment for relative head winds.

CONCLUSION

The wind forces acting on a large container ship as a function of the container configuration were investigated in wind tunnel tests of a simplified 1:450 model of a container ship in the wind tunnel's naturally occurring boundary layer. The measurements were transformed to a reference height and corrected for blockage in the wind tunnel.

Primarily, the results serve as an indication of the magnitude of wind forces acting on large container ships depending on the container configuration on deck rather than for the purpose of assessing the full scale wind resistance of a given container ship.

For reducing the longitudinal force in relative winds from fore it is advantageously to make the container configuration as smooth as possible, and streamlining can reduce the longitudinal force for head winds further. However, streamlining of the configuration on the aft deck is a trade-off as it increases the yaw moment compared to full load on the aft deck. High container stacks (i.e. a bay protruding up over the remaining bays) in the configuration appear to increase the longitudinal force more than a corresponding "hole" (i.e. low or empty container bays) in the configuration.

The transverse force, of concern in beam winds, depends largely on the side area of the ship, and for a fully stacked ship it can be reduced by reducing the stacking height in the outermost stacks.

The yaw moment in relative winds from fore can be reduced by aiming at achieving full stacking on the aft of the ship and thereby possible reduced the resistance induced from drift and increased rudder angle.

A general recommendation would be to make the configuration as smooth as possible and furthermore to ensure that the centre of gravity of the side area is as far aft as possible.

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APPENDIX A

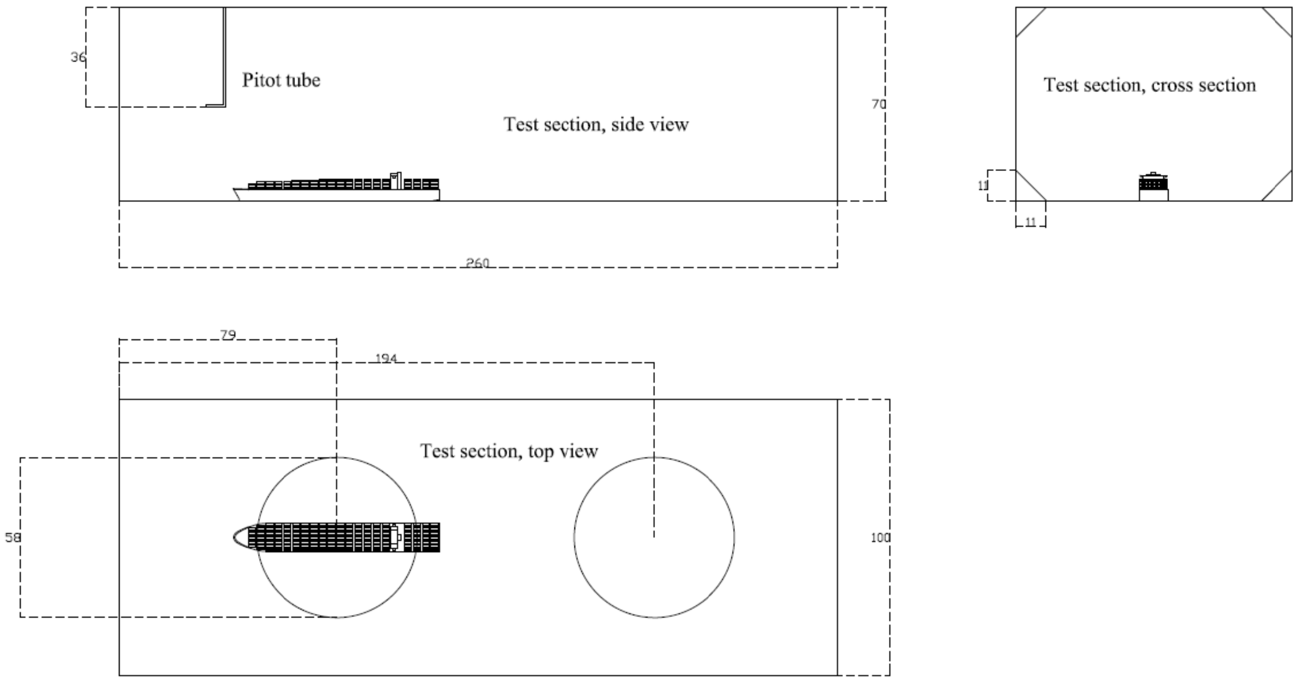

Figure A1 - Outline of the wind tunnel's test section. Dimensions in cm.

Figure A2 - Wind tunnel at FORCE Technology.