Wind Resistance Generated by Containers on Reefer Vessels

Master Thesis

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Abstract

The use of containers is steadily increasing and traditional container ships have been taking market shares from the specialized reefer ships. The reefer shipping industry loads its cargo on pallets that are loaded inside environmentally controlled cargo holds and reefer containers on the ships weather deck. The main concern of this investigation is to investigate the effects on the wind resistance generated from the varying deck load of containers. Specific ships in the NYK Cool fleet are used to exemplify and quantify the resistances. This is done by modeling the wind resistance of a ship with varying container loads using coefficient estimations from [Fujiwara et al. 2006] semi-empirical model. A wind load model is developed that gives for a full load of containers a mean increase of the total resistance of 1% when averaging over all wind directions. When also taking into account the lateral aerodynamic forces of the ship a mean increase of 4% is noted. Further a process to evaluate stored voyage data from ships performance and weather conditions is developed and presented. The method is exemplified using the typical reefer ships. Due to uncertainties in the database extract no conclusive results to support the wind load model could be found from the database analysis.
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My family and friends for always encouraging me to do my best and giving me assistance when needed.

Navigare necesse ist, vivere non necesse est!
-Pompeius

Solna, March 2008,

Christian Lindeen
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Nomenclature

$A_F$ Frontal projected area [$m^2$]

$A_L$ Lateral projected area of the hull [$m^2$]

$A_T$ Area of immersed transom [$m^2$]

$A_{BT}$ Cross-sectional area of the bulb [$m^2$]

$A_{OD}$ Over deck projected area [$m^2$]

$B$ Breadth molded [m]

$C$ Horizontal distance from $\bar{c}$ of the aerodynamic pressure center [m]

$C_B$ Block coefficient []

$C_H$ Roll angle coefficient []

$C_M$ Midship area coefficient []

$C_P$ Prismatic coefficient of the ship []

$C_{AK}$ Roll wind moment coefficient []

$C_{AN}$ Yaw wind moment coefficient []

$C_{AX}$ Longitudinal wind force coefficient []

$C_{AY}$ Lateral wind force coefficient []

$C_{WP}$ Waterplane area coefficient []

$D$ Propeller diameter [m]

$F_P$ Propeller thrust force [N]

$F_x$ Longitudinal force [N]

$F_y$ Lateral force [N]

$F_{ALF}$ Additional longitudinal drag []
$F_{CF}$  Cross-flow drag $[\text{N}]$

$F_{LF}$  Longitudinal-flow drag $[\text{N}]$

$F_{XH0}$  Calm water resistance in $x$ direction $[\text{N}]$

$F_{XH}$  Hydrodynamic hull force in $x$ direction $[\text{N}]$

$F_{XLI}$  Lift induced drag $x$ direction $[\text{N}]$

$F_{YH}$  Hydrodynamic hull force in $y$ direction $[\text{N}]$

$F_{YLI}$  Lift induced drag $y$ direction $[\text{N}]$

$HFC$  Hourly fuel consumption $[\text{Tonnes/hour}]$

$H_C$  Vertical distance from waterline to the aerodynamic pressure center $[\text{m}]$

$H_L$  Mean lateral height $[\text{m}]$

$H_{BR}$  Bridge height from keel line $[\text{m}]$

$I_{95\%}$  95% confidence interval $[\text{ton/h}]$

$J$  Propeller advance ratio $[]$

$K$  Roll moment $[\text{Nm}]$

$K_H$  Hydrodynamic rolling moment around $x$ axis $[\text{Nm}]$

$K_Q$  Propeller moment coefficient $[]$

$K_{PT}$  Propeller thrust coefficient $[]$

$L_{oa}$  Length overall $[\text{m}]$

$L_{pp}$  Length between perpendiculars $[\text{m}]$

$N$  Yaw moment $[\text{Nm}]$

$N_H$  Hydrodynamic yawing moment around $z$ axis $[\text{Nm}]$

$Q$  Propeller moment $[\text{Nm}]$

$R_A$  Model-ship correlation resistance $[\text{N}]$

$R_B$  Additional pressure resistance of bulbous bow near the water surface $[\text{N}]$

$R_F$  Frictional resistance $[\text{N}]$

$R_W$  Wave resistance $[\text{N}]$
$R_{APP}$ Appendage resistance [N]

$R_{TR}$ additional pressure resistance due to transom immersion [N]

$R_{hydro}$ Hydrodynamic resistance [N]

$S_{app}$ Surface area of rudder [$m^2$]

$T$ Draft summer load line [m]

$U_A$ Apparent wind speed [m/s]

$U_I$ Incident water speed at the propeller [m/s]

$U_T$ True wind speed [m/s]

$U_{kt}$ Service speed [knots]

$\Delta$ Mass displacement [Tonnes]

$\Psi_A$ Apparent wind angle [$^\circ$]

$\Psi_T$ True wind angle [$^\circ$]

$\beta$ Yaw angle of the ship [$^\circ$]

$\breve{\gamma}$ Amidships section []

$\eta_0$ Propeller efficiency []

$\bar{GM}$ Transverse metacentric height [m]

$\phi$ Roll angle [$^\circ$]

$\rho_A$ Air density [$kg/m^3$]

$\rho_h$ Water density [$kg/m^3$]

$\sigma$ Standard deviation [ton/h]

$h_b$ Height of the bulb from keel line [m]

$k_1$ Hull form factor []

$l_{cb}$ Longitudinal center of buoyancy forward of $\breve{\gamma}$ [m]

$lim_{confint}$ Confidence interval limit []

$n$ Number of data points []

$n$ Rotational speed of propeller [rev/s]

$q_A$ Aerodynamic pressure [N]
\( u_x \) Longitudinal wind speed [m/s]
\( u_y \) Lateral wind speed [m/s]
\( w \) Taylor wake fraction \( \| \) 
\( x_i \) Residual fuel consumption [ton/h]
IFO Intermediate Fuel Oil [tonnes]
MDO Marine Diesel Oil [tonnes]
ME Main Engine
Chapter 1

Investigation

1.1 Background

The use of reefer containers is steadily increasing and traditional container ships have been taking market shares from the specialized reefer ships. The reefer shipping industry loads its cargo on pallets that are loaded inside environmentally controlled cargo holds. Pallets can also be loaded into reefer containers which are loaded on the weather deck of the reefer ships or onboard container ships. To match the increased competition from container lines the specialized reefer ships have increased their capacity for reefer containers. The competition also calls for efforts in optimization of fuel usage and voyage routing.

NYK Cool apply a model for fuel consumption evaluation. This model takes into account both the hydrodynamic and aerodynamic resistance of the ship. Fuel consumption is modeled by taking into account the seagoing characteristics for typical reefer ships and correction factors for loading condition and for weather direction and force. The loading correction factor is exclusively dependant of the deadweight and not the volume of containers.

The weather correction factor relating to the weather force and direction can be used to normalize the fuel consumption so it can be compared to standard voyage conditions without the influence of weather. The correction factor does not take into account the variation of the wind resistance due to the varying number of loaded containers on deck. To study the wind resistance it is necessary to quantify how the wind affects a ship and use these results to expand or adjust the current models weather correction factor.

In the studies of wind induced forces and moments scaled tank test and semi-empirical models are used. Several models are presented in the literature and publications with varying degrees of complexity. Here the models by Fujiwara et al. [2006], Fujiwara et al. [2001], Blendermann [1994] and Isherwood [1972] are studied. The more modern models use regression analysis of scaled tank tests to produce equations that can be used to calculate the
wind related forces and moments for different types of ships. In standard scaled resistance tank test a simple wind correction factor relating to the frontal projected area of a ship is used to correct for different wind speeds. This resistance usually only pertains to the ahead resistance which changes only slightly when containers are added due to the frontal projected area of the superstructure and ship. The lateral or side projected area, which is usually not included, is highly affected by the number of containers on deck producing a substantial lateral force. The lateral force will produce a leeway as well as roll and yaw moments. The moments have to be balanced by the ships hydrodynamics resulting in a change in the roll and yaw angles of the ship.

1.2 Objectives

The main concern of this investigation is to investigate and quantify the effects on the wind resistance from the varying deck load of containers. Wind resistances for different container loading conditions are calculated and investigated. Of further interest is to compare these resistances with the hydrodynamic resistance. A semi-empirical model is used to provide estimations of the wind forces and their effects on a ship with containers. A comparison of the modeled results with actual voyage data for several ships is made. The voyage data is analyzed with the aim of finding trends in fuel consumption due to the loading of containers. The voyage data analysis results are investigated as a possible verification of the results from the calculation models.

Questions to be answered are:

- Does the number of containers greatly affect the resistance of the ship?
- Can trends be seen in the ships resistance for certain wind forces or directions as well as ships draft or speed?
- Can actual voyage data be used to verify the theoretical results?

1.3 Method

To provide for a sound investigation several methods are required. A wind load model is used to quantify the forces and moments acting on a ship. A variation of container loading conditions is used to find trends in the aerodynamic loading of a ship. Results are compared with hydrodynamic modeling of the ships resistance. The model is implemented on varying reefer ships in the NYKCool fleet. An analysis of voyage data for several ships is also investigated to find trends in actual conditions on the fuel consumption of the vessels. A comparison from voyage data with modeled total ships resistance provides further insight into the effect of a varying deck load of
containers on the aerodynamic loading of the ships. General parameters used in the comparisons and modeling are the ships draft and speed as well as wind force and direction while the number of containers loaded on the weather deck is varied.

1.4 Wind load models

Studies of the literature provide several models to estimate the wind resistance of ships. Most of these are semi-empirical and relate to wind tunnel tests made on several different types of ships. Fujiwara et al. [2006] present a model based on the physical components of ship responses. Included are the contributions from hull, rudder, propeller and above waterline structure in conjunction with the wind and sea state. Part of the model is the calculations of wind induced forces and moments on a vessel. The model is based on wind tunnel and towing tank tests. Actual ships parameters are used to calculate the forces and moments. This wind load model is an extension of the model presented in Fujiwara et al. [2001].

Other models are also presented in literature. Isherwood [1972] presents a semi-empirical model that provides for wind forces and moments based on actual ships parameters but is based on a smaller sample of test data compared to Fujiwara et al. [2006]. A later model is the one by Blendermann [1994] that is based on general coefficients for several different types of ships. Data for reefer ships or similar ships is not provided for. Both of these models do not provide for different parameters based on the projected area of the ships hull and the projected area of the over deck structures and cargo.

The wind load model presented by Fujiwara et al. [2006] is here chosen to model the wind forces and moments on the ship from the varying load of containers due to several factors. Primarily it is claimed by Fujiwara et al. [2006] to have a higher accuracy level than the previously presented models. The number of basic ships factors needed is lower and the calculations more rational compared to Fujiwara et al. [2001]. Also the possibility to connect the wind loads with the other physical components affecting the ship is of interest. The model can also be implemented directly to actual ships dimensions and parameters to calculate wind load coefficients rather than using general coefficients for different types of ships.

The model is implemented in Matlab by The MathWorks Inc. [2007] so that variables can be easily changed and adapted. In this way the code can be used for several different ships. Data sets can also be produced so as to facilitate comparisons with the database of previous journeys. The implementation of the model includes the ability to change the number of containers loaded and their positions onboard.
1.5 Comparisons of wind forces and hydrodynamic forces

In order to quantify the effects of containers onboard the ships a comparison between the modeled wind loads and the hydrodynamic resistance of the hull is required. This is accomplished using the Holtrop-Mennen model of ships resistance. Using general ships data the hydrodynamic resistance is calculated for the chosen example vessels. The results can then be used to compare the hydrodynamic resistance and the aerodynamic resistance variation caused by the varying number of containers.

1.6 Database

The main goal of the database analysis is to see if the data can be used to study the effects from deck loaded containers on the fuel consumption of the ships. This is quantified in a plot of the hourly fuel consumption against the number of containers on the weather deck. A further goal is to develop a method to analyze the data and find trends in the effects from different parameters. The outlining of trends is achieved by using states of similar parameter conditions as a more quantitative approach is possible when relating to data sets grouped into states instead of individual data points. Filtering is achieved as averages can be calculated for each state while still keeping a spread over the total data. The analysis method is also aimed at using the trend results in a comparison with the theoretical wind load model.

The data compromise several vessels in the NYK Cool fleet. The primary goal is to find trends for the individual ships and not to do a general analysis for the whole fleet. Many ships are sister ships and therefore it is advantageous to group these ships together and see if any trends arise for the class of ships.

The data is divided according to several factors. The division limits for the factors are set up into groups in order to achieve a proper spread between the states. These divisions are changed to include states that are relevant to the investigation or exclude less relevant states. Discretisation of data is such that a proper number of data points are present in each state to achieve a sound data spread.

1.7 Studied ships

Several ships are analyzed. The ships are chosen since they represent modern reefer ships with capability to load reefer containers on the weather deck and can be seen in figure 1.1. A table of ships particulars for the investigated ships can be seen in table 1.1.
Figure 1.1: Ships studied in the report. Photos courtesy of NYK Cool AB.
Table 1.1: Ships data used in the modeling calculations.

<table>
<thead>
<tr>
<th>Ship class</th>
<th>Crown</th>
<th>Family</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall $L_{oa}$ [m]</td>
<td>152</td>
<td>164</td>
<td>169</td>
</tr>
<tr>
<td>Breadth molded $B$ [m]</td>
<td>23</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Height of bridge from keel line $H_{BR}$ [m]</td>
<td>19</td>
<td>22</td>
<td>21.6</td>
</tr>
<tr>
<td>Draft summer load line $T$ [m]</td>
<td>8.7</td>
<td>10</td>
<td>9.5</td>
</tr>
<tr>
<td>Length between perpendiculars $L_{pp}$ [m]</td>
<td>139.4</td>
<td>150.6</td>
<td></td>
</tr>
<tr>
<td>Service speed $U_{kt}$ [knots]</td>
<td>21</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Container capacity on weather deck, empty containers [FEU]</td>
<td>98</td>
<td>138</td>
<td>82</td>
</tr>
</tbody>
</table>
Chapter 2
Models

The Fujiwara et al. [2006] semi-empirical model takes into account the forces from the hull hydrodynamics in both calm seas as well as in waves and coordinates it with the wind effects into a steady state solution. The external loads modeled are the longitudinal and lateral force, roll and yaw moments using the contributions from the hull, propeller, waves and wind. From the model presented by Fujiwara et al. [2006] only the wind induced loads are calculated. Hull hydrodynamic resistance forces are calculated using the Holtrop-Mennen method. Parameters for ship and on deck sources for wind resistance are derived from general arrangements and loading plans. These are then used to calculate wind load coefficients according to Fujiwara et al. [2006]. The coefficients are used to calculate the wind forces and moments acting on the ship. Wave induced forces are not calculated as only conditions between 0-5 beaufort are part of the analysis. Propeller data and general methods for propeller force calculations are used to calculate the propeller induced forces. The number of loaded containers and conditions affecting the ships are varied to see how they affect the forces and moments acting on the ships.

2.1 Wind load modeling

2.1.1 Model

The steady state equations that govern the motion of the ship around the center of gravity in longitudinal, lateral, yaw and roll degrees of freedom are:

\[ F_X = 0 \quad (2.1) \]
\[ F_Y = 0 \quad (2.2) \]
\[ N = 0 \quad (2.3) \]
\[ K - \Delta \cdot \bar{G}M \sin \phi = 0 \quad (2.4) \]
here the definitions of the external loads acting on a ship are the longitudinal, $F_X$, and lateral, $F_Y$, forces as well as the yaw, $N$, and roll, $K$, moments. These are oriented as seen in figure 2.1. The mass displacement, $\Delta$ and transverse metacentric height, $GM$, together with the roll angle, $\phi$, balance the roll moment equation.

The components of the external forces and moments acting on a ship are identified by Fujiwara et al. [2006] using subscripts as being the hull, $H$, propeller, $P$, rudder, $R$, wind, $A$, and waves, $W$. This results in the following equations:

$$
F_X = F_{XH0} + F_{XH} + F_P + F_{XR} + F_{XA} + F_{XW} \\
F_Y = F_{YH} + F_{YR} + F_{YA} + F_{YW} \\
N = N_H + N_R + N_A + N_W \\
K = K_H + K_R + K_A
$$

(2.5)

The hydrodynamic loads on the hull are comprised of the calm water resistance in $x$ direction, $F_{XH0}$, and the hydrodynamic hull loads $F_{XH}$, $F_{YH}$, $N_H$ and $K_H$. Hydrodynamic hull forces arise when the ships are given a yaw, $\beta$, and/or roll, $\phi$, angle. These are usually derived from towing tank tests. Since no towing tank test are available only the wind related forces and moments are studied together with $F_{XH0}$ and $F_P$. $F_{XH0}$ is approximated using the Holtrop-Mennen method and $F_P$ according to general methods as described in the following section. The wave and rudder induced forces are not studied for reasons explained later in this report.
For the wind related forces and moments [Fujiiwara et al. 2006] calculates estimations for the longitudinal-force coefficient, $C_{AX}$, lateral-force coefficient, $C_{AY}$, yaw-moment coefficient, $C_{AN}$, and roll-moment coefficient, $C_{AK}$, as follows:

\[
F_{XA} = C_{AX}(\Psi_A)q_A A_F \quad (2.6)
\]
\[
F_{YA} = C_HC_{AY}(\Psi_A)q_A A_L \quad (2.7)
\]
\[
N_A = C_HC_{AN}(\Psi_A)q_A A_L L_{OA} \quad (2.8)
\]
\[
K_A = C_HC_{AK}(\Psi_A)q_A A_L H_L \quad (2.9)
\]
\[
q_A = \frac{1}{2} \rho A U_A^2 \quad (2.10)
\]
\[
H_L = \frac{A_L}{L_{oa}} \quad (2.11)
\]

The coefficients are dependent on the parameters presented in figure 2.2 and in table 2.1. They are calculated using estimations by Fujiiwara et al. [2006] presented in appendix A. The changes in position of the aerodynamic pressure and size of the projected areas when the number of containers is varied can be seen in figure 2.3. Variables describing the aerodynamic properties of the hull and superstructure are derived from General Arrangement plans as well as Capacity and Deadweight plans for each ship.

Table 2.1: Parameters used by [Fujiiwara et al. 2006] to calculate the wind force and moment coefficients.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_A$</td>
<td>Apparent wind velocity</td>
</tr>
<tr>
<td>$\rho_A$</td>
<td>Air density</td>
</tr>
<tr>
<td>$A_F$</td>
<td>Frontal projected area</td>
</tr>
<tr>
<td>$A_L$</td>
<td>Lateral (side) projected area of the hull</td>
</tr>
<tr>
<td>$A_{OD}$</td>
<td>Over deck projected area</td>
</tr>
<tr>
<td>$q_A$</td>
<td>Aerodynamic pressure</td>
</tr>
<tr>
<td>$H_L$</td>
<td>Mean lateral height</td>
</tr>
<tr>
<td>$H_{BR}$</td>
<td>Bridge height from keel line</td>
</tr>
<tr>
<td>$C$</td>
<td>Horizontal distance from $\Psi$ to the aerodynamic pressure center</td>
</tr>
<tr>
<td>$H_C$</td>
<td>Vertical distance from waterline to the aerodynamic pressure center</td>
</tr>
<tr>
<td>$\Psi_A$</td>
<td>Apparent wind angle</td>
</tr>
<tr>
<td>$C_H$</td>
<td>Roll angle coefficient</td>
</tr>
</tbody>
</table>

As seen in figure 2.3, the addition of containers on the weather deck of the Crown and Summer ships has only minimal effect on the position of the center of aerodynamic pressure and the projected areas. For the Family class a large difference is noted as the center of dynamic pressure is further aft and moves steadily forward with the addition of containers. For all the ship classes $A_F$ is not affected since the addition of containers generally falls within the bounds of the ships superstructure. A large increase in the lateral
Figure 2.2: Parameters used by Fujiwara et al. [2006] to estimate wind force coefficients, Fujiwara et al. [2006].

above deck projected area, $A_{OD}$, is seen upon the addition of containers. The Crown class ships almost triple their $A_{OD}$ with 98 FEU\(^1\) loaded compared to 0 FEU. The general increase in the total lateral projected area, $A_{OD} + A_L$, upon the addition of containers is generally between 36% to 47%. The ships hull lateral projected area $A_L$ is the largest area for all the ships but the superstructure and container area, $A_{OD}$, can be of the same size upon the addition of the full load of containers. The only major difference between the classes is the position of $q_A$ for the Family class ships being further behind than for the other ships.

2.1.2 Wind Profile

Relative wind velocity, $U_A$, and direction, $\Psi_A$, are calculated using the longitudinal, $u_x$ and lateral, $u_y$ wind speeds and the true wind speed, $U_T$, ship speed, $U_S$, and true wind angle, $\Psi_T$. Also the conventions of figure 2.1 are used as follows:

\[
\begin{align*}
  u_x &= U_T \cos \Psi_T + U_S \cos \beta \\
  u_y &= U_T \sin \Psi_T - U_S \sin \beta \\
  U_A^2 &= u_x^2 + u_y^2 = U_T^2 + U_S^2 + 2U_T U_S \cos(\Psi + \beta) \\
  \Psi_A &= \tan^{-1} \left( \frac{u_x}{u_y} \right) = \tan^{-1} \left( \frac{U_T \cos \Psi_T + U_S \cos \beta}{U_T \sin \Psi_T - U_S \sin \beta} \right)
\end{align*}
\]

How the wind profile of the apparent wind angle, $\Psi_A$, varies with true wind angle, $\Psi_T$, can be seen in figure 2.4

The apparent wind affecting the ships is highly influenced by the ship speed. Two wind profile types can occur. The first case is when the wind always appears to come forward of amidships even when the true wind comes

\(^1\)FEU: Forty foot Equivalent Unit, Standard measurement used to quantify the number of 40 foot containers carried onboard.
(a) Summer, $T=8$ m, $A_L = 1088 \text{ m}^2$, 40% increase in total lateral projected area, $A_L + A_{OD}$, due to containers.

(b) Crown, $T=8$ m, $A_L = 982 \text{ m}^2$, 47% increase in total lateral projected area, $A_L + A_{OD}$, due to containers.

(c) Family, $T=8$ m, $A_L = 1202 \text{ m}^2$, 36% increase in total lateral projected area, $A_L + A_{OD}$, due to containers.

Figure 2.3: Longitudinal distance of the aerodynamic pressure from $\tilde{j}$ and size of projected areas with varying number of forty foot container, FEU.
from behind. The true wind speed is then not high enough in relation to the ship speed to allow the apparent wind to come from behind the ship, instead the apparent wind speed is then greatly reduced. The second wind profile that can occur is when the true wind speed is higher than the ship speed and the wind force assist the ship propulsion for true wind angles behind amidships. If the apparent wind came in from behind it then pushes the ship forward and thereby producing a “negative” wind resistance.

For all the states studied in this investigation with $U_T$ below force 6 beaufort and with $U_S$ generally above 18 knots the wind profile always is such that the wind forces acts as added resistance and not as a propulsor. This is seen in figure 2.4. The effect is that $U_A$ becomes minimal for astern winds and the wind loads become almost nonexistent for these directions. The resulting effect of adding containers on deck in these conditions is therefore minimal in comparison to when the $U_A$ is ahead or abeam.

These conditions change when the wind speed is increased above force 6 beaufort or the ships speed is slowed below 18 knots. These new conditions, which are not studied, produce the effect that the additions of containers help to reduce the ships resistance.

2.1.3 Assumptions

Several assumptions and parameters are here fixed in the calculation of the wind loads. The calculations are made for the three vessels to achieve a spread in results. The number of containers is varied from 0 to full load of empty containers. The resulting change in the center of aerodynamic pressure and the longitudinal projected area is calculated. These are then used to calculate a varying wind force and moment for different numbers of containers and wind directions. In order to make comparisons to the voyage
database the lateral and frontal area of the hull are compensated from the summer draft conditions according to the examined draft in each case.

Further forty foot high cube containers are assumed so as to achieve a maximum influence from containers. Forty foot high cube containers are also the most used size in reefer containers. Dimensions are seen in table 2.2. It is assumed that containers are loaded so as to fill up one tier at a time as well as providing an adequate trim for the ship by loading from the center of the ship and out.

Table 2.2: Dimensions for forty foot high cube container used in wind load model

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>12.192</td>
</tr>
<tr>
<td>Width [m]</td>
<td>2.438</td>
</tr>
<tr>
<td>Height [m]</td>
<td>2.896</td>
</tr>
</tbody>
</table>

2.1.4 Results for calculations of wind loads

The changes in wind forces and moments due to the varying load of containers can be seen in figure 2.5 for each ship. The Summer and Crown ships wind forces and moments are seen to have similar behavior. There is an increase in the forces with the increase of containers. For the wind direction a maximum can be clearly seen for wind angles between $45^\circ$ and $90^\circ$. This also includes an increase in $F_{AX}$ as the winds go from head on to of the bow. As the wind starts coming of the bow the apparent cross-sectional area increases which causes an increased longitudinal drag. As the winds move more astern $U_A$ decreases and thereby the aerodynamic pressure also decreases. The Family class behaves in a similar way with the exception of the yawing moment. Here the number of containers and $\Psi_T$ have a very distinct effect as can be seen in $N_A$ of figure 2.5(c). This probably relates to the Family class having the center of aerodynamic pressure well abaft of amidships compared to the other two examined classes, which is seen in figure 2.3. The forces and moments all present a very harmonic and smooth shape while the wind variable parameters from figure 2.3 are discontinuous. The discontinuities provide for different spacing an relative order of the smooth curves for each force and moment in figure 2.5.

2.1.5 Verification of wind load model implementation

In order to verify implementation of the wind load model several comparisons are made. In the article presented by Fujiwara et al. [2006] a large passenger ship is used to exemplify the calculations. The same ships data is here used to confirm a correct implementation of the wind load model and compared to implementations presented by Fujiwara et al. [2006]. The results are seen
Figure 2.5: Changes in wind forces and moments on the ships.

(a) Summer, $U_{kt} = 20$ knots, $U_T = 10$ m/s, $T = 8$ m

(b) Crown, $U_{kt} = 20$ knots, $U_T = 10$ m/s, $T = 8$ m

(c) Family, $U_{kt} = 20$ knots, $U_T = 10$ m/s, $T = 8$ m
in figure 2.6. The results of Fujiwara et al. [2006] are replicated with only minimal differences. The differences are assumed to be caused by slight differences in input values and uncertainty on values not stated by Fujiwara et al. [2006] and that are here approximated. The wind moment calculated for the exemplified ships is compared to the roll angle required to achieve an equal hydrostatic righting moment. The resulting values are highly dependent on the guessed $GM$. These do fall within reasonable ranges and therefore the calculated moments are assumed to be reasonable and within proper margins for the analysis done.

(a) Fujiwara et al. [2006] results for large passenger ship. (b) Implementation of same ships data for large passenger using implemented wind load model.

Figure 2.6: Comparison of coefficients from Fujiwara et al. [2006] and implementation of wind load model.

### 2.2 Hull hydrodynamic resistance

The hydrodynamic resistance of the Crown class is calculated according to the widely used Holtrop-Mennen method. This is done to allow quantitative comparisons between the hydrodynamic and aerodynamic forces. The Holtrop-Mennen method is described in Holtrop and Mennen [1978], Holtrop and Mennen [1982] and Holtrop [1984]. This method is chosen since it uses basic ship data and other factors relating to resistance of the hull to provide for a good estimation of the hydrodynamic resistance. The Holtrop-Mennen approximation of the ships resistance, $R_{\text{hydro}}$, is calculated to approximate the hydrodynamic calm water resistance, $F_{XHO}$, acting on the hull. The resistance components are divided into:

$$ R_{\text{hydro}} = R_F(1 + k_1) + R_{\text{APP}} + R_W + R_B + R_{TR} + R_A \quad (2.15) $$

where:
\[ R_F = \text{frictional resistance} \]
\[ 1 + k_1 = \text{form factor of the hull} \]
\[ R_{APP} = \text{appendage resistance} \]
\[ R_W = \text{wave resistance} \]
\[ R_B = \text{additional pressure resistance of bulbous bow near the water surface} \]
\[ R_{TR} = \text{additional pressure resistance due to transom immersion} \]
\[ R_A = \text{model-ship correlation resistance}. \]

Calculation of the resistance components can be seen in appendix B. These calculations are done for the Crown class ships. No appendage other than the rudder is accounted for. Since the ships usually are not loaded to the load lines no additional resistance from the immersed transom is included. The hull hydrodynamic resistance calculations are done using the data provided in table 1.1 and table 2.3. Linear interpolation of the hull hydrodynamic resistance from the mean drafts \( T = 4.5, 6, 8 \) is used to calculate the resistance for a specified draft. In figure 2.7 resistance curves can be seen for the Crown class at typical drafts and speeds.

Table 2.3: Data used for the Crown class in the Holtrop-Mennen resistance calculations

<table>
<thead>
<tr>
<th>Mean draft</th>
<th>( T )</th>
<th>4.5</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block coefficient</td>
<td>( C_B )</td>
<td>[ ]</td>
<td>0.4929</td>
<td>0.5260</td>
</tr>
<tr>
<td>Midship area coefficient</td>
<td>( C_M )</td>
<td>[-]</td>
<td>0.9108</td>
<td>0.9331</td>
</tr>
<tr>
<td>Waterplane area coefficient</td>
<td>( C_{WP} )</td>
<td>[-]</td>
<td>0.6029</td>
<td>0.6478</td>
</tr>
<tr>
<td>Prismatic coefficient of the ship</td>
<td>( C_P )</td>
<td>[-]</td>
<td>0.5411</td>
<td>0.5637</td>
</tr>
<tr>
<td>Longitudinal center of buoyancy forward of</td>
<td>( l_c b )</td>
<td>[m]</td>
<td>0.83703</td>
<td>1.3616</td>
</tr>
</tbody>
</table>

| Cross-sectional area of the bulb approximated | \( A_{BT} \) | \( m^2 \) | 3.14 |
| Height of the bulb from keel line | \( h_b \) | [m] | 2 |
| Surface area of rudder | \( S_{app} \) | \( m^2 \) | 23.107 |
| Area of immersed transom | \( A_T \) | \( m^2 \) | 0 |
2.3 Propeller forces

A comparison between the total ships resistance and propulsive power is done using the propeller thrust force. The effective propeller thrust force, $F_P$, is calculated using propeller thrust diagrams produced by Lindgren and Bjärne [1967] and presented by Garne [2007] together with the methods and coefficients presented in appendix C. For the Crown class ships data according to table 2.4 and the propeller thrust coefficient, $K_{PT}$, from Lindgren and Bjärne [1967] is used to calculate the propeller thrust force, $F_P$, defined as:

$$F_P = K_{PT} \rho D^4 n^2$$

(2.16)

Calculations are made for a draft of $T = 8$ m resulting in a wake factor approximation according to equation [C.5] of $w = 0.23$ with results seen in table 2.4. The value in table 2.4 for the propeller force shows a good correlation with the total resistance calculated in the model when $R_{hydro}$ is added to $F_A$. 

Figure 2.7: Holtrop-Mennen hydrodynamic resistance of Crown class
Table 2.4: Propeller force characteristics and results for Crown class

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller diameter D [m]</td>
<td>6.2</td>
</tr>
<tr>
<td>Propeller revolutions RPM [rev/min]</td>
<td>105</td>
</tr>
<tr>
<td>Number of blades</td>
<td>5</td>
</tr>
<tr>
<td>Expanded Area Ratio</td>
<td>0.61</td>
</tr>
<tr>
<td>Ships speed U_kl [knots]</td>
<td>21</td>
</tr>
<tr>
<td>Incidence speed U_I [knots]</td>
<td>16.17</td>
</tr>
<tr>
<td>Advance ratio J_w</td>
<td>0.7667</td>
</tr>
<tr>
<td>Thrust force coefficient K_PT</td>
<td>0.2</td>
</tr>
<tr>
<td>Propeller Thrust F_p [kN]</td>
<td>905</td>
</tr>
</tbody>
</table>

2.4 Force comparison

2.4.1 Wind loads

Several forces and moments are calculated for the ships being analyzed. These are the wind induced forces in longitudinal, $F_{XA}$, and lateral, $F_{YA}$ directions together with wind induced moments in roll, $K_A$ and yaw, $N_A$. Also the hydrodynamic resistance, $R_{hydro}$ and the counteracting propeller force, $F_p$ are calculated. Of interest is to study how these forces and moments change when the number of loaded containers changes. This is done without changing the ships draft and speed or wind force and direction. The change is made in the projected areas and the position of the center of dynamic pressure corresponding to the addition of the containers. This counteracts the change in draft usually arising from changes in the number of loaded containers. These values can be seen in figure 2.3. For all the ships examined the frontal projected area does not change upon the addition of containers since the superstructure and other parts of the ships already covered these surfaces. Changes in the ships center of gravity are not examined as it does not affect the wind related forces.

The subject of this investigation is how much the different wind induced forces and moments change when containers are added. Therefore a mean value for wind directions $0^\circ \leq \Psi_T \leq 180^\circ$ for each number of containers is calculated for $F_{XA}$, $F_{YA}$, $N_A$ and $K_A$. The average force and moment is then compared to the baseline of 0 containers and plotted to see how the number of containers relatively affects the wind loads. This can be seen in figure 2.8

The addition of a full load of containers has a 10% to 30% relative increase in $F_{AX}$. The lateral force $F_{AY}$ has almost a 40 to 50% relative increase. The high relative increase in the lateral forces is to be given high consideration when doing comparison to the other forces acting on the ships.

The yawing moment for the Crown and Summer class ships have a similar behavior. Here the relative shape of $C$ from figure 2.3 has a clear effect
Figure 2.8: Average wind forces and moments spanning over wind directions $0^\circ \leq \Psi_T \leq 180^\circ$ compared to baseline of 0 containers.
on the mean relative yawing moment. The high change for the last added containers is due to the position of these containers being high up on the foredeck of the ships. For the Family class the true wind angle and the large superstructure produce a yawing moment which dramatically changes when the number of containers onboard is increased. The large lever arm produced by the position of the aerodynamic pressure center, \( C \), has in this case a big influence on the yawing moment.

### 2.4.2 Wind loads compared to hydrodynamic resistance

The influence of the containers compared to the hydrodynamic resistance needs to be compared to provide a clear understanding of how the varying number of containers affect the ship’s total resistance and thereby the fuel consumption. Just comparing the longitudinal forces is not enough since a ship is affected by lateral forces when the wind affects the ship from different directions. The lateral forces cause a lateral drift as well as the rolling and yawing moments. To counteract these, the ship is given an incident angle relative to the direction of travel in the water producing a lifting hydrodynamic force. This results in an increased drag on the ship in the longitudinal direction. To approximate the effects of this on the ship’s total resistance and the effect from the increased lateral wind force due to a changing number of containers a total wind force, \( F_A \), is calculated using:

\[
F_A = \sqrt{F_{XA}^2 + F_{YA}^2}
\]

This approximation probably overestimates the effect from the lateral wind force since no compensation is made for the ship having a leeway or hydrodynamic lifting force due to an incident angle of the hull to the water.

In figure 2.9 \( F_A \) and \( F_{XA} \) are compared relative to \( R_{hydro} \) with means over \( 0^\circ \leq \Psi_T \leq 180^\circ \) for each added container. The maximum and minimum values are also presented. Rawson and Tupper [2001] state that the aerodynamic resistance can be 2-4% of the total resistance in full speed conditions if no wind is present and quadrupled to 4-16% if there is a head wind of the same speed as the ship. The figure 2.9 shows that when only the longitudinal forces are studied the aerodynamic resistance is up to 15% of \( R_{hydro} \) as would be expected. If the lateral wind forces also are accounted for the aerodynamic resistance it up to 30% of \( R_{hydro} \). It is therefore of interest to study how this relationship changes upon the addition of containers. The mean values and the maximum values show a very slight increase when the number of containers is increased.

To isolate the effect from containers the relative change in total resistance, \( R_{tot} \), compared to the baseline of no containers is calculated for both \( R_{tot} = F_{AX} + R_{hydro} \) and \( R_{tot} = F_A + R_{hydro} \). Results are shown in figure 2.10. The figure shows how the addition of a full load of containers changes the total
Figure 2.9: Comparison between the aerodynamic and hydrodynamic resistances for Crown class with $U_S = 20$ knots, $U_T = 10$ m/s and $T = 8$ m. In the left figures the max, mean and min is calculated over $0^\circ \leq \Psi_T \leq 180^\circ$. In the right figure the max, mean and min is calculated over all the containers.

Figure 2.10: Max, mean and min effect on the total resistance from containers. In the left figures the mean is calculated over all the wind angles. In the right figure the mean is calculated over all the containers.
resistance. On average a 1% increase is noted when only looking at forces in the x direction. When also taking into account $F_{AY}$ a mean 4% increase is noted. These are the figures that best represent the effect from a full load of containers on the resistance of the Crown class.

In general it can be said that the addition of containers on deck causes an increase in the forces affecting the ship even when the wind comes from astern. Since the apparent wind never comes from behind in the typical ships speed and wind range studied the addition of containers does not reduce the total resistance. The variation of the wind angle has a large effect on the relative size of the aerodynamic and hydrodynamic forces. The highest effect of the wind angle after being averaged over all container conditions is seen for wind conditions between of the bow and abeam.

### 2.5 Alternative factors

Are there other factors that are not taken into consideration that could affect the results? By doing the calculations for wind forces below 6 beaufort it is assumed that the effect from the waves is minimal. In the wind load model factors that are not accounted for are the rudder and wave induced forces. Introducing the rudder forces would also provide for the need to take into account the lifting force from the hull. This lifting force arises when the hull is given an incident angle to the inflowing water. The lifting force balances the yawing moment and lateral force from the wind. The resulting induced drag on the hull would then be a complement to the calculation of forces affecting the hull. An attempt to take this into account is done when comparing the aerodynamic force $F_A$ to $R_{hydro}$. Further when the ship is given a roll angle due to the wind load $R_{hydro}$ will change. These are the hydrodynamic loads $F_{XH}$, $F_{YH}$, $N_H$ and $K_H$ presented by Fujiiwara et al. [2006] whom also state that these forces can become substantial and affect the ships speed. Another factor that can be discussed is the stacking order and position of containers. This might have an effect on the aerodynamic character of the ships which changes the relationships governing the approximations for the wind load coefficients. Since it was assumed in the model that the containers were loaded in a basic way, based on stability, this need not be a factor.
Chapter 3

Database

A parallel investigation to the theoretical process is made through analysis of stored vessel voyage data. The method for database analysis is here outlined and applied on a database extract. The aim is to make a qualitative analysis of effects on the IFO\textsuperscript{1} and MDO\textsuperscript{2} ME\textsuperscript{3} fuel consumption due to the added wind resistance from containers on the weather deck.

3.1 Reported data

The data consists of several vessels daily reports from voyages over several years. Each day the ships masters report the status of the ship and the weather conditions. This is then stored by the land organization for evaluation and follow-up of the ships. Two classes of ships are analyzed from the database. For the Family class four sister ships daily voyage data is used from the latest eight years compromising 11785 data points. Five ships in the Crown class with voyage data from the latest four years compromising 7923 data points are used. The fuel consumption against the number of containers for both ships can be seen in figure 3.1 for all data points. A wide spread can be seen for both classes. This is caused by the large variation in the loading conditions and in uncertainties in the reported data as discussed in the following sections. For the Crown class a slight increasing trend can be noted. The variations for the Family class are larger and no trend is clearly visible which might pertain to the Family class having a variable pitch propeller, VPP. The VPP highly affects the fuel consumption of the ships as the engines can be run at a higher efficiency for more loading conditions than the Crown class fixed propellers.

\textsuperscript{1}IFO: Intermediate Fuel Oil are fuels blended from diesel and bunker fuels classified into different grades as specified by the universally adopted SI (System International d'Unites) metric system of measurement. Petron\textsuperscript{[2007]}

\textsuperscript{2}MDO: Marine Diesel Oil

\textsuperscript{3}ME: Main Engine
Figure 3.1: Fuel consumption against number of containers for Crown and Family class ships. All data points.
The reported data consists of estimated and measured values collected by the crew. Only the data used in conjunction with this report is discussed. Constant data for each voyage is the number of containers onboard. The reports only contain the number of containers loaded on the weather deck and not their positions. Recorded data is seen in table 3.1.

<table>
<thead>
<tr>
<th>Data</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>day</td>
<td></td>
</tr>
<tr>
<td>Sailed time</td>
<td>h</td>
<td></td>
</tr>
<tr>
<td>Sailed distance</td>
<td>Nm</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>knots</td>
<td></td>
</tr>
<tr>
<td>IFO consumption</td>
<td>tones</td>
<td></td>
</tr>
<tr>
<td>MDO consumption</td>
<td>tones</td>
<td></td>
</tr>
<tr>
<td>Wind force</td>
<td>Beaufort</td>
<td>24 h mean</td>
</tr>
<tr>
<td>Wind direction</td>
<td>See figure 3.2</td>
<td>24 h mean</td>
</tr>
<tr>
<td>Propeller revolutions</td>
<td>RPM</td>
<td></td>
</tr>
<tr>
<td>Draft fore and aft</td>
<td>m</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2: Wind direction codes. Calm = 0, Variable = 9

Measurements are made by the crew on a daily basis. The main parts of the measurements are to be taken as having rather high accuracy. Most of the measurements are made manually and this can have an effect on the results. Care is to be taken into data sets where special conditions apply that brings the data outside of the objective of this investigation. Such circumstances are transits to and from harbors and sea passages, increased resistance due to changes in hull and propeller conditions before and after docking. Other factors that affect the accuracy of the results is the lack of
container positions in the reports.

A discrepancy is noted in the extracted data that affects the conclusive nature of the results in this report. As can be seen in figure 3.1(a) for the Crown class ships there are several data points where the reported number of FEU containers on deck highly exceeds the maximum loading condition of 98 FEU. For the Family class the number of data points exceeding the maximum number of 138 FEU only accounted for a few voyages. For the Family class voyage data is compared to another NYK Cool database and it is found that the majority of the examined container on deck fields are erroneously reported into the voyage database. Possible causes for the wrong figures in the voyage database can be tracked down to a mix of FEU and TEU\(^4\) containers being reported instead of the equivalent number of FEUs. Further some containers carried by the ship were loaded in the cargo holds and these containers were reported in the voyage database as being on deck.

The comparison with the second NYK Cool database is done for 29 voyages of the Family class. These voyages are spread over the whole span of container loading conditions with emphasis on the voyages over the ships maximum on deck FEU loading. Most of the data for FEU containers on deck is found to be wrongly reported or can not be checked. The voyages where correct data is found are corrected but this is only a small amount of voyages compared to all data points. The corrected values are the ones plotted for the Family class in figure 3.1(b). The Crown class data points are assumed to have the same bad reliability when it comes to the number of reported containers on deck. Because of these different sources of uncertainties in the database the focus in this report is on developing a methodology for finding trends from database results rather than actually finding trends applicable to the exemplified vessels.

3.2 Breakdown of analysis

In order to calculate the fuel consumption dependency on the numbers of loaded containers the database data has to be prepared for analysis. A diagram of this algorithm is presented in figure 3.3 with a detailed explanation in the following sections. Here a short description is made. Firstly the data is sorted into states, by state meaning a set spread of factors and conditions affecting the ships fuel consumption. Each data point is sorted into a specific state if the factors and conditions represented by the data point fall within the set spread of sorting factors for that state. An even spread of data into the states is assured by choosing limits for the sorting factors affecting the fuel consumption. The spread in conditions for each state is represented by the intervals in the sorting factors. Once the data is sorted into states a

\(^4\)TEU: Twenty foot Equivalent Unit, Standard measurement used to quantify the number of 20 foot containers carried onboard.
linear regression is done for each state and a confidence interval calculated for the regression. The regression results are then discussed to find trends in the fuel consumption dependency on the number of loaded containers.

3.2.1 Sorting factors

As seen in figure 3.3 the first step is to sort the data points into states. Two main factors other than the weather conditions affect the consumption for the ship; these are the vessel’s displacement and its speed. It is of importance to divide the data sets into states in terms of intervals of vessels displacement since the hydrodynamic resistance has a major effect on the consumption. The displacement discretisation is chosen to cover from ballast condition to fully laden vessel. The mean draft, $T$, of the vessels is used as the displacement discretisation variable.
The next part of the sorting step is to divide the data according to ships speeds. Ships are ordered to maintain a certain speed depending on the nature of the time table and cargo type onboard. Further the ships crew might choose to lower the speed due to weather conditions or other factors. The ships speeds are highly influenced by the hulls free streaming and wave making resistance. The usage of ships speed to sort the data points means that both the hulls free streaming and wave making resistance is accounted for. The ships speed, $U_S$, is used as the discretisation variable for hydrodynamic resistance.

The wind force has an effect on the fuel consumption and speed of the vessels. Since the wind force is reported in beaufort a first division is made according to the beaufort scale. An upper limit for the wind force is used. This since the wave induced resistance will start to have an effect on the ships performance as well as the crew opting to voluntarily reduce speed when the wind force is high. The upper limit is set to include data up to beaufort force 5.

A division according to wind direction also has to be done. The symmetry of the vessels is used to sort data points into states according to table 3.2 using direction codes presented in figure 3.2.

<table>
<thead>
<tr>
<th>Wind direction codes</th>
<th>Wind direction codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahead wind</td>
<td>1, 0, 9</td>
</tr>
<tr>
<td>Of the bow wind</td>
<td>2, 8</td>
</tr>
<tr>
<td>Beam wind</td>
<td>3, 7</td>
</tr>
<tr>
<td>Of the stern wind</td>
<td>4, 6</td>
</tr>
<tr>
<td>Stern wind</td>
<td>5</td>
</tr>
</tbody>
</table>

Each state now represents a group of data points with similar conditions. The main remaining factor that differentiates the data within a state is the number of containers loaded on the weather deck and the fuel consumption which is the basis for the following analysis. Other factors still remain such as the swell size and direction, ships trim, and time since dry docking amongst others. These are in this first basic analysis disregarded. The usage of wind force and direction, ships speed and draft will provide for a good basic first analysis which is the aim of this investigation.

3.2.2 Interval selection

The four main sorting factors for placing data points into states are thus the ships speed and draft, wind direction and wind force. Each state comprises data points sorted according to intervals of these four sorting factors. The sizes of the intervals are different but keeping an even number of data points in each interval is prioritized to keep balanced intervals. The intervals are
chosen in both length and number so that the data points are evenly spread over the ships speed and draft. Wind direction and force are already in an interval grouping and kept that way.

A spread of the data for the Crown and Family class ships can be seen in figure 3.4. Two counteracting factors affect the choice of interval. The first is the need for a high number of data points in each state so that the linear regression has a high number of data points which provides for a stable regression. This demands wide intervals to get a high number of data points in each state. The second counteracting factor is the need for distinct results so that a continuous analysis over varying conditions can be applied with consistent and smooth results. This demands that the intervals be made as small as possible and increased in number. The smaller the intervals the larger the number of states thus leading to the data points being spread thinly into all the states and thereby not allowing for accurate regressions due to lack of data points.

3.2.3 Linear regression

The second step in figure 3.3 is to do a linear regression. Once the data points are sorted into states an analysis is made within each state to find the dependancy of the ME fuel consumption against the number of containers loaded on the weather deck. The mean Hourly Fuel Consumption, $HFC$, is calculated for each data point. The usage of IFO is predominant throughout the voyage data. The $HFC$ is then compared to the number of containers on deck. From the theoretical studies a linear dependency is observed in the forces. Therefore for the database investigation a first degree polynomial is the assumed dependency of the number of containers on the fuel consumption. Further the interval or span of the conditions within a state are small. This means that a linear approximation of the dependency of the fuel consumption on the number of loaded containers is a viable if simple approximation.

For each state a linear regression is made using the method of least squares on a first degree polynomial. The inclination of this line represents the $HFC/container$ coefficient with the unit tones of fuel per hour per container. This coefficient represents the effect of containers on the fuel consumption. The linear dependency is plotted onto the data points in each state to see the congruence of the data points and the regression, see figure 3.5. Further the residuals, $x_i$, being the distance from the regression line and the data points is calculated. The standard deviation, $\sigma$, of the residuals is calculated and used in the calculation of a 95% confidence interval, $I_{95\%}$.
Figure 3.4: Spread of the data points for both Crown and Family class ships.
This is done using:

\[
\sigma = \left( \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{\frac{1}{2}} \quad (3.1)
\]

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad (3.2)
\]

\[
I_{95\%} = \lambda_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad (3.3)
\]

where \( n \) is the number of data points within the state on which the regression is based, \( \lambda_{\alpha/2} = 1.6449 \) for the assumed normal distribution and for a 95% confidence interval and where \( \bar{x} \) is the mean for the residual. By 95% confidence interval it is meant that 95% of the residuals fall within the confidence interval from the regression line. The confidence interval is here calculated and used to give a general assumption of the quality of the regression, not as a confidence interval for the regression itself. The smaller the confidence interval, the better the regression curve is fitted to the data points in the state and the higher the concentration of data points around the regression curve. The confidence interval is not meant to be a quantitative measure to be used in the calculation of coefficients but rather as a qualitative measure to how accurate the regression coefficients are.

### 3.2.4 State selection for comparison

In order to find trends in the data a selection is made to study the states with the highest accuracy and quality as well as trends over several states to achieve a general conclusion. Two criteria are chosen to pick out the states with the highest accuracy and quality in the regression. Firstly the number of data points in the regression and secondly the size of the confidence interval. The more points used in a regression the better the regression. A problem arises if the spread of the data points is high, due to erroneous data, resulting in a loss of quality in the regression.

Using the confidence interval as a selection criteria means that the states with the lowest confidence interval are the ones with the best quality of regression results. The confidence interval will decrease in size with increasing number of data points in the state but also having very few data points results in a small standard variation producing a small confidence interval. These states of few data points have to be filtered out in the analysis since the few data points do not produce indicative regressions for that state. Therefore when the confidence interval is used as selection criteria a lower limit, \( \text{lim}_{\text{confint}} \), for the number of data points in a state is used in the selection process. The \( \text{lim}_{\text{confint}} \) is presented in the figures when used and is generally around 10 data points. The effects of this is seen in section D.5.
The two selection criteria are used to pick the 18 states with highest number of data points and the 18 states with the smallest confidence interval. This is done for grouped data for wind forces 0-5 beaufort and 0-2 beaufort for the Family and Crown class. In figure 3.5 examples for both the highest number of data points in a state and the regression with the smallest confidence interval, $I_{95\%}$, are presented for both ships. Complete figures for the first 18 states selected according to the number of data points and smallest $I_{95\%}$ is presented in appendix D. The results for the selected states is found in tables D.1 to D.6. In appendix D.3 the spread of $I_{95\%}$ is presented as well as the choice of lower limit, $\lim_{\text{confint}}$, for the number of data points used in the selection according to $I_{95\%}$.

Figure 3.5: States with most data points for regression and the smallest confidence interval, $I_{95\%}$, for Crown and Family class. Wind force span for selection of data points 0-5 beaufort.

Another possible way of selecting states which can be used to draw conclusions on the fuel dependency of containers on deck is to do a convergence analysis. This is achieved by studying the coefficients in the regression analysis using smaller sample sets for the regression calculations. Then with added number of data points the coefficients converge to certain values. The
rate of convergence and relative change in size of the coefficients can be used to ascertain when a coefficient has achieved the required accuracy and quality. It is also possible to select states on this basis of fast convergence to do further analysis. This convergence analysis is implemented but no results are presented since no good and consistent results are found due to lack of data points and accuracy.

3.2.5 Discussion

In the implementation on the Crown and Family class ships a conclusion could not be made over all states. This since not enough data points could populate all states and still have a linear regression with a good confidence interval for each state. A possible solution is to increase the interval for each state but then the spread of the data points grows and the linear approximation is no longer based on the container number to fuel consumption relation but also on the sorting factors themselves. The methods for selection of states still provide for a good means of comparison since they take into account the number of data points used in the regression as well as the spread of these data points.

Further for the implementation it can be seen in the result tables of appendix D that the first degree polynomial regression used within each state does not provide for a conclusive figure on the $FHC/container$ coefficient. For both the Family and Crown class the effect of changing the numbers of containers is inconclusive in this analysis having both negative and positive coefficients and no general trend can be seen. What can be seen is that the magnitude of adding or removing one container provides for a change in the fuel consumption by either increasing or decreasing the fuel consumption by 0.01-1 kg of fuel per hour. This translates into a % change in the total fuel consumption for each container added. There is not even any trend when looking at the sorting factors on when the $FHC/container$ coefficient changes sign.

If only the lower wind speeds of 0-2 beaufort are used in the analysis no new results arise. For the Crown class too few states are populated with enough data points to give any viable results. The Family class has more highly populated states but does not provide any conclusive initial trends.

Several things could be affecting the fact that no trend is seen for the fuel consumption coefficients. The main factor is thought to be the uncertainty in the reported values of containers on deck. Further factors could be that the intervals set for the speed and draft are too wide and that a smaller subdivision into states is necessary. Also a larger database extract might be necessary.
3.2.6 Trends over several states

To study trends over several states the FHC/container coefficient is studied for fixed conditions for one of the sorting factors, while the others are varied. The aim here is to find trends for a variation in each sorting factor. This is accomplished by identifying the states for a set value of one of the sorting factors and calculating the mean coefficient value, mean number of data points and mean confidence interval for these states. This then includes values for a variation of all the other sorting factors and makes it possible to isolate the effect of a certain sorting factors. In this manner it is possible to find general trends for each of the sorting factors. The mean value of $I_{95\%}$ for the regression is also calculated in the same process and used as a way of measuring the relative accuracy of the comparison. Figure 3.6 shows these means for the Crown and Family class ships in the division into states using wind forces 0-5 beaufort.

It is seen that most of the means are >0. This falls in line with the wind load model results that the addition of containers should increase the fuel consumption. The means that were <0 for the Crown class are when the draft is shallow at 4.95 m and when the wind direction is astern. Also the highest ship speed at 22 knots gave a mean decrease in the fuel consumption coefficient. A possible explanation for these results is that at these points when the aerodynamic pressure is large and the lateral cross-sectional area is large the addition of containers causes a slipstreaming effect for Crown class ships when the wind has a more rounded body to move over. This then decreases the fuel consumption.

The Family class showed general increase in fuel consumption for the means for each sorting factor except for the largest draft at 8.675 m and low wind forces of 0 and 2 beaufort. For the low wind speeds to give an effect of lowering the fuel consumption upon the addition of containers it might be due to a more aerodynamic and slipstreamed form as the Family class have a large square superstructure. At the low wind speeds the apparent wind direction is for the most part straight ahead and the containers then provide for a more slipstreamed frontal projected area.
(a) Crown, WindD = Wind direction code, WindF = Wind force beaufort, Speed in knots and draft T in m.

(b) Family, WindD = Wind direction code, WindF = Wind force beaufort, Speed in knots and draft T in m.

Figure 3.6: Effects of the isolated sorting factors on the fuel consumption coefficient. Wind force division 0-5 beaufort.
3.3 Reliability of results

The use of the voyage database to verify the results of the wind load model would be ideal. However due to the uncertainty in the quality of the reported number of containers on deck the results done from the database analysis are not conclusive. To just remove the data points that lie outside the maximum range of allowed FEU on deck is not an option. The data points that were independently checked showed there could be a lot of wrongly reported points within the selected data sets. Since the figure of containers on deck is critical to the work in this investigation a big uncertainty arises in the assumptions made from the database analysis.

3.4 Alternative analysis in database

If no trends can be found in the data alternate methods could be explored. One method is to make corrections in the data sets by normalizing for the sorting factors and other factors. It can be assumed that within the small states of data sets the fuel consumption due to displacement, speed and weather behaves linearly. By making a linear regression within the states for the ships draft and speed, wind forces and directions a correction factor for the consumption valid for the data points within that state can be calculated. The consumption is then normalized within the state and only the number of containers loaded will be left as a factor. Another possible method is to make a regression for the ships whole data. The curves can then be used to normalize the consumption according to ships draft and speed, wind forces and directions so as to leave the number of containers as sole factor.

Further factors can be analyzed and used to sort the data points used in the analysis. Factors that might reduce the quality of the measurements are the engine, hull and propeller conditions of the ships. Also since the ships are docked and serviced periodically it might be necessary to remove data sets around the time of docking since hull condition will then have an adverse effect on the analysis.
Chapter 4

Comparison Model and Database

The use of the database results from the previous chapter to verify the results of the wind load model produced in chapter 2 is here discussed. The values being compared are factors of different types. The model provides for a factor that describes how much the total resistance changes for a certain state when containers are added and relates to the forces involved. The database provides for each state a factor of change in fuel consumption dependent on a change in number of containers. A comparison between these two factors will not provide for a numeric verification but an indication of the trends.

In order to compare the theoretical results to the database, wind load model calculations are made for specific states. For these states the wind forces $F_A$ and $F_{AX}$ are modeled and compared to the hydrodynamic resistances. The total resistance for both aerodynamic forces is calculated using respectively:

$$ R_{tot} = R_{hydro} + F_A $$

$$ R_{tot} = R_{hydro} + F_{AX} $$

The total resistance will change with the addition of containers due to the change in the aerodynamic forces. To better isolate the effect of adding containers on the total resistance a baseline total resistance is calculated using the aerodynamic forces when no containers are loaded as follows:

$$ R_{F0} = R_{hydro} + F_A(0 \text{ containers}) $$

$$ R_{F0} = R_{hydro} + F_{AX}(0 \text{ containers}) $$

The aerodynamic forces from the containers is then isolated from the ships aerodynamic forces and used to calculate a relative effect using $F_{containers}/R_{tot}$ and $F_{containers}/R_{F0}$. An average linear relative effect from the addition of containers and the inclination coefficient, $\Delta F_{Acontainers}/R_{tot}$, is also calculated for each case. Figure 4.1 shows an example of these figures.
From the database analysis the HFC/container coefficient, from section 3.2.3, is normalized using the mean HFC within the state to calculate the relative effect of the addition of containers on the fuel consumption. This factor is named $\Delta HFC/container$. This is compared to the factor $\Delta F_{\text{Acontainers}}/R_{\text{tot}}$ calculated as above for the conditions in each state for the Crown class and presented in table 4.1. A comparison between the two right columns shows that no clear correlation can be seen for the coefficients from each state in the database extract and the corresponding modeled coefficient. The results from the database extract are clearly affected by the uncertainties and discrepancies mentioned in section 3.1.

The only conclusion that can be made is that a change produced by each container is a change by 0.001 to 0.01% in the forces and fuel consumption. If this is compared to the full load of containers less than 1% relative change is produced in the states to be compared with the similar results in section 2.4.2. The modeled forces all produce a relative increase while the fuel consumption according to the analyzed database extract is very random to if it is a relative increase or decrease.
Table 4.1: Comparison of relative fuel consumption coefficient $\Delta HFC/container$ with wind model forces $\Delta F_{A\text{containers}}/R_{\text{tot}}$. Comparison made for Crown class with selection based on $I_{95\%}$ and wind forces 0-5 beaufort.

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>Wind Force</th>
<th>Mean speed</th>
<th>Mean T</th>
<th>$\Delta HFC/container$ Database</th>
<th>$\Delta F_{A\text{containers}}/R_{\text{tot}}$ Wind load model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>20.5</td>
<td>7</td>
<td>3.70E-04</td>
<td>8.46E-06</td>
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<tr>
<td>1</td>
<td>4</td>
<td>19.5</td>
<td>7</td>
<td>1.68E-04</td>
<td>1.23E-05</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>19.5</td>
<td>7,95</td>
<td>5.76E-04</td>
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<td>2.23E-04</td>
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<tr>
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<td>19.5</td>
<td>7</td>
<td>3.06E-04</td>
<td>1.63E-05</td>
</tr>
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<td>5</td>
<td>19.5</td>
<td>7,95</td>
<td>5.12E-05</td>
<td>1.39E-05</td>
</tr>
<tr>
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<td>-4.56E-05</td>
<td>4.54E-04</td>
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<tr>
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<td>-5.99E-04</td>
<td>4.67E-04</td>
</tr>
<tr>
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<td>5</td>
<td>19.5</td>
<td>7,95</td>
<td>-1.48E-04</td>
<td>7.46E-04</td>
</tr>
<tr>
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<td>4</td>
<td>20.5</td>
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<td>5.87E-04</td>
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<td>3</td>
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<td>1.61E-04</td>
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<td>6</td>
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<td>3.21E-04</td>
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<td>-8.52E-05</td>
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<td>1.68E-04</td>
<td>4.31E-04</td>
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Chapter 5

Conclusion

5.1 Effect from containers on deck

In order to study the effects from loading containers on the weather deck of ships this investigation had two parts, a wind load model and a voyage database analysis. For the wind load model the ships speeds were generally 20 knots with a draft of 8 m and a wind speed of force 5 beaufort. The wind load model gave reasonable results that the longitudinal aerodynamic forces increase by 10% with the addition of a full load of containers. The lateral aerodynamic forces have an even larger increase of up to 40%. However these forces have to be put into relation with the hydrodynamic resistance of the hull. When looking at the effect of a full deck load of FEU containers on the total resistance of the Crown class ships the wind force model provides for an increase of 1% when averaging over all wind directions. When taking into account the lateral aerodynamic forces a mean increase of 4% is noted. However since the lifting force of the hull is not taken into account to balance the lateral aerodynamic force an assumption can be made that the effect of a full load of containers on the ships total resistance is between 1 and 4%. This means that the relative effect of loading one container onboard is that the wind forces will increase by 0.01 to 0.04%.

The second part of the investigation was to do an analysis of voyage data stored in a database. A method was presented in this report which provides for such an analysis. This was done by dividing the data in states of similar data points were certain conditions are kept within intervals. These conditions are the ships draft and speed while also sorting the data according to the prevailing wind direction and force. For each state a linear regression was made of how the fuel consumption varies with the addition of containers. By then looking at the linear regressions for different groups of states a conclusion of the fuel consumption under certain conditions could be made. This process was done to data for the Family and Crown class. However due to uncertainties in the database material it was not possible to draw
any conclusive results. Neither was it possible to confirm the results from the wind model predictions. The results indicate that a change in both increase and decrease in fuel consumption due to containers is in the order of magnitude between 0.01-1 kg of fuel per hour for each loaded container. This has to be taken into relation that the mean fuel consumption is between 1.4-1.9 tones per hour for the ships. The relative change in the fuel consumption is then in the same order of magnitude as the change in the forces modeled.

5.2 The next step

Several aspects can be addressed for continuation of this investigation. For the wind force model it is possible to expand the model with the rudder forces and the effects of an incident angle on the hull to the hydrodynamic forces. The effects of different configurations of containers with respect to aerodynamic slipstreaming and the effects of turbulence could also be examined. For the database analysis it would be interesting to improve the data collection and thereby do a proper comparison to the wind load model. The sub division into states can be further refined by normalizing the fuel consumption within in each state for the exact values of the sorting factors. This could also be done for the whole data set by using non dimensional factors and use this to compare ships from different classes. Another assumption than the linear dependency of fuel consumption to number of containers can also be tested.
Bibliography


Appendix A

Fujiwara et al. [2006] wind force coefficient calculations

This chapter describes the calculations proposed by Fujiwara et al. [2006] to calculate the wind force parameters seen in equations 2.6 to 2.9 and seen here in equations A.1 to A.4.

\[ F_{XA} = C_{AX}(\Psi_{A})q_{A}A_{F} \] (A.1)

\[ F_{YA} = C_{H}C_{AY}(\Psi_{A})q_{A}A_{L} \] (A.2)

\[ N_{A} = C_{H}C_{AN}(\Psi_{A})q_{A}A_{LL_{OA}} \] (A.3)

\[ K_{A} = C_{H}C_{AK}(\Psi_{A})q_{A}A_{HL_{L}} \] (A.4)

The coordinate system and definition of forces is discussed in section 2.1 and presented in figure A.1. The coefficients are calculated using the parameters in table A.1 and shown in figure A.2.

Figure A.1: Coordinate system and definitions of force and moment sign conventions for ship under wind loading, Fujiwara et al. [2006].

The longitudinal and lateral wind force coefficients are then defined as follows:

\[ C_{AX}(\Psi_{A}) = F'_{LF} + F'_{XLI} + F'_{ALF} \]
Table A.1: Parameters used by Fujiwara et al. [2006] to calculate the wind force and moment coefficients.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_A$</td>
<td>Relative wind velocity</td>
</tr>
<tr>
<td>$\rho_A$</td>
<td>Air density</td>
</tr>
<tr>
<td>$A_F$</td>
<td>Frontal cross-sectional area</td>
</tr>
<tr>
<td>$A_L$</td>
<td>Lateral (side) cross-sectional area</td>
</tr>
<tr>
<td>$A_{OD}$</td>
<td>Over deck cross-sectional area</td>
</tr>
<tr>
<td>$q_A$</td>
<td>Aerodynamic pressure</td>
</tr>
<tr>
<td>$H_L$</td>
<td>Mean lateral height</td>
</tr>
<tr>
<td>$H_{BR}$</td>
<td>Bridge height</td>
</tr>
<tr>
<td>$C$</td>
<td>Horizontal distance from $\ddagger$ to the aerodynamic pressure center</td>
</tr>
<tr>
<td>$H_C$</td>
<td>Vertical distance from waterline to the aerodynamic pressure center</td>
</tr>
<tr>
<td>$\Psi_A$</td>
<td>Relative wind angle</td>
</tr>
<tr>
<td>$C_H$</td>
<td>Roll angle coefficient</td>
</tr>
</tbody>
</table>

Figure A.2: Parameters used by Fujiwara et al. [2006] to estimate wind force coefficients.
\[ C_{LF} \cos \Psi_A + \]
\[ + C_{XLI} (\sin \Psi_A - 1/2 \sin \Psi_A \cos^2 \Psi_A) \cdot \sin \Psi_A \cos \Psi_A + \]
\[ + C_{ALF} \sin \Psi_A \cos^3 \Psi_A \]
\[ C_{AY}(\Psi_A) = F'_{CF} + F'_{YLI} \]
\[ = C_{CF} \sin^2 \Psi_A + \]
\[ + C_{YLI} (\cos \Psi_A + 1/2 \sin^2 \Psi_A \cos \Psi_A) \cdot \sin \Psi_A \cos \Psi_A \]

using the longitudinal-flow drag, \( F'_{LF} \), lift induced drag, \( F'_{XLI} \), and additional longitudinal drag, \( F'_{ALF} \). For the lateral force coefficient the cross-flow drag, \( F'_{CF} \), and the lift induced drag, \( F'_{YLI} \), in the lateral direction are used.

The roll angle coefficient is calculated using
\[ C_H = 0.355 \phi + 1.0 \]

with the heel angle \( \phi \) [rad].

Table A.2: Non-dimensional parameters for wind load estimation equations

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{ij} )</td>
<td>0.404</td>
<td>0.368</td>
<td>0.902</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{ij} )</td>
<td>-0.922</td>
<td>-0.507</td>
<td>1.162</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma_{ij} )</td>
<td>0.116</td>
<td>3.345</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \delta_{ij} )</td>
<td>0.458</td>
<td>3.245</td>
<td>-2.313</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \epsilon_{ij} )</td>
<td>-0.585</td>
<td>-0.906</td>
<td>3.239</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Using the values from table A.2 the cross-flow and longitudinal-flow coefficients are:

\[ C_{CF} = \alpha_0 + \alpha_1 \frac{A_F}{BH_{BR}} + \alpha_2 \frac{H_{BR}}{L_{OA}} \]  
\[ C_{0^\circ \leq \Psi \leq 90^\circ} = \beta_{10} + \beta_{11} \frac{A_L}{L_{OA}B} + \beta_{12} \frac{C}{L_{OA}} \]
\[ C_{90^\circ \leq \Psi \leq 180^\circ} = \beta_{20} + \beta_{21} \frac{B}{L_{OA}} + \beta_{22} \frac{H_{C}}{L_{OA}} + \beta_{23} \frac{A_{OD}}{L_{OA}^2} + \beta_{24} \frac{A_F}{B^2} \]

The lift and induced drag coefficient in the term \( F'_{YLI} \):

\[ C_{YLI} = \pi \frac{A_L}{L_{OA}^2} + C_{YM} \]  
where the corrective term, \( C_{YM} \), affected from the ship hull form above sea level separates into wind direction dependent coefficients as follows:

\[ C_{YM}^{0^\circ \leq \Psi \leq 90^\circ} = \gamma_{10} + \gamma_{11} \frac{A_F}{L_{OA}B} \]
\[ C_{YM}^{90^\circ \leq \Psi \leq 180^\circ} = \gamma_{20} + \gamma_{21} \frac{A_{OD}}{L_{OA}^2} \]  

The lift and induced drag coefficients in the term \( F'_{XLI} \):

\[ C_{XLI}^{0^\circ \leq \Psi \leq 90^\circ} = \delta_{10} + \delta_{11} \frac{A_L}{L_{OA}H_{BR}} + \delta_{12} \frac{A_F}{BH_{BR}} \]
\[ C_{XLI}^{90^\circ \leq \Psi \leq 180^\circ} = \delta_{20} + \delta_{21} \frac{A_L}{L_{OA}H_{BR}} + \delta_{22} \frac{A_F}{A_L} + \delta_{23} \frac{B}{L_{OA}} + \delta_{24} \frac{A_F}{BH_{BR}} \]  

The coefficient \( C_{ALF} \) in the term \( F'_{ALF} \):

\[ C_{ALF}^{0^\circ \leq \Psi \leq 90^\circ} = \epsilon_{10} + \epsilon_{11} \frac{A_{OD}}{A_L} + \epsilon_{12} \frac{B}{L_{OA}} \]
\[ C_{ALF}^{90^\circ \leq \Psi \leq 180^\circ} = \epsilon_{20} + \epsilon_{21} \frac{A_{OD}}{A_L} \]  

The yaw and heel moment coefficients are calculated using the lateral wind force coefficient:

\[ C_{AN}(\Psi_A) = C_{AY}(\Psi_A) L_N(\Psi_A) \]
\[ = C_{AY}(\Psi_A) \left[ 0.927 \times \frac{C}{L_{OA}} - 0.149 \times (\Psi_A - \frac{\pi}{2}) \right] \]
\[ C_{AK}(\Psi_A) = C_{AY}(\Psi_A)L_K \]
\[ = C_{AY}(\Psi_A)(0.0737 \times (\frac{H_C}{L_{OA}})^{-0.821}) \text{ for } \frac{H_C}{L_{OA}} \leq 0.097 \]
\[ = C_{AY}(\Psi_A)(0.500) \text{ for } \frac{H_C}{L_{OA}} > 0.097 \quad \text{(A.15)} \]
Appendix B

Holtrop-Mennen

B.1 Resistance factor calculations

The total resistance of the ship is calculated according to:

\[ R_{hydro} = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \]  \hspace{1cm} (B.1)

The frictional resistance is defined according to the ITTC-57 formula:

\[ R_F = \frac{1}{2} \rho U_S^2 C_F S_{tot} \]  \hspace{1cm} (B.2)

\[ C_F = \frac{0.075}{(\log_{10}(R_n) - 2)^2} \]  \hspace{1cm} (B.3)

where \( \rho \) is the water density, \( U_S \) is the ships speed, \( C_F \) frictional coefficient, \( S_{tot} \) is the total wetted surface area and \( R_n = U_S L \nu \) the Reynolds number based on waterline length \( L \) and kinematic viscosity \( \nu \) of water.

For the form factor Holtrop [1984] suggests the following formula:

\[ 1 + k_1 = 0.93 + 0.487118 c_{14} (B/L)^{1.06806} (T/L)^{0.46106} \]
\[ (L/L_R)^{0.121563} (L^3/\nabla)^{0.36486} (1 - C_P)^{-0.604247} \]  \hspace{1cm} (B.4)

where \( B \) is the molded breadth, \( T \) the molded depth, \( \nabla \) the volume displacement and \( C_P \) the prismatic coefficient.

The coefficient \( c_{14} \) pertains to the shape of the stern and is for all the ships modeled equal to 1. \( L_R \) is defined as:

\[ L_R = L(1 - C_P + 0.06C_P lcb/(4C_P - 1)) \]  \hspace{1cm} (B.5)

with \( lcb \) being the longitudinal position of the center of buoyancy forward of \( \nabla \) as percentage of \( L \).

The wetted surface area of the ship can be approximated using, Holtrop and Mennen [1982]:

\[ S_{tot} = L(2T + B)\sqrt{C_M}(0.453 + 0.4425 C_B - \cdots) \]
\[ -0.2862C_M - 0.003467 B/T + 0.3696C_{WP} + \cdots \]
\[ + 2.38 A_{BT}/C_B \]  \hspace{1cm} (B.6)
where $C_M$ is the amidships section coefficient, $C_B$ the block coefficient, $C_{WP}$ the water plane area coefficient and $A_{BT}$ the transverse sectional area for the bulb at the forward perpendicular.

For the appendage resistance, $R_{APP}$, the same equation as (B.2) can be used but with the appendage surface area, $S_{APP}$, instead of $S_{tot}$ and appendage form factors $(1 + k_2)$ where Holtrop and Mennen [1982] provides $(1 + k_2) \approx 1.7$ for rudder behind skeg and $(1 + k_2) \approx 1.4$ for rudder behind stern.

The wave resistance, $R_W$, is given by Holtrop [1984] for ships with Froude numbers below 0.4 as:

$$R_W = c_1c_2c_6 \sqrt{\rho e^{m_1F_d^4 + m_4 \cos(\lambda F_e^{-2})}}$$  \hspace{1cm} (B.7)

with:

\[
\begin{align*}
c_1 &= 2223105c_7^{3.78613}(T/B)^{1.07961}(90 - i_E)^{-1.37565} \quad \text{(B.8)} \\
c_7 &= 0.229577(B/L)^{0.3333} \text{ when } B/L < 0.11 \quad \text{(B.9)} \\
c_7 &= B/L \text{ when } 0.11 < B/L < 0.25 \quad \text{(B.10)} \\
c_7 &= 0.5 - 0.0625L/B \text{ when } B/L > 0.25 \quad \text{(B.11)} \\
c_2 &= e^{-1.89\sqrt{c_3}} \quad \text{(B.12)} \\
c_3 &= 0.56A_{BT}^{1.5}/\{BT(0.31\sqrt{A_{BT} + T_F - h_b})\} \quad \text{(B.13)} \\
c_6 &= (1 - 0.8A_T/(BTC_M)) \quad \text{(B.14)} \\
m_1 &= 0.0140407L/T - 1.75254\sqrt[3]{L} - 4.79323B/L - c_{16} \quad \text{(B.15)} \\
c_16 &= 8.07981C_P - 13.8673C_P^2 + 6.984388C_P^3 \text{ when } C_P < 0.8 \quad \text{(B.16)} \\
c_16 &= 1.73012 - 0.7067C_P \text{ when } C_P > 0.8 \quad \text{(B.17)} \\
d &= -0.9 \quad \text{(B.18)} \\
m_4 &= c_{15}0.4e^{-0.034F_p^{-3.29}} \quad \text{(B.19)} \\
c_{15} &= -1.69385 \text{ when } L^3/\sqrt{L} < 512 \quad \text{(B.20)} \\
c_{15} &= -1.69385 + (L/\sqrt[3]{L} - 8)/2.36 \quad \text{when } 512 < L^3/\sqrt{L} < 1726.91 \quad \text{(B.21)} \\
c_{15} &= 0 \text{ when } L^3/\sqrt{L} > 1726.91 \quad \text{(B.22)} \\
\lambda &= 1.446C_P - 0.03L/B \text{ when } L/B < 12 \quad \text{(B.23)} \\
\lambda &= 1.446C_P - 0.36 \text{ when } L/B > 12 \quad \text{(B.24)}
\end{align*}
\]

where $A_T$ is the transverse area of the inverted transom at zero speed, $h_b$ the center of the transverse area of the bulbous bow, $A_{BT}$, above the keel line and $T_F$ the forward draft.

The half angle of entrance $i_E$ is defined by Holtrop and Mennen [1982] between $1^\circ$ to $90^\circ$ as:

$$i_E = 1 + 89\exp(-L/B)^{0.80856}(1 - C_{WP})^{0.30484}$$

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\[(1 - C_P - 0.0225lcb)^{0.6367}(L_R/B)^{0.34574} \]
\[\{100 \nabla /L^3\}^{0.16302}\} \quad \text{(B.25)}

For the resistance of a bulbous bow near the surface \cite{Holtrop1982} provide the following formula:
\[R_B = 0.11e^{-3P_B^2}F_{ni}^3A_{BT}\rho g/(1 + F_{ni}^2) \quad \text{(B.26)}\]
where the emergence of the bow is measured by the coefficient \(P_B\) and the Froude number based on immersion, \(F_{ni}\):
\[P_B = 0.56\sqrt{A_{BT}/(T_F - 1.5h_b)} \quad \text{(B.27)}\]
\[F_{ni} = U_s/\sqrt{g(T_F - h_b - 0.25\sqrt{A_{BT}}) + 0.15U_s^2} \quad \text{(B.28)}\]

Further the immerse transom produces an additional resistance as:
\[R_{TR} = 0.5\rho U_s^2A_Tc_6 \quad \text{(B.29)}\]
with \(c_6\) related to the Froude number based on the transom immersion \(F_{nT}\):
\[c_6 = 0.2(1 - 0.2F_{nT}) \text{ when } F_{nT} < 5 \quad \text{(B.30)}\]
\[c_6 = 0 \text{ when } F_{nT} > 5 \quad \text{(B.31)}\]
\[F_{nT} = U_s/\sqrt{2gA_T/(B + BC_{WP})} \quad \text{(B.32)}\]
where \(C_{WP}\) is the water plane area coefficient.

In order to have a better congruence of results from model test to full scale trials a model-ship correlation resistance \(R_A\) is calculated by \cite{Holtrop1982} as:
\[R_A = \frac{1}{2}\rho U_s^2SC_A \quad \text{(B.33)}\]
with:
\[C_A = 0.006(L + 100)^{-0.16} - 0.00205 + \cdots \]
\[+0.003\sqrt{L/7.5C_Bc_2(0.04 - c_4)} \quad \text{(B.34)}\]
\[c_4 = T_F/L \text{ when } T_F/L \leq 0.04 \quad \text{(B.35)}\]
\[c_4 = 0.04 \text{ when } T_F/L > 0.04 \quad \text{(B.36)}\]

\(C_A\) is to be increased if another figure of the standard roughness \(k_s = 150\mu m\) is used.
Appendix C

Propeller force calculations

C.1 Propeller non-dimensional coefficients

Principles of Naval Architecture, Lewis [1988, p 145], uses the following non-dimensional coefficients to describe a propeller advance ratio, \( J \), thrust coefficient, \( K_{PT} \), and moment coefficient, \( K_Q \) as well as the propeller efficiency, \( \eta_0 \) according to:

\[
J = \frac{U_I}{nD} \quad \text{(C.1)}
\]
\[
K_{PT} = \frac{F_P}{\rho_n n^2 D^4} \quad \text{(C.2)}
\]
\[
K_Q = \frac{Q}{\rho_n n^2 D^5} \quad \text{(C.3)}
\]
\[
\eta_0 = \frac{J}{2\pi} \times K_T \frac{K_T}{K_Q} \quad \text{(C.4)}
\]

where \( K_{PT} \), \( K_Q \) and \( \eta_0 \) are functions of \( J \). In equations C.1 to C.4 the variables used are incident water speed at the propeller or advance speed, \( U_I \) [m/s], rotational speed, \( n \) [rev/s], propeller diameter, \( D \) [m], thrust force, \( F_P \) [N], propeller moment, \( Q \) [Nm], and water density, \( \rho_n \) [kg/m\(^3\)]. The coefficients presented here are read from open water curves produced for propellers by Lindgren and Bjärne [1967] and presented in Garne [2007].

C.2 Taylor wake fraction, \( w \)

Propeller testing is done in an open configuration where the incident water is free from disturbances. When the propeller is placed behind the hull of a ship the incident water is affected by the hull. One of the effects is that the water behind the hull has been accelerated by the hull in the direction of travel. This produces a wake behind the ship that makes the propeller work in water with a lower incidence speed, \( U_I \), than \( U_S \). The difference between
the speeds is defined by the Taylor wake fraction, $w$, as presented in [Lewis 1988, p 145-6]:

$$w = \frac{U_S - U_I}{U_S} \rightarrow$$  
$$\rightarrow U_I = U_S(1 - w)$$  

Seventy approximations of the wake fraction are presented in the literature. Here the approximation for single screw ships by Tornblad [1990] as cited by Garme [2007, eq. 61] is used:

$$w = 0.5C_B - 0.05$$  

(C.7)

C.3 Force calculation

The propeller force is calculated using equations C.1 and C.5 to derive a corrected advance ratio:

$$J_w = \frac{U_S(1 - w)}{Dn}$$  

(C.8)
Appendix D

Data plots for selected states in database analysis
D.1 Crown, Number of data points

(a) 1-9 highest number of data points

(b) 10-18 highest number of data points

Figure D.1: Plots of the highest number of data points in each state for Crown class, Wind force 0-5 beaufort
<table>
<thead>
<tr>
<th>Wind Force</th>
<th>Mean Speed</th>
<th>Mean HFC/container</th>
<th>95% Confidence</th>
<th>Number of Data Points</th>
<th>PHC/container</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>10</td>
<td>0.0146</td>
<td>-0.0002296</td>
<td>4</td>
<td>-0.0001479</td>
</tr>
<tr>
<td>1</td>
<td>1.5523</td>
<td>1.6374</td>
<td>5.12E-05</td>
<td>2</td>
<td>1.6394</td>
</tr>
<tr>
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<td>1.6293</td>
<td>1.6260</td>
<td>-4.56E-05</td>
<td>2</td>
<td>1.6269</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
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<td>1.6195</td>
<td>0.0001677</td>
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<td>1.6195</td>
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</table>

**Table D.1:** Crown class results for number of containers from database. Wind force 0-5 Beaufort, Limit for PHC = 10.
Figure D.2: Plots of the highest number of data points in each state for Crown class, Wind force 0-2 beaufort
D.2 Crown, $I_{95\%}$

![Plots of the states with the smallest confidence interval $I_{95\%}$ for Crown class, Wind force 0-5 beaufort](image)

Figure D.3: Plots of the states with the smallest confidence interval $I_{95\%}$ for Crown class, Wind force 0-5 beaufort
Table D.2: Crown class results for $I_{95\%}$ from database. Wind force 0-5 beaufort, $lim_{confint} = 10$.

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>Wind Force</th>
<th>Mean speed</th>
<th>Mean $I_{95%}$</th>
<th>Coefficient $FHC/container$</th>
<th>Number of data point</th>
<th>Mean fuel consumption</th>
<th>$\Delta HFC/container$</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>5</td>
<td>19,5</td>
<td>7,95</td>
<td>0,0102</td>
<td>8,39E-05</td>
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<td>0,0009477</td>
<td>100</td>
<td>1,6448</td>
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<td>4</td>
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<td>0,0194</td>
<td>-0,0001284</td>
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</table>
Figure D.4: Plots of the states with the smallest confidence interval $I_{95\%}$ for Crown class, Wind force 0-2 beaufort.
D.3 Family, Number of data points

(a) 1-9 highest number of data points

(b) 10-18 highest number of data points

Figure D.5: Plots of the highest number of data points in each state for Family class, Wind force 0-5 beaufort
<table>
<thead>
<tr>
<th>Direction</th>
<th>Force Speed</th>
<th>FHC/container</th>
<th>T</th>
<th>Mean</th>
<th>95%</th>
<th>Coefficient</th>
<th>Number of</th>
<th>Mean Fuel Consumption</th>
<th>Data Point</th>
<th>HFC/container</th>
</tr>
</thead>
</table>
Figure D.6: Plots of the highest number of data points in each state for Family class, Wind force 0-2 beaufort
Table D.4: Family class results for number of containers from database. Wind force 0-2 beaufort, limits = 10.

<table>
<thead>
<tr>
<th>Wind</th>
<th>Direction</th>
<th>Force speed</th>
<th>FHC/container</th>
<th>Point</th>
<th>Mean fuel consumption</th>
<th>Coefficient</th>
<th>95% Confidence</th>
<th>Number of containers from database</th>
<th>Wind mean</th>
<th>Wind mean %</th>
<th>Wind % Mean</th>
<th>Mean fuel consumption</th>
<th>Mean fuel consumption</th>
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<td>0.0010100</td>
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<td>0.0010100</td>
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<tr>
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<td>0.0010100</td>
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<td>0.0010100</td>
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<td>0.0010100</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.900</td>
<td>22</td>
<td>0.0790</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
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<td>0.0010100</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.900</td>
<td>22</td>
<td>0.0790</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
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<td>0.0010100</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.900</td>
<td>22</td>
<td>0.0790</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
<td>0.0010100</td>
</tr>
</tbody>
</table>
D.4 Family, $I_{95\%}$

Figure D.7: Plots of the states with the smallest confidence interval $I_{95\%}$ for Family class, Wind force 0-5 beaufort
Table D.5: Family class results for I 95% from database. Wind force 0-5 beaufort, lim confint = 10.

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>Mean Speed</th>
<th>Mean</th>
<th>Mean FHC/container</th>
<th>Mean ∆HFC/container</th>
<th>Mean data point consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>19.5</td>
<td>5.25</td>
<td>0.0249</td>
<td>-0.0004480</td>
<td>103 1.7163</td>
</tr>
<tr>
<td>2</td>
<td>19.5</td>
<td>5.75</td>
<td>0.0254</td>
<td>0.0004554</td>
<td>115 1.7774</td>
</tr>
<tr>
<td>4</td>
<td>21.3</td>
<td>5.25</td>
<td>0.0262</td>
<td>0.0001704</td>
<td>36 1.7897</td>
</tr>
<tr>
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<td>5.25</td>
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<td>-0.0010350</td>
<td>68 1.7561</td>
</tr>
<tr>
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<td>7.5</td>
<td>0.0270</td>
<td>0.0003234</td>
<td>123 1.9046</td>
</tr>
<tr>
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<td>5.75</td>
<td>0.0278</td>
<td>-0.0001840</td>
<td>24 1.8422</td>
</tr>
<tr>
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<td>7.5</td>
<td>0.0284</td>
<td>-0.0004280</td>
<td>64 1.9228</td>
</tr>
<tr>
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<td>0.0298</td>
<td>0.0004649</td>
<td>40 1.8216</td>
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<tr>
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<td>0.0302</td>
<td>0.0002545</td>
<td>89 1.5063</td>
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<tr>
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<td>0.0005286</td>
<td>109 1.7171</td>
</tr>
<tr>
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<td>5.75</td>
<td>0.0303</td>
<td>9.13E-05</td>
<td>63 1.7437</td>
</tr>
<tr>
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<td>5.75</td>
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<td>0.0012482</td>
<td>89 1.7202</td>
</tr>
<tr>
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<td>5.75</td>
<td>0.0319</td>
<td>0.0002625</td>
<td>62 1.8659</td>
</tr>
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</tr>
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</tr>
<tr>
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</tr>
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<td>5.75</td>
<td>0.0344</td>
<td>0.0011813</td>
<td>27 1.8160</td>
</tr>
</tbody>
</table>
Figure D.8: Plots of the states with the smallest confidence interval $I_{95\%}$ for Family class, Wind force 0-2 Beaufort
Table D.6: Family class results for I95% from database. Wind force 0-2 beaufort, limit confidence = 10.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Force speed</th>
<th>Data point</th>
<th>Couldn’t</th>
<th>Mean and</th>
<th>Wind 95%</th>
<th>Mean 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.0000</td>
<td>0.0622</td>
<td>29</td>
<td>0.0059</td>
<td>2.5</td>
<td>3.5</td>
<td>7.5</td>
</tr>
<tr>
<td>1.0000</td>
<td>1.3922</td>
<td>18</td>
<td>0.0084</td>
<td>2.5</td>
<td>3.5</td>
<td>7.5</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.6980</td>
<td>18</td>
<td>0.0059</td>
<td>2.5</td>
<td>3.5</td>
<td>7.5</td>
</tr>
<tr>
<td>1.0000</td>
<td>1.3922</td>
<td>18</td>
<td>0.0084</td>
<td>2.5</td>
<td>3.5</td>
<td>7.5</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.6980</td>
<td>18</td>
<td>0.0059</td>
<td>2.5</td>
<td>3.5</td>
<td>7.5</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.6980</td>
<td>18</td>
<td>0.0059</td>
<td>2.5</td>
<td>3.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Note: Table D.6: Family class results for I95% from database. Wind force 0-2 beaufort, limit confidence = 10.
D.5 Spread of $I_{95\%}$

The spread of $I_{95\%}$ can here seen as well as the detailed spread above the chosen lower limit for the number of data points used in the selection according to $I_{95\%}$.

(a) Wind force 0-5 beaufort. Lower limit 10 data points

(b) Wind force 0-2 beaufort. Lower limit 5 data points

Figure D.9: Spread of $I_{95\%}$ for Crown class
Figure D.10: Spread of $I_{95\%}$ for Family class