ASSESSMENT OF BULBOUS BOW PERFORMANCE OVER OPERATIONAL PROFILES USING FULL SCALE DATA

H F M Way, **D Hudson, S R Turnock**, University of Southampton, UK

SUMMARY

A method of calculating the effects of a bulbous bow on delivered power has been developed. The method takes the full scale measured shaft power of a vessel with a bulbous bow, and compares this to a calculated calm water shaft power of the same vessel without a bulb. This enables the performance of the bulbous bow to defined in terms of a change in shaft power. The shaft power of the bulb-less vessel is calculated using the Holtrop and Mennen statistical prediction. Many of the inputs to Holtrop and Mennen are draft dependent, therefore these variables are calculated for the measured draft of the full scale data, using geometrical and empirical formula. Propulsive efficiency is calculated via draft corrected wake and thrust deduction (empirically) and assuming a Wageningen B-series propeller. The effective power prediction of Holtrop and Mennen is then converted to shaft power via the calculated propulsive efficiency.

The performance of the bulbous bow is defined as the change in residual shaft power due to the addition of the bulbous bow. This change is made non-dimensional to remove the effects of hull shape and a similar performance formula to that of Kracht [1]. Two power effecting bulbous bow parameters, as defined by Kracht [1] ,the depth parameter coefficient and vessel Froude number are shown to widely range over the operational profile of 7 sister LNG vessels. The performance of the bulbous bow is calculated over these ranges. It was found that the bulbous bow performance improves in general with increasing Froude number, and that for a given Froude number range there is an optimal bulb-depth parameter for ballast and laden conditions.

Once the performance of a bulbous bow over an operational profile has been identified, it can enable the vessel operator to make operational changes, in order to ensure the bulb is working in optimal power-reducing conditions. Additionally, this performance indicator could be used to decide as to the requirement of a re-design of the bulbous bow. The performance of this bulbous bow is found to be dependent on the full-scale measurement accuracy and the accuracy of Holtrop and Mennen to predict effective power. A future sensibility analysis of this method is needed to understand the reliability of the bulb performance value. Despite this, this method still shows the expected trends of a bulbous bow from the literature, and can therefore be used for operational optimisation, via ensuring the bulb depth parameter is in an optimal condition for the given Froude number range.

NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
υ	Kinematic viscosity (N s m^{-2})
ρ	Density of water (kg m^{-3})
η_D	Propulsive efficiency
P	Pressure (N m^{-2})
F_N	Froude number
C_B	Block coefficient
C_F	Skin Friction coefficient
C_T	Total resistance coefficient
C_R	Residual resistance coefficient
C_W	Wave resistance coefficient
C_{ZB}	Bulbous bow depth parameter
$C_{P\nabla R}$	Residual power displacement coefficient
V_S	Vessel speed (knots)
t	Thrust deduction
w	Wake fraction
$P_{D,FS}$	Delivered Power (kW)
$\Delta C_{P\Delta R}$	Kracht's Change in Residual power coefficient
ΔC_{FB}	Change in C_F due to the bulb
ΔC_{RB}	Change in C_R due to the bulb

Δ	Vessel displacement (m^3)
$(1 + k)$	Form factor
RPM	Revolutions per minute (rpm)
WSA	Wetted Surface Area (m^3)

1. INTRODUCTION

Bulbous bows are primarily designed to reduce wave-making resistance for the design speed and draught of a vessel. However, in real operations many ships are operated over a range of speeds and draughts due to loading condition, fuel price, and route. In these cases, the bulbous bow may actually be detrimental to vessel performance.

In this study, the performance of bulbous bows for 7 sister LNG carriers is assessed using full scale data, recorded over a year at 2 samples/minute.

This study has developed a method of isolating the effect a bulbous bow has on fuel consumption, over an operational profile, from full scale data. Performance parameters of bulbous bows, as may be used in design, are defined to quantify how the bulbous bow is affecting the

measured shaft power, and hence the fuel consumption over the actual operational profile.

The 'performance' of a bulbous bow is defined as a change in shaft power for a given speed in Laden and Ballast conditions. A parameter representing bulb height is shown to be the main factor causing a change in shaft power for a given speed. Use of this single parameter enables vessel operators to gain additional fuel savings through draught and trim optimisation with vessels in service.

2. LITERATURE REVIEW

2.1 EFFECTS OF BULBOUS BOWS

The original use of a bulbous bow was to reduce the wave making component of total resistance. This was achieved by designing a bulb to create a wave system which is out of phase of the 'hull-only' wave system, such that destructive interference occurs, causing the vessels overall wave-system to be reduced in size. The earliest theoretical study on the effectiveness of bulbous bows was carried out by Wigley [2]. A fundamental study of hull and bulbous bow interaction was carried out by Ferguson and Dand [3].

It has been additionally found that a bulbous bow can influence the viscous as well as wave making component of resistance; adding or reducing each component's contribution to total resistance. A bulb tends to realign the flow around the fore end, which is carried downstream, influencing values of wake fraction and thrust deduction (hull efficiency) [1]. Consequently, this affects the propulsive efficiency. From tests on models with normal and bulbous bows, Steele and Pearce [4] have shown that a bulb can reduce friction drag at high speeds.

The longitudinal position of the bulb relates to the bulb-hull phase difference, while its volume is related to wave amplitude. Additionally, the submergence of the bulb relative to the free surface, plays an important role on the wave interference effect. Kracht [1] shows that bulb depth parameter, C_{ZB}, follows linear interference theory as the bulb height moves closer to the free surface. i.e. the interference between bulb and hull wave system increases from 0 to a maximum, decreases subsequently, and finally becomes negative due to the increasing resistance of an emerging bulb.

At low speeds, where hull wave systems are small, the increase in skin friction arising from an increase in wetted surface area due to the bulb is likely to cancel out any reductions in resistance [5]. At higher speeds, a bulb can improve the flow around the hull and reduce the skin friction [4] component of total resistance.

At the design stage of a vessel, typical sources providing guidance and suitability of bulbous bow design include the work of BSRA [6] and Kracht [1]. The BSRA series shows that the largest reduction (up to 20%) in power due to the bulb, occur at lower C_B and higher speeds. For higher C_B and lower speeds, the reductions are generally much smaller and can even increase required power by up to 6%. However, the BSRA series bulbs do not reflect current design practice.

There are six bulb shape parameters, to which Kracht [1] has shown, have an influence on the bulbs performance as a function of Froude number. The three linear parameters are the length, breadth and depth parameter. The three non-linear parameters are the cross section, volumetric and lateral parameter. In the design stage of the bulb, these parameters will be optimised for the design condition of the vessel, assuming the vessel will spend most of its time in the design condition.

From the literature, it has been shown that a bulbous bow can have both positive and negative effects on total resistance and propulsive efficiency, and hence plays a major role in the rate fuel consumption. Two of the main attributes of a bulb's performance are its depth parameter (defined by Kracht's parameter C_{ZB}) and vessel Froude number, both of which can vary significantly over a vessels operational profile. The depth parameter has been defined in Figure 1, as the height of the fore-most part of the bulbous bow, divided by the draft at the forward perpendicular. Draft can be a widely changing variable over an operational profile and hence so is the depth parameter. For this reason, it was decided to calculate the performance of a bulb from full scale measured data, to show how the bulb was performing over an operational profile in terms of vessel Froude number and bulb depth parameter.

2.2 Performance of Bulbous Bows

Kracht [1] defines the performance of a bulbous bow in terms of the reduction in residual resistance for a range of shape characteristics. A residual reduction coefficient is defined, $\Delta C_{P\nabla R}$, which is a measure of the percentage reduction in residual power when using a bulb compared with a normal bow; a larger value represents a larger reduction in power. This parameter assumes that the bulb has no effect on frictional resistance, which is contrary to [4].

A change of propulsive efficiency of $\pm 3\%$ affects the $C_{P\nabla R}$ by $\pm 4\%$ at low Froude numbers and $\pm 1.5\%$ at high Froude numbers. Kracht defines this as negligible, however in terms of fuel consumption and emissions, vessel operators may make operational changes to gain a 1.5% reduction, over their fleet.

There are two empirical studies for the performance of bulbous bows based on model scale measurements, namely Holtrop and Mennen [7], and Harvald [8]. These studies provide equations to roughly predict the performance on the bulbous bow quickly at the design stage. Holtrop and Mennen predicts a change in wave making resistance and an additional pressure resistance due to bulb transverse area and depth from the free surface

to the centre of transverse area. Harvald states that effect of the bulbous bow on residual resistance is a function of prismatic coefficient, C_P , and Froude number F_N. He provides a correction factor to residual resistance for a given C_P and F_N , in laden conditions only. A recent study [9] has updated these correction factors by predicting residual power using Harvald without a bulbous bow and subtracting this value from total power measured in a towing tank at model scale.

The Holtrop and Mennen (H&M) method of predicting effective power, is based on the regression analysis of 334 ship models with a range of dimension ratios and is often used in the early design stage (IMO Level 1 stage). Recently [10] found Holtrop and Mennen to be accurate in predicting effective power but lacks accuracy in shaft power prediction, relative to model scale measurement of 7 modern bulk carriers and tankers ($0.09 \leq F_N \leq 0.18$). The general trend in laden conditions is an over prediction of shaft power up to 6% at low F_N decreasing down to a maximum under prediction of 27% at higher F_N. In all Ballast conditions, shaft power was under predicted severely by 10-45%. This suggests an inaccuracy in the estimation of propulsive efficiency η_D.

Although there is much literature on predicting the performance effects of a bulbous bow on power at full scale, no such studies are found to define the in-service performance of a bulb from full scale data. The basis of the method, developed in this study, takes the statistical prediction of shaft power for a bulb-less vessel, and compares this to measured shaft power at full scale.

Once the bulbous bow performance has been calculated from the full-scale data, these curves could be used either for operational optimisation, or at the design stage to account for the range of speeds and bulb submersions experienced in realistic conditions. Furthermore, for a given in-service vessel and operational profile, these performance curves can be used to decide on whether the bulb needs to be re-designed.
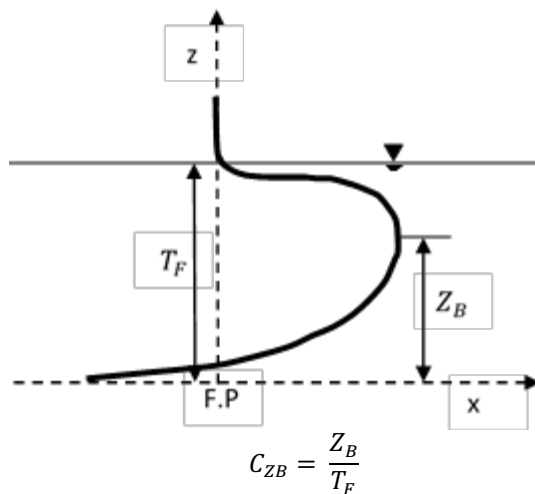

$$C_{ZB} = \frac{Z_B}{T_F}$$

Figure 1: Bulbous bow diagram.

3. METHOD
3.1 The Method

In order to calculate the performance of the bulbous bow, a reference shaft power as a function of a change in draft over an operational profile is needed. The hull parameters which change as a function of draft are: Block Coefficient C_B , Midship section Coefficient C_M, Prismatic coefficient C_P, displacement volume Δ, and wetted surface area WSA, thrust deduction. It is assumed that Kinematic viscosity and water density remain constant over the operational profile. The Holtrop and Mennen shaft power prediction method, allows shaft power to be calculated as a function of the above-mentioned parameters, once the parameters have been updated for the new draft value. Table 1, gives the references as to how these parameters are updated for a given draft.

The change in total resistance coefficient due to the bulbous bow, ΔC_{TB}, is calculated via taking the difference between Equation 1 and 2, as shown in Equation 3. This is obtained by taking the difference between measured C_T of a full-scale vessel with a bulbous bow and the predicted C_{TH} from Holtrop and Mennen, of the same vessel without a bulbous bow. Subscript H and FS represent Holtrop and Mennen and Full Scale respectively.

$$C_T = C_F(1 + k) + C_W + \Delta C_{RB} + \Delta C_{FB} \quad (1)$$

$$C_{TH} = C_F(1 + k_H) + C_{WH} \quad (2)$$

$$\Delta C_{TB} = \Delta C_{RB} + \Delta C_{FB} = C_T - C_{TH} \quad (3)$$

At full scale, shaft power is measured, therefore it is required to convert C_T to delivered power P_D. Equations 1-3 are now represented in terms of delivered power, where:

$$P_{D,FS} = P_{R,FS} + P_{F,FS} + \Delta P_{RB,FS} + \Delta P_{FB,FS} \quad (4)$$

$$P_{D,H} = P_{R,H} + P_{F,H} \quad (5)$$

$$\Delta P_{TB} = \Delta P_{RB,FS} + \Delta P_{FB,FS} = P_{D,FS} - P_{D,H} \quad (6)$$

$$Bulb\ Effectiveness = \frac{\Delta P_{TB}}{P_{D,H}} \quad (7)$$

In order to remove other shaft power changing factors, such as added wave resistance and trim, a filter has been applied to the full-scale data. Additionally, the filtering criteria set out by ISO 19030-2 is also applied to remove accelerative periods and outlying data points. The filter criteria are as follows:

- ISO 19030-2 - Sections E1 and E2
- Wind speed < 11 knots
- Trim < 0.5m
- Speed Through water – speed over ground < 0.1 knots

Once filtered, equation 7 is evaluated as shown by the Flowchart in Figure 2. Table 1 summarises which Holtrop and Mennen inputs are given, calculated and assumed from empirical formula.

In Holtrop and Mennen, to calculate η_D:
- Hull efficiency η_H is calculated through empirical formula for wake and thrust deduction
- Relative-rotative efficiency, η_R, is calculated from empirical formula
- Open water efficiency, η_O, is calculated assuming a Wageningen B series

It was found that the bulb effectiveness is highly dependent on the accuracy of the Holtrop and Mennen prediction of shaft power. To reduce the error in Holtrop and Mennen shaft power due to hull shape, shaft power is made non-dimensional to create the residual power displacement coefficient. This is identical to the Kracht [1] residual power coefficient. C_F is calculated from the ITTC skin friction law.

$$C_{P\Delta R} = \left[\frac{P_{D,R}}{\rho/2V_S^3 \sqrt[3]{\nabla^2}} - \frac{C_F WSA}{\eta_D \sqrt[3]{\nabla^2}} \right] \quad (8)$$

Equation 7, can now be rearranged to form Kracht's change is residual power coefficient, due to the bulbous bow (Equation 9). Where the $C_{P\Delta R}$ without a bulb in Kracht's equation has been replaced with the Holtrop and Mennen prediction:

$$\Delta C_{P\Delta R} = 1 - \frac{C_{P\Delta R,FS}}{C_{P\Delta R,H}} \frac{\eta_{D,FS}}{\eta_{D,H}} \quad (9)$$

This change is residual power coefficient, due to the bulbous bow (Equation 9), will include the bulbous bow effects on added frictional resistance due to the bulb at high Froude numbers.

As $\eta_{D,FS}$ is unknown, it has to be assumed that it is equal to $\eta_{D,H}$. The error in this assumption has been discussed above.

3.2 Limitations Of The Method

In order to isolate the effects of the bulbous bow on shaft power it was needed to remove the effects of trim from the full-scale data. This was achieved by filtering out data corresponding to trim > 0.5. In reality when trim optimisation is undertaken, the effects of trim are coupled to the effects of the bulbous bow.

This method relies heavily on the use of empirical formula to calculate the unmeasured variables, which means there will be error in comparison to the true value. However, this method also enables the performance of the bulbous bow to be calculated without the expense of further measurement. E.g. Model scale experiments to measure propulsive efficiency.

This developed method is therefore designed to give a qualitative representation of the bulbous bow's performance and not a definitive quantitative value.

Figure 2: Flowchart of method to isolate the performance of a bulbous bow in full scale operational data.

Table 1: Summary of hull and propeller characteristics: Given, Calculated and Assumed.

Holtrop and Mennen Inputs	Calculated	Assumed from empirical formulae
Hull		
L_{BP}	$C_{P @T\,measured}$	LCB [11]
B	L_{wl}	C_F - ITTC
T_{des}	Fn	C_M [11]
$C_{B\,des}$	Rn	
V_{des}	$WSA_{@T\,measured}$	WSA [9]
$V measured$	$C_{B @T\,measured}$	t [7]
$T measured$		$t_{@T\,measured}$ [12]
	∇	w [7]
	$\nabla_{@T\,measured}$	$w_{@T\,measured}$ [12]
	η_H	$\eta_S = 0.99$
Propeller		
P/D	η_O	K_T [13]
Z	RPM	K_Q [13]
		EAR – Keller formula
		η_R [7]

4. CASE STUDY: 7 SISTER LNG CARRIERS

4.1 Data Overview

High frequency operational data was captured on board 7 sister LNG vessels over 1 year at 2 samples per minute. This totals a database of 1572667 data points. After filtering, this is reduced to 27882 data points. For each vessel, the data is then averaged over 10-minute intervals, and the bulbous bow performance calculated. The 10 minute averaging is not necessary, and serves only to make the plotted results more readable.

As an initial indicator for the performance of the bulbous bow, a comparison to the BSRA series can be made. A change in C_B , due to change in draft from design conditions, is calculated for the range of drafts found in the data. It was found that C_B ranges from 0.714 to 0.750 over a year's operational profile for the combined vessels. For the given data, C_B is plotted against speed over ground and overlaid over the BSRA series as shown in Figure 3, in terms of a density plot. The darker the region in Figure 3, the larger the number of data points located there. According to the BSRA series, from Figure 3, it can be seen that the bulb spends the majority of the operational profile in power reducing conditions, although after 16 knots speed over ground this is an extrapolated conclusion.

The extent to which the two power affecting bulb characteristics, F_N and bulb depth parameter C_{ZB}, vary over a year's operational profile can be seen in Figure 4 and 5. In these figures, the F_N and C_{ZB} range found in the data, has been split into 50 bins and the frequency density calculated, such that the area of each bin is equal to the number of data points in each bin. A normal distribution is then fitted over the corresponding histogram, to produce the Figures shown.

4.2 The Performance of the Bulbous Bow

A comparison of Holtrop and Mennen predicted and measured residual shaft power, for increasing Froude number can be seen in Figure 6 (bottom). Here the residual shaft power coefficient has been normalised against the maximum Holtrop and Mennen predicted value. Both measured and predicted follow the expected $\sim x^3$ relationship between Froude number and residual power. At low Froude numbers in Ballast and Laden conditions, Holtrop and Mennen, at first appears to predict well in comparison to measured. However, there is a minimum difference of ~4% and a maximum of ~60% in Ballast and ~1% to 40% in Laden conditions. At higher
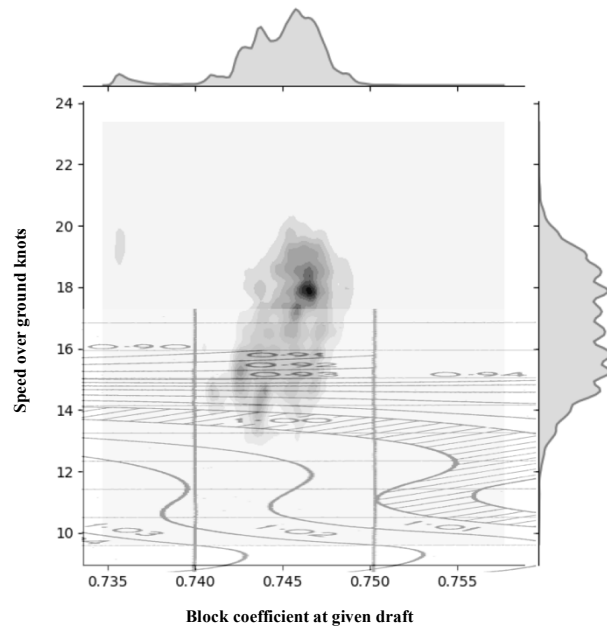

Figure 3: Density plots with histograms showing the distribution of Block coefficients against speed for the combined 7 sister LNG vessel data. Overlaid is the BSRA series contours of power with bulb / power without bulb. Darker colour means more data points in that region.
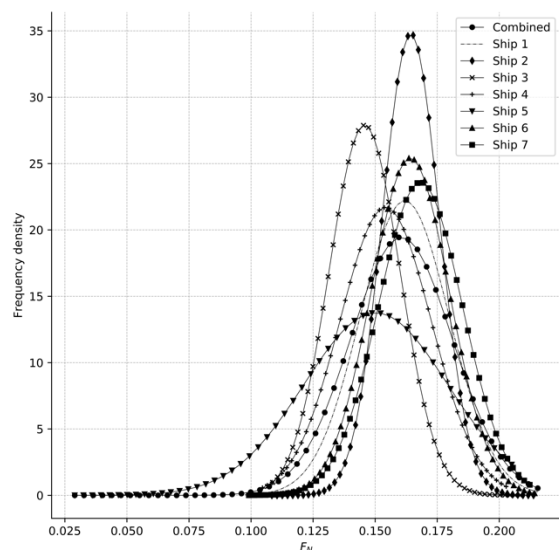

Figure 4: Frequency density histogram of Froude number. Data is 7 sister LNG carriers over 1 year. No. Bins = 50
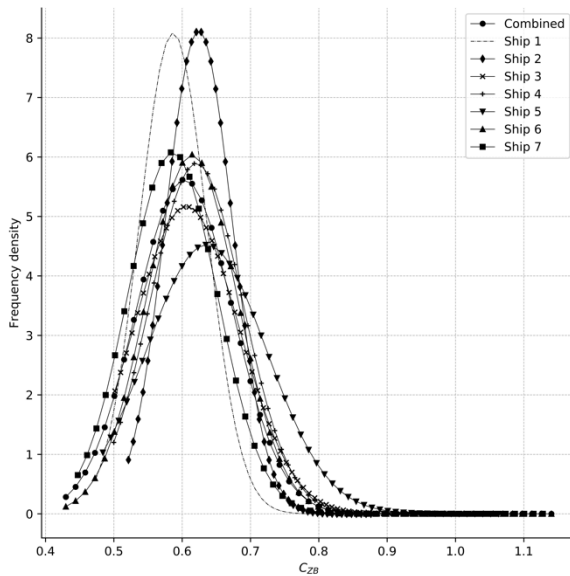
Figure 5: Frequency density histogram of Bulb depth parameter. Data is from 7 sister LNG carriers over 1 year. No. Bins = 50.

Froude numbers the Holtrop and Mennen continuously overpredicts by up to 40% in Ballast and 37% in Laden. This difference cannot be put down to the performance of the bulb alone. Errors in the measured data include the accuracy of vessel speed and draft measurement. This measurement error is propagated into the Holtrop and Mennen model as they the predictions inputs. Further errors are in the prediction of effective power and propulsive efficiency as they are calculated from empirical formula. Despite these errors the expected trends in bulb performance are still shown. The bulb performance values can therefore be used for operational optimisation, but cannot be expected to actually reduce shaft power by the stated amount.

The performance of the bulbous bow, in terms of residual power reduction coefficient, for the 7 sister ships can be seen in Figure 6 (top). As expected an increase in Froude number causes a general increase in the performance of the bulbous bow in both Ballast and Laden conditions. This is due to the better wave-drag reducing performance of the bulbous bow at higher Froude numbers and possibly a reduction in friction drag as described by [4]. At low Froude numbers the negative performance of the bulbous bow could be due to the bulbs influence on hull efficiency, due to a change in wake and thrust deduction. Additionally, the bulb may add more frictional resistance at low Froude numbers relative to its wave reducing performance.

The markers on Figure 6 (top) represent the given bin for the Kracht bulb height parameter C_{ZB}. There are clear groups of given C_{ZB} bins, for a given Froude number range, suggesting that bulb C_{ZB} is clearly affecting required shaft power. To view this relationship in more detail, C_{ZB} is plotted against a change in residual shaft

power, $\Delta C_{P\Delta R}$, for given Froude number bins in Figures 7 and 8. From Figure 7, In the range $0.115 \leq F_N \leq 0.13$, it appears that further emerging the bulb through the waterline, increases the performance of the bulbous bow. For $0.14 \leq F_N \leq 0.145$, there appears to be an optimum C_{ZB} of 0.67, then further increasing C_{ZB}, increases residual shaft power coefficient. For $0.145 \leq F_N \leq 0.16$, $\Delta C_{P\Delta R}$ is almost constant with increasing C_{ZB}. In higher F_N , there is a negative trend between C_{ZB} and F_N, however the bulb is seen to be continuously reducing shaft power coefficient in this high Froude number range.

In Laden conditions, as seen in Figure 8, the bulbous bow is always completely submerged. It is in the Laden conditions where it is expected that the bulbous bow would have the best performance. From Figure 8, it can be seen that this is, in general the case in higher Froude number ranges. For all Froude numbers, it is seen that increasing C_{ZB} reduces the performance of the bulbous bow. This suggests that in Laden conditions, the bulb has been designed to be at the optimal C_{ZB} value at the design draft. I.e. C_{ZB} has been chosen as the maxima of the C_{ZB}, F_N curve and the slope after this becomes negative. This is a very different trend to that seen in Ballast conditions.

An in-detail sensitivity analysis, of the how the measurement errors and the error of the H&M prediction of shaft power, affects the calculated bulb performance, is beyond the scope of this study. It was found however, that a small change in the input parameters of H&M, translates the performance curves up and down. As the expected trends of bulb performance from the literature can still be seen, this method can still be used for optimisation. Nevertheless, expecting a change in the given parameter to actually change the residual power by the stated amount, cannot be relied upon.

To improve this method, a sensitivity analysis needs to be undertaken. A confidence factor for the calculated bulb performance can then be stated. The performance curves can then be used to calculate how the bulb is affecting fuel consumption or emission rates over an operational profile. If the bulb is found to be increasing these factors, either a change in the operational profile is required, or a new bulbous bow designed.
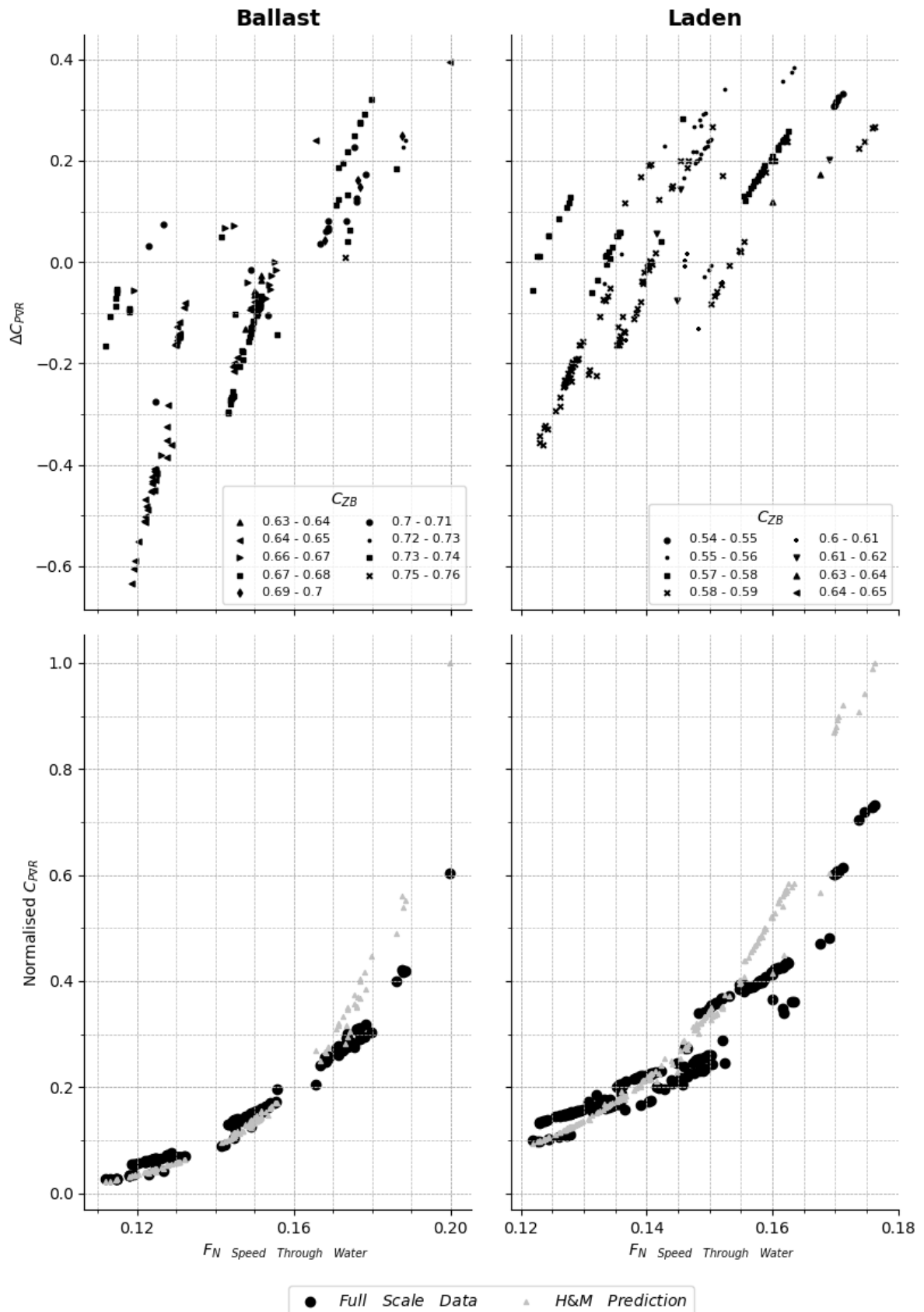
Figure 6 : Residual power reduction coefficient (top) and Normalised Residual power coefficient (bottom) with increasing 'speed through water' based Froude Number in Ballast (left) and Laden (right) conditions. Data is from combined 7 sister LNG carriers over 1 year, averaged over 10-minute intervals after filtering.
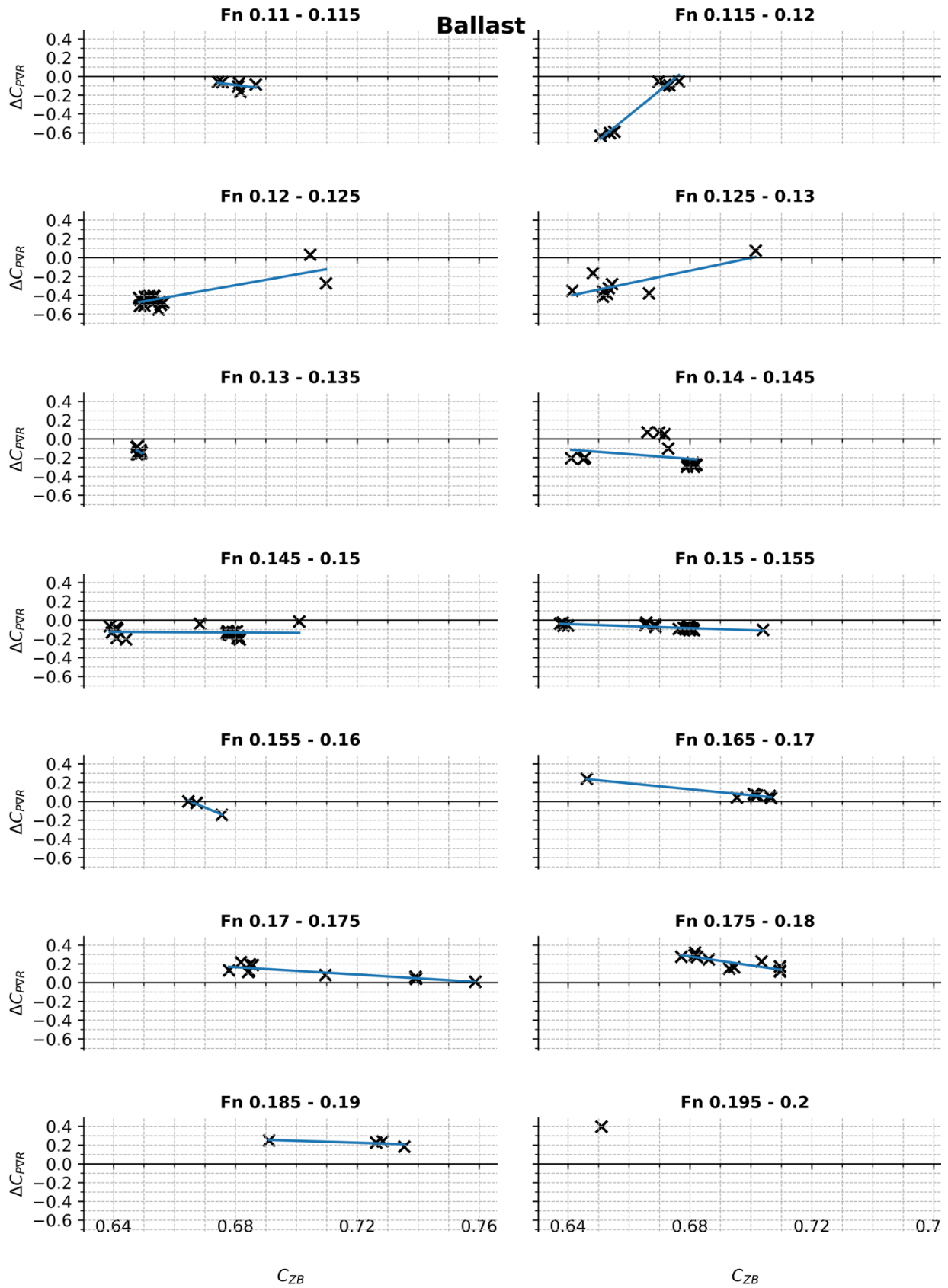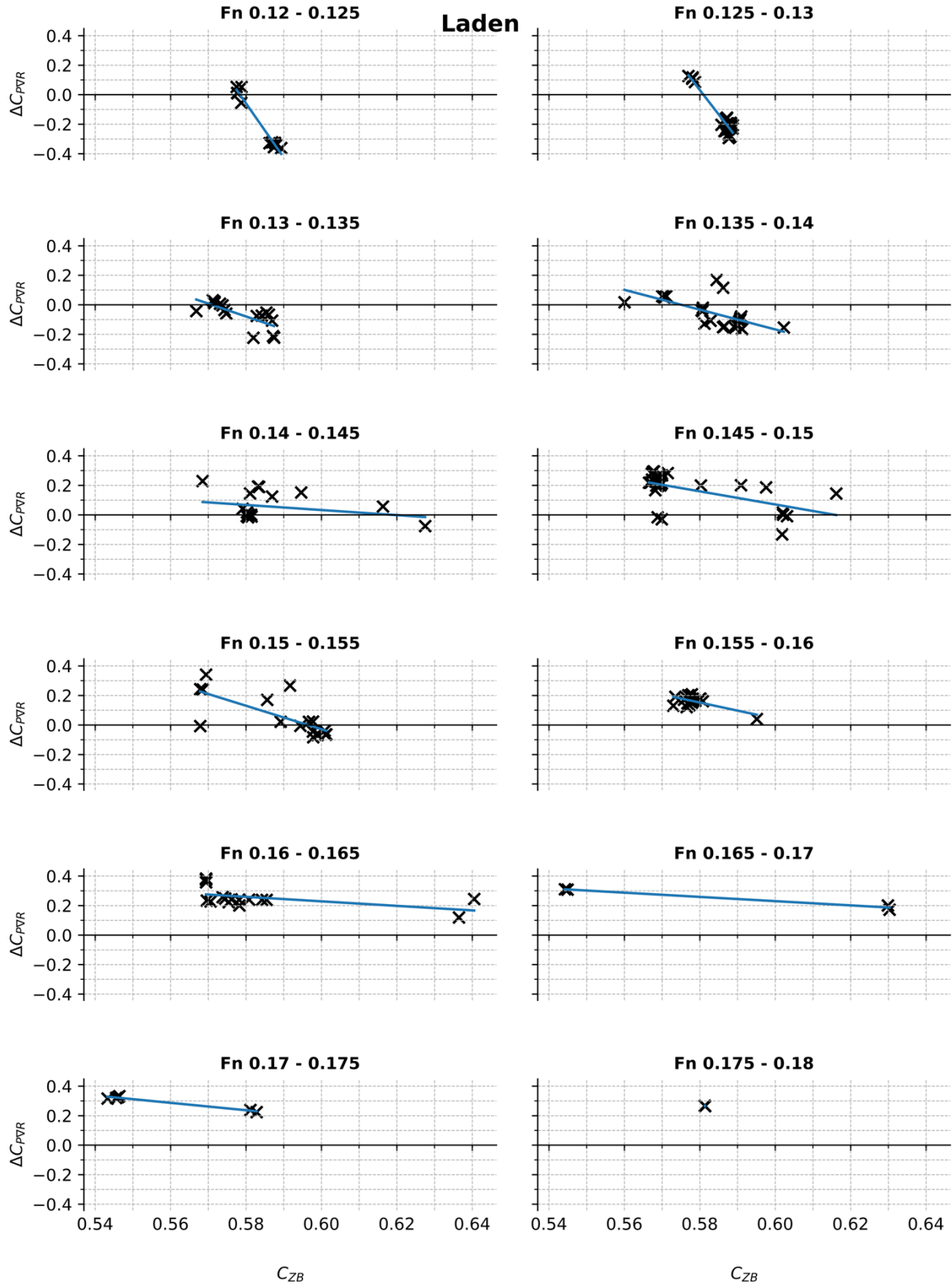
Figure 7: Residual power reduction coefficient with increasing bulbous bow depth parameter, for the given Froude number range, in Ballast conditions. A linear line of best fit has been plotted over the data.

Figure 8: Residual power reduction coefficient with increasing bulbous bow depth parameter, for the given Froude number range, in Laden condition. A linear line of best fit has been plotted over the data.

7. CONCLUSIONS

A method of calculating the performance of the bulbous bow using full scale measured data and the statistical predictions of Holtrop and Mennen. Supplementing Holtrop and Mennen are various other empirical formula to evaluate unknown variables needed for Holtrop and Mennen.

A performance coefficient is defined, similar to that of Kracht [1], where Kracht's residual power of a vessel without a bulb is replaced by the bulb-less vessel prediction of Holtrop and Mennen.

Two parameters affecting the performance of the bulbous bow, the depth parameter C_{ZB} and vessel F_N are shown to widely vary over an operational profile. The extent to which these parameter's affect residual shaft power is then shown using the change in residual power coefficient.

The performance coefficient is found to be highly dependent on the accuracy of full-scale measurements and the accuracy of Holtrop and Mennen to predict shaft power. However, as the expected trends of bulb performance from the literature can still be seen, this method can still be used for design and operational optimisation. Nevertheless, the absolute change in residual shaft power with respect to a given bulb parameter, may not be accurate.

To improve this method, a sensitivity analysis needs to be undertaken. A confidence factor for the calculated bulb performance can then be stated. The performance curves can then be used to calculate how the bulb is affecting fuel consumption or emission rates over an operational profile. If the bulb is found to be increasing these factors, either a change in the operational profile is required, or a new bulbous bow designed.

8. ACKNOWLEDGEMENTS

9. REFERENCES

[1]   A. Kracht, "Design of Bulbous Bows," *SNAME Trans.*, vol. 86, pp. 197–217, 1978.

[2]   W. C. S. Wigley, *The Theory of the Bulbous Bow and Its Practical Application*, Vol. 52. North East Coast Institution of Engineers and Shipbuilders, 1935.

[3]   A. M. Ferguson and I. Dand, "Hull and bulbous bow interaction," in *Publication of: Royal Institution of Naval Architects*, 1970, vol. 3, pp. 421–441.

[4]   B. N. Steele and G. B. Pearce, "Experimental determination of the distribution of skin friction on a model of a high speed liner," *Trans. R. Inst. Nav. Archit.*, vol. 110, pp. 79–100, 1968.

[5]   A. F. Molland, S. R. Turnock, and D. A. Hudson, *Ship resistance and propulsion : practical estimation of ship propulsive power*. Cambridge University Press, 2011.

[6]   BSRA, *Methodical series experiments on single-screw ocean-going merchant-ship forms. Extended and revised overall analysis.*, NS333 ed. BSRA, 1971.

[7]   J. Holtrop and G. G. . Mennen, "An Approximate Power Prediction Method," *Int. Shipbuild. Prog.*, vol. 31, pp. 272–276, 1984.

[8]   S. A. Harvald, *Resistance and propulsion of ships*. Wiley, 1983.

[9]   H. O. Kristensen and M. Lützen, "Prediction of resistance and propulsion power of ships," 2013.

[10] L. Nikolopoulos and E. Boulougouris, "A Study on the Statistical Calibration of the Holtrop and Mennen Approximate Power Prediction Method for Full Hull Form, Low Froude Number Vessels," *J. Sh. Prod. Des.*, no. February, 2018.

[11] H. Schneekluth and V. Bertram, "Ship Design for Efficiency and Economy," *ButterworthHeinemann*, p. 226, 1998.

[12] D. . Moor and F. R. . O'connor, "Resistance and propulsion factors of some single-screw ships at fractional draft," *Trans. North East Coast Inst. Eng. Sh. Build.*, vol. 80, pp. 185–202, 1964.

[13] M. M. Bernitsas, D. Ray, and P. Kinley, "Wageningen B-Series," *Kt, Kq and Efficiency curves for the wageningen B-series Propellers*. p. 102, 1981.

10. AUTHORS BIOGRAPHY

Henry Way holds the current position of PhD candidate as the University of Southampton. His research is focused on the unsteady pressure measurement of bulbous bow-hull flows.

Dominic Hudson is the Shell Professor of Ship Safety and Efficiency at the University of Southampton. He has research interests in all aspects of ship hydrodynamics, performance management and operational efficiency. He has published over 110 papers in journals and proceedings of refereed conferences. He is a Chartered Engineer and member of both RINA and IMechE. He is presently a member of the 29th ITTC Specialist Committee on Ships in Operation at Sea.

Professor Stephen R Turnock is Professor of Maritime Fluid Dynamics and Head of the Civil, Maritime and Environmental Engineering and Science Academic Unit within Engineering and the Environment at the University of Southampton.