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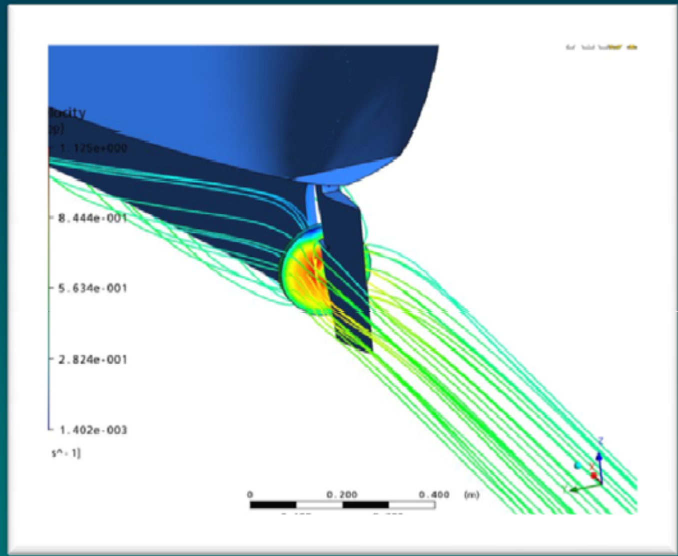
Energy efficiency of ship propulsive systems: rudder-propeller interaction



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School of Engineering Sciences,
University of Southampton, SO17 1BJ, UK.

Why consider the rudder when investigating propulsive efficiency?

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(1) Main function of a rudder is to initiate a course change or to maintain a given course.

(2) Aim of rudder design is to develop enough sideforce to fulfil (1).

(3) There is a continual resistance penalty associated with the rudder; which increases with rudder angle.

(4) Presence of rudder influences flow through propeller and alters effective thrust.

Is rudder too small a component to make a difference?

Aim of presentation

Examine physics of rudder-propeller interaction and propose designs that minimise overall energy budget while maintaining rudder manouevring capability

Contents:

(1) Energy Budget

(2) Rudder Fundamentals

(3) Physics of interaction

(4) Design Tools

(5) Case Studies

Energy Budget of Ship

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Table 2 Potential savings in resistance and propulsive efficiency

RESISTANCE (a) Hull resistance	Principal dimensions: main hull form parameters, U or V shape sections
	Local detail: bulbous bows, vortex generators
	Frictional resistance: WSA, surface finish, coatings
(b) Appendages	Bilge keels, shaft brackets, rudders: careful design
(c) Air drag	Design and fairing of superstructures. Stowage of containers
PROPULSIVE EFFICIENCY (d) Propeller	Choice of main dimensions: D,P/D, BAR, optimum diameter, rpm.
	Local detail: section shape, tip fins, twist, tip rake, skew etc
	Surface finish
(e) Propeller-hull interaction	Main effects: local hull shape, U,V or 'circular' forms [resistance v propulsion]
	Changes in wake, thrust deduction, hull efficiency.
	Design of appendages: such as shaft brackets and rudders.
	Local detail: such as pre and post swirl fins, upstream duct, twisted rudders.

Resistance components

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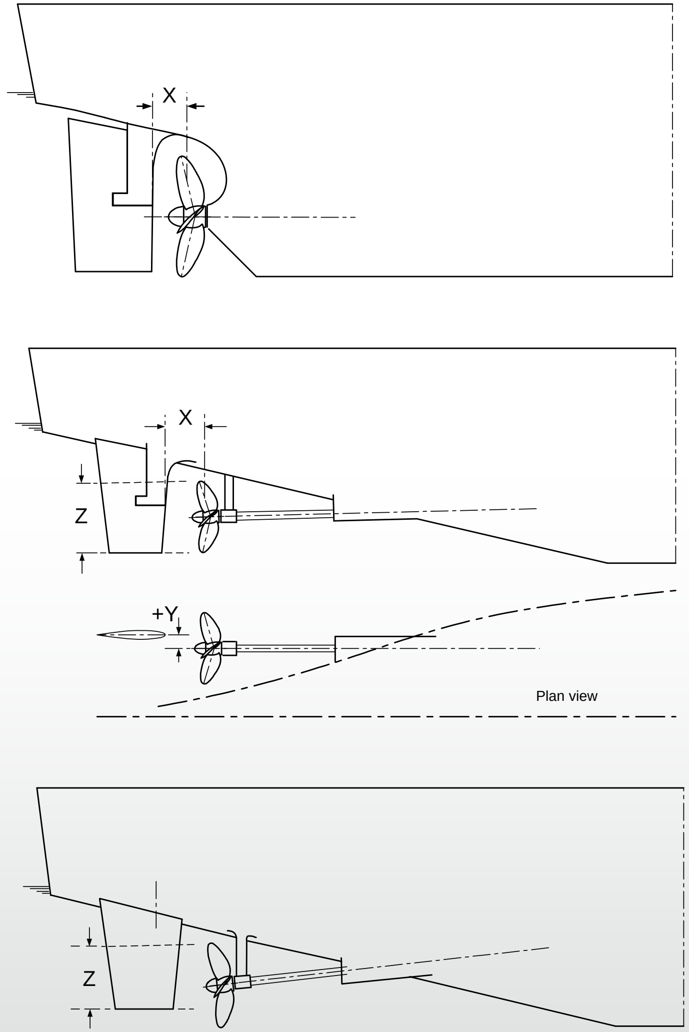
Table 1 Approximate distribution of resistance components

Type	Lbp (m)	C_B	Dw (tonnes)	Service speed (Knots)	Service power (kW)	Fn	Hull resistance component			Air drag %
							Friction %	Form %	Wave %	
Tanker	330	0.84	250000	15	24000	0.136	66	26	8	2.0
Tanker	174	0.80	41000	14.5	7300	0.181	65	25	10	3.0
Bulk carrier	290	0.83	170000	15	15800	0.145	66	24	10	2.5
Bulk carrier	180	0.80	45000	14	7200	0.171	65	25	10	3.0
Container	334	0.64	100000 10000 TEU	26	62000	0.234	63	12	25	4.5
Container	232	0.65	37000 3500 TEU	23.5	29000	0.250	60	10	30	4.0
Catamaran ferry	80	0.47	650 pass 150 cars	36	23500	0.700	30	10	60	4.0

- Key is the multiplier effect, eg reductions in resistance, require ‘smaller’ propeller, which mean less shaft, gearbox and engine losses and hence less fuel.
- Seeking cost-effective techniques for energy savings. Best strategy is to identify components where improvements can be made at low cost.

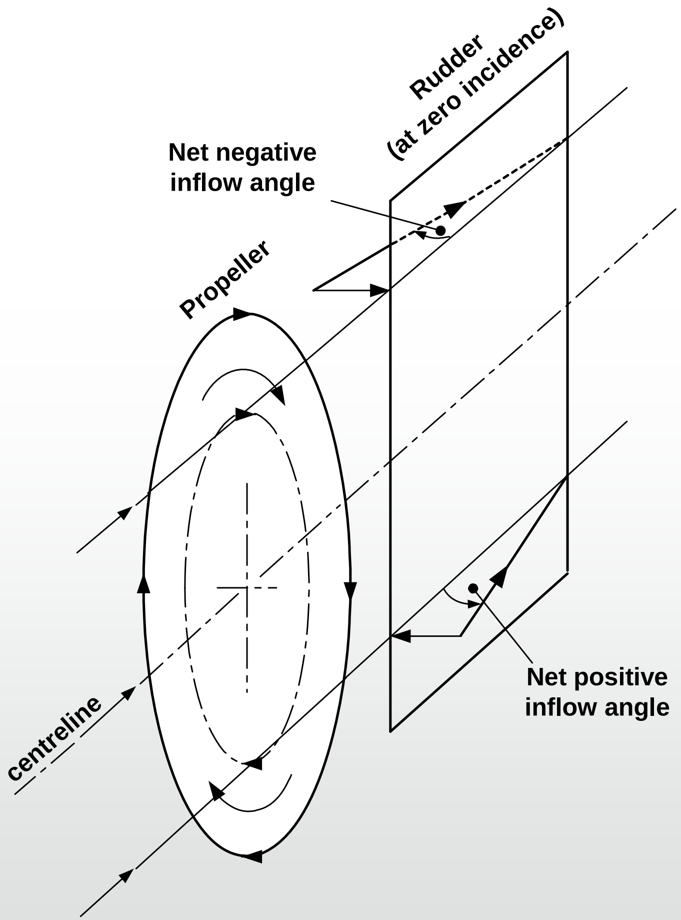
Rudder fundamentals

- Typically sits in race of propeller.
- Small and easily forgotten during design process.
- Will a small additional design effort result in a significant performance dividend?



Physics of rudder-propeller interaction

- Effects are
  - Propeller accelerates and swirls flow arriving at rudder.
  - Rudder blocks and diverts flow through propeller
- Magnitude of interaction depends on the propeller thrust loading, relative location and effective rudder incidence



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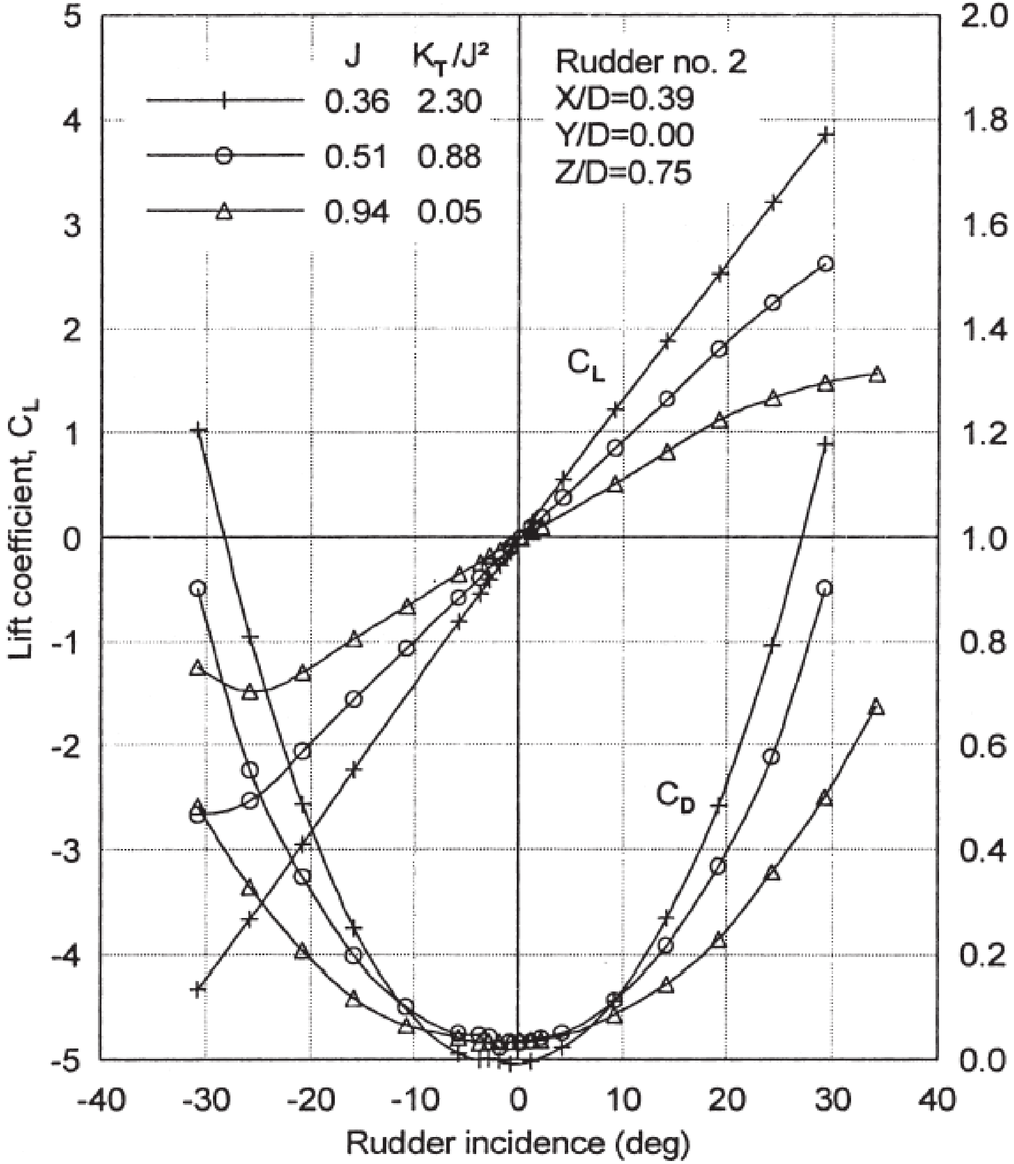

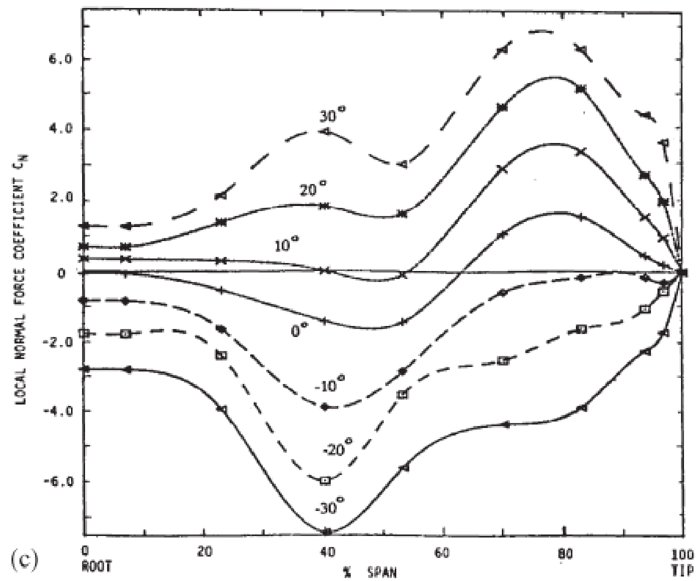

Net propulsive thrust, K_T'

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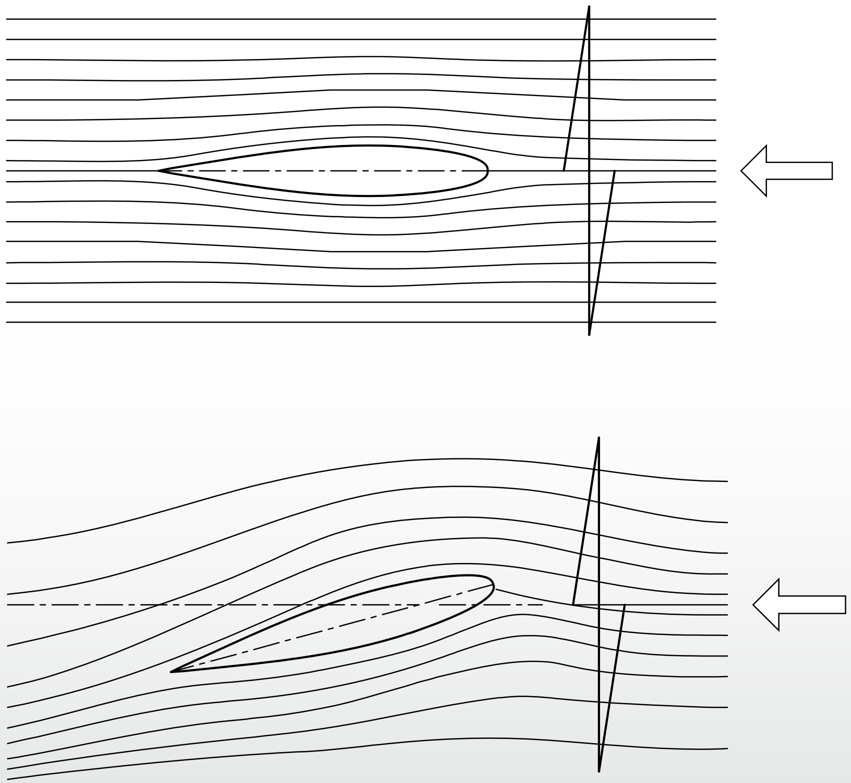
- Arises from the change to propeller thrust and increase/decrease in rudder drag
- Rudder blocks/diverts flow through propeller, changing wake fraction and relative rotative efficiency

$$K_T' = K_T - C_D J^2 \left(\frac{S\bar{c}}{2D^2} \right)$$

- Both K_T and C_D are functions of relative position of propeller-rudder system



Propeller Thrust Loading

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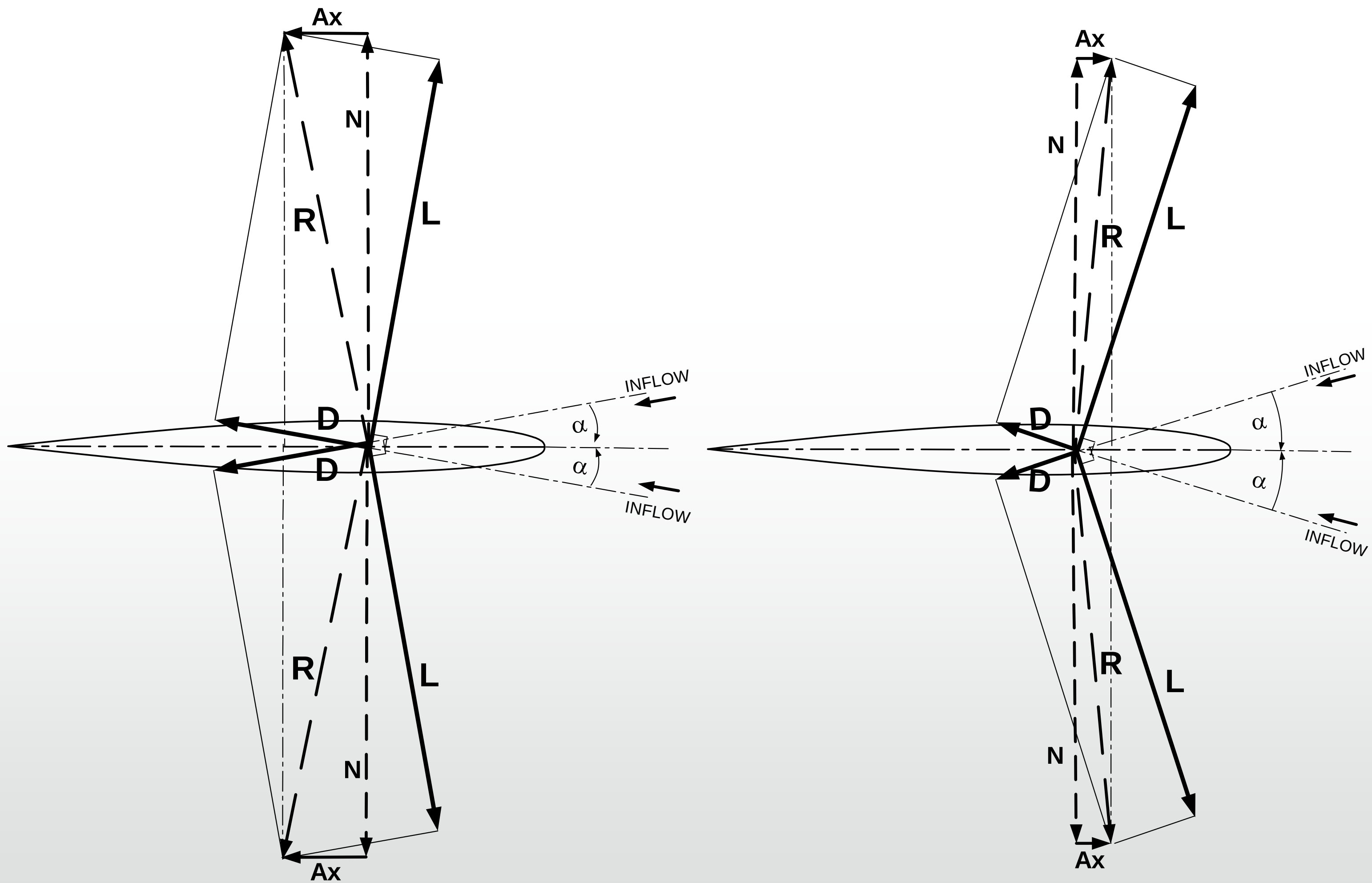
- Net rudder (a) Drag (b) Thrust



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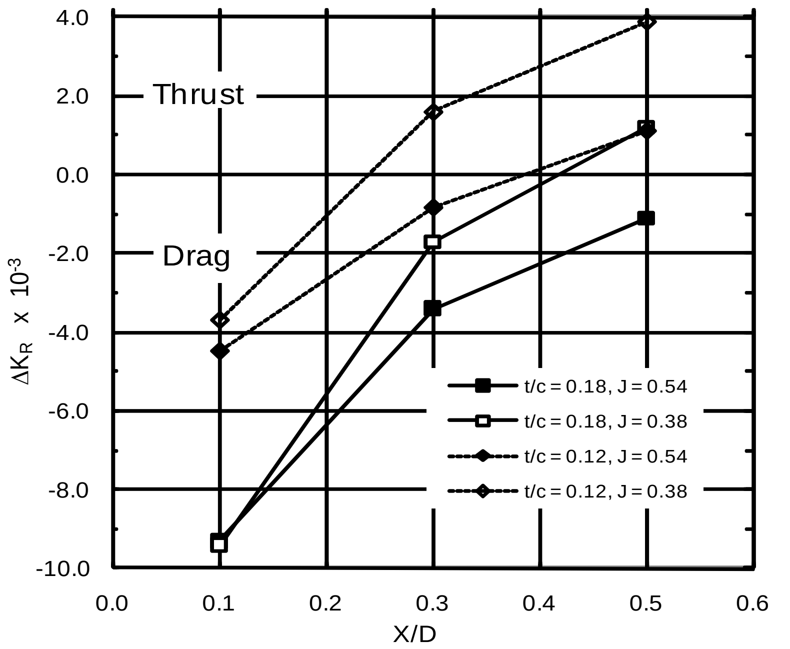
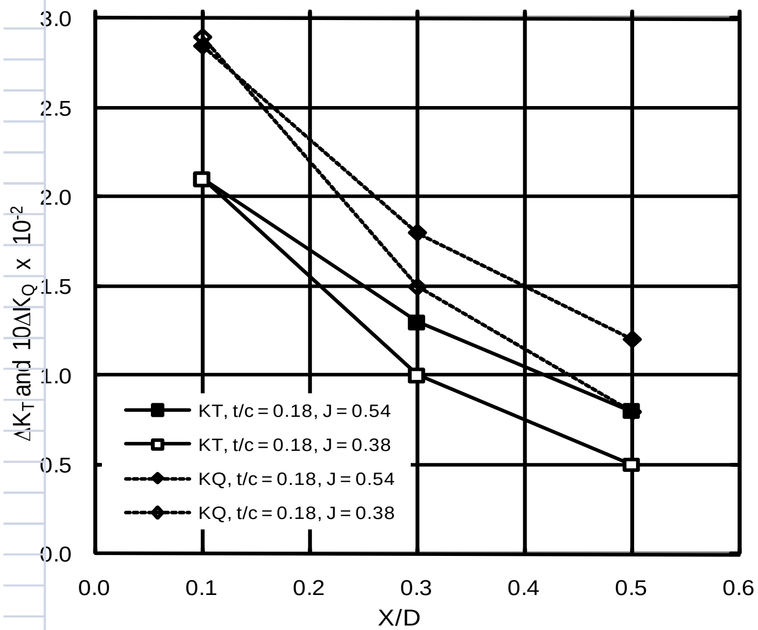
Longitudinal Separation





Rudder Drag

Propeller Thrust

Cross plots from Stiermann's Data, ISP(1989)

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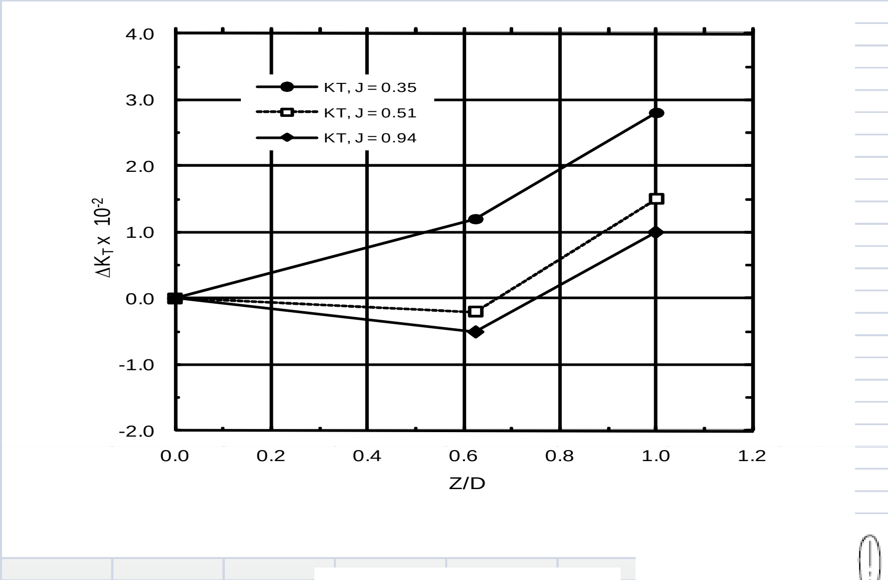
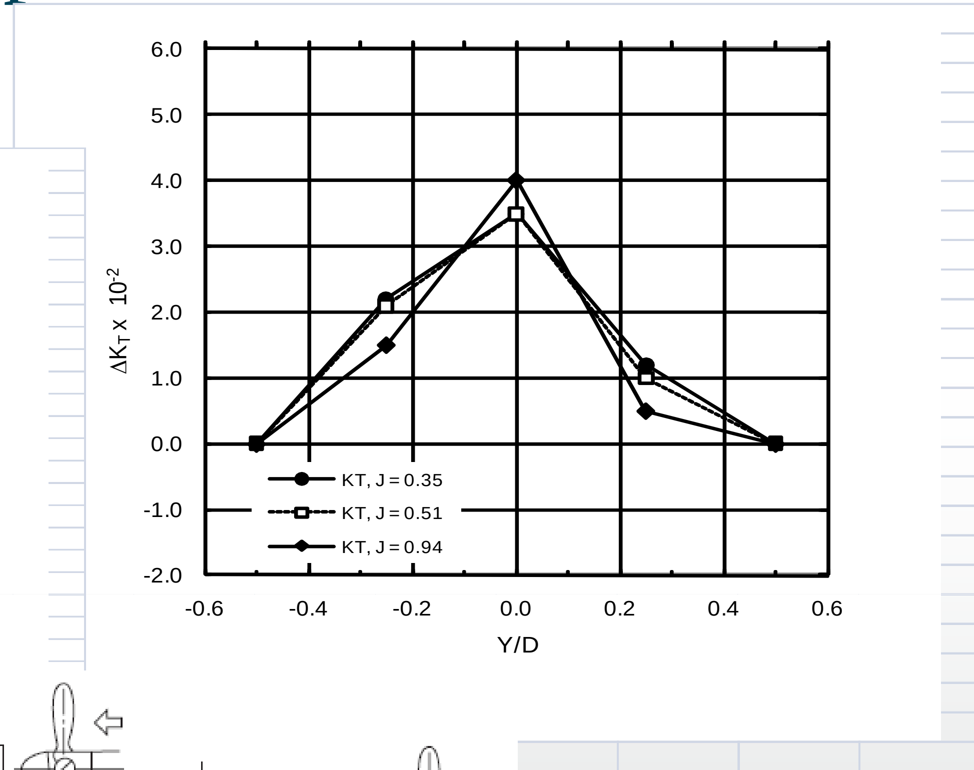
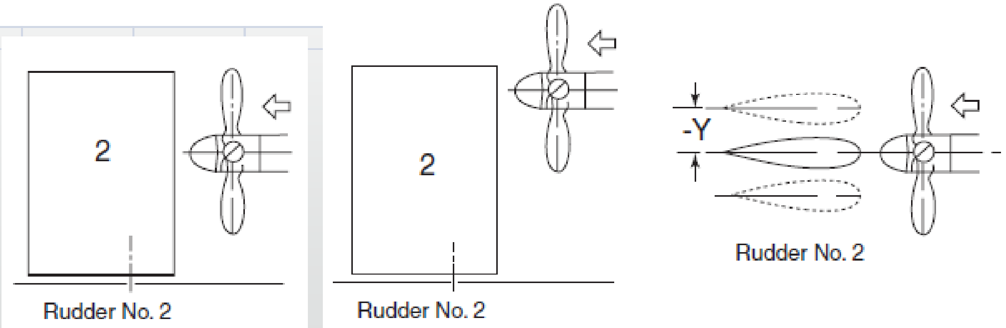
Lateral/Vertical Separation







Design tools-
Computational Fluid Dynamics

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COST

- Large Eddy Simulation
- Unsteady Reynolds Averaged Navier Stokes (RANS)
- Coupled Blade Element Momentum/RANS
- Surface Panel Method using interaction velocity field
- Blade Element Momentum + Lifting Line+viscous correction

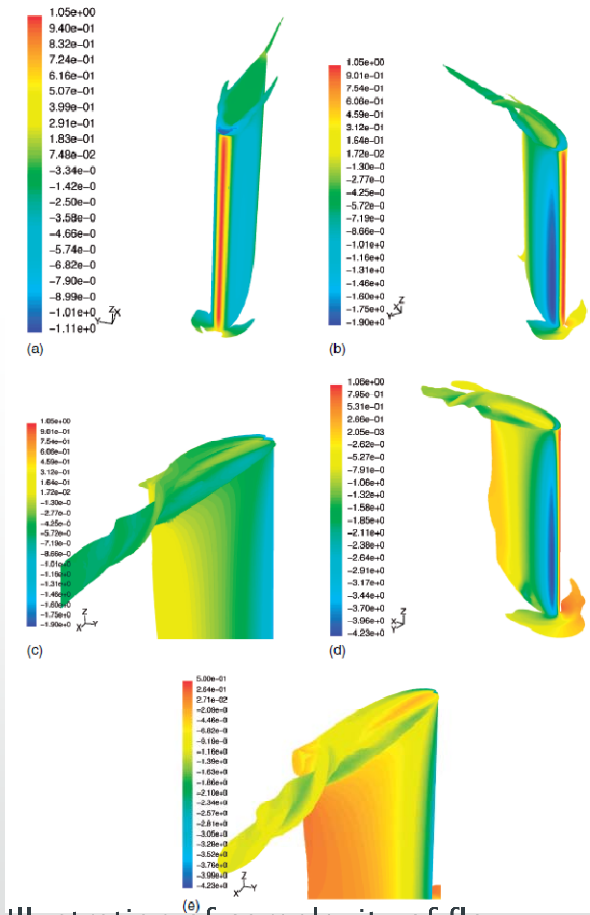
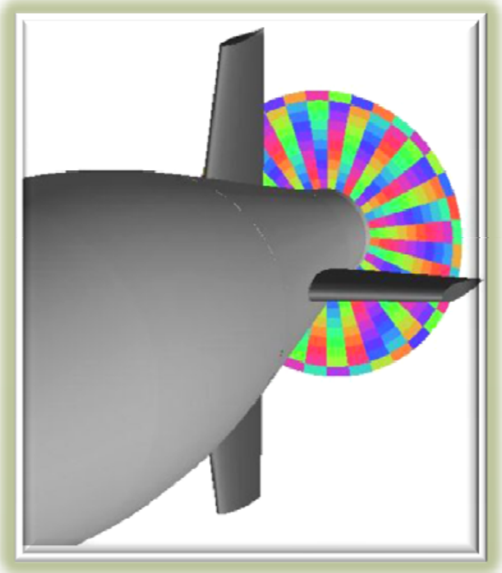
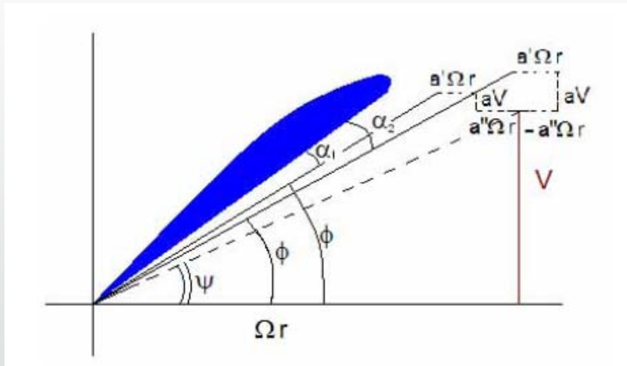


Illustration of complexity of flow at rudder tip in freestream using CFD

Blade Element Momentum Theory RANS-BEMT

- T and Q vary depending on geometry of propeller, RPM, Ua
- Existing Fortran77 code called from within CFX
- Divide propeller disk into 10 radial and 36 circumferential zones
- For each zone use local axial velocity to determine zonal thrust/torque contribution (allows rudder effects, and hull wake to be captured)
- BEMT evaluates axial a and circumferential a' velocity factors and hence swirl and axial momentum





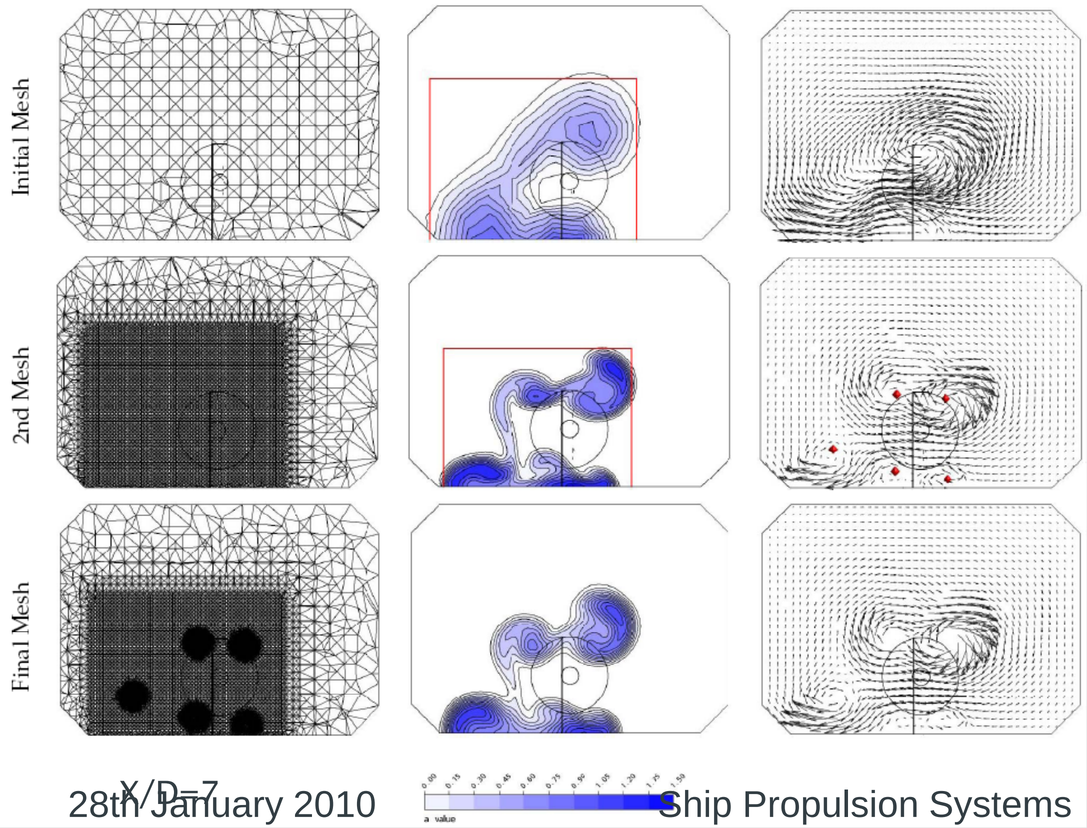
Submiited PhD of Alex Phillips

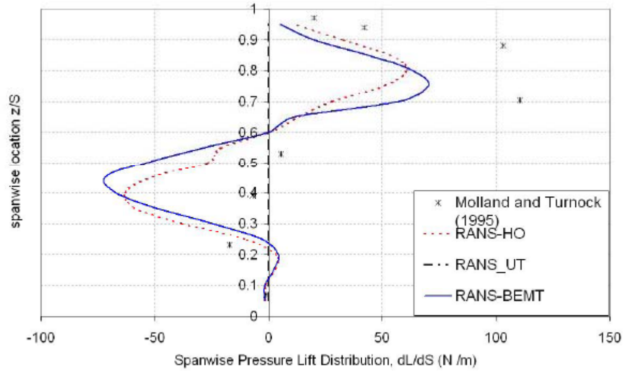
RANS framework ANSYS CFX v11

Parameter	Setting
Mesh Type	Unstructured with local refinement in vortical regions
No. of Elements	approximately 10M
Computing	Iridis 2 Linux Cluster
Run Type	Parallel (8 partitions run on 4 $\times$ dual core nodes each with 2Gb RAM)
Turbulence Model	Shear Stress Transport
y^+	30-60 on rudder
	30 on floor outside propeller race
	80 on floor where propeller race interacts with the floor
Wall Modelling	Automatic Wall Functions
Spatial Discretization	High Resolution
Pseudo Time Step	0.1s
Convergence Control	RMS residual $< 10^{-5}$
Simulation Time	Typically 2.5-3hrs

Table 7.2: Mesh sensitivity - propeller-rudder interaction.

Case	Parameter	Coarse	Medium	Fine
J=0.35, $\delta = 10$, HO	No. of Elements	1.5M	4.4M	9.5M
	Pressure Drag, C_{D_P}	0.0710	0.0986	0.1111
	Skin Friction Drag, C_f	0.0592	0.05938	0.0619
	Lift, C_L	1.389	1.433	1.330





(a) $\delta = 0°$

Force Data – Lift and Drag

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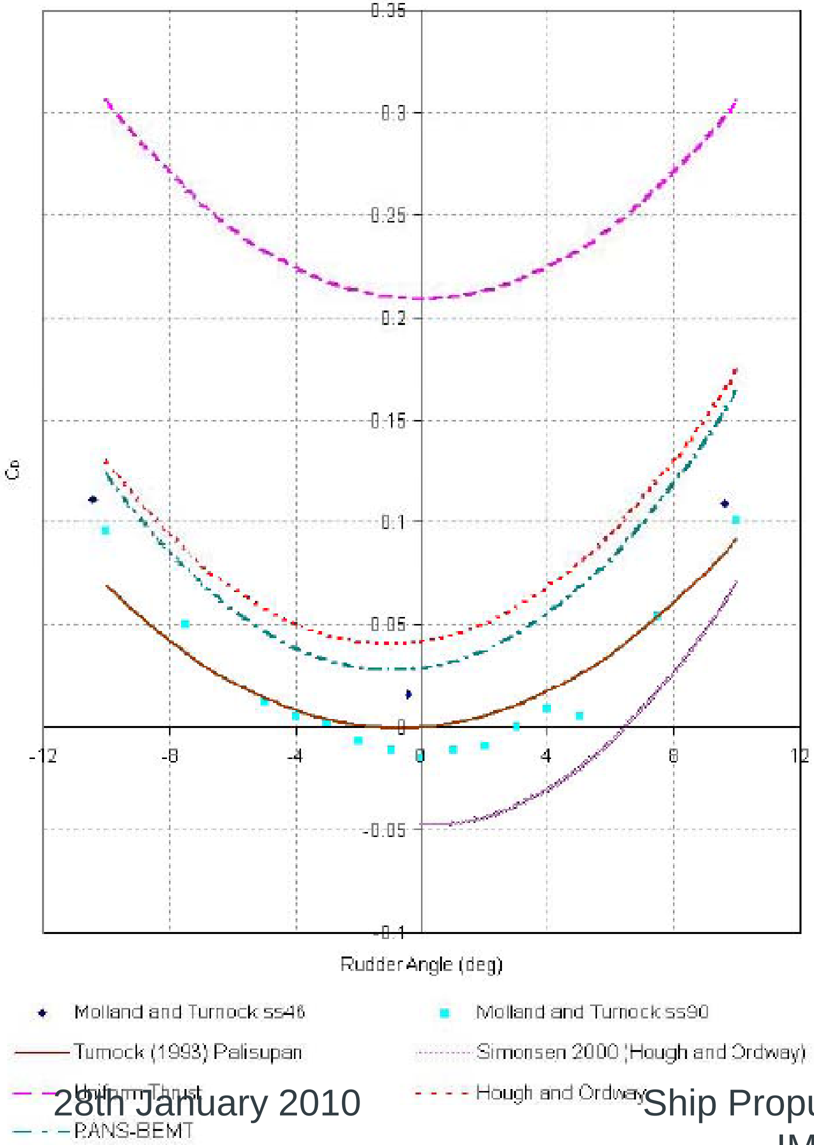

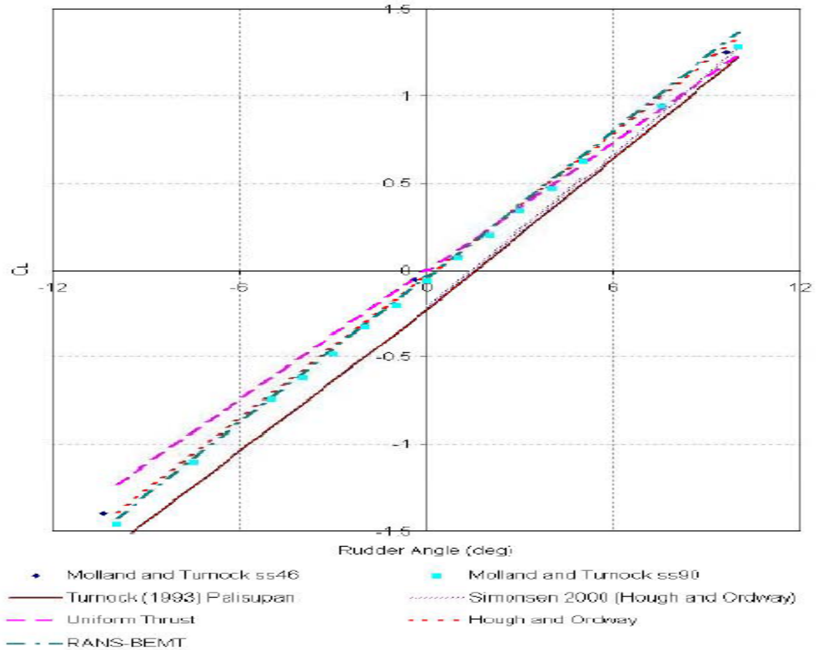

Data Set	$\frac{dCL}{d\delta}$	δ_0
Molland and Turnock SS46	0.132	0.093
Molland and Turnock SS90	0.136	0.526
Turnock (1993)	0.140	1.376
Simonsen 2000	0.147	1.383
RANS-UT	0.123	0.000
RANS-HO	0.136	0.213
RANS-BEMT	0.139	0.227

Surface Pressures J=0.35, 0 deg

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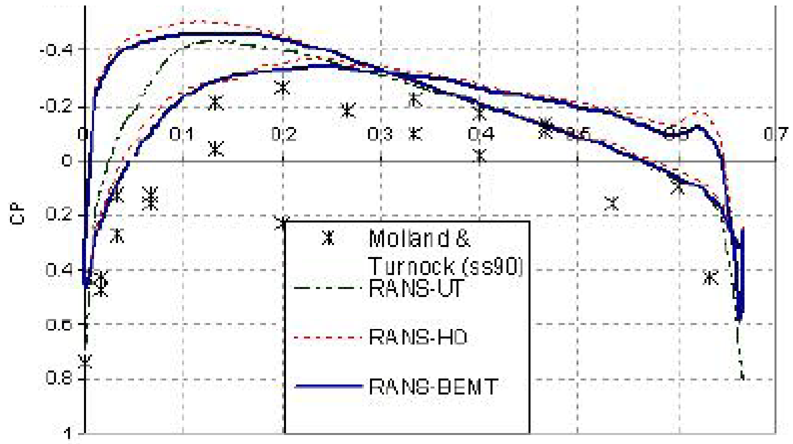
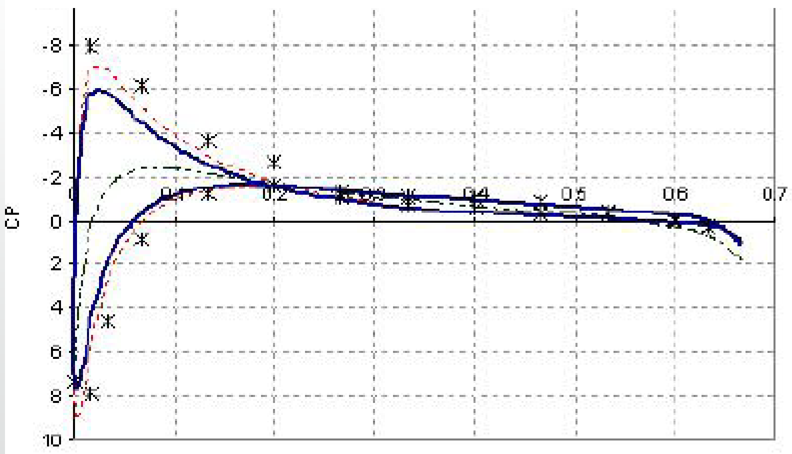
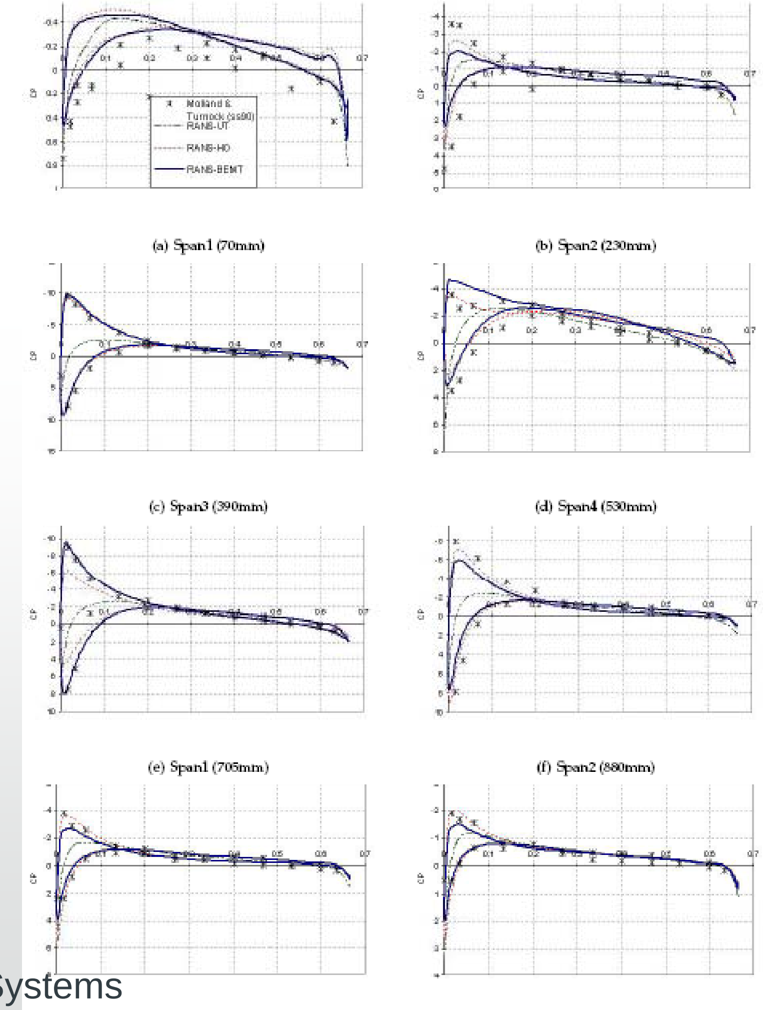


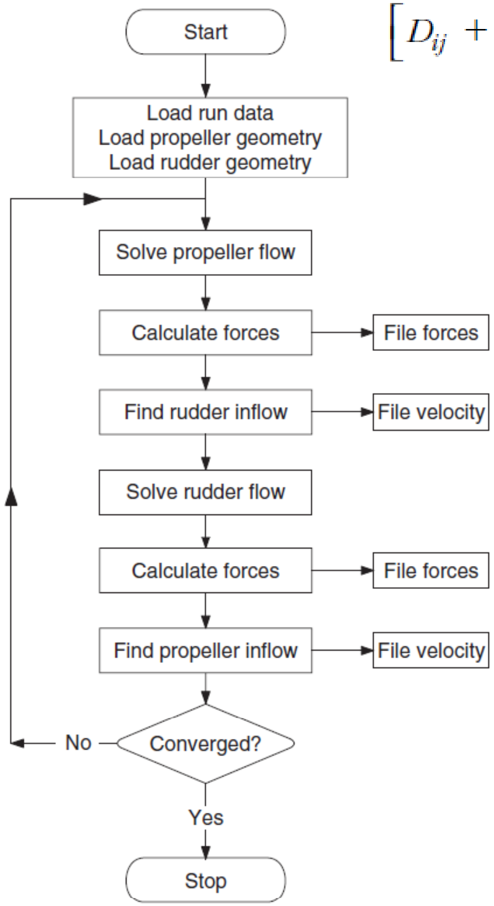
(a) Span1 (70mm)



(f) Span2 (880mm)



Interaction velocity field –surface panel



$$\left[D_{ij} + W_{ik}\right]\phi = \left[S_{ij}\right]U_{\infty}\cdot n_j - \left[W_{ik}\right]\left(\frac{\mathrm{d}\Delta\phi}{\mathrm{d}\Delta p}\Delta p\right)$$

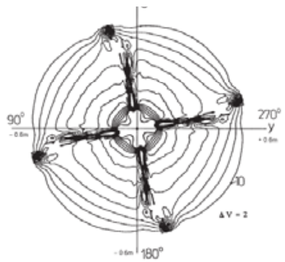
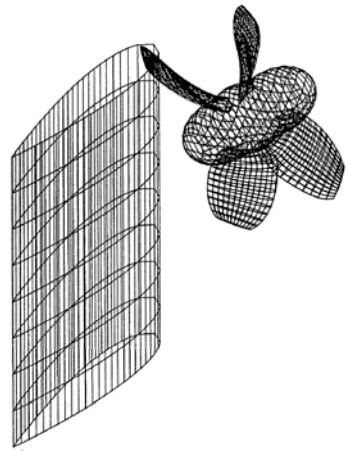
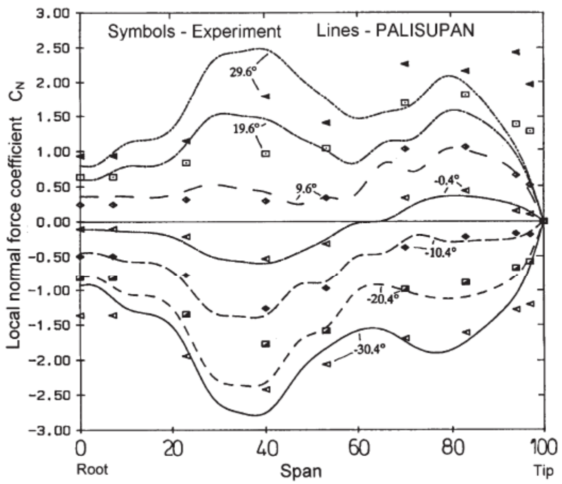
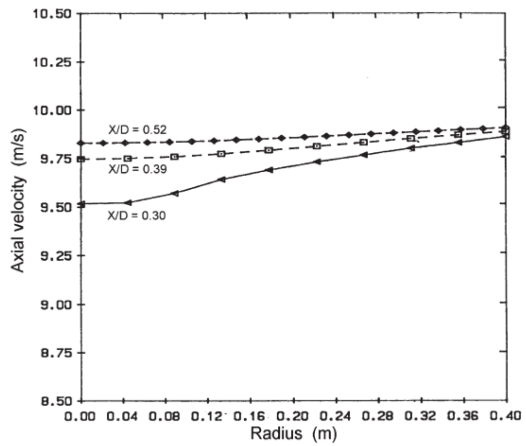


Figure 6.34 Contour plot of total velocity for vertical plane downstream of propeller; X/D = 0.39, J = 0.35







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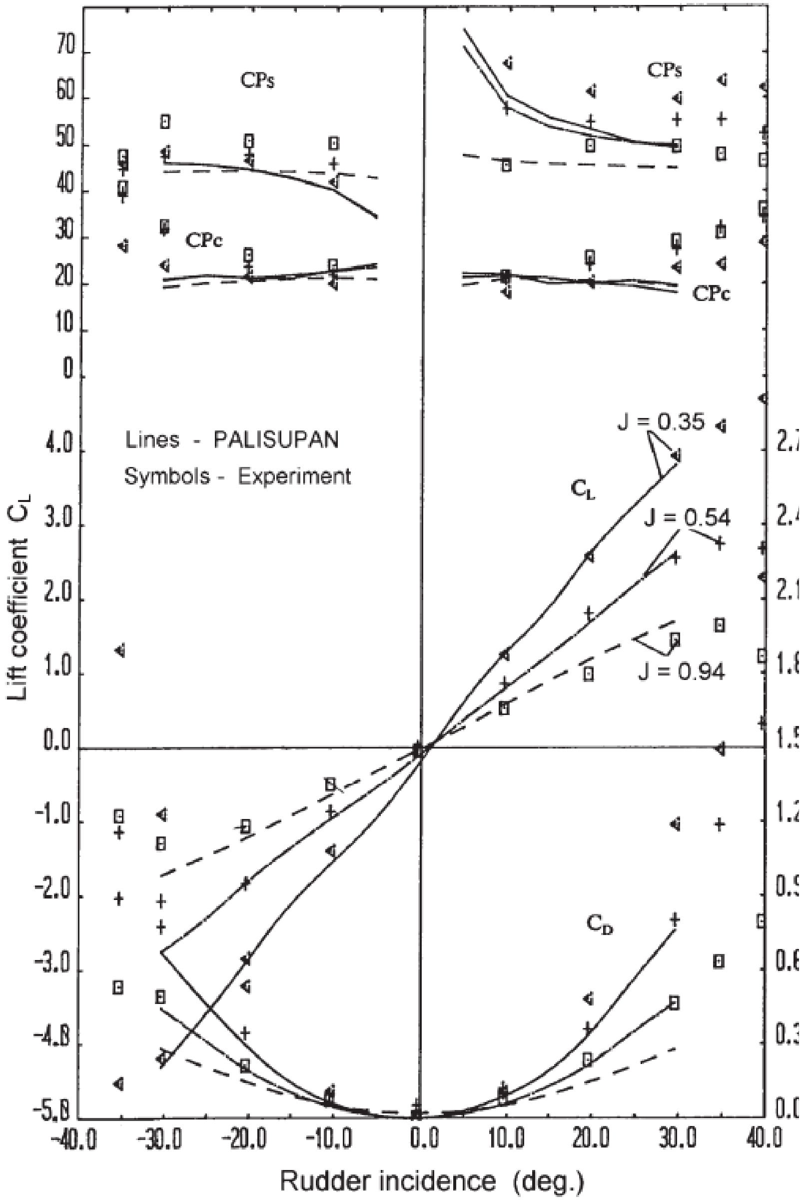

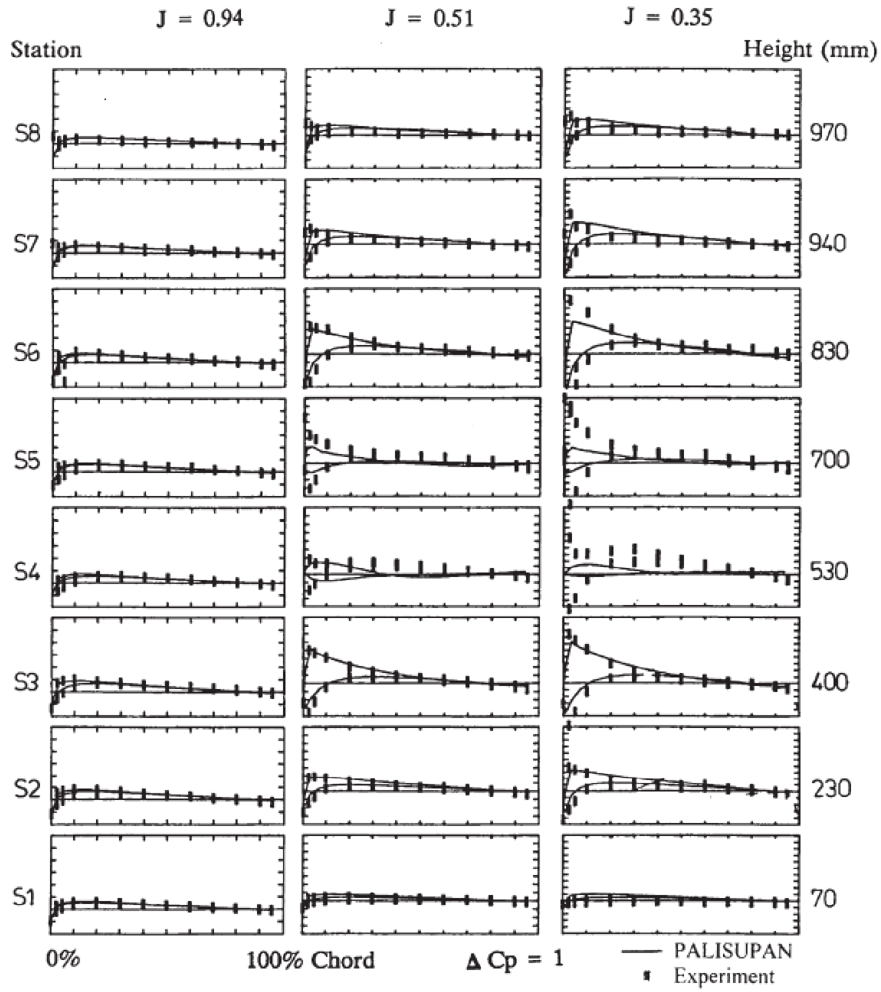

Blade Element/Lifting line

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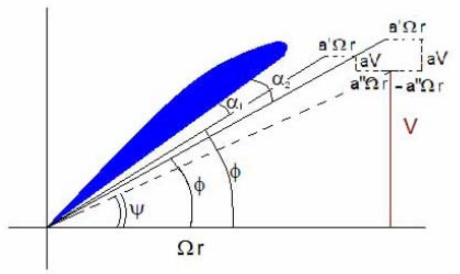
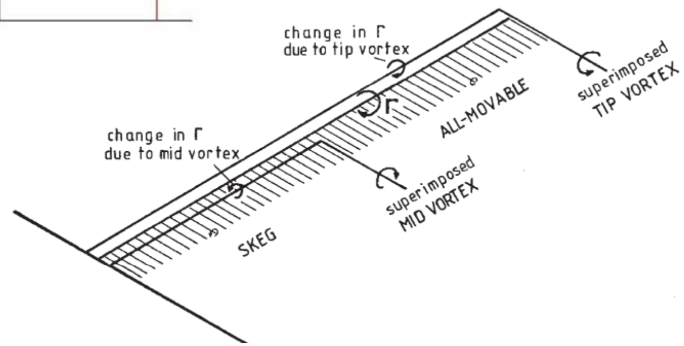
•Blade Element Momentum balances the sectional performance of the propeller with axial and angular momentum changes a, a'.

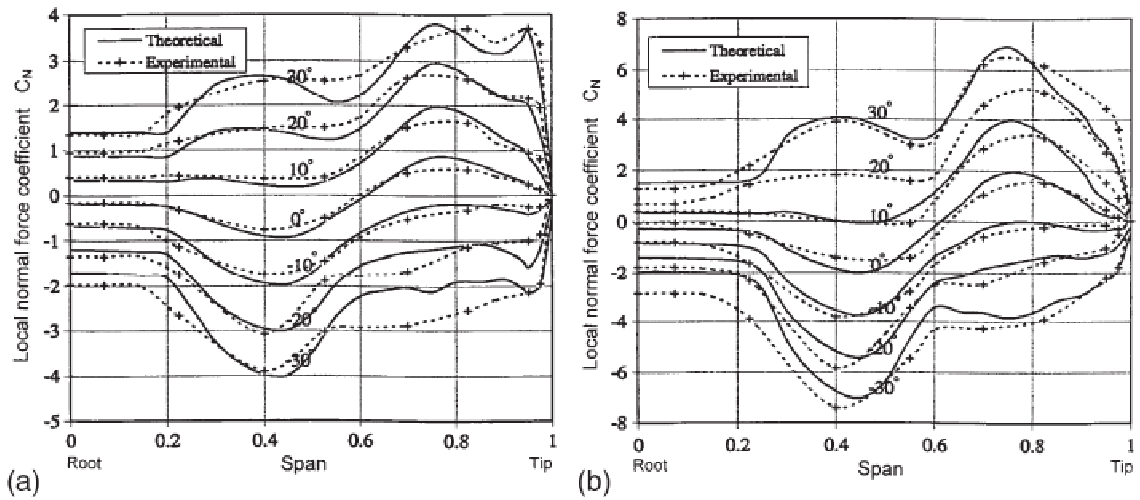
•To apply to propeller –rudder interaction need to investigate how the propeller race contracts and a, a' increase

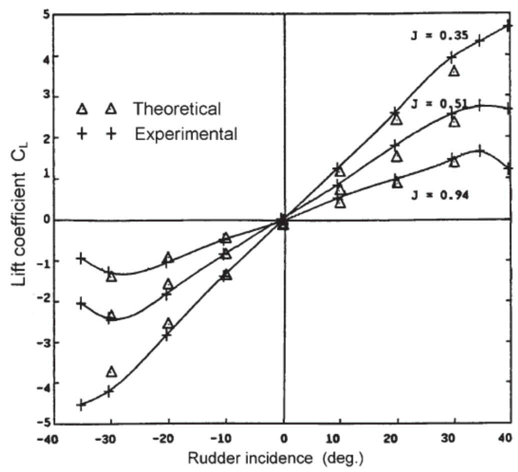
•The modified velocities are applied to a lifting line representation of the rudder to derive lift and induced drag components

•A viscous friction correction is estimated









.32 Comparison of lifting-line theoretical total lift predictions and experimental results; Rudder No. 2, X/D = 0.39

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Case Studies

- The three design analysis approaches allow trade-offs to be made between rudder manoeuvring effectiveness and propulsive effects
- The associated cost depends on the complexity of the stern

The following three scenarios examine aspects of rudder design related to propulsion

(1) Twisted rudder

(2) Kite assisted ship

(3) Cathodic protection

(1) Twisted rudder

- Offers opportunity to reduce cavitation risk on rudder sections by reducing effective angle of attack
- Can also be used to alter effective thrust/drag of rudder by recovering rotational energy from propeller race
- Requires alternative construction techniques and is obvious route for use of composites

Source: NWSCCDDesigned by Dr. Young T. Shen of the Naval Surface Warfare Center, this all-

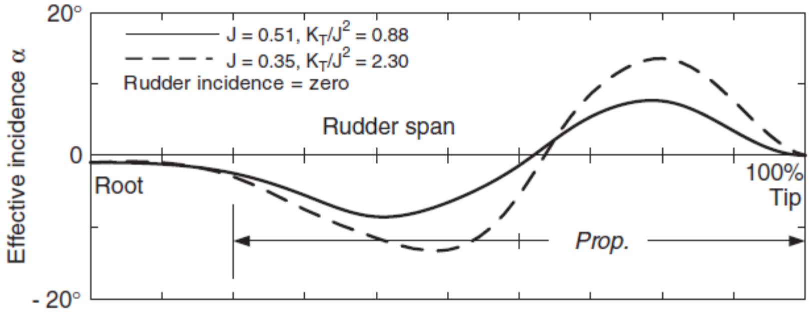
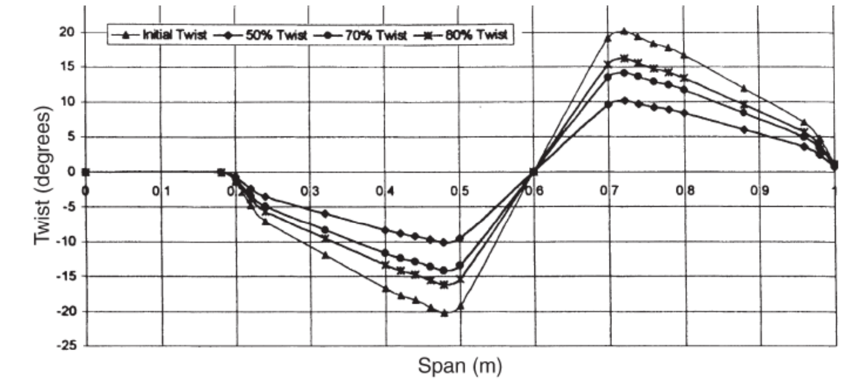
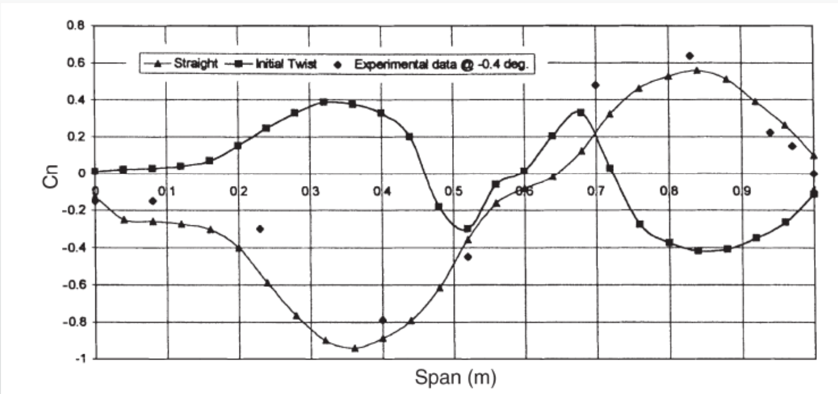
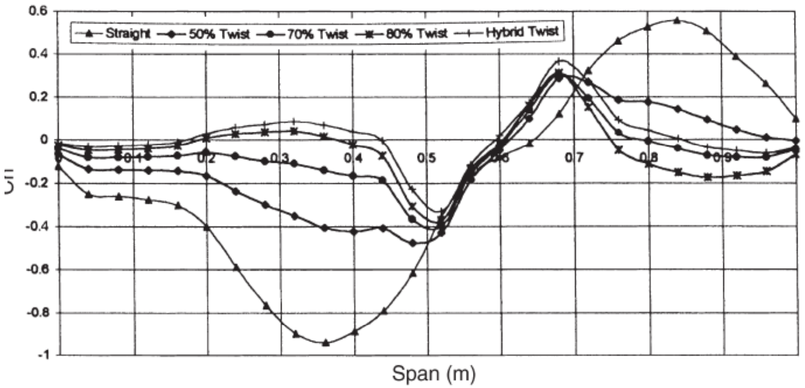


Figure 5.126 Distribution of effective incidence across span at zero rudder angle







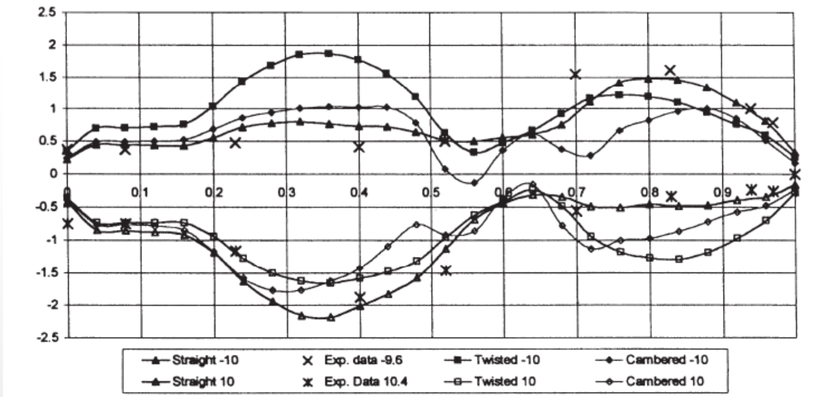


Table 11.5 Minimum values of pressure coefficient C_P

Rudder type	*Incidence*		
	−10°	*0°*	*10°*
Straight	−14.78	−9.59	−17.89
Twisted	−11.02	−6.63	−11.51
Cambered	−27.75	−20.81	−32.13

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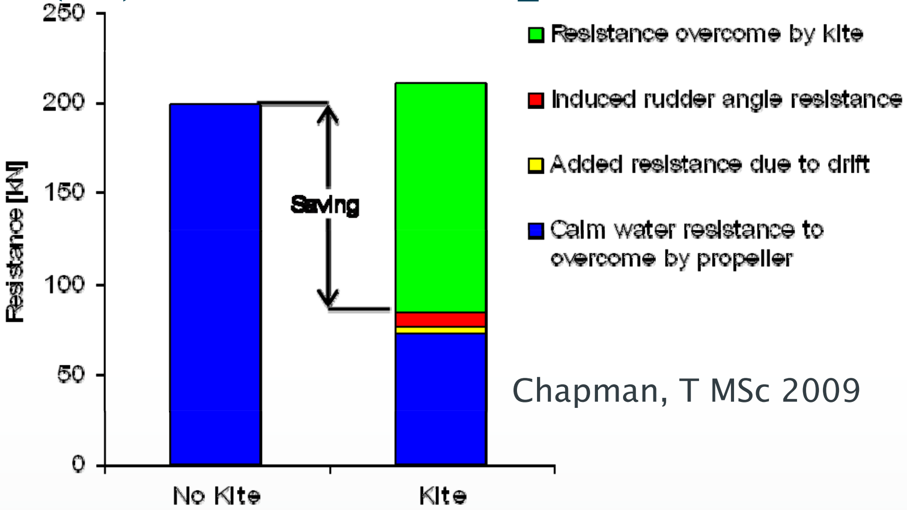
(2) Kite Propulsion



Chapman, T MSc 2009

- Examine effect of incidence angle on rudder drag as proportion of that at zero helm

alpha	0	5	10	20
Cd/Cdo	1	1.6	3	8
%RT	2	3.2	6	16
Cd	0.05	0.08	0.15	0.4

(3)Cathodic Protection

- Assume 8 to 16 (N) passive cathodes of height h, width s added to rudder of Span S and chord c at position of maximum thickness, that Cd of each is 1.0, speed at cathode location *f* is 1.5 times propeller race. What is increase in rudder drag?

$$\frac{drag\ of\ cathodes}{drag\ of\ rudder} = \frac{C_{D\_cathode} N \tfrac{1}{2} \rho h s f^2 U_o^2}{C_{D\_rudder} \tfrac{1}{2} \rho c S U_o^2} = N f^2 \left(\frac{h}{c}\right)\left(\frac{s}{S}\right)\frac{C_{D\_cathode}}{C_{D\_rudder}}$$

- Conservative assumptions for height *h*, width *s* can at least double drag and will also have blockage effects on propeller

Getting this wrong would cause a persistent increase of resistance, difficult to identify on a full scale ship, but which would last the whole life of the vessel

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Is it worth it?

Table 3 Potential savings in fuel and CO_2 emissions

Ship type	Deadweight (tonnes) or TEU	Speed (knots)	Length of round voyage (nm)	Round voyages/year	Annual fuel (tonnes)	Annual CO_2 (tonnes)	1% saving in fuel consumption	
							Annual fuel saving (£)	Annual CO_2 saving (tonnes)
Bulk carrier	45,000	14	5,000	17	8,400	26,700	12,600	270
Tanker	250,000	15	10,000	10	30,700	97,000	46,000	970
Container	10,000 TEU	26	20,000	10	90,600	287,000	136,000	2870

If a 25% reduction in rudder drag equates to a 1% saving in fuel…

Other users of our wind tunnel...

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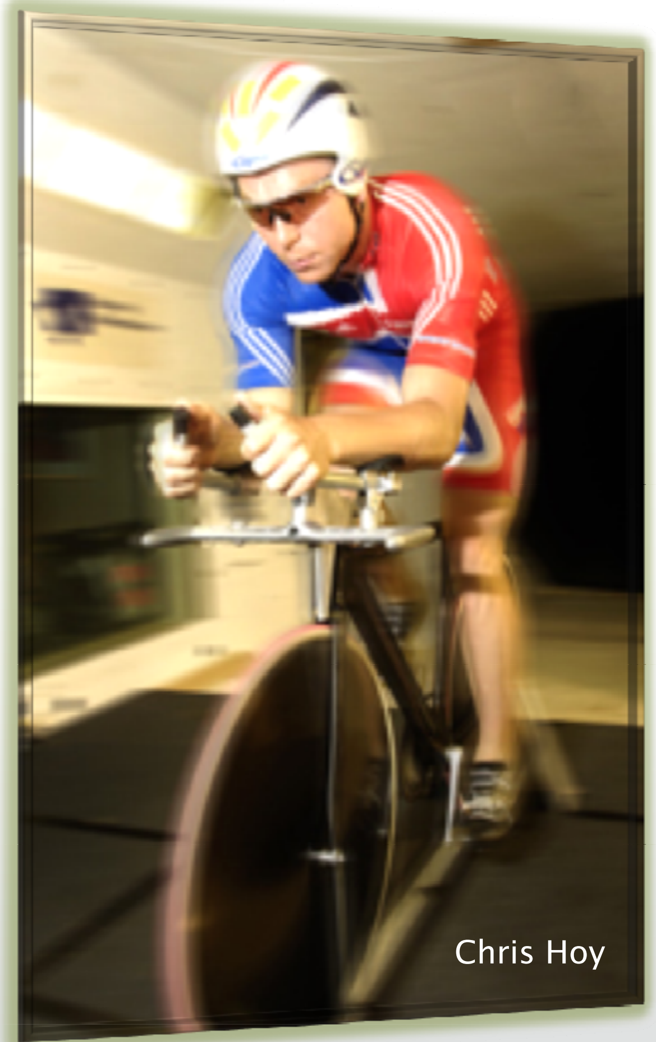

Chris Hoy

"We've got this saying, 'performance by the **aggregation of marginal gains,'"** Brailsford continued. "It means taking the 1% from everything you do; finding a 1% margin for improvement in everything you do. That's what we try to do from the mechanics upwards.

Quote from David Brailsford, Performance Director, GB Cycling http://www.skysports.com/story/0,19528,17547_5792058,00.html

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Concluding remarks

- Rudders need to be designed in conjunction with the propulsor and due account taken of the trade-offs between manoeuvring effectiveness and net propulsive thrust
- It is in the attention to small details that cumulative improvements will be found that allow shipping to meet targets for reduced emissions per kg per km
- The future rudder will have a complex shape tuned to the ship stern and propulsor arrangement. Such rudders are likely to be of composite construction.
- Computational based rudder design optimisation requires careful validation

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Thank you, any questions?

References

Molland, A.F. and Turnock, S.R. (2007) Marine rudders and control surfaces: principles, data, design and applications, Oxford, UK, Butterworth-Heinemann, 386pp.

Molland, A.F., Turnock, S.R. and Hudson, D.A. (2009) Design metrics for evaluating the propulsive efficiency of future ships. In, IMDC 2009: 10th International Marine Design Conference, Trondheim, Norway, 26-29 May 2009. Trondheim, Norway, Tapir Academic Press, 17pp, 209-225.

Phillips, A.B., Furlong, M.E. and Turnock, S.R. (2009) Accurate capture of rudder-propeller interaction using a coupled blade element momentum-RANS approach. In, 12th Numerical Towing Tank Symposium, Cortona, Italy, 4-6 Oct 2009. 6pp.

Phillips, A.B., Turnock, S.R. and Furlong, M.E. (2009) Evaluation of manoeuvring coefficients of a self-propelled ship using a blade element momentum propeller model coupled to a Reynolds averaged Navier Stokes flow solver. Ocean Engineering, 36, 1217-1225. (doi:10.1016/j.oceaneng.2009.07.019)