Hogere Zeevaartschool Antwerpen

University of Strathclyde Glasgow

A generic approach predicting the effect of fouling control systems on ship performance

By

Prof Mehmet Atlar

Dep't of Naval Architecture, Ocean and Marine Engineering (NAOME)
University of Strathclyde, UK

THE 2ND AMACORT SYMPOSIUM ON CORROSION AND FOULING
APRIL 1, 2019 - ANTWERP, BELGIUM

Hogere Zeevaartschool Antwerpen

University of Strathclyde Glasgow

Presentation layout

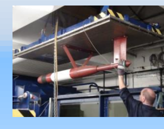
- Background & Objectives
- Description of approach
- Applications of approach
- Validation of approach
- Recent R&D in Dep't of NAOME
- Concluding remarks

THE 2ND AMACORT SYMPOSIUM ON CORROSION AND FOULING
APRIL 1, 2019 - ANTWERP, BELGIUM

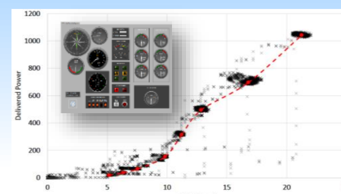
2

Background & Objectives

- There are many **ongoing drivers**, which can be economical or environmental or both, requiring **for a rational approach** to predicting the effect of biofouling and their control systems on "in-service" performance of ships.
- **Accumulated knowledge and experience** based on some experimental and numerical studies conducted in the **Universities of Newcastle & Strathclyde** involving the presenter over the past two decades have encouraged him to propose:

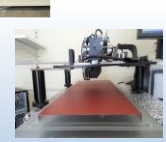


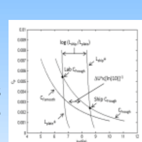
A rational & preferably **generic approach for ship performance prediction** by bridging the gap between laboratory based experimental methods and numerical (CFD) procedures that can be validated by dedicated full-scale ship performance monitoring / analysis systems, *Atlar et al (2018)*

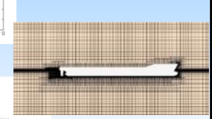


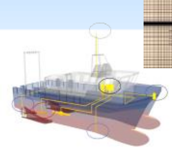
Description of approach

1. Flat test panels with different types of hull coatings and surface finishes (which can be simulated) are to represent ship hull surfaces as well as propeller blade surfaces
2. Surface (roughness) characteristics of the test panels are analysed by using different types of roughness measurement devices (preferably non-contact optical) surface profilometry devices
3. Hydrodynamic drag characteristics of the test surfaces are measured using different testing methods (e.g. direct boundary layer or indirect skin friction drag / pressure drop measurements)
4. Effect of biofouling on the test surfaces can be included using dynamic growing methods in laboratory or at sea in a controlled manner
5. Data produced in the above (through 2 through 4) can form basis for a suitable extrapolation method which may allow to estimate the additional "Skin Friction" due to different coating roughness and biofouling for full-scale hull, based on a flat plate approach.
6. Experimental roughness data (e.g. as hydrodynamic roughness function) can be built in a CFD solver to estimate the additional skin friction, and hence ship resistance including 3D effects.
7. Validate the predictions by means of a transparent onboard ship performance monitoring systems



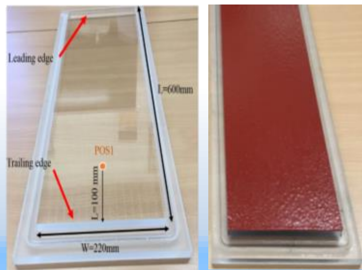






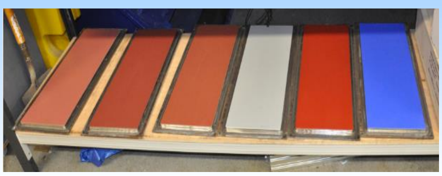
4

1. Hull surface representation by flat test panels



UNEW standard test panels
Smooth reference surface (left); Coated surface (right)

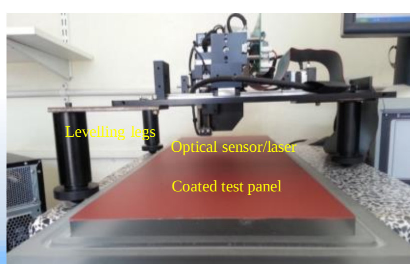
Two different surface finishes:
Spraying with normal finish (top);
Simulated roughness (bottom)



Clean test panels with different fouling control coating systems

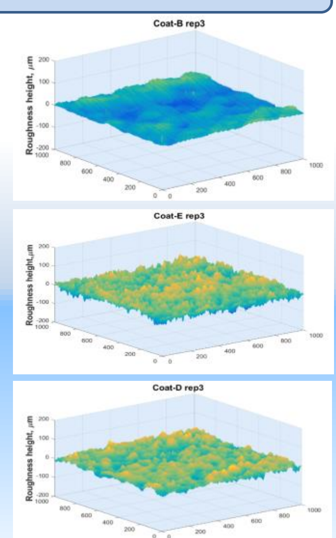
Coated test panel subjected to biofilm (slime)

2. Roughness characterisation of coated test panels



Optical Laser profilometer

TQC Hull Roughness Gauge



Foul release

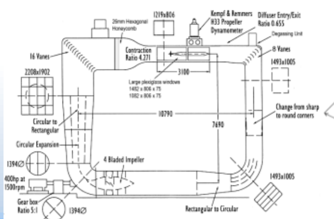
SPC

CDP

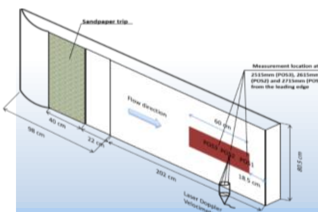
Topographical views of test surfaces with different coatings using Optical Profilometry
(25x25mm; 25 mic sampling interval)

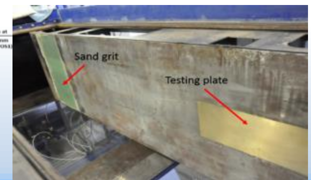
6

3. Hydrodynamic performance assessment



Emerson Cavitation Tunnel



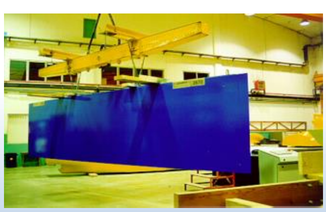


Test bed (high speed insert)

Boundary Layer Measurement Set-up in Emerson Cavitation Tunnel using 2D-LDA system

7

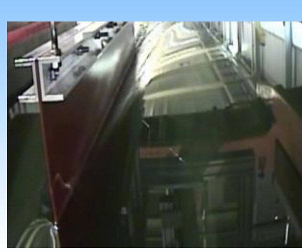
3. Hydrodynamic performance assessment (Alternative test methods)



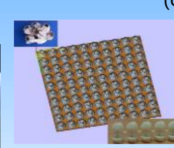
Large friction plane tested in CEHIPAR tank

Axisymmetric body tested in Emerson Cavitation Tunnel

Rotating drum Apparatus (UNEW)



Small friction test panel in UoS Kelvin Hydrodynamics Laboratory Towing Tank



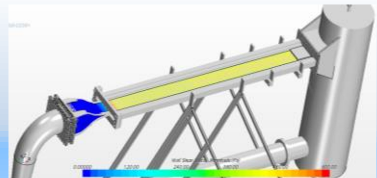
Scanned & 3D printed artificial barnacles

8

3. Hydrodynamic performance assessment
(Alternative test method)

Fully turbulent (sea) water channel

Designed to measure pressure drop and hence determine skin friction of flat test panels in fully turbulent seawater flow including biofilm (e.g. slime) with rapid turnovers



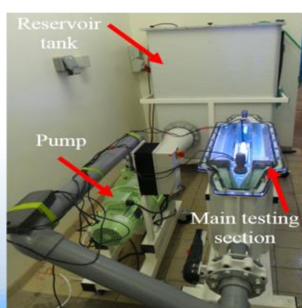
Test (pressure drop) section of turbulent channel

An overall view of UNEW fully turbulent seawater channel

Test panel with biofilm installed in pressure drop section

9

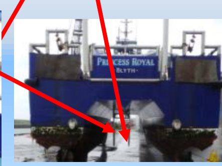
4. Simulating biofouling (slime) on test panels



General view of UNEW slime farm to grow slime in lab environment with rapid turn over

Lab – grown biofilm facility

Field – grown biofilm facility



Testing section and test panel arrangement in slime farm

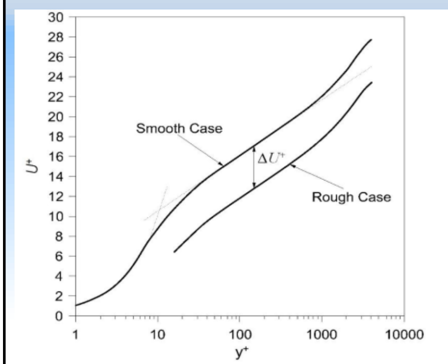
UNEW Research Vessel strut arrangement to collect naturally and dynamically grown biofilm on test panels

10

5. Extrapolation procedure

- Based on "Similarity law scaling procedure" of Granville. This enables to predict the effect of specific roughness (due to coating, fouling etc.) on the friction drag of a surface in full-scale by using "**Roughness Function**" of the particular roughness which can be determined in laboratory based tests, *Granville (1958)*.

*where, **Roughness Function** (or velocity loss function) is further retardation of flow in the boundary layer over a rough surface due to the physical roughness of that surface, which manifests itself as additional drag, relative to smooth surface.*



U^+: Non-dimensional boundary layer velocity

y^+: Non-dimensional normal distance from boundary

ΔU^+: Roughness Function

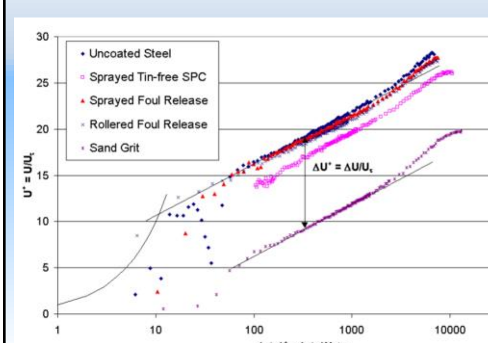
$$\Delta U^+ = U^+_{smooth} - U^+_{rough}$$

Roughness Function (ΔU^+) representation

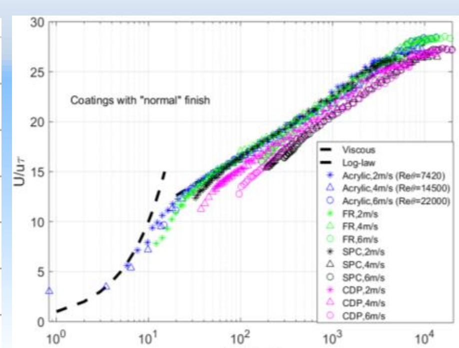
11

5. Extrapolation procedure

- Roughness Function of a representative rough surface can be determined by measuring the boundary layer characteristics of test surfaces (direct method), or alternatively, by measuring frictional drag of the test surfaces (indirect method) coated with different coating systems with or without fouling
- Roughness Function (ΔU^+) data of representative test surfaces are the main input to Granville's algorithm to predict resulting added friction drag due to the effect of coating and fouling roughness



Candries (2001)

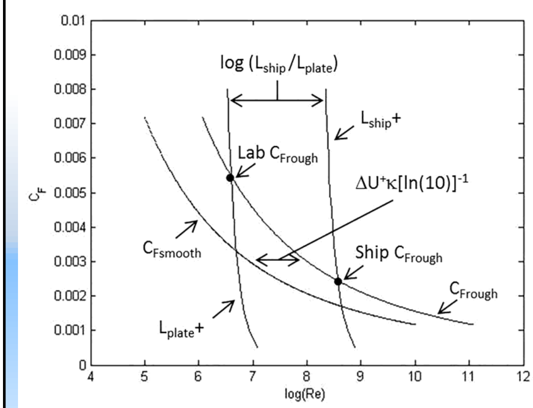


Yeginbayeva (2017)

Analysed Roughness Function (ΔU^+) characteristics of different surfaces

12

5. Extrapolation Algorithm



Schematic representation Granville's algorithm, *Schultz (2007)*

L_{plate} = Test surface length
L_{ship} = Ship length
$C_{F\ smooth}$ = Smooth surface drag coeff's
$C_{F\ rough}$ = Rough surface drag coeff's

$$L^{+} = \mathrm{Re}\left(\sqrt{\frac{C_F}{2}}\left(1 - \kappa\sqrt{\frac{C_F}{2}}\right)\right)$$

Re = Reynolds number, length based
K = von Karman Constant

ΔU^{+} = Roughness Function

$C_{F\ smooth}$, ΔU^{+}, L_{plate} , L_{ship} → **Input**

$C_{F\ rough}$ for ship → **To be predicted**

Change in Frictional Drag Coeff's ➡ $\Delta C_F = \frac{C_{F\ rough} - C_{F\ smooth}}{C_{F\ smooth}}$

6. Use of CFD for predictions

- It may be more rational if the experimentally determined "Roughness Functions" for different surface conditions can be built in the "**wall functions**" of CFD solvers,

$\Delta U^{+} = f(k^{+})$, *where k^{+} is the Roughness Reynolds number*

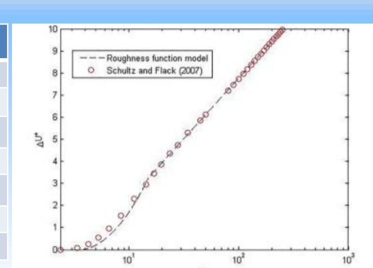
Wall functions *are mathematical expressions to link the zone between the wall and log-law region of the boundary layer.*

- Such an attempt has been made by Demirel who modified the wall functions of a commercial URANS solver (Star-CCM+) by using *Schultz & Flack (2007)* experimental Roughness Function data for different fouling conditions, *Demirel (2015)*

Description of condition	NSTM rating*	k_s (mm)	Rt_{50} (mm)
Hydraulically smooth surface	0	0	0
Typical as applied AF coating	0	30	150
Deteriorated coating or light slime	10-20	100	300
Heavy slime	30	300	600
Small calcareous fouling or weed	40-60	1000	1000
Medium calcareous fouling	70-80	3000	3000
Heavy calcareous fouling	90-100	10000	10000

A range of representative coatings and fouling conditions, *Schultz (2007)*

*NSTM (2002)



Proposed CFD roughness function model for experimental *Schultz & Flack (2007)* **roughness function data**

14

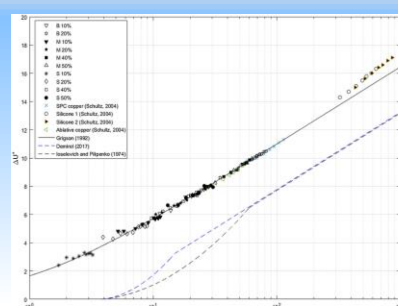
6. Use of CFD for predictions

- Flat panels covered with pseudo barnacles were towed at KHL of USTRATH by *Demirel et al (2017)* to present new set of roughness function models for **systematically varying size and coverage of barnacles** which can provide basis for Granville's extrapolation as well as CFD based predictions

Table Experimentally obtained roughness length scales, k_G, and measurable surface properties of the test surfaces with varying size barnacles.

Test surface	k_G (μm)	(Regression)	h (mm)	coverage (%)
B 10%	174	174	5	10
B 20%	489	445	5	20
M 10%	84	91	2.5	10
M 20%	165	176	2.5	20
M 40%	388	386	2.5	40
M 50%	460	445	2.5	50
S 10%	24	24	1.25	10
S 20%	63	60	1.25	20
S 40%	149	171	1.25	40
S 50%	194	181	1.25	50

Three different size and four different coverage area combination of test panels



Proposed roughness function models based on experiments using varying size pseudo barnacles

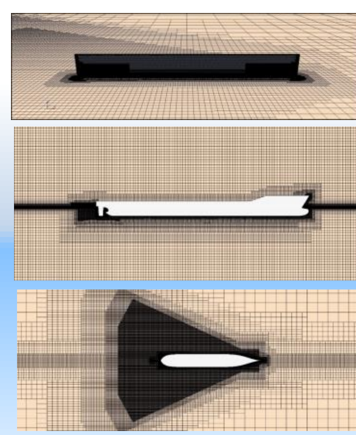
15

Applications of approach

University of Strathclyde Glasgow

Table - Benchmark KRISO Container vessel, Kim et al. (2001)

Length between the perpendiculars (L_{BP})	230.0 m
Length of waterline (L_{WL})	232.5 m
Beam at waterline (B_{WL})	32.2 m
Depth (D)	19.0 m
Design draft (T)	10.8 m
Wetted surface area	9498 m^2
Displacement (Δ)	52030 m^3
Block coefficient (C_B)	0.6505
Design Speed	24 knots
Froude number (Fr)	0.26



Applications of approach

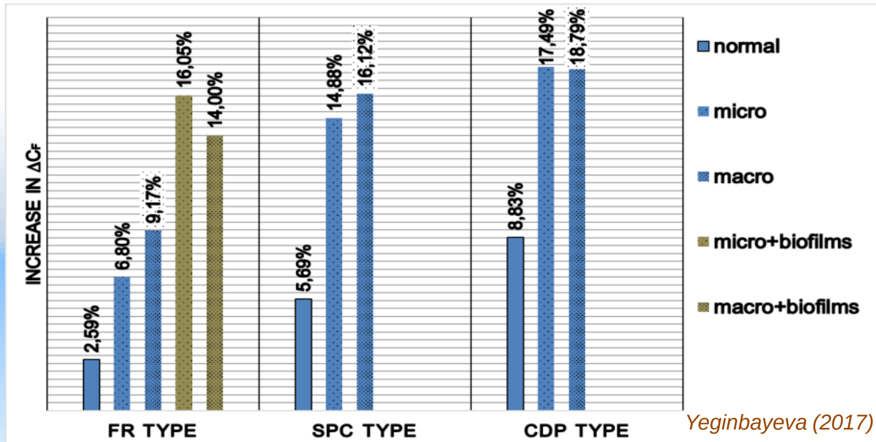
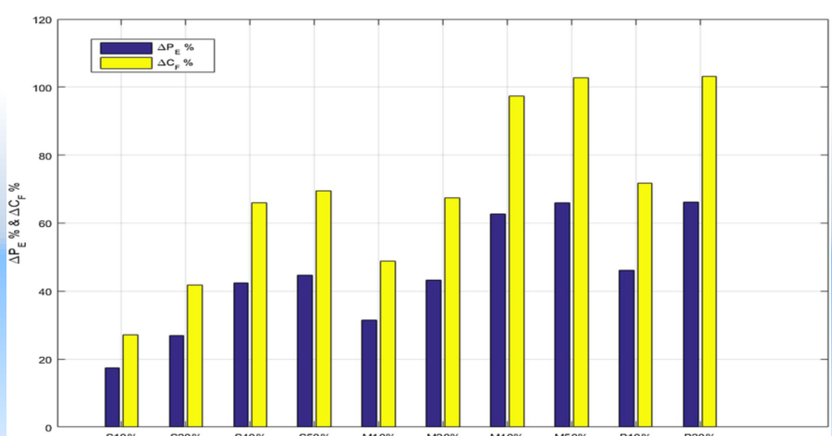


Figure - Increase in frictional resistance, $\%\Delta C_F$ for KRISO Container Ship for different coatings types (FR, SPC and CDP) and hull surface conditions at 24 knots design speed,

Estimation is based on Granville's extrapolation method (Flat Plate)

17

Applications of approach

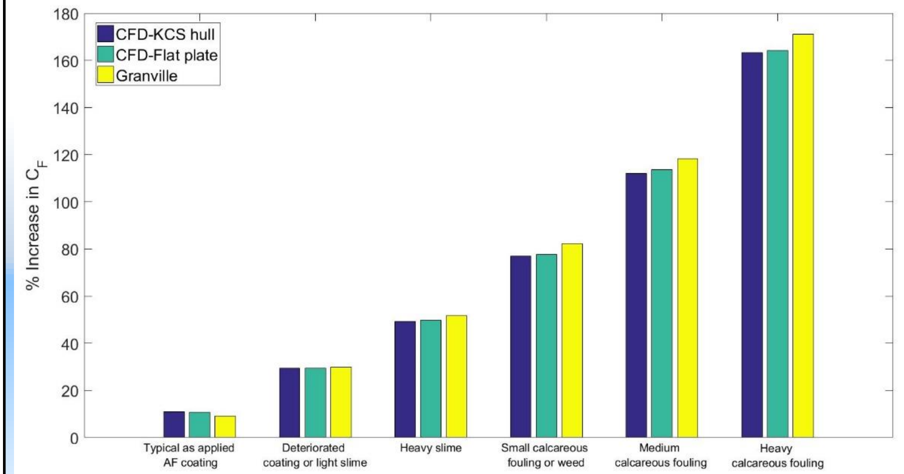


Increase in frictional resistance, $\%\Delta C_F$ and effective power, $\%\Delta P_E$ for KRISO Container Ship for different size coverage of **barnacles** at 24 knots design speed, *Demirel et al (2017)*

Estimation is based on Granville's extrapolation method (Flat Plate)

18

Applications of approach

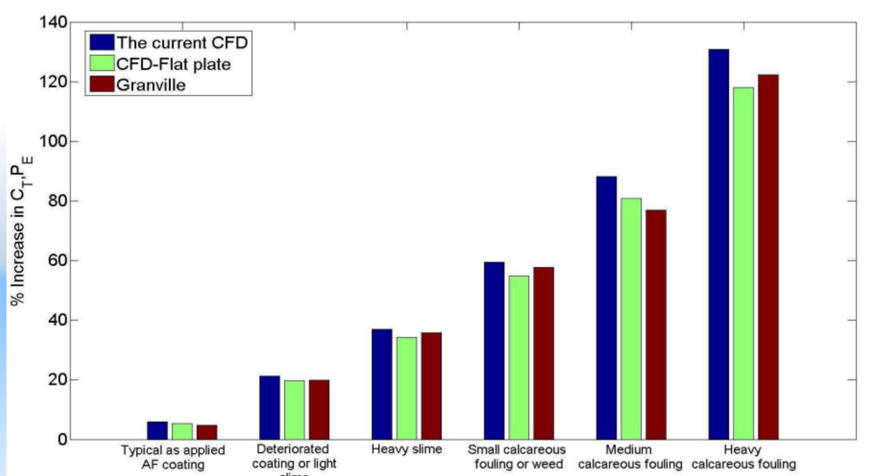


Increase in frictional resistance for KRISO Container Ship due to different surface conditions at **24 knots,** *Demirel (2017)*

Estimation are based on three different methods; i.e. Granville's; CFD (Flat Plate; 3D Hull)

19

Applications of approach



Increase in frictional resistance for KRISO Container Ship due to different surface conditions at **19 knots (slow steaming),** *Demirel (2017)*

Estimation are based on three different methods; i.e. Granville's; CFD (Flat Plate; 3D Hull)

20

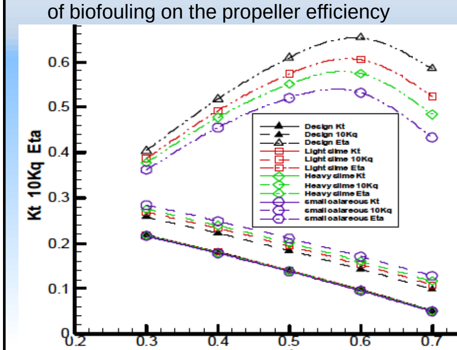
Description & Applications of approach

- Effect of blade surface condition with different grades of biofouling on Propeller Efficiency can be modelled by using low- and high-fidelity CFD models, *Atlar et al (2002, 2003)*
- *Seo et al (2017)* built Schultz's roughness function model in an unsteady lifting surface based propeller flow model and demonstrated the effect of different grades of biofouling on the propeller efficiency

Case study - 95,000t motor tanker propeller

Table – Tanker propeller main particulars

Diameter	6.85m
Pitch ratio	0.699
Blade area ratio	0.524
Number of blades, Z	4
Design advance coefficient (J)	0.48
Direction of rotation	Right-[illegible]
Year Built	1992



Effect of different grades of slime on the propeller performance of a tanker vessel

Table - Roughness model

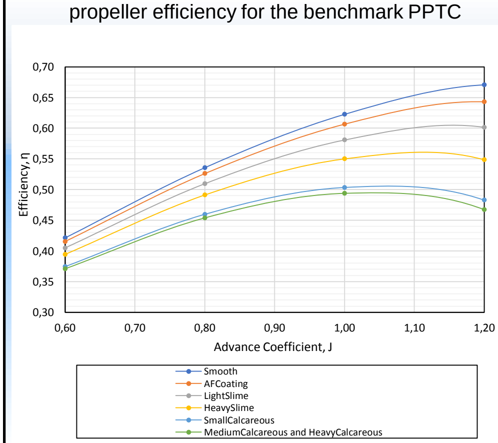
Description of condition	k_s (m)
Light slime	0.0001
Heavy slime	0.0003
Small calcareous fouling	0.001

Table – Efficiency loss due to different fouling conditions

J	% Loss in efficiency			
	smooth	light slime	heavy slime	small calcareous fouling
0.3	0.00	4.43	6.84	10.45
0.4	0.00	4.99	7.88	12.10
0.5	0.00	5.84	9.46	14.55
0.6	0.00	7.32	12.11	18.50
0.7	0.00	10.42	17.38	26.10

Description & Applications of approach

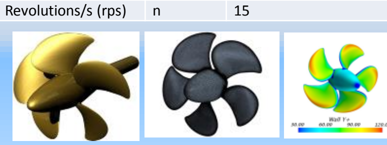
- Recently, *Owen et al (2017)* based on the same approach but using high-fidelity CFD tool (Unsteady RANS Solver) and Schultz's roughness functions, demonstrated the effect of different grades of biofouling on the propeller efficiency for the benchmark PPTC

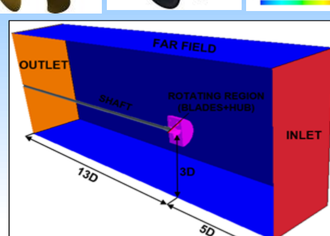


Effect of different grades of biofuling on the efficiency of Potsdam Test Case Propeller

Table – Potsdam Propeller Test Case (PPTC) parameters

Parameter	Symbol	Value
Diameter	D	0.250
Pitch Ratio r/R=0.7	$P_{0.7}/D$	1.635
Area Ratio	A_E/A_O	0.779
Chord Length$_{0.7}$ (m)	$C_{0.7}$	0.104
Skew (deg)	θ	18.837
Hub Ratio	D_h/D	0.300
No. of Blade	Z	5
Rotation	Direction	Right
Revolutions/s (rps)	n	15

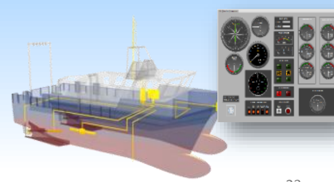




Validation of approach

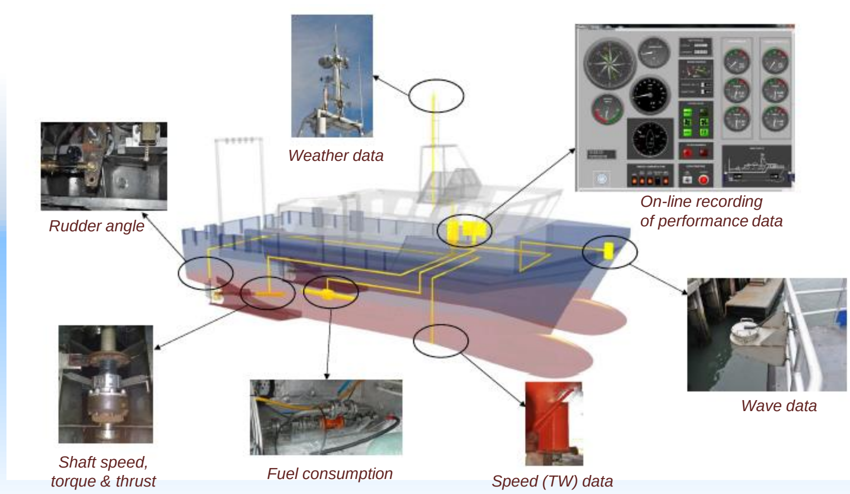
University of Strathclyde Glasgow

- Ship Performance Monitoring System (SPMS) onboard the RV "The Princess Royal" dedicated to the analysis of biofouling growth and fouling control system performance, *Carchen et al (2016, 2017)*
- Deterministic method of performance analysis is preferred over Machine Learning and Hybrid methods
- Data collection is conducted by "Dedicated Trials" as well as "in-service" by remote on-line monitoring system
- Data collected is normalized is based on the speed and torque identity method of ITTC for the analysis of sea trials
- Vessel performance against fouling is assessed based on the major Key Performance Indicators (KPI)



23

Validation of approach



Performance measurement on-board RV *"The Princess Royal"*

24

Validation of approach

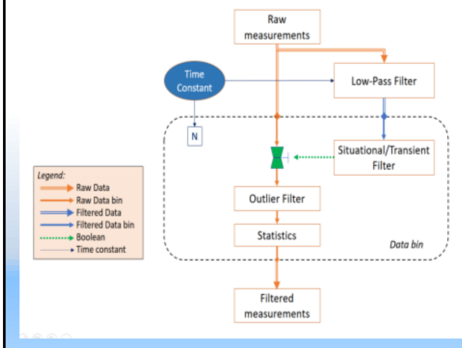


Figure - Data flow through the filtering procedures

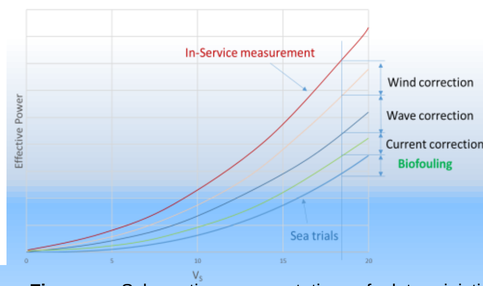
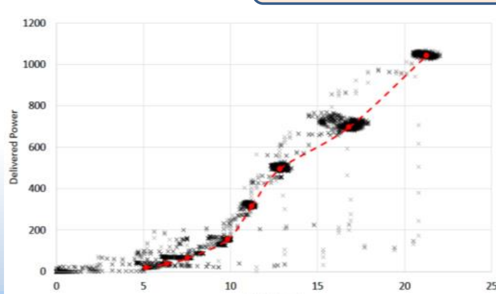


Figure - Schematic representation of deterministic corrections for external disturbances

Figure – Dedicated sea trials & remote performance Monitoring in the North Sea, off the coast of Blyth, UK (55 09' N, 1 28' W)

25

Validation of approach



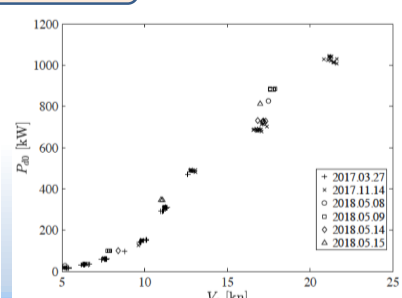


Fig - Raw performance measurements (Grey markers) and normalised performance data (red line and markers) performance measurements on the Princess Royal, *Carchen et al (2017)*

Normalised delivered power

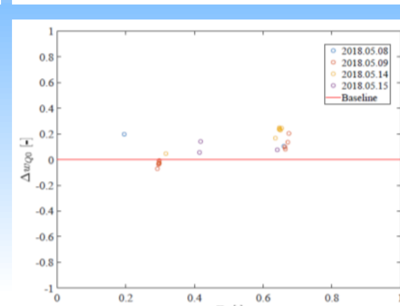
$$P_{d0} = 2\pi\rho D_p^5 K_{Q0} n_0^3 \eta_s$$

Power based KPI

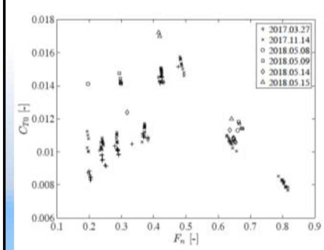
$$\Delta P_{d0}(t, V_s) = \frac{P_{d0}(t, V_s)}{P_{d0}(t_{\text{ref}}, V_s)} - 1$$

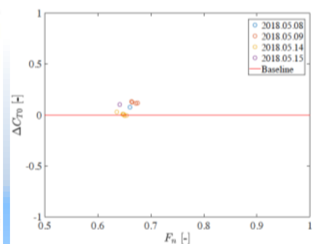
Wake based KPI

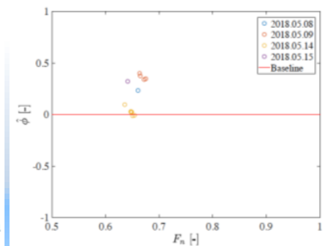
$$\Delta w_{Q0}(t, V_s) = \frac{w_{Q0}(t, V_s)}{w_{Q0}(t_{\text{ref}}, V_s)} - 1$$



Validation of approach







Total ship resistance breakdown $\Rightarrow$ $R_T = (1+\phi)R_v + R_w + R_{add}$

Total added drag breakdown $\Rightarrow$ $R_{add} = \overline{R}_{AA} - \overline{R}_{AA0} + \overline{R}_{AW} + R_{\Delta} + R_{\rho}$

Resistance coefficients $\Rightarrow$ $C_T = (1+\phi)C_v + C_w$ $\quad C_v = C_f(1+\kappa)$

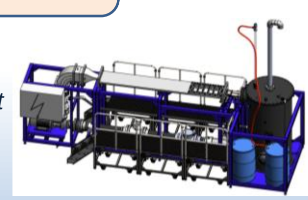
Fouling coefficient KPI $\Rightarrow$ $$\hat{\phi}(t, V_s) = \frac{\hat{C}_v(t, V_s)}{C_v(t_{\text{ref}}, V_s)} - 1$$

27

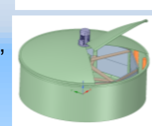
Recent R & D activities in Dep't of *NAOME*

University of Strathclyde Glasgow

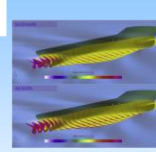
- Design and commissioning of a new "*Fully Turbulent Flow Channel*" (FTFC)



- Design and future commissioning of a new "*slime farm*"



- Further development of "barnacle fouling" modelling



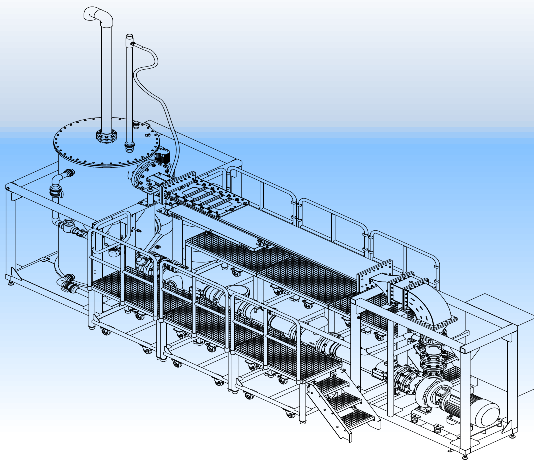
- "Dimples" for drag reduction and fouling control

- "Tubercles" for drag reduction and fouling control

28

Design and commissioning of a new "*Fully Turbulent Flow Channel*" (FTFC)

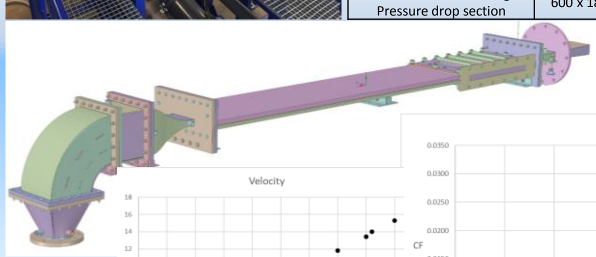
- We have designed and recently commissioned a ***Fully Turbulent Flow Channel (FTFC)*** at the Kelvin Hydrodynamics Lab' which allow us to measure flow and drag characteristics of various surfaces covered with different control fouling systems as well as drag reduction mechanisms including the effect of marine biofouling

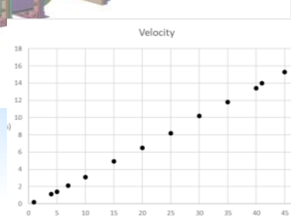


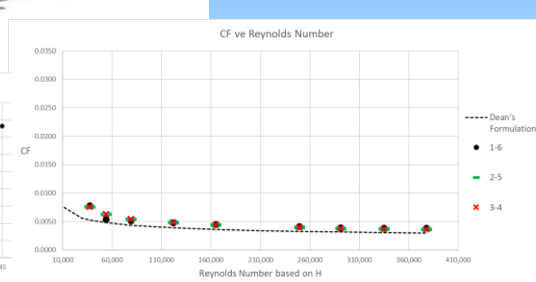
New Fully Turbulent Flow Channel (*FTFC*)

Main Features of FTFC

Upstream Length:	2.40	m
Test Plate Length:	0.60	m
Channel Width:	0.18	m
Channel Height:	0.0225	m
Bulk Velocity Range:	~ 0.5 – 15.0	m/s
Reynolds Number Range:	~ 10.000 – 350.000	
Pressure taps No & range	6 taps & 20 -1000	mbar
Tank capacity	2.6	m^3
LDA & PIV Access through Pressure drop section	600 x 180 x 22.5	mm

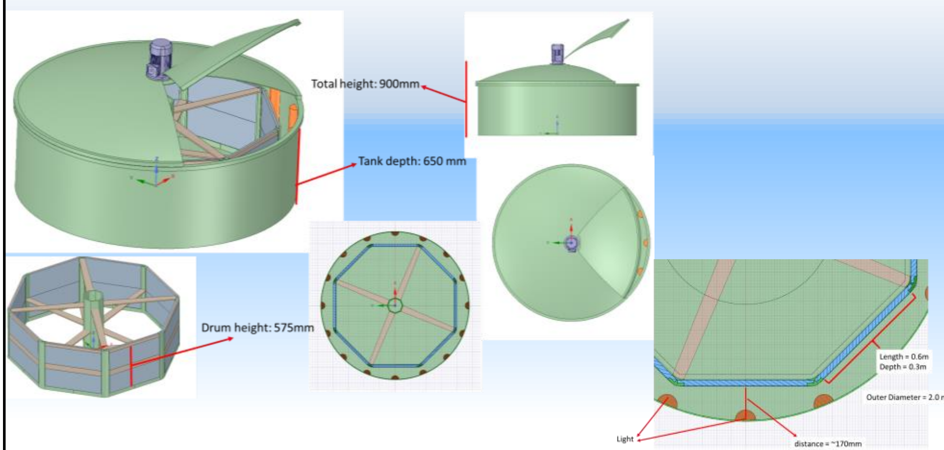






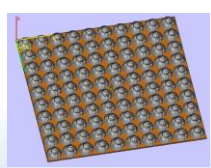
New Dynamic Biofouling Farm

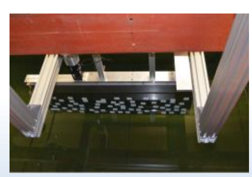
- Based on our previous experience with "jet" type dynamic flow action using pump, we have designed a new biofouling farm with dynamic flow action created by rotating drum. This is more practical and cost economical system
- We are in the process of manufacturing the farm in-house



Further developments in "BARNACLE fouling" modelling

Towing test with artificial barnacles

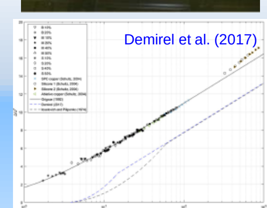




↓

Roughness function for barnacles

$k^+, \Delta U^+$
For varying sizes/ coverages



↓

Utilisation into CFD

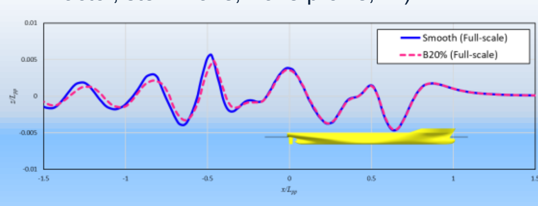
↓

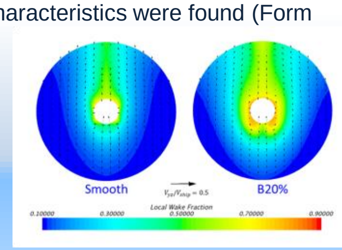
Ship resistance characteristics	Propeller performance	Ship self-propulsion performance
Song et al. (2019a)	Song et al. (2019b)	In progress

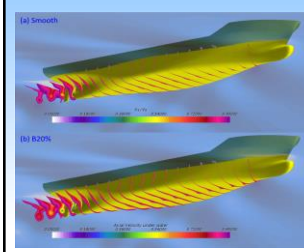
Demirel, Y. K., et al. (2017). "Predicting the effect of biofouling on ship resistance using CFD." Applied Ocean Research **62: 100-118.**
Song, S., et al. (2019a). "An investigation into the effect of biofouling on the ship hydrodynamic characteristics using CFD." Ocean Engineering **175: 122-137.**
Song, S., et al. (2019b). "An investigation into the effect of biofouling on full-scale propeller performance using CFD". OMAE, Glasgow.
32

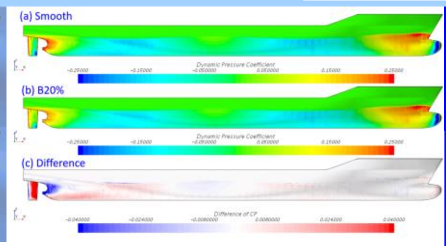
CFD simulations for the effect of barnacles on ship performance

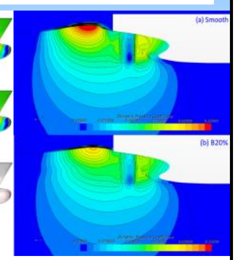
- Up to 93% and 60% increase in C_F and P_E observed
- Roughness effect on different resistance components were investigated
  - C_{VP} increases while C_W decreases due to surface fouling
- Roughness effect on other ship hydrodynamic characteristics were found (Form factor, stern wake, wave profile, …)





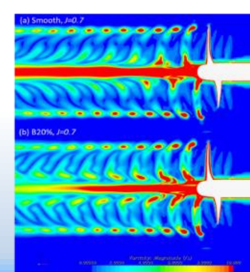


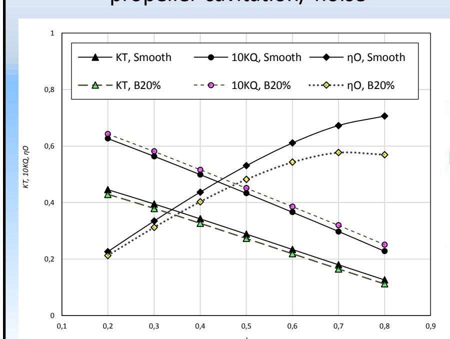


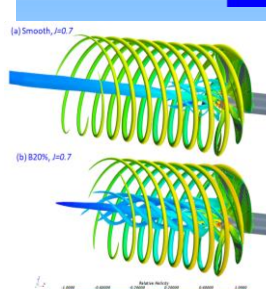


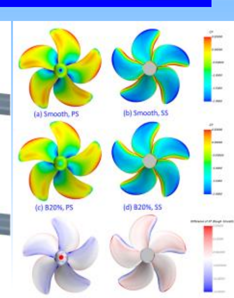
CFD simulations for the effect of barnacles on propeller performance

- Thrust (T) decreases while torque (T) increases due to propeller fouling
  - Thus overall efficiency decreases
- Reduced tip/hub vorticity observed
  - Strategic roughness may have positive impact on propeller cavitation/ noise









Further validation study for Granville's approach

Towing tank tests using sandgrid coated flat plate/ model ship

Smooth plate towing test

Rough plate towing test

Smooth model ship towing test

Rough model ship towing test

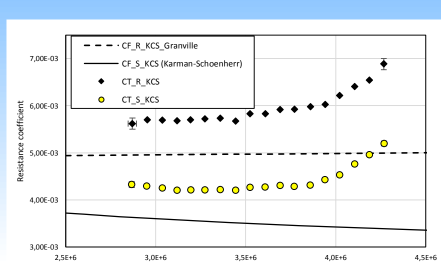
Roughness function acquisition & Granville's extrapolation

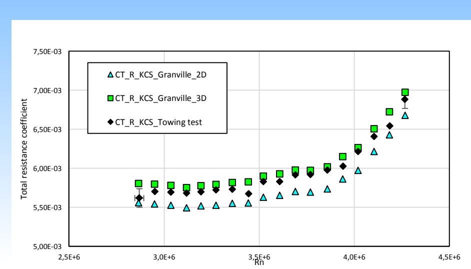
Prediction of added resistance due to roughness

Comparison & validation

Further validation study for Granville's approach

- Total resistance coefficients were predicted using the Granville's extrapolation & smooth model ship result
  - 2D method
    - $C_{T\_Rough} = C_{T_{Smooth}} + \Delta C_{F,Granville}$
  - 3D method
    - $C_{T\_Rough} = C_{T_{Smooth}} + (1+k)\Delta C_{F,Granville}$
- Compared with rough model ship result
  - 3D method shows better agreement compared to 2D method
    - Can be attributed to the roughness effect on viscous pressure resistance

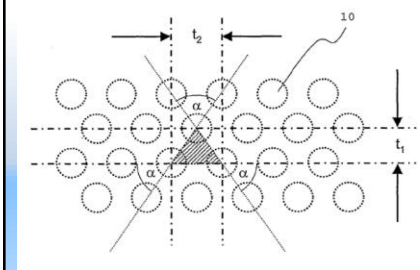


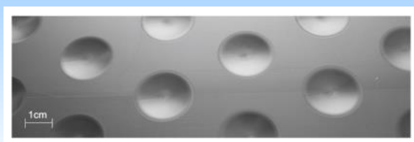


36

"DIMPLES" for drag reduction and fouling control

Three dimensional surface structure for reduced friction resistance and improved heat exchange [1] .





Benefits

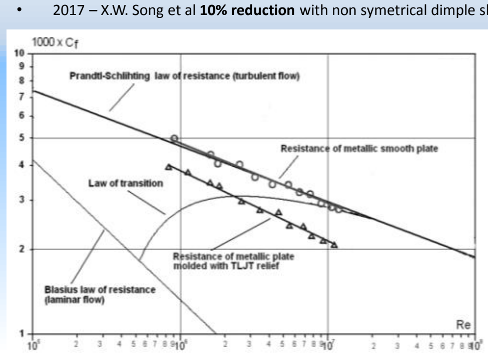
A dimpled surface may pose an elegant alternative passive solution to the reduction of turbulent drag.

- It is a passive method.
- Ease of use (while comparing with riblets about maintenance problems)
- These method that introduce spanwise components cause large scale motions of the fluid near the wall. Riblets which act on the flow at the small near wall viscous scales. With increasing Re number, their very small physical size when used in high Re number applications introduces wear problems.

[1] Vida, N., "Three-dimensional surface structure for reduced friction resistance and improved heat exchange," US20070193726A1, 2003.
[2] van Nesselrooij, M., L. L. M. Veldhuis, B. W. van Oudheusden, and F. F. J. Schrijer, "Drag reduction by means of dimpled surfaces in turbulent boundary layers," *Exp. Fluids*, vol. 57, no. 9, p. 142, Sep. 2016.

History of DIMPLES & Sample data from the open literature

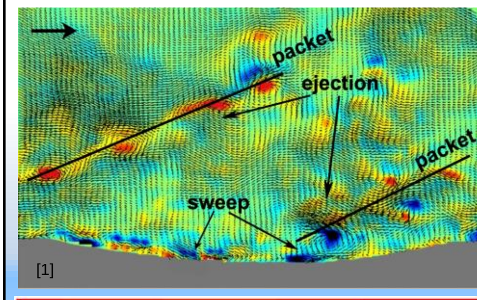
- 1998 - Alekseev, Gachechiladze, Kiknadze, & Oleinikov reported **20% drag reduction**
- 2004 – Vida patented up to **34% possibility**
- 2004 – Wüst up to **20% reduction** (Der Spiegel)
- 2005 – G.I. Kiknadze, A.A. Gachechilazade reported **20% reduction**
- 2008 – H. Lienhart et al, reported **reduction levels are ignorable**.
- 2009 – L.L.M. Veldhius and E. Vervoort reported up to **15% reduction**, up to **17% increase**
- 2009 – G.I. Kiknadze et al reported **33% reduction** on skin friction coefficient.
- 2011 – C.M. Tay upto **%2 reduction**
- 2015 – C.M. Tay et al up to **3% reduction**
- 2016 – M. Van Nesselrooij et al up to **4% reduction**, up to **18% increaase** in some cases
- 2017 – X.W. Song et al **10% reduction** with non symetrical dimple shapes(non-ovoid)

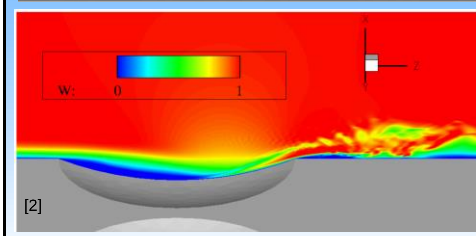


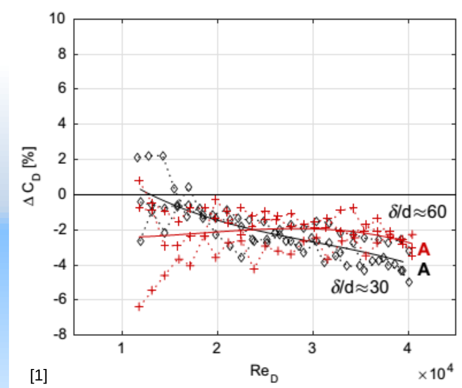
The Reynolds number dependence of the coefficient of friction drag Cf of flat plates with smooth metal and elastic surfaces subjected on one side to a flow of liquid (water) compared to the similar coefficient for similar plates with the surface shaped by three-dimensional concave relief subjected to flow under the same conditions.

Kiknadze, G. I., I. A. Gachechiladze, and A. Y. Gorodkov, "Self-Organization of Tornado-Like Jets in Flows of Gases and Liquids and the Technologies Utilizing This Phenomenon," no. 43581. pp. 547–560, 2009.

Sample data from the open literature







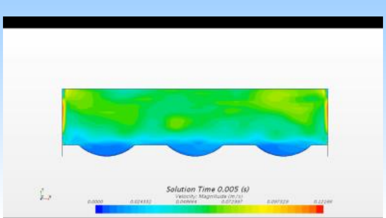
[1] van Nesselrooij, M., L. L. M. Veldhuis, B. W. van Oudheusden, and F. F. J. Schrijer, "Drag reduction by means of dimpled surfaces in turbulent boundary layers," *Exp. Fluids*, vol. 57, no. 9, p. 142, Sep. 2016.

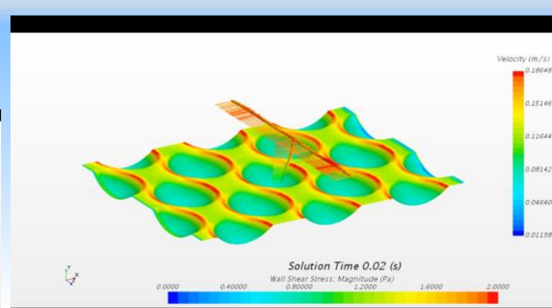
[2] Mode, J. M., "Simulation of the Flow Over a Flat Dimpled Plate," Arizona State University, 2010.

39

Target Re range for CFD and model tests

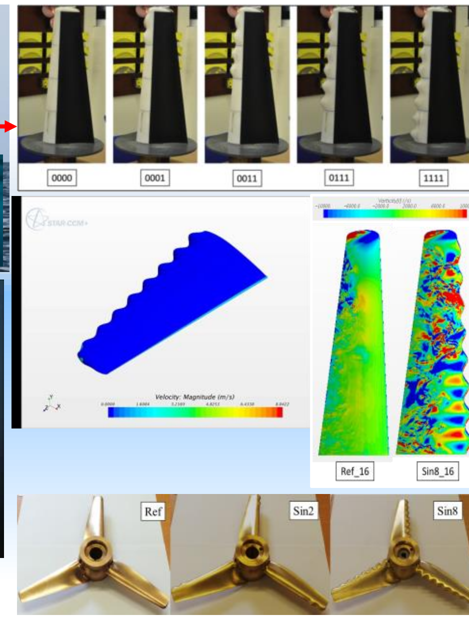
- Most of the available data about drag characteristics of dimpled surfaces;
  - 5.000< Re_{ch} <70.000 (Reynolds number based on channel height is at the approximate)
  - 6.000< Re_{dimple} <200.000 (Reynolds number based on dimple diameter)
- Targeted ranges at NAOME for CFD and FTFC tests;
  - 44.000< Re_{ch} <330.000
  - 200.000< Re_{dimple} <1.000.000





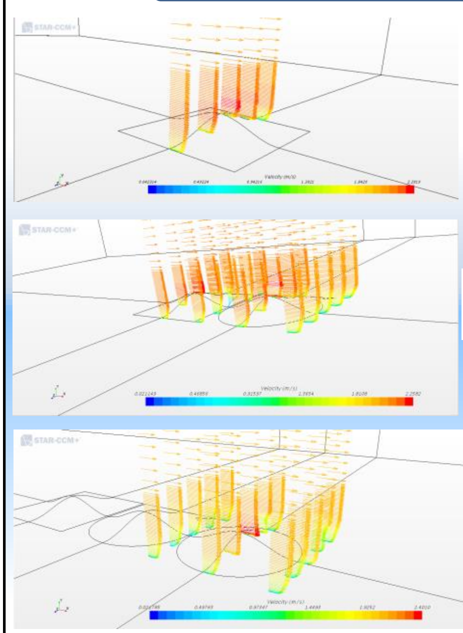
40

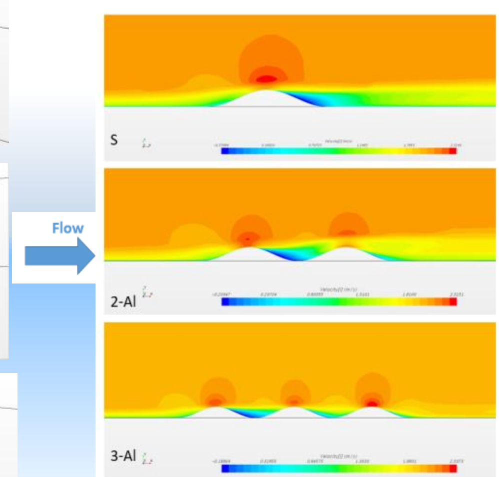
TUBERCLES for drag reduction & fouling control ?



Shi, W., Atlar M. Norman R. "Detailed flow measurement of the field around tidal turbines with and without biomimetic leading-edge tubercles", Renewable Energy, V 111, 2017, PP 688-707

TUBERCLES for drag reduction & fouling control ?

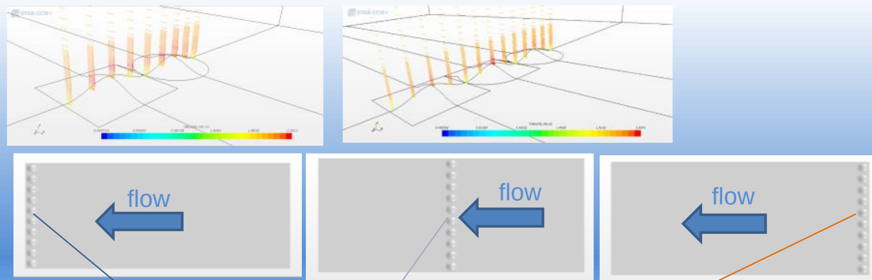


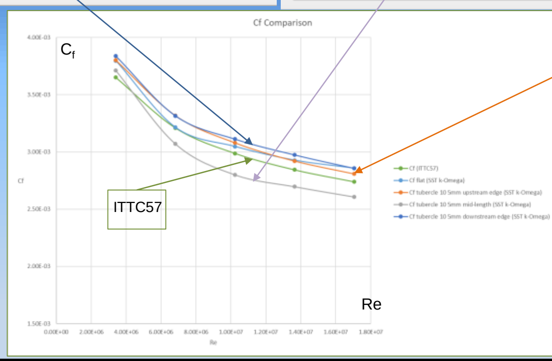


Marino, M., Atlar, M., Demirel, Y, "An investigation of the effect of biomimetic tubercles on a flat plate", OMAE 2019 - 96276, Glasgow.

42

TUBERCLES for drag reduction & fouling control ?





- Further optimisation study using CFD
- Validation with FTFC tests
- Impact on fouling pattern

Marino, M., Atlar, M., Demirel, Y, "An investigation of the effect of biomimetic tubercles on a flat plate", OMAE 2019 - 96276, Glasgow (TBP)

Concluding remarks

- The proposed approach is **generic**; can be applied to any ship type and hull coating system in the presence of biofouling, and it may be combined with passive drag reduction systems.
- **Experimental data** with representative surface finishes **is essential** both for the extrapolation and CFD methods. The CFD should be preferred for more accurate and direct estimation of the performance prediction at full-scale.
- The strength of the approach is to use the experimental method in combination with the CFD but **avoiding** the most challenging barrier of **describing the actual hull surface condition** numerically in the CFD.
- **Validation** of the proposed approach requires further **full-scale data** using the developed **bespoke performance monitoring and analysis** system which is under progress.

44

Acknowledgements

Akzo-Nobel:

- Candries (2001), Hasselaar (2011), Politis (2012 -),Yeginbayeva (2017) **Ex-PhDs**
- Carchen, A. (2015 -) **Current PhD**
- UNEW multi-purpose flume facility (FP6-AMBIO, FP7-SEAFRONT)
- Part of the performance monitoring system on-board The Princess Royal.

EU Commission:

- EU-FP6 **AMBIO** project, FP7 **TARGETS** project, FP7 **FOUL-X-SPEL** project and FP7-**SEAFRONT** Project

Personnel of:

- The Emerson Cavitation Tunnel **(UNEW),** The Princess Royal **(UNEW)** and Kelvin Hydrodynamics Laboratory **(UoS).**

NAOME Hydro-Team

- Marino, A (2016 -), Song, S (2017 -), Ilter, K. (2016 -) **Current PhDs**
- Dr Demirel, YK

45

Hogere Zeevaartschool Antwerpen

THANK YOU

e-mail: mehmet.atlar@strath.ac.uk
URL: www.strath.ac.uk/naome

Department of Naval Architecture, Ocean & Marine Engineering,
University of Strathclyde, Glasgow, UK

THE 2ND AMACORT SYMPOSIUM ON CORROSION AND FOULING
APRIL 1, 2019 - ANTWERP, BELGIUM

46

REFERENCES

Anderson, C., Atlar, M., Callow, M., Candries, M. and Townsin, R.L. (2003) The Development of Foul-Release Coatings for Seagoing Vessels, Journal of Marine Design and Operations, No. B4, pp. 11-23.

Atlar, M., Yeginbayeva, I., Turkmen, S., Demirel, Y., Carchen, S., Marino, A. and Williams, D. (2018)A rational approach to predicting the effect of fouling control systems on "in-service" ship performance, 3rd Intl Conference on Navalk Architecture and Maritime, Yildiz Technical Univeristy, Istanbul, 24-29 April.

Atlar, M. (2011) Recent Upgrading of Marine Testing Facilities at Newcastle University, Proceedings of the 2nd International Conference on Advanced Model Measurement Technology for EU Maritime Industry (AMT'11). Newcastle Upon Tyne

Atlar, M., Ünal, B., Ünal, U. O., Politis, G., Martinelli, E., Galli, G., Davies, C. & Williams, D. (2013a) An experimental investigation of the frictional drag characteristics of nanostructured and fluorinated fouling-release coatings using an axisymmetric body. Biofouling, 29, 39-52.

Atlar, M., Aktas, B., Sampson, R., Seo, K.C., Viola, M.I., Fitzsimmons P., Fetherstonehaug, C. (2013b) A multi-purpose marine science and technology research vessel for full-scale observations and measurements. 3rd International conference on advanced model measurement technology for the maritime industry (AMT'13), September, Gdansk.

Atlar, M., Bashir, M., Turkmen, S., Yeginbayeva, I., Carchen, A. and Politis, G. (2015) Design, Manufacture and Operation of a Strut System Deployed on a Research Catamaran to Collect Samples of Dynamically Grown Biofilms In-Service, Proceedings of the 4th International Conference on Advanced Model Measurement Technology for Maritime Industry (AMT'15). Istanbul, Turkey.

Atlar, M., Glover, E.J., Candries, M., Mutton, R., Anderson, C.D. (2002) The effect of a Foul Release coating on propeller performance, Conference Proceedings Environmental Sustainability (ENSUS). University of Newcastle.

Candries, M. (2001) Drag and Boundary Layer On Antifouling Paint. PhD thesis. University of Newcastle-Upon Tyne.

Candries, M., Atlar, M., (2003) On the Drag and Roughness Characteristics of Antifoulings, International Journal of Maritime Engineering, RINA, Vol. 145 A2.

Candries, M., Atlar, M., Mesbahi, E. and Pazouki, K. (2003) The Measurement of the Drag Characteristics of Tin-Free Self-polishing Co-polymers and Fouling Release Coatings Using a Rotor Apparatus, Biofouling, 19 (Supplement), pp. 27-36.

Carchen, A., Pazouki, K., and Atlar, M., (2017a) Development of an Online Ship Performance Monitoring System Dedicated for Biofouling and Anti-Fouling Coating Analysis". Hull Performance and Insight Conference, HullPIC, Ulrichshusen, De.

Carchen, A., Turkmen, S. Pazouki, K., Murphy, A., Aktas, B. and Atlar, M., (2017b) Uncertainty analysis of full-scale ship performance monitoring onboard the Princess Royal. Proceedings of the 5th International Conference on Advanced Model Measurement Technology for Maritime Industry (AMT'15) Glasgow, UK.

Demirel, Y.K. (2015) Modelling the roughness effects of marine coatings and biofouling on ship frictional resistance, PhD Thesis, Department of Naval Architecture, Ocean and Marine Engineering. University of Strathclyde.

REFERENCES

Demirel, Y.K., Turan, O., Incecik, A., (2016) Predicting the effect of biofouling on ship resistance using CFD. Applied Ocean Research 62, 100-118.

***Granville P. S. (1958)** The frictional resistance and turbulent boundary layer of rough surfaces. Journal of Ship Research. 2:52-74.*

Demirel, Y. K., et al. (2017). "Predicting the effect of biofouling on ship resistance using CFD." Applied Ocean Research 62: 100-118.

Granville, P.S. (1987) Three Indirect Methods for the Drag Characterization of Arbitrarily Rough Surfaces on Flat Plates, Journal of Ship Research, 31, pp. 70-77.

Hasselaar, T. W.F. (2011) An investigation into the development of an advanced ship performance monitoring and analysis system, PhD Thesis, Newcastle University.

ITTC (2014) Analysis of Speed/Power Trial Data, Recommended Procedures and Guidelines: Full Scale Measurements.

Marino, M., Atlar, M., Demirel, Y, (2019) "An investigation of the effect of biomimetic tubercles on a flat plate", OMAE 2019 - 96276, Glasgow.

Naval Ships' Technical Manual (2002) Waterborne underwater hull cleaning of navy ships. S9086-CQ-STM-010/CH-081R5. Naval Sea Systems Command. 2002.

Patel, V. C. (1998) Perspective: Flow at high Reynolds number and over rough surfaces—Achilles heel of CFD. Journal of Fluids Engineering, 120, 434-444.

Politis, G., Atlar, M., Kidd, B. and Stenson, P. (2013) A Multipurpose Flume for the Evauation of Hull Coatings', Proceedings of the 3rd International Conference on Advanced Model Measurement Technology for the Maritime Industry (AMT'13). Gdansk, Poland.

Schultz, M.P. (2007) Effects of coating roughness and biofouling on ship resistance and powering. Biofouling 23 (5), 331-341.

Schultz, M.P. and Flack, K.A. (2013) Reynolds-Number Scaling of Turbulent Channel Flow', Physics of Fluids, 25(025104), pp. 1-13.

Schultz, M.P., Flack, K., (2007) The rough-wall turbulent boundary layer from the hydraulically smooth to the fully rough regime. Journal of Fluid Mechanics 580, 381-405.

SEAFRONT (2014-2017) Synergistic Fouling Control Technologies. Available at: http://seafront-project.eu/.

Seo, K-C, Atlar, M. and Goo B. (2016) A study on the hydrodynamic effect of biofouling on marine propeller", Journal of the Korean Society of Marine Environment & Safety, V 22, No1, 123-128.

Song, S., Demirel, Y.K, Atlar, M.(2019a). "An investigation into the effect of biofouling on the ship hydrodynamic characteristics using CFD." Ocean Engineering 175: 122-137.

Song, S., Demirel, Y.K, Atlar, M. (2019b). "An investigation into the effect of biofouling on full-scale propeller performance using CFD". OMAE, Glasgow.

Taniguchi, K. and Tamura, K. (1966) On a new method of correction for wind resistance relating to the analysis of speed trial results, 11th ITTC.

REFERENCES

TARGETS, (2011) *Targeted Advanced Research for Global Efficiency of Transportation Shipping-TARGETS, EU-FP7 Collaborative Project, SST.2010-RTD-1-26600*

Yeginbayeva, I. (2017) *An investigation into hydrodynamic performance of marine coatings "in-service" conditions, PhD Thesis, Newcastle University.*

Yeginbayeva, I., Atlar, M., Turkmen, S., Kidd, B. and Finnie, A.A. (2016) *Investigating The Impact Of Surface Condition On The Frictional Resistance Of Fouling Control Coating Technologies, The 31st Symposium On Naval Hydrodynamics (SNH). Monterey, USA, 11-16 September*