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

By

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Presentation layout

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

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
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

- Topographical views of test surfaces with different coatings using Optical Profilometry (25x25mm; 25 mic sampling interval)
3. Hydrodynamic performance assessment

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

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
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.

An overall view of UNEW
fully turbulent seawater channel

Test (pressure drop) section
of turbulent channel

Test panel with biofilm
installed in pressure drop
section

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
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 (1959).

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
\[ \Delta U^* \] : Roughness Function

\[ \Delta U^* = U_{\text{smooth}}^* - U_{\text{rough}}^* \]

Roughness Function (\( \Delta U^* \)) representation

• 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 (\( \Delta U^* \)) 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.
5. Extrapolation Algorithm

\[ L_{\text{plate}} = \text{Test surface length} \]
\[ L_{\text{ship}} = \text{Ship length} \]
\[ C_{F\text{ smooth}} = \text{Smooth surface drag coeff's} \]
\[ C_{F\text{ rough}} = \text{Rough surface drag coeff's} \]
\[ L^+ = \text{Re} \left( \sqrt{\frac{C_F}{2}} \left( 1 - \frac{k^+}{C_F} \right) \right) \]
\[ \text{Re} = \text{Reynolds number, length based} \]
\[ K = \text{von Karman Constant} \]
\[ \Delta U^* = \text{Roughness Function} \]

\[ \Delta C_F = \frac{C_{F\text{ rough}} - C_{F\text{ smooth}}}{C_{F\text{ smooth}}} \]

Schematic representation Granville’s algorithm, Schultz (2007)

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)

<table>
<thead>
<tr>
<th>Description of condition</th>
<th>NSTM rating*</th>
<th>( k_s ) (mm)</th>
<th>( R_{\text{mu}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulically smooth surface</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Typical as applied AF coating</td>
<td>0</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>Deteriorated coating or light slime</td>
<td>10-20</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>Heavy slime</td>
<td>30</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>Small calcareous fouling or weed</td>
<td>40-60</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Medium calcareous fouling</td>
<td>70-80</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Heavy calcareous fouling</td>
<td>90-100</td>
<td>10000</td>
<td>10000</td>
</tr>
</tbody>
</table>

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

* NSTM (2002)
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.

<table>
<thead>
<tr>
<th>Test surface</th>
<th>$k_G$ ($\mu$m)</th>
<th>Regression $h$ (mm)</th>
<th>Coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 10%</td>
<td>174</td>
<td>174</td>
<td>5</td>
</tr>
<tr>
<td>B 20%</td>
<td>440</td>
<td>445</td>
<td>5</td>
</tr>
<tr>
<td>M 10%</td>
<td>334</td>
<td>31</td>
<td>2.5</td>
</tr>
<tr>
<td>M 20%</td>
<td>305</td>
<td>276</td>
<td>2.5</td>
</tr>
<tr>
<td>M 40%</td>
<td>388</td>
<td>366</td>
<td>2.5</td>
</tr>
<tr>
<td>M 50%</td>
<td>460</td>
<td>445</td>
<td>2.5</td>
</tr>
<tr>
<td>S 10%</td>
<td>24</td>
<td>24</td>
<td>1.25</td>
</tr>
<tr>
<td>S 20%</td>
<td>63</td>
<td>60</td>
<td>1.25</td>
</tr>
<tr>
<td>S 40%</td>
<td>140</td>
<td>171</td>
<td>1.25</td>
</tr>
<tr>
<td>S 50%</td>
<td>194</td>
<td>181</td>
<td>1.25</td>
</tr>
</tbody>
</table>

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

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

Applications of approach

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between the perpendiculars ($L_{bp}$)</td>
<td>230.0 m</td>
</tr>
<tr>
<td>Length of waterline ($L_{wl}$)</td>
<td>232.5 m</td>
</tr>
<tr>
<td>Beam at waterline ($B_{wl}$)</td>
<td>32.2 m</td>
</tr>
<tr>
<td>Depth (D)</td>
<td>19.0 m</td>
</tr>
<tr>
<td>Design draft (T)</td>
<td>10.8 m</td>
</tr>
<tr>
<td>Wetted surface area</td>
<td>9498 m²</td>
</tr>
<tr>
<td>Displacement ($\Delta$)</td>
<td>52030 m³</td>
</tr>
<tr>
<td>Block coefficient ($C_{bp}$)</td>
<td>0.6505</td>
</tr>
<tr>
<td>Design Speed</td>
<td>24 knots</td>
</tr>
<tr>
<td>Froude number (Fr)</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Background & Objectives

- Description of approach
- Applications of approach
- Validation of approach
- Recent R&D in NAOME
- Concluding remarks
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, estimated based on Granville's extrapolation method (Flat Plate).

**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)*.
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)

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)
• 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

Table – Tanker propeller main particulars

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>6.58 m</td>
</tr>
<tr>
<td>Pitch ratio</td>
<td>0.009</td>
</tr>
<tr>
<td>Blade area ratio</td>
<td>0.521</td>
</tr>
<tr>
<td>Number of blades, N</td>
<td>4</td>
</tr>
<tr>
<td>Design advance coefficient (i)</td>
<td>0.88</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Right</td>
</tr>
<tr>
<td>Year Built</td>
<td>1992</td>
</tr>
</tbody>
</table>

Case study - 95,000t motor tanker propeller

Table - Roughness model

<table>
<thead>
<tr>
<th>Description of conditions</th>
<th>k_n (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light slime</td>
<td>0.0001</td>
</tr>
<tr>
<td>Heavy slime</td>
<td>0.0003</td>
</tr>
<tr>
<td>Small calcareous fouling</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table – Efficiency loss due to different fouling conditions

<table>
<thead>
<tr>
<th>J</th>
<th>% Loss in efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>smooth</td>
<td>light</td>
</tr>
<tr>
<td>0.3</td>
<td>4.43</td>
</tr>
<tr>
<td>0.4</td>
<td>4.99</td>
</tr>
<tr>
<td>0.5</td>
<td>5.84</td>
</tr>
<tr>
<td>0.6</td>
<td>7.32</td>
</tr>
<tr>
<td>0.7</td>
<td>10.42</td>
</tr>
</tbody>
</table>

Table – Potsdam Propeller Test Case (PPTC) parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>D</td>
<td>0.250</td>
</tr>
<tr>
<td>Pitch ratio r/R=0.7</td>
<td>Pr/D</td>
<td>1.635</td>
</tr>
<tr>
<td>Area Ratio</td>
<td>A_p/A_o</td>
<td>0.779</td>
</tr>
<tr>
<td>Chord Length (m)</td>
<td>C_p</td>
<td>0.104</td>
</tr>
<tr>
<td>Skew (deg)</td>
<td>θ</td>
<td>18.837</td>
</tr>
<tr>
<td>Hub Ratio</td>
<td>D_h/D</td>
<td>0.300</td>
</tr>
<tr>
<td>No. of Blade</td>
<td>Z</td>
<td>5</td>
</tr>
<tr>
<td>Rotation</td>
<td>Direction</td>
<td>Right</td>
</tr>
<tr>
<td>Revolutions/s [rps]</td>
<td>n</td>
<td>15</td>
</tr>
</tbody>
</table>

Effect of different grades of biofouling on the efficiency of Potsdam Test Case Propeller
Validation of approach


• 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)

Performance measurement on-board RV “The Princess Royal”
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)

**Validation of approach**

- Raw performance measurements (grey markers)
- Normalised performance data (red line and markers)

**Fig** - Performance measurements on the Princess Royal, *Carchen et al. (2017)*

- Normalised delivered power: $P_{d0} = 2\pi \rho D_p^3 K_{Q0} n_0^3 \eta_s$
- Power based KPI: $\Delta P_{d0}(t, V_s) = \frac{P_{d0}(t, V_s)}{P_{d0}(t_{ref}, V_s)} - 1$
- Wake based KPI: $\Delta w_{Q0}(t, V_s) = \frac{w_{Q0}(t, V_s)}{w_{Q0}(t_{ref}, V_s)} - 1$
Validation of approach

Total ship resistance breakdown

\[ R_T = (1 + \phi) R_0 + R_w + R_{add} \]

Total added drag breakdown

\[ R_{add} = R_{AA} - R_{AA0} + R_{AW} + R_\Lambda + R_p \]

Resistance coefficients

\[ C_T = (1 + \phi) C_v + C_w \quad C_T = C_f(1 + \kappa) \]

Fouling coefficient KPI

\[ \hat{\phi}(t, V_s) = \frac{\hat{C}_v(t, V_s)}{\hat{C}_v(t_{ref}, V_s)} - 1 \]

Recent R & D activities in Dep’t of NAOME

- 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
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*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Length</td>
<td>2.40 m</td>
</tr>
<tr>
<td>Test Plate Length</td>
<td>0.60 m</td>
</tr>
<tr>
<td>Channel Width</td>
<td>0.18 m</td>
</tr>
<tr>
<td>Channel Height</td>
<td>0.0225 m</td>
</tr>
<tr>
<td>Bulk Velocity Range</td>
<td>~ 0.5 – 15.0 m/s</td>
</tr>
<tr>
<td>Reynolds Number Range</td>
<td>~ 10,000 – 350,000</td>
</tr>
<tr>
<td>Pressure taps No &amp; range</td>
<td>6 taps &amp; 20 - 1000 mbar</td>
</tr>
<tr>
<td>Tank capacity</td>
<td>2.6 m³</td>
</tr>
<tr>
<td>LDA &amp; PIV Access through</td>
<td>Pressure drop section 600 x 180 x 22.5 mm</td>
</tr>
</tbody>
</table>

*Velocity vs Reynolds Number*

*Drag vs Reynolds Number*
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

Demirel et al. (2017)
Song et al. (2019a)
Song et al. (2019b) In progress

Song, S., et al. (2019a). “An investigation into the effect of biofouling on the ship hydrodynamic characteristics using CFD.” Ocean Engineering. 175, 122-137.

**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

- Prediction of added resistance due to roughness
- Comparison & validation

- 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
“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.


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. Veldhuis 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 92% reduction
• 2015 – C.M. Tay et al up to 3% reduction
• 2016 – M. Van Nesselrooij et al up to 4% reduction, up to 18% increase in some cases
• 2017 – X.W. Song et al 16% reduction with non symetrical dimple shapes(non-ovoid)

The Reynolds number dependence of the coefficient of friction drag Cl 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.

Sample data from the open literature


Target Re range for CFD and model tests

- Most of the available data about drag characteristics of dimpled surfaces;
  - $5,000 < \text{Re}_{\text{ch}} < 70,000$ (Reynolds number based on channel height is at the approximate)
  - $6,000 < \text{Re}_{\text{dimple}} < 200,000$ (Reynolds number based on dimple diameter)

- Targeted ranges at NAOME for CFD and FTFC tests;
  - $44,000 < \text{Re}_{\text{ch}} < 330,000$
  - $200,000 < \text{Re}_{\text{dimple}} < 1,000,000$

TUBERCLES for drag reduction & fouling control?

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

Marino, M., Altar, 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.
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- Dr Demirel, YK

---

**Hogere Zeevaartschool Antwerpen**

**THANK YOU**

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