Predicting the Drag on Ships with Biofouling

Karen A. Flack
Michael P. Schultz
Jessica M. Walker
Elizabeth A.K. Murphy

United States Naval Academy
Annapolis, MD
**Fundamental Issue**

All surfaces are rough in the limit of high unit Reynolds number resulting in significant drag/performance penalties.

*FFG-7 at cruising speed – 15 kts*

<table>
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<tr>
<th>Description of Condition</th>
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Schultz (2007) *Biofouling*
Fundamental Issue

All surfaces are rough in the limit of high unit Reynolds number resulting in significant drag/performance penalties.

Hull fouling results in increased fuel cost of $1 million per ship per year (2011)

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Schultz (2011) Bio fouling
Accounting for Drag: Ship Resistance

At cruise speed, frictional drag accounts for 70% or total drag

\[ C_T = \frac{\text{Drag}}{\frac{1}{2} \rho V^2 A} \]

\[ \text{Re} = \frac{VL\rho}{\mu} \]

\[ Fr = \frac{V}{\sqrt{gL}} \]

Accounting for Drag: Pipe Flow

Moody (1944), Colebrook (1939)

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Equivalent Roughness $\varepsilon$ (mm)</th>
</tr>
</thead>
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<tr>
<td>Riveted steel</td>
<td>0.9 – 9.0</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.3 – 3.0</td>
</tr>
<tr>
<td>Wood stave</td>
<td>0.18 – 0.9</td>
</tr>
<tr>
<td>Cast iron</td>
<td>0.26</td>
</tr>
<tr>
<td>Galvanized iron</td>
<td>0.15</td>
</tr>
<tr>
<td>Commercial steel</td>
<td>0.045</td>
</tr>
<tr>
<td>Drawn tubing</td>
<td>0.0015</td>
</tr>
<tr>
<td>Plastic, glass</td>
<td>0.0 (smooth)</td>
</tr>
</tbody>
</table>

$\varepsilon = k_s$
equivalent sandgrain roughness

Moody (1944), Colebrook (1939)
Modeling Roughness/Predicting Drag

Turbulent boundary layer velocity profile

\[ U^+ = \frac{1}{\kappa} \ln y^+ + B - \Delta U^+ \]

\[ U^+ = \frac{U}{U_\tau} \]

\[ y^+ = \frac{y U_\tau}{v} \]

\[ U_\tau = \sqrt{\tau_w / \rho} \]

\[ \Delta U^+ = \text{Change in velocity due to drag from rough surface} \]
Modeling Roughness/Predicting Drag

Turbulent boundary layer velocity profile

\[ U^+ = \frac{1}{k} \ln y^+ + B - \Delta U^+ \]

Roughness function

\[ k^+ = \frac{kU_\tau}{v} \]

Valid for a specific roughness

\[ \Delta U^+ = f(k^+) \]

Computational models
Modeling Roughness/Predicting Drag

Turbulent boundary layer velocity profile

\[ U^+ = \frac{1}{k_s} \ln y^+ + B - \Delta U^+ \]

\[ \Delta U^+ = \frac{1}{k_s} \log k_s^+ + A - B \]

\[ k_s^+ = \frac{k_s U_\tau}{v} \]

Fully rough asymptote

Valid for any roughness in fully rough regime

Computational models
Modeling Roughness/Predicting Drag

Turbulent boundary layer velocity profile

\[ U^+ = \frac{1}{k} \ln y^+ + B - \Delta U^+ \]

\[ \Delta U^+ = f(k^+) \]

Valid for a specific roughness

Computational models

\[ \Delta U^+ = f(k_s^+) \]

Valid for any roughness in fully rough regime
Modeling Roughness/Predicting Drag

\[ Re_L = \frac{L^+}{\sqrt{C_F} \left( 1 - \frac{1}{\kappa \sqrt{C_F}} \right)} \]

Granville (1978, 1987)

Lab Results to Ship Scale
Modeling Roughness/Predicting Drag

\[ \frac{2}{C_F}^{1/2} = -2.186 \ln \left( \frac{k_s}{L} \right) + 0.495 \]

Transitionally Rough Regime

Fully Rough Regime

Smooth

Karman-Schoenherr

Flack & Schultz (2010)
Biofilm Roughness

- 72” x 36” x 48” PE Tank
- horizontal axis rotation
- 24” diameter drum
- panel capacity - 8

- test panels mount along the length of the drum
- rotational speeds of 60 & 120 rpm (4 & 8 knots)
- timed lighting (18h light / 6h dark) & temperature control (25° C)
- inoculated with diatoms collected from Florida bottom paints
Biofilm Roughness

Diatom genera present in biofilms:
Amphora, Achnanthes, Entomoneis and Navicula

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Specimen A</td>
<td>Silicone Fouling-Release System</td>
</tr>
<tr>
<td>Specimen B</td>
<td>Fluoropolymer Fouling-Release System</td>
</tr>
<tr>
<td>Specimen C</td>
<td>Fluoropolymer Fouling-Release System (Slime Release)</td>
</tr>
</tbody>
</table>
High Reynolds number channel

- 2.5cm ($H$) x 20.3cm ($W$) x 3.25m ($L$)
- $U_e = 0.5 – 11.0$ m/s
- $Re_m = 1.2 \times 10^4 – 3.1 \times 10^5$
- $Re_\tau = 350 – 6,100$ (smooth wall)
- 90$H$ Development Region
- 10 pressure taps in fully developed region ($\tau_w +/ - 1\%$)
- 6 replicate runs
Biofilm Roughness

Specimen A
coverage = 19.6%
thickness, $k = 545 \, \mu m$

Specimen B
coverage = 11.8%
thickness, $k = 433 \, \mu m$

Specimen C
coverage = 6.4%
thickness, $k = 574 \, \mu m$

Acrylic Control
coverage = 18.1%
thickness, $k = 527 \, \mu m$

3 months exposure
Biofilm Roughness

Specimen A
coverage = 14.2%
thickness, $k = 520 \mu m$

Specimen B
coverage = 13.7%
thickness, $k = 433 \mu m$

Specimen C
coverage = 49.2%
thickness, $k = 98 \mu m$

Acrylic Control
coverage = 27.8%
thickness, $k = 392 \mu m$

6 months exposure
Biofilm Roughness


3 months exposure
Biofilm Roughness


6 months exposure

error bars represent total uncertainty at 95% confidence

$C_f$ vs. $Re_m$
Biofilm Roughness

$k^+ = \frac{kU_\tau}{\nu}$

$k$ not effective by itself in collapsing the roughness function

Significant variability in roughness function behavior

Biofilm Roughness

Effective hydraulic length scale appears to be related to biofilm thickness and % cover

\[ k_s \approx k_{eff} = 0.055k(\%\text{cover})^{\frac{1}{2}} \]

**Biofilm Roughness**

Effective hydraulic length scale appears to be related to biofilm thickness and % cover

\[ k_s \approx k_{\text{eff}} = 0.055k(\% \text{ cover})^{\frac{1}{2}} \]

- Coverage = 27.8%
  - Thickness, \( k = 392 \, \mu m \)
  - \( k_s = 115 \, \mu m \)

- Coverage = 49.2%
  - Thickness, \( k = 98 \, \mu m \)
  - \( k_s = 35 \, \mu m \)

Biofilm Roughness

Onset of roughness effects seems to occur at $k_{eff}^+ \sim 2-3$

Roughness functions don’t exhibit the typical asymptotic behavior

% Coverage < 25%?

Modeling Roughness/Predicting Drag

\[ \Delta U^* / (\ln(10)/k) \]

\[ Re_L = \frac{L^+}{\sqrt{C_F} \left( 1 - \frac{1}{K \sqrt{C_F}} \right)} \]

Granville (1978, 1987)

Lab Results to Ship Scale
Biofilm Roughness

Scale Up of Results – 3 Months Exposure*

<table>
<thead>
<tr>
<th>Surface</th>
<th>ΔSP (%) at 15 kts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen A</td>
<td>6.3</td>
</tr>
<tr>
<td>Specimen B</td>
<td>4.8</td>
</tr>
<tr>
<td>Specimen C</td>
<td>1.5</td>
</tr>
<tr>
<td>Acrylic Control</td>
<td>6.2</td>
</tr>
</tbody>
</table>

*changes in shaft power are calculated with respect to the hydraulically-smooth condition

Predicted Increase in Shaft Power for DDG-51@ 15 knots
Biofilm Roughness

Scale Up of Results – 6 Months Exposure*

<table>
<thead>
<tr>
<th>Surface</th>
<th>ΔSP (%) at 15 kts</th>
</tr>
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<tbody>
<tr>
<td>Specimen A</td>
<td>10.1</td>
</tr>
<tr>
<td>Specimen B</td>
<td>5.3</td>
</tr>
<tr>
<td>Specimen C</td>
<td>2.3</td>
</tr>
<tr>
<td>Acrylic Control</td>
<td>10.1</td>
</tr>
</tbody>
</table>

*changes in shaft power are calculated with respect to the hydraulically-smooth condition

Predicted Increase in Shaft Power for DDG-51@ 15 knots
Modeling Roughness/Predicting Drag

Heavy slime fouling

Table 1. Roughness parameters of the biofilm-fouled plate and the smooth plate.

<table>
<thead>
<tr>
<th></th>
<th>$U_2$ (m s$^{-1}$)</th>
<th>$\delta$ (mm)</th>
<th>Re$^+$</th>
<th>$\Delta U^+$</th>
<th>$k_+^+$</th>
<th>$k_+$ (mm)</th>
<th>$C_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>1.2</td>
<td>33.5</td>
<td>1.64 $\times$ 10$^3$</td>
<td>0.047</td>
<td>–</td>
<td>–</td>
<td>2.9 $\times$ 10$^{-3}$</td>
</tr>
<tr>
<td>Biofilm</td>
<td>1.1</td>
<td>30.0</td>
<td>2.5 $\times$ 10$^2$</td>
<td>0.076</td>
<td>12.8</td>
<td>736</td>
<td>9.0 $\times$ 10$^{-3}$</td>
</tr>
</tbody>
</table>

$\delta^+$ is the friction Reynold number.

Modeling Roughness/Predicting Drag

Heavy slime fouling

Three week biofilm, slight growth – Trial 3W3

Five week biofilm, moderate growth – Trial 5W3

Ten week biofilm, heavy growth – Trial 10W2

Ceccio, et al. ONR Program review 2019
Modeling Roughness/Predicting Drag

Frictional Performance of Trial 3W2

\[ \Delta C_f = 152 \%-23\% \]

\[ \Delta C_f = 152 \%-23\% \]

Ceccio, et al. ONR Program review 2019
Modeling Roughness/Predicting Drag

Light calcareous tubeworm fouling

Table 2. Tabulated data on the FFG-7 Oliver Perry class frigate (Schultz 2007). Data in the shaded columns are calculated for the tubeworm fouling.

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>(v) (m(^2)s(^{-1}))</th>
<th>(C_A)</th>
<th>(U) (m s(^{-1}))</th>
<th>(Fr)</th>
<th>(Re)</th>
<th>(\bar{C}_f/C_R)</th>
<th>(% \Delta \bar{C}_f)</th>
<th>(% \Delta R_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>124</td>
<td>8.97 \times 10^{-7}</td>
<td>0.0004</td>
<td>Cruising</td>
<td>7.7</td>
<td>0.22</td>
<td>1.06 \times 10^9</td>
<td>~0.7</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Full-speed</td>
<td>15.4</td>
<td>0.44</td>
<td>2.13 \times 10^9</td>
<td>~3.3</td>
<td>59%</td>
</tr>
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Conclusions

• Bio-films cause a significant drag penalty
  – ~10% increase in ship power for light slime
  – ~20% increase in ship power for heavy slime

• What else is needed to address questions
  – Additional lab experiments and numerical simulations of realistic ship hull roughness
  – Methods of in-situ measurements of ship hull roughness
  – Shear stress/boundary layer measurements over full scale ships with accurate documentation of surface roughness
Acknowledgements

• USNA Hydromechanics Lab
• USNA Technical Support Division
• Office of Naval Research
• Many roughness collaborators

Questions?