PREDICTION AND VERIFICATION OF FULL-SCALE SHIP PERFORMANCE OF FRICTIONAL DRAG REDUCTION COATING

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ABSTRACT

In the previous study of the authors, a novel FDR-SPC was first synthesized. The drag reducing functional radical such as PEGMA (Poly(ethylene) glycol methacrylate) has been utilized to participate in the synthesis process of the SPC. In the high-Reynolds number flow measurement with a flush-mounted balance and a LDV (Laser Doppler Velocimeter), the skin friction of the present FDR-SPC is found to be smaller than that of smooth plate throughout the range of Reynolds number, with the average drag reduction efficiency being 13.5% over the smooth plate. These results strongly support that the present FDR-SPC gives rise to the Toms effect based on chemical reaction at the surface of the coating. The low frictional AF coating based on the FDR-SPC has been comerciallized as Bn Green Guard FS, which is found to give 25% skin friction reduction compared with conventional AF coating.

With the advent of various types of low frictional AF marine coating, there have been proposed a variety of measurement techniques to evaluate frictional performance in laboratory scale, including a towed flat-plate drag measurement, a flush-mounted skin friction balance, a rotor torque measurement and a model ship total drag measurement. However, differences in the flows associated with such various setups make it extremely difficult to compare one test results with the other. When it comes to the extrapolation from lab scale results to the full scale ship performance, there hardly exist a systematic method ever proposed. In this study, a similarity transform is attempted to predict full scale ship performance based on such lab test method as towed flat-plate drag measurement and rotor torque measurement. This is an extension of the Granville similarity transform method used in Schultz (2007). Greater care is also taken to account for the low frictional AF coatings.

FRICTIONAL DRAG REDUCTION BASED ON NOVEL POLYMER MATERIAL

The reduction of frictional drag of turbulent boundary layer is of great importance for the fuel economy of ship. Along with the development of hull form optimization technique, the wavemaking resistance has become less than 20% of the total drag of most modern ships. Therefore, the advantage from the reduction of the remaining frictional drag would be enormous. The fuel consumption of global ocean shipping in 2003 was estimated 2.1 billion barrel/year (Corbett and Koehler, 2003), which corresponds to approximately 200 billion US$/year. Thus, 10% reduction of frictional drag would lead to saving of 16 billion US$/year. The skin frictional drag is closely associated with the coherent structures, e.g. hairpin vortices in the turbulent boundary layer flow. Various control strategies toward the attenuation of the drag-inducing flow structure have been proposed during several decades. One of the most effective drag reduction strategies is the polymer injection, which was first introduced by Toms (1949). Toms (1949) found that addition of few ppm of a high molecular weight polymer to a turbulent water flow can result in large (up to 80%) reduction of skin friction drag. Added long chain polymer molecule extracts the turbulent energy out of the adjacent flow by coiling its chain structures and then releases the energy by becoming stretched back in the shear flow. The turbulent energy transfer between the freestream and the near-wall flow is thus interfered, leading to a significant skin friction reduction. This is named Toms effect after who discovered it. The polymer injection has been put into practice for the pipeline transportation of petroleum, demonstrating one of the most effective examples of drag reduction.

It has been suggested that the polymer injection be applied to the frictional drag reduction for ships. There have been various researches to exemplifying the drag reduction efficiency of polymer injection in turbulent boundary layer (Somandepalli *et al.* 2010). From the aspect of implementation, however, the polymer injection is impractical for ship application. This is because it necessarily requires the injection holes to be installed onto the hull surface, which would cause significant structural strength issues. As a feasible alternative to the polymer injection method, Yang *et al.* (2014) proposed a PEO-containing AF paint. They reported the release of PEO, the well-documented drag reducing agent leading to Toms effect, from the surface of coating. It was found that the PEO-mixed paint exhibited significant drag reduction efficiency in ex-cess of 10% from various lab tests. In their paint, however, the PEO powders were physically mixed with the paint matrix, thereby giving rise to an increase in surface roughness and rapid release associated with the solubility of PEO in water. These factors may be detrimental to the longevity of drag reduction performance.

With a view to overcoming the drawbacks of the PEO-mixed paint in the previous research, a novel FDR-SPC was first synthesized by the authors. The drag reducing functional radical such as PEGMA (Poly(ethylene) glycol methacrylate) has been utilized to participate in the synthesis process of the SPC. The types of the baseline SPC monomers, the molecular weight and the mole fraction of PEGMA were varied in the synthesis process. The resulting SPCs were coated to the substrate plates for the subsequent hydrodynamic test for skin friction measurement. In the high-Reynolds number flow measurement with a flush-mounted balance and a LDV (Laser Doppler Velocimeter), the skin friction of the present FDR-SPC is found to be smaller than that of smooth plate in the entire Reynolds number range, with the average drag reduction efficiency being 13.5% over the smooth plate.

Based on the FDR-SPC, a low frictional AF (Anti-Fouling) marine coating was then commercialized (BN GreenGuard FS). Tested in a high-Reynolds number facility shown in Fig. 1, the present low frictional coating was found to give rise to 25% skin friction reduction compared with conventional AF coating (Fig. 2). Compared with the previous type coating with drag reducing additive (Yang *et al.* 2014), the present coating can achieve the longevity of drag reduction performance. The low frictional coating approach taken by the authors is regarded to be practically meaningful. This is because this can avoid the drawbacks of concentrated polymer injection method, which are the downstream degradation of drag reduction effect due to the cross-stream diffusion of polymer and the structural weakening due to the presence of injection holes.

Fig. 1 Photos of the experimental apparatus and samples

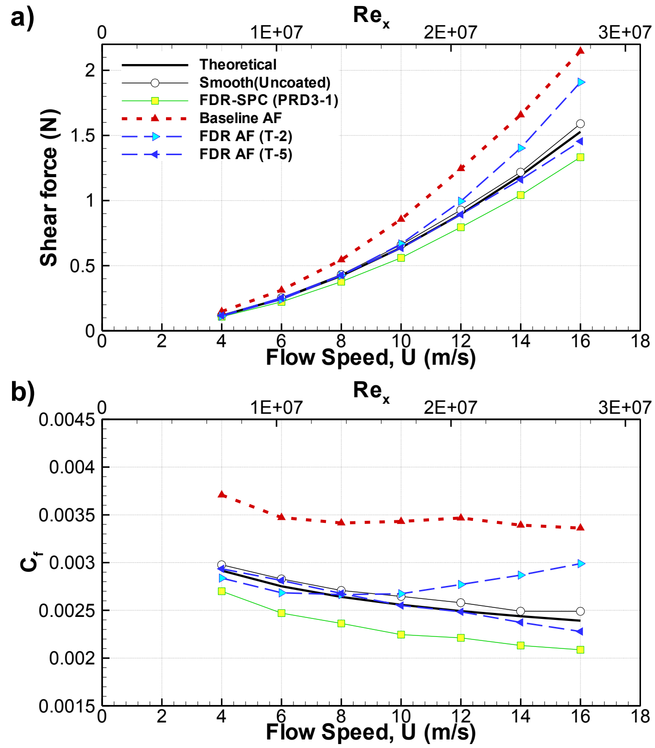


Fig. 2 Comparison of frictional drag in high Reynolds number flow for FDR-SPC and FDR AF coatings

FULL SCALE PERFORMANCE PREDICTION OF FRICTIONAL DRAG REDUCTION COATING

In order to extrapolate lab-scale skin friction measurement data obtained for two different surface roughness condition, an appropriate scaling needs to be performed to give nondimentional roughness $k^+$and roughness function ΔU^+. This can usually be achieved by comparing nondimensional velocity profiles for smooth and rough walls. This is called the direct characterization method, which is prone to be affected by various measurement uncertainties. Granville (1987) proposed three indirect methods for skin frictional drag characterization. Among those methods, the local indirect method is adopted in this study. In this method, the local skin frictional stresses are measured for smooth and rough surfaces and the skin friction characterization values are given as

$$\Delta U^+ = \left(\sqrt{\frac{2}{c_f}}\right)_S - \left(\sqrt{\frac{2}{c_f}}\right)_R - 19.7\left[\left(\sqrt{\frac{2}{c_f}}\right)_S - \left(\sqrt{\frac{2}{c_f}}\right)_R\right] \quad (1)$$

The extrapolation of the difference in the local skin friction coefficient to the difference in the skin frictional drag coefficient in full scale (ΔC_{FS}) is carried out based on the method of Schultz (2007). At first, the baseline AF coating data is extrapolated to give skin frictional drag coefficient C_{FS} in full scale, as depicted in Fig. 3. For the baseline AF, ΔC_{FS} was calculated to be 4.197×10^{-4}. On the other hand, $\Delta C_{FS} = 7.061\times10^{-5}$ was obtained for the low frictional AF (Fig. 4).

Table 1 lists the values of resistance coefficients for the 176k bulk carrier at the service speed of 14.8knots. From the model test with the scaling ratio $\lambda = 37.04$, the residuary resistance coefficient was found to be $C_{RM} = 3.580\times10^{-5}$ at 14.8knots. The total resistance coefficient C_{TS} was obtained by adding air resistance coefficient C_{AA} and the skin frictional resistance coefficient C_{FS} as follows;

$$C_{TS} = C_{FS} + C_{RM} + C_{AA} \tag{2}$$

Table 1 Comparison of Resistance Coefficients with Different Coatings at 14.8 knots

Item	Baseline AF	Low Frictional AF
C_{RM}	3.580×10^{-5}	3.580×10^{-5}
C_{FS}	1.842×10^{-3}	1.493×10^{-3}
C_{AA}	4.282×10^{-5}	4.282×10^{-5}
C_{TS}	1.921×10^{-3}	1.572×10^{-3}
ΔC_{TS} (%)	-	18.2

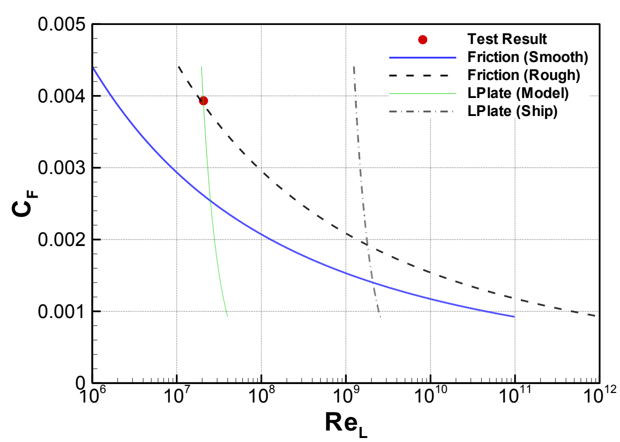


Fig. 3 Granville's Similarity Scaling Result for Baseline AF

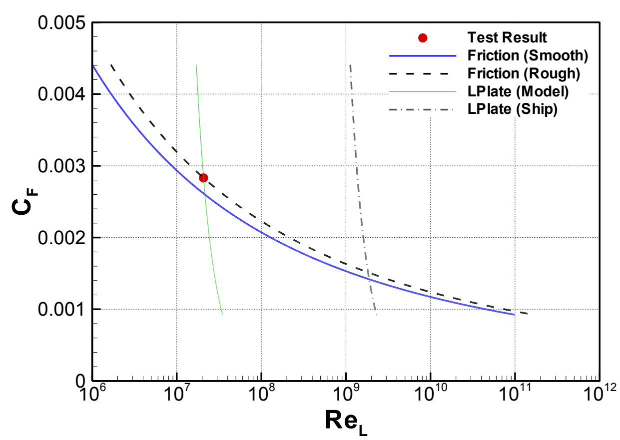
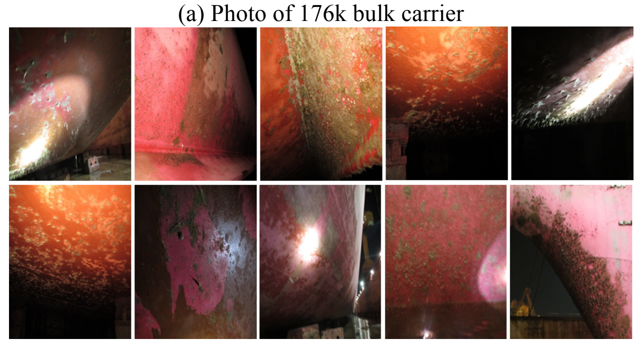


Fig. 4 Granville's Similarity Scaling Result for Low Frictional AF

As seen in Table. 1, the resulting total resistance coefficients C_{TS} for the baseline AF and the low frictional AF were obtained as 1.921×10^{-3} and 1.572×10^{-3}, respectively. This corresponds to 18.2% drag reduction for full scale ship due to the present low frictional AF coating.

(a) Photo of 176k bulk carrier



(b) Hull Condition before Redocking

(c) Hull Condition after Redocking

Fig. 5 Comparison of frictional drag in high Reynolds number flow for FDR-SPC and FDR AF coatings

FULL SCALE SHIP APPLICATION OF LOW FRICTIONAL AF PAINT

The low frictional AF coating in the present study has been comerciallized as BN Green Guard FS. After the antifouling efficiency had been confirmed through the patch test during a couple of years, this product was chosen to be painted on the whole underwater surface of a 176k bulk carrier, shown in Fig. 5 (a) to evaluate the full-scale energy saving performance during service. The repainting was finished in December 2015. Figures 5 (b) and (c) presents the hull surafce condition before and after repanting. Whlist the hull surface before redocking was fouled significantly, the hull surface after redocking became devoid of any conspicous surface defect.

The propulsion performance of the 176k bulk carrier as well as the weather condition is being recorded during service. It is imperative that the hull coating performance be evaluated without being affected by the additional resistance component associated with such weather condition as wind and wave. It is ISO/DIS19030 that is being proposed as a new international standard for that purpose. The aim of this standard is to prescribe practical methods for measuring changes in ship specific hull and propeller performance and to define a set of relevant performance indicators for hull and propeller maintenance, repair and retrofit activities. The methods are not intended for comparing the performance of ships of different types and sizes (including sister ships) nor to be used in a regulatory framework.

Hull and propeller performance is closely linked to the concepts of ship propulsion efficiency and ship resistance. The performance model is based on the relation between the delivered power and the total resistance where delivered power, P_D, can be expressed as

$$P_D = \frac{R_T V}{\eta_D}, \qquad R_T = R_{SW} + R_{AA} + R_{AW} + R_{AH}$$
$$R_{AH} = \frac{R_D \eta_D}{V} - (R_{SW} + R_{AA} + R_{AW}) \qquad (2)$$

Here, R_T is the total in-service resistance, V is the ship speed through water, η_D is the quasi-propulsive efficiency. R_T is given as the sumation of various resistance components, which are still-water resistance R_{SW}, added resistance due to wind R_{AA}, added resistance due to wave R_{AW} and added resistance due to changes in hull condition (fouling, mechanical damages, bulging, paint film blistering, paint detachment, etc.) R_{AH}. It can be said that the ISO19030 is aimed at the quantification of R_{AH} and its related speed drop during vessel's service.

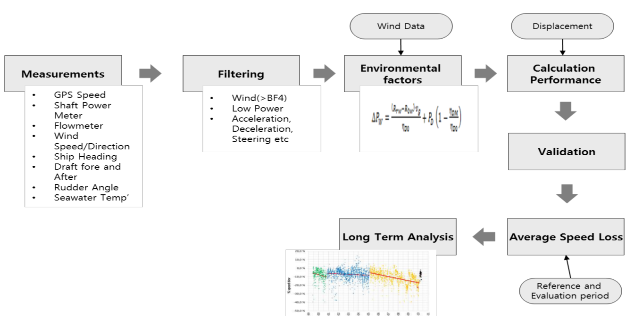


Fig. 6 Measurement and analysis process of ISO19030

Table 2 Validation and filtering criteria for environmental parameters

Parameter	Unit	Filtering	Validation	Correction
Speed over ground	[knots]	10.0 ~ 16.5	std. dev < 0.5knots	-
Shaft Power	[kW]	4,000~20,000	-	-
Relative wind speed and direction	[knots], [°]	< 15.6 knots (below BF4)	-	same as ISO15016
Ship heading	[°]	-	-	
Shaft revolutions	$[\mathrm{min}^{-1}]$	-	std. dev < 3RPM	
Static draught fore and aft	[m]	-	-	
Water depth	[m]	-	-	
Rudder angle	[°]	±5°	std. dev < 1°	
Seawater temperature	[°]	over 2°	-	

Figure 6 depicts the process of ISO19030, consisting of navigation data compilation, filtering, validation and analysis. As seen, the measured variables are ground speed, ship heading, shaft power, wind speed, wind direction, drafts, seawater temperature, rudder angle, etc. These variables are supposed to be measured at a constant rate, typically every 10 seconds. It is well known that the ship speed and shaft power are prone to be affected by such various environmental variables and influences from those variables needs to be adaquately removed by either filtering or compensation. The first step is the filtering. In the retrieved data set, outliers and missing values shall be marked invalid. To this end in consecutive, nonoverlapping blocks spanning 10 minutes, data for every parameter shall be filtered according to Chauvenet's criterion. Table 2 lists validation criterion for each environmental parameters. It is found that outliers associated with enviromental paramters are mostly filtered out with the exception being the wind resistance which is compensated after the ISO15016 sea trial analysis method.

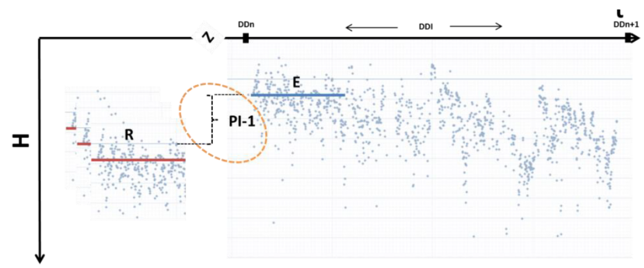


Fig. 7 Performance values and dry-docking performance indicator

Table 3 Basic hull and propeller Performance Indicators (PIs)

Performance Indicator (PI)	Definition
Dry-Docking Performance	Change in hull and propeller performance following present out-docking (Evaluation period) as compared with the average from previous outdockings (Reference periods).
In-service performance	Average change in hull and propeller performance from a period following out-docking (Reference period) to the end of dry-docking interval (Evaluation period).
Maintenance trigger	Change in hull and propeller performance from the start of the dry-docking interval (Reference period) to a moving average at a given point in time (Evaluation period)
Maintenance effect	Change in hull and propeller performance from before (Reference period) to after a maintenance event (Evaluation period).

After the effect from the environmental factors are either removed or corrected, the performance value is quantified as the percentage speed drop the at measured shaft power as follows;

$$\mathrm{PV} = \frac{(measured\ speed) - (expected\ speed)}{expected\ speed} \times 100 \qquad (3)$$

Here, the expected speed at the mesured shaft power is looked up from the speed-power curve obtained during either the speed trial or the model test. Exemplary performance values caluclated over a certain period of time is given in Fig. 7.

Measurements of ship specific changes in hull and propeller performance can be used in a number of relevant performance indicators to determine the effectiveness of hull and propeller maintenance, repair and retrofit activities. Table 3 outlines four basic hull and propeller performance indicators. Figure 7 illustrates how the dry docking performance indicator is calculated from the time history of performance values.

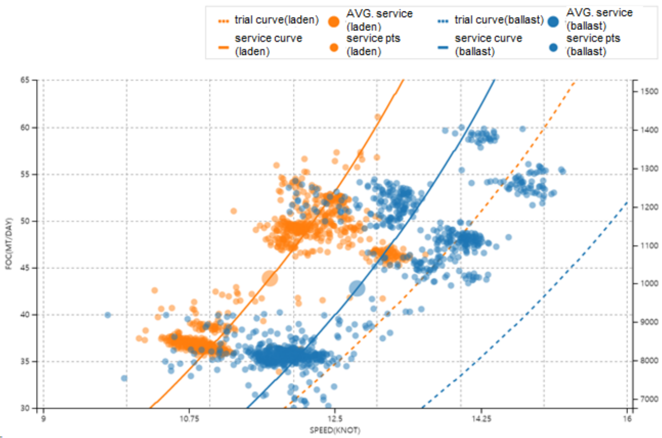


Fig. 8 PV analysis result during 8 months before drydocking

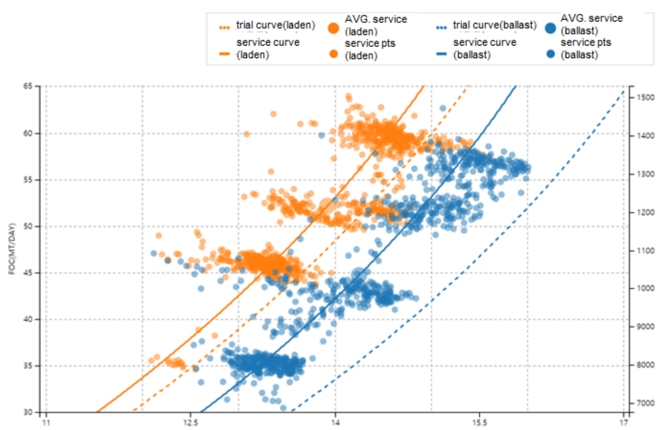


Fig. 9 PV analysis result during 8 months after drydocking

Table 4 Summary of maintenance effect for 8 months before and after redocking of the 176k bulk carrier

Before redocking (8 months)		After redocking (8 months)	
Speed (laden)	DFOC (laden)	Speed (laden)	DFOC (laden)
-13.05%	58.16%	-2.87%	10.10%
Before redocking (8 months)		**After redocking (8 months)**	
Speed (ballast)	DFOC (ballast)	Speed (ballast)	DFOC (ballast)
-14.96%	81.21%	-6.65%	28.53%

Based on the ISO19030 standard, the in-service navigation data collected from the 176k bulk carrier has been analyzed to give an assessment of energy saving performance of the present low frictional AF coating. Data have been collected in total of 16 months, 8 months before and after drydocking, respectively. The corresponding analysis results are plotted in terms of speed-power relationship as Figs. 8 and 9. In Fig. 8, the power increased considerably over the trial curve, indicating significant speed drop during the navigation before redocking. On the other hand, Fig. 9 revelas relatively small power increase after redocking. Table 4 gives an average estimates on the maintenance effect, where the speed drops at the laden draft are 13.05% and 2.87% before and after redocking, respectively. Therefore, the maintenance effect is quantified as a speed increase by 10.18%. Similarly, the DFOC (fuel oil consumption) for the laden draft is shown to be reduced by 48.06% with the maintenance. This is really a large effect, exceeding the usual maintenance effect experiences. It is worth mentioning that the present redocking was involved in a few energy saving measures including the paiting of the present low frictional AF, the installation of energy saving device of PBCF (Propeller Boss Cap Fin) and the addition of fuel additives. Therefore, this effect is a combined one from all those aforementioned sources as well as the hull cleaning effect. The energy saving effect of the present low frictional AF, however is not negligible considering the large effect obtained in the present case. Further studies towards the isolation of those effects will be the topic of future research.

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