Fouling Kontrol Boyalarının Servis Durumundaki Gemi Performansı Üzerine Etkilerinin Tahmini için Rasyonel bir Yöntem

M. Atlar[1], I.A. Yeginbayeva[2], S. Turkmen [3], Y.K. Demirel[4], A. Carchen[5], A. Marino[6], D. Williams[7]

mehmet.atlar@strath.ac.uk[1], irmay@chalmers.se[2], serkan.turkmen@ncl.ac.uk[3], yigit.demirel@strath.ac.uk[4]

[1] University of Strathclyde, UK

[2] Chalmers University of Technology, Sweden

[3]Newcastle University, UK

[4] University of Strathclyde, UK

[5]Newcastle University, UK

[6] University of Strathclyde, UK

[7] Akzo-Nobel, UK

Özet

Bu çalışma laboratuvar ölçümleri ve gemi performansı tahmini arasında ilişki kuran, son 20 yıldır gerçekleştirilen çalışmaları değerlendirmekte ve yine bu amaç için rasyonel bir yöntem sunmaktadır. Bu yöntem günümüzdeki modern fouling control sistemlerinin gemi üzerindeki performanslarının tahmini için kullanılan deneysel ve sayısal yöntemlerin bir kombinasyonudur. Burada “rasyonel” kelimesi tekne (ve pervane) koşullarını ve gemi boya sistemlerinin bu koşullar altında değerlendirilmesi anlamını taşımaktadır. Önerilen yaklaşım karmaşık gemi performansı problemi için tam bir çözüm sunmaktadır. Bu yöntem günümüz modern boya sistemlerinin genel özelliklerini, bahsi geçen deneysel ve modern sayısal yöntemlerin yardımıyla değerlendirdiği için “rasyonel” olarak tanımlanmaktadır. Önerilen yöntem genel kapsamlı olup herhangi bir gemi tipine ve gemi üzerinde bulunan boya sistemine uygulanabileceği gibi pasif direnç düşürücü sistemlerin değerlendirmesi icin de kullanılabilir. Bu yöntem gemi üzerindeki farklı yüzey koşullarını temsil eden düz levhalar kullanılarak elde edilen deneysel veriler ve bu verilerin gerçek gemi ölçeğine ekstrapolasyonunu içermektedir. Fakat gemi ölçeğinde daha gerçekçi ve direkt olarak performans tahmini için, kullanılan ekstrapolasyon prosedürü yerine Hesaplamalı Akışkanlar Dinamiği (HAD) yöntemi de kullanılabilmektedir. Bu yöntem özellikle yüzey kirliliği (fouling) dolayısıyla bozulan tekne yüzeyinin modellenmesinde kullanılmaktadır. Bu yöntemi kullanmak icin de deneysel veriler gereklidir. Önerilen yöntemin gerçekçiliği ve gücü “servis durumundaki” tekne yüzeylerinin etkilerini temsil etmesi ve son modern deneysel yöntem ve verilerin kullanılıyor olmasıdır. Bu yöntem araştırmacılara iki tahmin olasılığı sunmaktadır; pratik ve hızlı perfromans tahmini için ekstrapolasyon, ikincisi ise HAD metodu kullanılma olanağıdır. Bu yöntem sayesinde HAD methodu kullanma olasılığı, detaylı yüzey pürüzlülüklerinin fiziksel olarak modellenmesi zorluğu bariyerini de aşabilmektedir. Önerilen yöntemin doğrulanması için bahsi geçen gemi performansı gözlemi ve analizi sistemi kullanılarak tam-ölçekte gemi verilerinin toplanması gerekmektedir. Bu sistem gemi boyalarının yüzey kirliliği durumundaki etkilerinin değerlendirilmesi için özel olarak geliştirilmektedir.

Anahtar Kelimeler: Fouling kontrol sistemi, Antifouling boya, Gemi yüzey kirliliği (biofouling), Direnç azaltımı, gemi performansı, deney, HAD

A Rational Approach to Predicting the Effect of Fouling Control Systems on "In-Service" Ship Performance

M. Atlar[1], I.A. Yeginbayeva[2], S. Turkmen [3], Y.K. Demirel[4], A. Carchen[5], A. Marino[6], D. Williams[7]

mehmet.atlar@strath.ac.uk[1], irmay@chalmers.se[2], serkan.turkmen@ncl.ac.uk[3], yigit.demirel@strath.ac.uk[4]

[1] University of Strathclyde, UK

[2] Chalmers University of Technology, Sweden

[3]Newcastle University, UK

[4] University of Strathclyde, UK

[5]Newcastle University, UK

[6] University of Strathclyde, UK

[7] University of Strathclyde, UK

Abstract

This paper reviews two decades of bridging the gap between laboratory measurements and predicting the performance of commercial maritime vessels and presents a rational approach, which is based on the combination of an experimental and a computational procedure, to predict the effects of modern-day fouling control systems on "in-service" ship performance. Here the word "rational" reflects ship hull (and propeller) conditions as well as the approach to predicting the effect of the hull coating systems under such conditions. The proposed approach arguably provides a full solution to the complex ship performance problem. It is "rational" in terms of tackling the main features of modern-day hull coating systems with the aid of bespoke experimental testing facilities and state-of-the-art computational methods. The proposed approach is generic and can be applied to any ship type and hull coating system in the presence of biofouling and it may even be combined with passive drag reduction systems. This approach involves both the combination of experimental data from flat test panels treated with representative surface finishes and extrapolation of this data to full-scale. However, for more accurate and direct estimation of performance prediction at full-scale, the extrapolation procedure needs to be replaced with Computational Fluid Dynamics (CFD) methods, especially for deteriorated hull surfaces due to fouling; at present, such experimental data are still required. The rational nature and hence strength of the proposed approach is to represent the effect of the actual hull surfaces "in-service" by using state-of-the art experimental methods and data. This provides the option of an extrapolation procedure for practical performance estimations and also enables the use of CFD methods by avoiding the most difficult barrier of describing the actual hull surface numerically in CFD. Validation of the proposed approach requires full-scale data to be collected using a bespoke ship performance monitoring and analysis system which is dedicated to assessing the effect of coating systems in the presence of fouling. Such a system is under development as detailed in an accompanying presentation.

Keywords: Fouling control system, Antifouling coating, Biofouling, Drag reduction, Ship Performance, Experiments, CFD

1. Background

Fouling control systems for ship hulls have been under continual developments for better performance of ships, mainly for fuel economy, see e.g. (Almeida et al, 2007), (Chambers et al., 2006) These developments have been taking place under further scrutiny due to increasing environmental protection, see e.g. (Hellio and Yebra, 2009), (IMO, 2009) Hence many stakeholders of marine transportation are under the major spotlight how to predict the effect of these coating systems on a ship's performance in a rational way which is the main purpose of this paper.

Here the word "rational" reflects ship hull (and propeller) conditions as well as the approach to predicting the effect of the hull coating systems under such conditions. The proposed approach arguably provides a full solution to the complex ship performance problem. It is "rational" in terms of tackling the main features of modern-day hull coating systems with the aid of bespoke experimental testing facilities and state-of-the-art computational methods. Within this framework, the approach has its roots in the long-term research works which are led or involved by the present authors e.g. (Candries and Atlar, 2003), (Demirel et al., 2016), (Yeginbayeva et al., 2017), (Carchen et al., 2017), Turkmen et al (2018), Atlar et al (2013a) and hence it is worthy to review some of the past research works, which have contributed to the development of this approach, as summarised in Section 2 of the paper.

The accurate prediction of ship performance is still one of the most challenging problems for naval architects and has great interest to many stakeholders of the shipping transport. This is not only to improve the transport efficiency but also due to increasing scrutiny to reduce environmental impact. Because of these reasons, the ship hull fouling control systems have been continually developing and hull surfaces have become more and more complex to analyse.

Traditionally naval architects assume that the ship hull resistance is made of the skin-friction, which is viscous in origin and hence closely associated with the hull surface conditions (including fouling control systems), and that of the pressure component due to the 3D effects of the hull and waves. Until recently, the naval architects have had the comfort of approximating the hull-skin friction based on the Froude's equivalent flat approach combined with the empirical correlation allowance factors for different surface finish (including fouling control system) values based on their experience. However, due to the recent developments in hull coating industry, new experimental measurement facilities and techniques as well as the computational (CFD) methods, this approach is now under the spot light as discussed in the following.

The ship hull surfaces have been changing, primarily, due to the use of different coating systems, which can have a physical or fouling release based control mechanism, e.g. (Anderson et al., 2003) or chemical, bio-based fouling control defence mechanism, e.g. (Zhou, 2015). In addition, due to further scrutiny, these coating systems are recently being combined with novel drag reduction mechanisms, e.g. riblets being embossed on fouling release coating system or compliant coating system, (SEAFRONT, 2014). These developments have been bringing about the question of using the traditional skin friction data based on the flat plates of different sizes and their extrapolation to full-scale for ship hulls. At least, the correlation allowance factors to reflect the surface finishes with these new coating systems would require upgrading. Recent developments in the CFD field have lifted the barriers, at least for the scale effect. As such, there is no need to employ the Froude's flat plate approach and it is hence possible to directly calculate the viscous hull resistance in full-scale by taking into account the 3D effects, e.g. (Demirel, 2015). Although this is very powerful, the CFD methods in representing the realistic hull surface finish including different fouling control systems are still in their infancy and hence requiring practical approaches which can make use of some critical surface hydrodynamics data from model experiments in a laboratory environment. For this purpose, experimentally determined roughness function (or velocity loss function) of representative hull surfaces, which can even include the effect of biofouling, is the most practical data to be able to use of the power of CFD. However, the provision of this experimental data still requires relatively systematic tests by using bespoke testing facilities (e.g. friction pipes, channels, towing tanks, rotating discs/drums etc.) with special measuring equipment (e.g. LDA's, pressures gauges, load cells etc.) and even in a special environment to use actual or artificial seawater. Furthermore, the measured hydrodynamic data should be related to the surface roughness/texture characteristics and hence requiring the accurate measurements of the surfaces and roughness characteristics using special measurement devices (e.g. preferably non-contact optical or sophisticated mechanical devices)

In using the above-mentioned facilities, in comparison to the friction pipe or rotating disc methods, the use of the friction plane methods is more practical in terms of the required surface finish applications, surface roughness and force measurements due to the use of simpler flat surfaces with zero pressure gradients. However, the necessity of using large towing tanks with preferably large flat planes to be towed at high speeds to achieve high Reynolds numbers is one of the downside of these facilities resulting in higher costs. On the other hand, the analysis of the skin friction characteristics by measuring the pressure drop in a friction pipe or by measuring the tow force on a friction plane is an "indirect" method but it is still practical and cost economical as opposed to the "direct" method which requires the measurement of boundary layer profiles on the test surfaces by using e.g. expensive and complex Laser Doppler Anemometry (LDA) or water unfriendly hot-wire anemometry facilities. The use of LDA will require more accessible channels and costly set-up systems, which may not be readily available and requires much longer data collection time that further increases testing costs. Perhaps one compromised facility, that has been increasing in applications, is the fully turbulent flow channel (FTFC), e.g. (Politis et al., 2013), (Schultz and Flack, 2013). The FTFC can circulate the fully developed turbulent flow at its rectangular cross-section of measuring section, which can accommodate interchangeable flat panels with different finishes, as opposed to the circular cross-section of the friction pipe and the pressure drop over the test panels due to the skin friction can be measured. The FTFC facilities, apart from being practical in terms of much quicker measuring time and size compared to the larger towing tanks and other channel facilities, they have the advantage of circulating seawater which is an invaluable feature for testing coating surfaces in the presence of biofouling.

It is a well-known fact that the main purpose of using fouling control system on ship hulls is to control the development of biofouling in the most cost economical way. However, as soon as a newly coated hull is subjected to seawater, light biofilm immediately starts to build up as the conditioner and to attract other fouling types. Depending upon the fouling control system type and many other complex factors which include the vessel's operating waters and operational profile, the biofilm types, coverage and grades vary. In fact, these have been the subject for many researchers and still heavily occupies the marine biofouling and technology community since most of the hull fouling control systems still suffers from the biofilm one way to other, e.g. (Callow and Callow, 2002), (Durr and Thomason, 2010). It is, therefore, more realistic to include, at least, the effect of light biofilm in the performance prediction of any coating type. Under the circumstances, perhaps the most practical and rational approach to include the biofilm effect is to grow them on representative test panels to measure their effects on skin friction using the above-mentioned test facilities. However, this will in turn require special facilities either to grow the biofilm on the test panels in natural sea environment (e.g. attached to ship hulls or other means), e.g. (Atlar et al., 2015) or using bespoke seawater circulating tanks (e.g. slime farms) to grow in laboratories, e.g. (Yeginbayeva, 2017)

In this section of the paper, so far, a general background information is presented which has motivated the authors to propose the prediction method presented. However, any prediction method will require validation and as far as the ship performance is concerned, such a validation task should involve performance measurements on board of a ship. Within this context, the interest to ship performance measurements can be as old as the history of ships occupying the naval architects with ever-growing pace. This is particularly true due to the recent scrutiny by IMO on the GHG emission control of ships as well as volatile fuel prices (IMO, 2009). As a result, there has been some companies in the market offering their services and equipment for ship performance monitoring and analysis. Some of these companies are using their hardware and software systems which can monitor, collect and analyse the performance on-board (on-line) using the collected data, e.g. (BMT SMART, 2017), (ENIRAM, 2017), while some of them are analysing the performance onshore based on the customers' data, whatever way the data is collected e.g. (CASPER, 2017), (Munk, 2006). Perhaps the most important point from the fouling control system performance point of view, how dedicated these systems are to monitor solely the effect of fouling build-up on the ship hull and propeller, and hence analysing the fouling control system performance with an acceptable uncertainty level. This will need robust hardware (i.e. torque gauge, speed log, weather pack etc.) supported by dedicated online data collection system with practical filtering ability and robust, deterministic analysis method to extract mainly the unwanted effect of the environment and others as attempted e.g. by (Carchen et al., 2017b). Within the framework of ship performance measurements, one should also mention about the new ISO 19030 for hull and propeller performance measurements (ISO, 2016). This voluntary standard has been recently established to enable ship owners and operators to compare hull and propeller solutions, including fouling control systems, and to select the most efficient option for their vessels and fleet. Therefore, its wide spread adoption is being taken up by major coating stakeholders and integrated in their commercial products for prediction technologies, e.g. Intertrac ® (Intertrac, 2017).

2. Review of Research Activities

This section presents a review of the past and current research works which have contributed to the development of the approach presented in this paper and conducted by the present authors or through their participation in these works.

The first major research work campaign contributing into the present study conducted in early 2000s to provide scientific evidence on the surface roughness, boundary layer and drag characteristics of newly applied two different types of hull coatings which were silicon-based "Fouling Release" (FR) and biocidal "Self-Polishing Co-polymer" type, e.g. (Candries, 2001), (Candries et al., 2003). This research work established the superior surface roughness/texture and hydrodynamic drag characteristics of the FR coatings over the SPC types by using some bespoke hydrodynamic testing facilities, e.g. the Emerson Cavitation Tunnel boundary (ECT) layer set-up as well as using the traditional towing tank and rotating drum facilities. The boundary layer set-up also necessitated the provision of the 2D-LDA facility and its use for the velocity profile measurements of large flat panels (1m long) covered with different coating systems and applications, e.g. "Spray vs Roller" applications. The most important contribution of this campaign was that the confirmation of the superior drag performance of the FR coatings with the provision of the systematic surface roughness, boundary layer and skin friction data by using the three different types of testing facilities. Amongst them, the boundary layer test set-up established in ECT and LDA facility was the dark horse of the research works and data produced in this campaign which involved coating applications in the laboratory for “cleanly or newly applied” ship performance conditions and hence did not represent the applications on “in-service” performance conditions.

Whereas ships operate at sea “in-service” conditions and the hull surfaces in these conditions cannot be represented by relatively smooth test surfaces where subject coatings are applied cleanly in laboratory conditions. Therefore the second follow-up research campaign, which was recently completed, involved an experimental investigation into the performance characteristics of modern FR, SPC and Control Depletion Polymer (CDP) coatings in “cleanly applied” as well as “in-service” conditions, e.g. (Yeginbayeva et al., 2016), (Yeginbayeva, 2017) In this second campaign the “in-service” condition is to reflect the representative hull roughness at least in terms of the average hull roughness height and representative modern day commercial coatings applied on the flat test panels which were tested in the presence of light biofilm (i.e. slime) and clean condition (i.e. freshly applied).

In complementing the above stated two major research campaigns, the third research campaign has started relatively later and has been still continuing to develop a bespoke ship performance monitoring and analysis system, see e.g. (Carchen et al., 2017a), (Carchen et al. 2017b). The main objective and hence difference of this campaign from other ship performance monitoring system developments is to investigate and hence develop a dedicated system to assess the effect of any fouling control system on the ship performance when it is cleanly applied as well as under the effect of fouling growth at acceptable uncertainty levels. This research campaign has its origin in an earlier research, (Hasselaar, 2011) which was conducted by using a modest hardware system installed on-board the old research vessel, R/V Bernicia, of Newcastle University. Although that initial research had only made a modest contribution to the above-stated objective of the current research, it had highlighted the complexity of the ship monitoring problem by using such level hardware on an old small vessel which is subject to continuous external disturbances and hence motion control problems. The follow-up current research, therefore, has been initiated to achieve this objective using state-of-the-art equipment on a modern research vessel as will be discussed below.

In addition to the above reported three doctoral research campaigns, which made use of physical tests conducted in model and full-scale, there were other complementary research campaigns which resulted in the developments of various major and modest level of testing apparatus and facilities and hence making important contributions into the development of the proposed prediction approach in this paper. These R&D activities are briefly involved: (a) introduction of the Newcastle University (UNEW) standard test panels; (b) surface measurements of the UNEW test panels using bespoke surface analysers; (c) further development of the Emerson Cavitation Tunnel (ECT) boundary layer test-set up; (d) design and commissioning of the UNEW Full Turbulent Flow Channel (FTFC) for pressure drop measurements; (e) design and commissioning of a laboratory based slime growth facility; (f) design and commissioning of the UNEW multi-purpose research vessel, The Princess Royal, with the bespoke strut arrangement for the collection of naturally grown slime at sea; (g) design and installation of a bespoke ship performance monitoring and analysis system.

(a) UNEW standard test panels

While the use of large and flat test panels is a preferred option to produce systematic roughness and hydrodynamic test data, when these panels will be tested in different facilities and under challenging environmental conditions (e.g. at sea) they have to be practical and hence compromised in terms of size and materials to be made of. By taking these restrictions into account, the size of the flat test panels, which are interchangeably used in the different test facilities of UNEW are limited to practical dimensions of 600 mm x 210 mm x 35 mm and made from acrylic for easy transport as shown in Figure 1 although the earlier versions were made from steel.

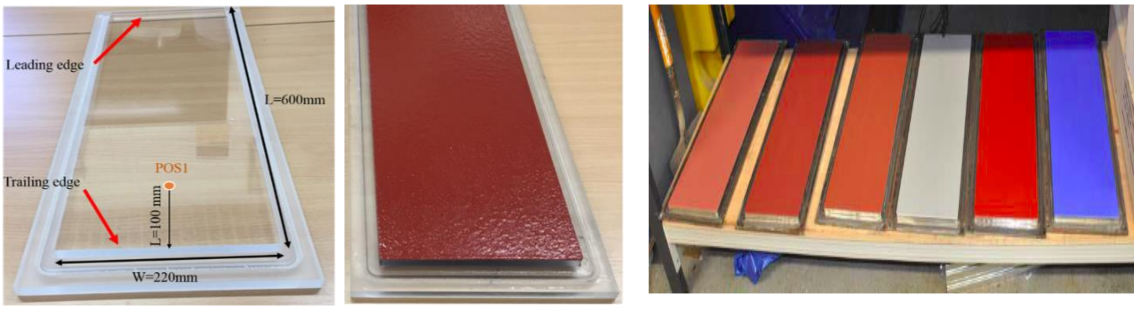


Fig. 1. UNEW Standard test panels

(b) Surface measurements of test panels

Accurate surface roughness measurements of the test panels with different finishes can be made by using different roughness measurement devices which can operate based on optical or mechanical principle. The manageable size of the UNEW test panels lend themselves to be surveyed by using the laser-based roughness profilometry device (see Figure 2) which provided the statistical roughness characteristics of these surfaces at focused areas with great accuracy. Furthermore, the measured data is independent of any potential surface contact problems that can be encountered with the mechanical contact based roughness devices especially with silicone based coatings.

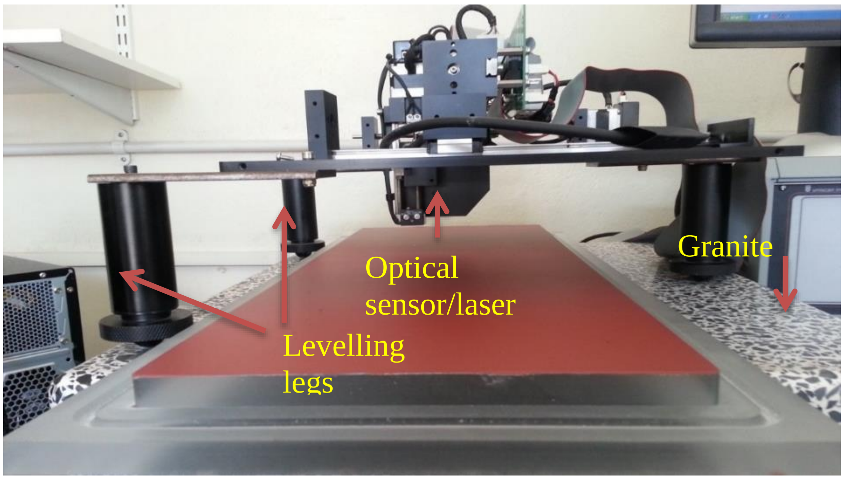


Fig. 2. Surface roughness profilometry device

(c) Further improvement of ECT boundary layer test set-up

While the Newcastle University has had the Emerson Cavitation Tunnel since 1949, this facility has never been used for coating research until the above mentioned 1st research campaign was started.

This facility, therefore, was equipped with the 1st boundary layer set-up in its testing section to accommodate 2.0 m long flat test panel, as shown in Figure 3, to measure the boundary layer development over the coated surfaces placed on the latter 1m part of the test panel.

Fig. 3. Initial boundary layer test set up in Emerson Cavitation Tunnel

While this set up served the purpose for the 1st research campaign, during the upgrading of the ECT in 2009, a specially designed insert section was commissioned to increase the tunnel inflow speed at the measuring section and a new boundary layer test set-up was combined with the insert, (Atlar, 2011). The new set-up was designed to accommodate the standard UNEW test panels at the latter part of the insert as opposed to the 1m long larger test plates used in the 1st research campaign which were not easy to handle and subject to vibrations. The improved test set-up would not only increase the tunnel inflow speed but also reduce vibration and efforts for the smaller size test panel installation. Furthermore, new measuring section of the ECT with enlarge and mono-block windows has provided much easier LDA access to the boundary layer set-up and hence more reliable and systematic boundary layer data collection with less effort. See Figure 4 for the current boundary layer set up at ECT.

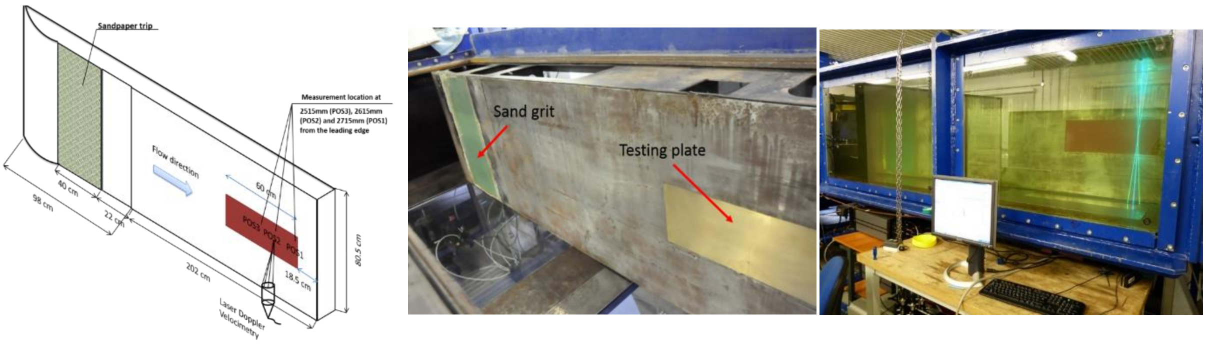


Fig. 4. Improved boundary layer test set up in Emerson Cavitation Tunnel

(d) Design and commissioning of Full Turbulent Flow Channel (FTFC)

As stated in the background section, hydrodynamic tests involving coating performance can benefit from bespoke facilities, e.g. FTFC, especially for tests in the presence of biofouling. Within this framework, classical flow cell facilities, which are used mainly by marine scientists, are designed to determine the shear force levels to release various type of marine biofouling (e.g. juvenile barnacles, slime etc.) grown on very small size test slides. The pressure drop across the surfaces of these test slides, which are located in the measuring section of the FTFCs, are measured by using differential pressure gauges at the measuring section.

An existing flow cell in the UNEW was converted to the FTFC for skin friction drag analysis by modifying its measuring section as such this section can accommodate two standard UNEW flat test panel at the top and bottom boundaries of the measuring section. By measuring the differential pressure along the test panels, which may be coated with different fouling control systems even in the presence of light biofilm, the skin friction characteristics of the test panels can be determined. Figure 5 shows the UNEW FTFC which was designed and commissioned as part of the recently completed FP7 SEAFRONT Project (SEAFRONT, 2014) Apart from developing a fully turbulent flow in its measuring section, a FTFC facility has the advantage of testing flat test panels with biofilms in sea water and with a very quick turn over time as opposed to longer testing times with more complex set-up of other testing facilities which have to use fresh water and costly to run, e.g. towing tanks, large circulation channels with LDA etc. The FTFC facilities, therefore, have been recently introduced in the hydrodynamic testing community, especially for coating research. FTFC facilities can be also used for ageing (or polishing) test of a SPC type coating system applied on these test panels. Such a multi-purpose system (i.e. to conduct ageing and pressure drop) has been designed and commissioned at the UNEW very recently to investigate the hydrodynamic performance of SPC type fouling control system "in-service" conditions, e.g. (Politis et al., 2013), (Yeginbayeva, 2017)

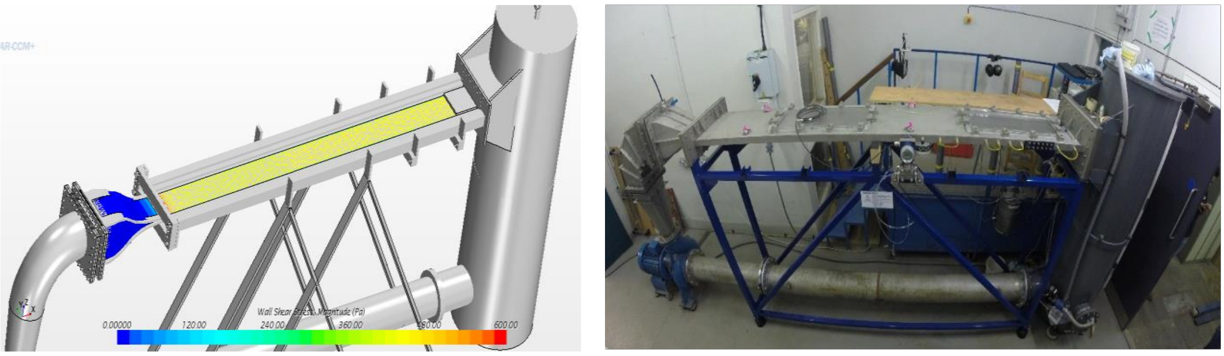


Fig. 5. UNEW Fully Turbulent Flow Channel: Testing section details (left); overall system view (right)

(e) Design and commissioning of a laboratory-based slime growth facility

As stated earlier, light biofilm or slime is an essential contribution to the "in-service" condition of a ship hull and hence should be part of the hydrodynamic modelling in performance assessment. As also discussed earlier, perhaps the most rational way of including the effect of biofilm in the performance assessment, is the experimental way by exposing the test panels coated with subject coatings to the slime growth. The exposure can be either naturally at sea, which will be discussed in the next section, or in specially designed tanks, which can be called as slime farm, at laboratories under controlled condition. Such a latter facility was designed and commissioned at the UNEW based on a jet flow based slime growth facility, which circulates the natural seawater at relatively slow speed to simulate the relatively dynamic action of the flow, as shown in Figure 6, (Yeginbayeva et al., 2016). This facility can accommodate four UNEW test panels and can develop slime much faster rate than grown at sea in a controlled manner.

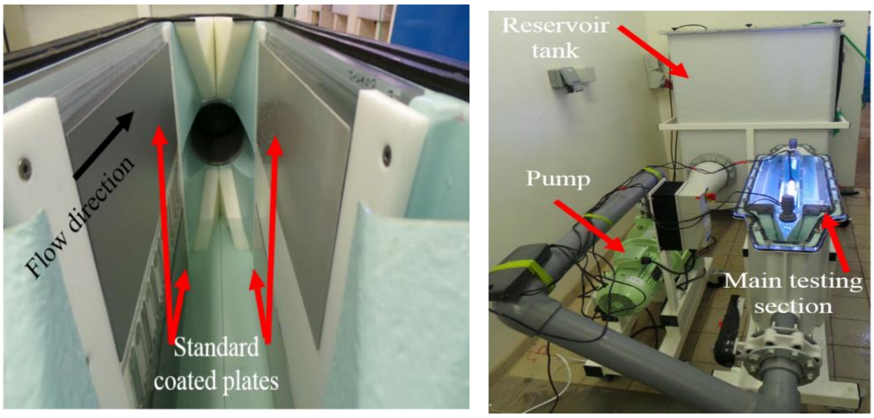


Fig. 6. UNEW laboratory-based slime growth facility

(f) ***Design and commissioning of multi-purpose research vessel with the bespoke strut arrangement for collection of naturally grown slime at sea***

In 2009 UNEW was replaced their ageing old research vessel RV *"Bernicia"* with a new 18m, 43t displacement of modern catamaran RV *"The Princess Royal"* that can achieve 20 kn max speed while mostly operating at 15 knots of design speed. As shown in Figure 7 the vessel was named after the HRH The Princess Royal and designed by the lead Author and his research group, e.g. (Atlar et al. 2013b). The mission of the vessel is a multi-purpose encompassing number of marine science and technology R&D activities including marine fouling control research and ship performance monitoring. Hence, the Princess Royal was equipped with a specially designed strut arrangement, which is attached to the moon pool plug of the vessel and this arrangement can accommodate eight UNEW test panels, as shown in Figure 8, (Atlar et al., 2015). These panels are to be exposed to the seawater and hence grow natural slime on them under the full dynamic condition of the vessel in her motions as naturally expected. Such set up may not necessarily represent the "in-service" conditions as a large commercial vessel at world seas but still represent much closer simulations of naturally grown slime under the controlled "in-service" condition to model its effect.

(g) ***Design and installation of a bespoke ship performance monitoring and analysis system***

As one of her most important missions and part of the ongoing research campaign on the ship performance monitoring, *The Princess Royal* has been equipped with a comprehensive bespoke performance monitoring hardware systems, as illustrated in Figure 8.

Fig. 7. UNEW RV- The Princess Royal (left) and its strut arrangement to carry fouling plates (right)

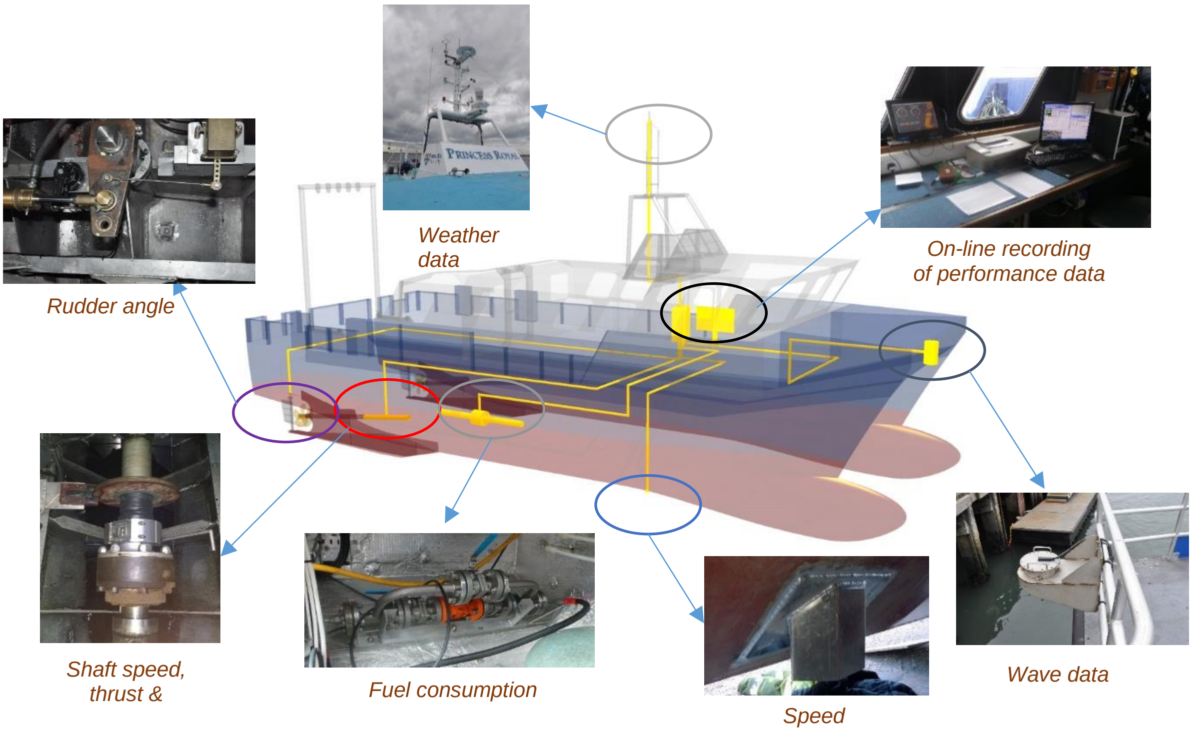


Fig. 8. UNEW Research Vessel performance monitoring hardware system

These hardware systems included tailor-made torque and thrust loading gauges on her both shafts as well as rotation speed gauges. In addition to the normal navigational data (e.g. speed over ground, heading course over ground etc.), the R/V exhibits a variety of speed logs to measure the vessel speed through the water and an accurate on-board weather station to measure the wind speed/direction. The wave height at forward vicinity of the vessel and vertical deck motions are measured through dedicated equipment located on board while the fuel consumptions of both engines are also measured by dedicated fuel meter systems. All these hardware systems are integrated and controlled by a specially developed software which collects and displays the collected data in time series or averaging on a dedicated display on the vessel navigation deck.

The above-reviewed activities, i.e. from *(a)* to *(g),* were mainly experimental and conducted by using the existing testing facilities of UNEW as well as recently developed new facilities. While these activities and facilities have provided great insight into the performance prediction of modern fouling control systems and collected invaluable data, the performance predictions in full-scale still require a sound extrapolation procedure or other prediction methods. Within this framework, (Granville, 1958 and 1987) proposed a similarity law scaling procedure to predict the effect of particular surface roughness on the frictional resistance of any arbitrary body covered with the same roughness, by extrapolation of data from flat plates with the particular roughness to full-scale lengths. This provides means of obtaining a plot of skin friction coefficient against the length based *Reynolds number* for different lengths of flat plates with the same roughness, in order to predict the full-scale resistance of ships having that roughness.

Based on his experimental work with different coating surfaces and grades of marine biofouling (Schultz, 2007) presented a simple and effective procedure in applying Granville's methodology to predict the effect of different ranges of coating roughness and biofouling on the resistance of a full-scale ship (*Oliver Hazard Perry class frigate or FF7*). In this procedure, the prediction of the effect of the roughness and fouling is restricted to the frictional resistance of a planar surface of arbitrary length which in fact represents both a test surface in model scale and an actual ship surface in full-scale with the same underwater length of the ship. In the algorithm of this procedure, the additional drag due to the coating roughness and fouling is predicted regarding roughness allowance, ΔC_F, to be included in the resistance coefficient of the ship. Within the assumptions of the Granville's extrapolation, Schultz's algorithm relies on the skin friction characteristics (mainly roughness functions) of the representative arbitrary length of flat surfaces with the same roughness. As long as the skin friction data is obtained from tests within model size test panel in a suitable hydrodynamic facility, this data can be extrapolated to full-scale flat plate, which represents the ship hull, by using the algorithm based on the wetted length of the full-scale ship and speed.

Practical application of Granville's extrapolation is based on the assumptions of flat plate and uniform distribution with the similar roughness function of the arbitrary size surfaces (i.e. model and full-scale). Apart from neglecting the 3D effects, the further assumption of the uniform and constant roughness function for one speed is another arguable assumption of Granville's approach even for a flat plate. This is due to the differences in local shear stress and hence expected change in the skin friction velocities along the flat plate. In order to improve these shortcomings, in his doctoral thesis, (Demirel, 2016) proposed a CFD based method, where the experimentally determined roughness functions, including the effects of biofouling, can be built in the wall functions of a commercial CFD code to predict the skin friction resistance of a ship hull in full-scale. Demirel demonstrated this effect on a representative full-scale ship by comparing the different approaches, which were all based on the Schultz's roughness function data (Schultz, 2007), namely by using: (1) Granville's extrapolation; (2) an unsteady RANS based CFD method but assuming that the hull still represented by flat plate; and (3) the same CFD method with the exact hull geometry.

While the above R&D activities mainly concentrated on the effect of coating roughness and fouling on ship hulls, the recent developments of hull coating systems, especially those of the FR types, have increased the applications of these coating systems on propellers to keep them free of biofouling. This has also triggered the investigations how to model the effect of the propeller surface roughness including the coatings and biofilm. Within this framework e.g. (Atlar et al., 2002) conducted numerical investigations on the open water performance analysis of propeller by using a boundary element theory based tool in which the effect of blade surface losses due to a different application of coating roughness was simulated in the appropriately selected drag coefficients of the propeller blade section. In this selection, the increase in sectional drag was represented by a semi-empirical formula which was related to different grades of measured paint application roughness based on various assumptions. In a later development, by taking advantage of the Granville's approach and its generic nature, which can be applied to any length of flat surface, Seo et al (2016) applied this approach to predict the blade surface losses for container ship propellers coated by foul release coatings, tested in EU-FP7 TARGETS Project, (TARGET, 2013) and different grades of biofoulings as proposed by (Schultz, 2007).

3. Main Objectives

Based up the background stated in *Section 1* and the review of the contributory research work in *Section 2* the main objective of this paper is to present a rational approach to predicting the effect of a modern-day fouling control system on "in-service" performance of ships as described in Section 4 and demonstrate its application *in Section 5*. Furthermore, the paper proposes a validation method for the proposed approach as described in *Section 6* and finally presents some concluding conclusions in *Section 7.*

4. Description of the Approach

As summarised in Section 2 the prediction approach, which is described in the following paragraphs from I to X, includes any of the following three procedures (1-3) that can be used depending on the level of accuracy required:

1) Granville's extrapolation with the flat plate assumption
2) CFD based method with the flat plate assumption
3) CFD method with the actual hull geometry

I. Each of the above methods is based on the hydrodynamic skin friction characteristics of the representative test surfaces which are flat panels. It is therefore essential to prepare these test surfaces which will be tested in a suitable hydrodynamic testing facility. Such practical test surfaces can be similar to e.g. UNEW standard test panel as described in Section 2 and shown in Figure 2.

II. Surface preparations of the test panels are critical, that should mimic the actual ship hull surface, in theory. Although this will not be possible in practice, a reasonable compromise can be made e.g. based on the experience and data of paint manufacturers or shipyards who regularly measure the hull roughness characteristics. If such data are available based on experience, this can be mimicked by using a suitable grade of sand grit to be applied on the standard test panels to represent the physical hull surface roughness excluding the paint. Next will be the application of the subject fouling control system using appropriate method (i.e. spraying or rollering etc.). Figure 9 shows the application of such surfaces and their roughness characteristics in Figure 11.

III. Surface preparation described in II excludes the effect biofilm which is an important contribution to the "in-service" condition. It is, therefore, necessary to expose the coated test panels to biofilm growth. As stated earlier this can be achieved either in a slime farm in the laboratory condition or naturally at sea which is preferable. Figure 10 shows the typical UNEW test panels having exposed to the slime growth on the strut arrangement of the UNEW research vessel.

	
Newly applied FR type with ‘low’ density of introduced sand grit	Newly applied FR type with ‘high’ density of introduced sand grit

Fig. 9. Flat test panels representing FR coatings with mimicked ‘low’ (left) and ‘high’ (right) density of hull roughness

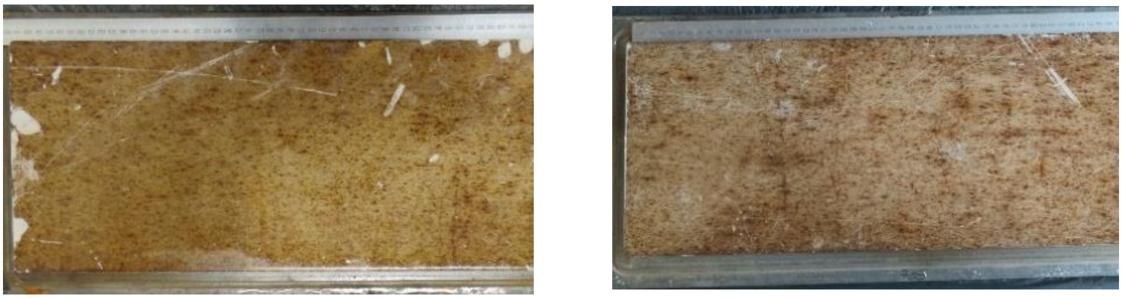


Fig. 10. Flat test panels with FR coatings (normal finish) exposed to natural slime growth for 6 months

IV. Having prepared and conditioned the test panels with representative “in-service” conditions, the next stage is to measure their surface roughness characteristics using, preferably, a laser-based optical profilometry device, e.g. as shown in Figure 2. Using such device enables to conduct detailed analysis with more detailed statistical roughness and texture parameters which in turn provides a better option for correlations with the skin friction data of the surfaces. For example, Figure 11 shows the sample test surface roughness characteristics with the FR coated surfaces applied using ‘normal’ and mimicked ‘high density’ hull roughness finishes.

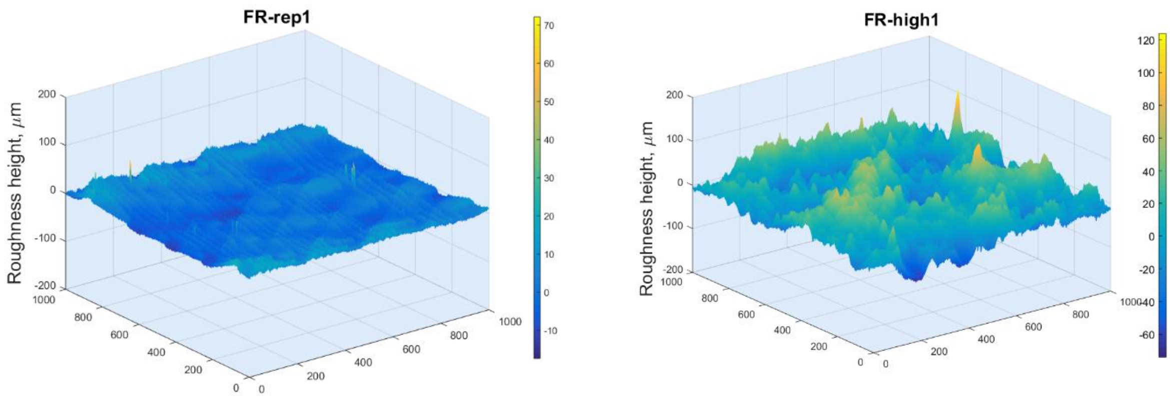


Fig. 11. Surface roughness images of FR test surfaces, normal finish (left); mimicked hull roughness (right)

The measurement of surface roughness with biofilm has its own challenges but can still be conducted by using the laser profilometry device when the test panel with the biofilm coverage is kept in the water.

V. Next stage of the procedure is to conduct basis hydrodynamic tests to determine the skin friction characteristics of the test panels. For this purpose, as reviewed in Section 2, various testing methods can be used. In this section, we refer to the well-established boundary layer measurement tests established in the Emerson Cavitation Tunnel using the 2D, LDV set up, as shown in Figure 4. These tests enable the measurements of boundary layer velocity profiles in 2 directions (in-flow and wall normal) at sufficient accuracy (e.g. 80 points vertically) at various longitudinal positions along the test panels as shown in Figure 12. It should be born in mind that the measured velocity profiles (and hence skin friction data) of the test panels are analysed and presented relative to the hydrodynamic characteristics of the hydraulically smooth reference surfaces (i.e. test panels), which are made usually made from clear acrylic and their hydrodynamic characteristics are also measured along the coated rough test panels.

VI. Whether Granville's extrapolation procedure or any of the above stated CFD methods will be used, there is a need to analyse the measured boundary layer velocity profiles in the previous step (V) using a suitable method and to represent this data in terms of "Roughness Function" of the representative surfaces.

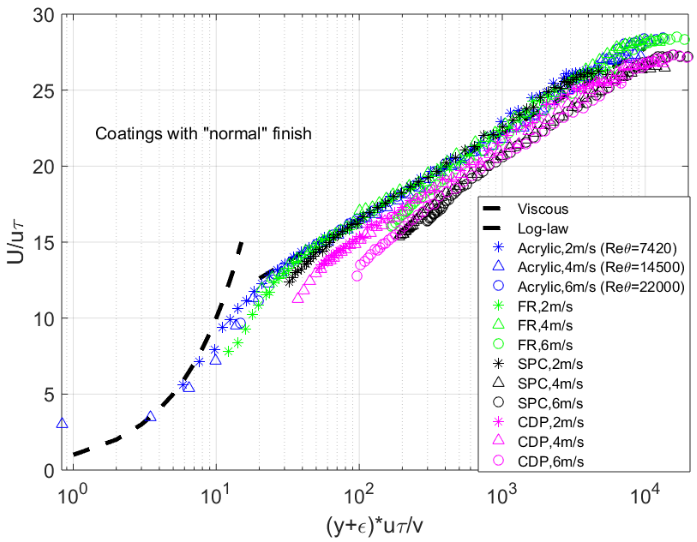


Fig. 12. Sample mean streamwise boundary layer velocity profiles of FR, SPC and CDP coatings with "normal finish". Inner scaling of velocity profiles normalised by skin friction velocity, u_τ and v/u_τ.

Here the roughness Function is further retardation (i.e. velocity loss) of the flow in the boundary layer due to the specific roughness of the test surfaces, which is caused by any of the mimicked hull roughness, coating, biofilm or combinations of these causes that manifest themselves as the additional skin friction drag. As given in Equation 1 and shown representatively in Figure 13, the determination of the Roughness Function ΔU+ requires the presentation of the measured boundary layer velocity data as the non-dimensional boundary layer velocity U+ against the non-dimensional normal distance y+ from the test surface.

(1)

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

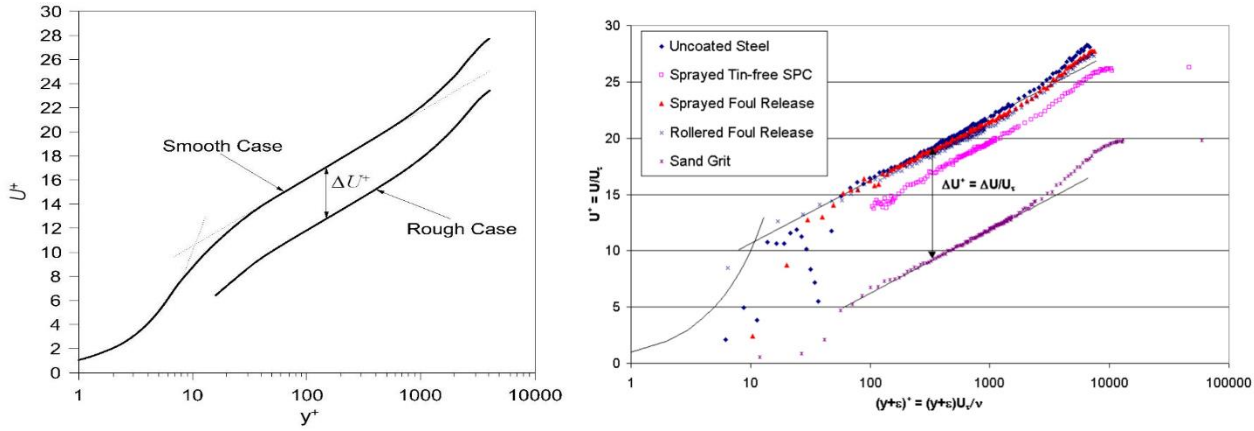
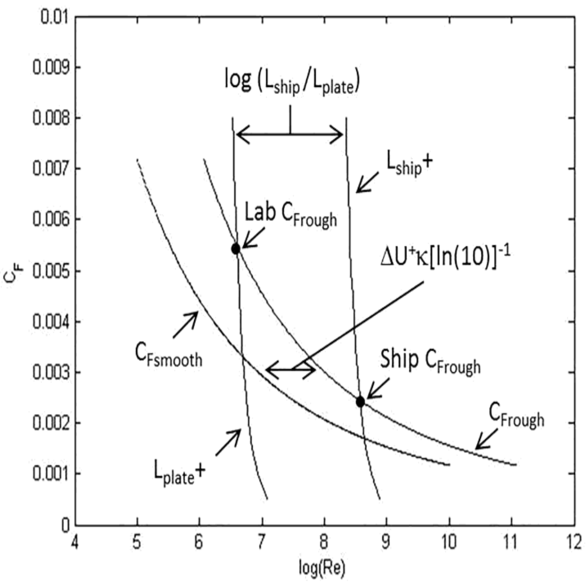


Fig. 13. Description (left) & sample determination of Roughness Function (right)

VII. Having determined the roughness function, which is non-dimensional and assumed to be the same for the full-scale hull at corresponding Reynolds number, if the Granville's extrapolation method will be preferred, all it remains to apply the Reynolds number based scaling by using the main input data which are: L_{PLATE}, the test surface length; L_{SHIP}, the ship wetted length; $C_{F,SMOOTH}$, the hydraulically smooth surface skin friction coefficient. By using Granville's extrapolation, as shown in Figure 14 schematically, Ship $C_{F,ROUGH}$, the skin friction coefficient of the ship in full-scale can be determined and hence the additional skin friction drag coefficient as in Equation 2:

$$\Delta C_F = \frac{C_{F,ROUGH} - C_{F,SMOOTH}}{C_{F,SMOOTH}} \tag{2}$$



L_{plate} = Test panel length

L_{ship} = Ship length

$C_{F,\ smooth}$ = Smooth surface friction drag coeff.

C_ . = Rough surface friction DC

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

Re = Reynolds number, length based

K = von Karman Constant

ΔU^{+} = Roughness Function

$C_{F\ smooth}$, ΔU^{+}, L^{+}_{plate}	→ Input
$C_{F\ rough}$ for ship	→ To be estimated

Fig. 14. Schematic representation of Granville's algorithm

VIII. The estimation of the additional skin friction in the above step (VII) is based on the flat plate and uniform roughness function assumptions. As reviewed earlier, in Section 2, these shortcomings can be overcome by building the experimentally determined roughness function data of specific surfaces (i.e. in terms of $\Delta U^{+} = f(k^{+})$, where k^{+} is the Roughness Reynolds number) in the wall function or in the turbulence model of a CFD code, as originally proposed by (Patel, 1998). Demirel recently implemented this approach by using Schultz's experimental data for a representative coating surface and different grades of biofoulings, as shown in Table 1, (Demirel, 2015).

Table 1. A range of representative coatings and fouling conditions, Schultz (2007).

Description of condition	NSTM rating*	k_s (μm)	Rt_{50} (μm)
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

*NSTM (2002)

This data was built in the wall functions of the commercial CFD software Star CCM+. The wall functions are mathematical expressions which relate the viscosity influenced regions between the surface (wall) and log-law of the boundary layer and hence makes the assumption that the near wall cells are positioned within the logarithmic region of the boundary layer. Their implementation in the code by no means is an easy matter by taking into account the different flow regimes (i.e. hydrodynamically smooth, transitional and fully rough) as function of k^{+} values. Figure 15 shows Demirel's proposed roughness function models, which are formulated as in Equation (3), to fit Schultz & Flack's experimentally determined roughness functions.

$$\Delta U^{+} = \begin{cases} 0 & \rightarrow \quad k^{+} < 3 \\ \frac{1}{\kappa}\ln\left(0.26k^{+}\right)^{\sin\left[\frac{\pi}{2}\frac{\log(k^{+}/3)}{\log(5)}\right]} & \rightarrow \quad 3 < k^{+} < 15 \\ \frac{1}{\kappa}\ln\left(0.26k^{+}\right) & \rightarrow \quad 15 < k^{+} \end{cases} \tag{3}$$

The above roughness function models were built based on the surface conditions given in Table 1. However, due to the fact that there is no universal roughness function for all roughness types, the roughness functions for any other particular surfaces need to be determined experimentally by using the experimental procedure described above and models need to be built-in the CFD software.

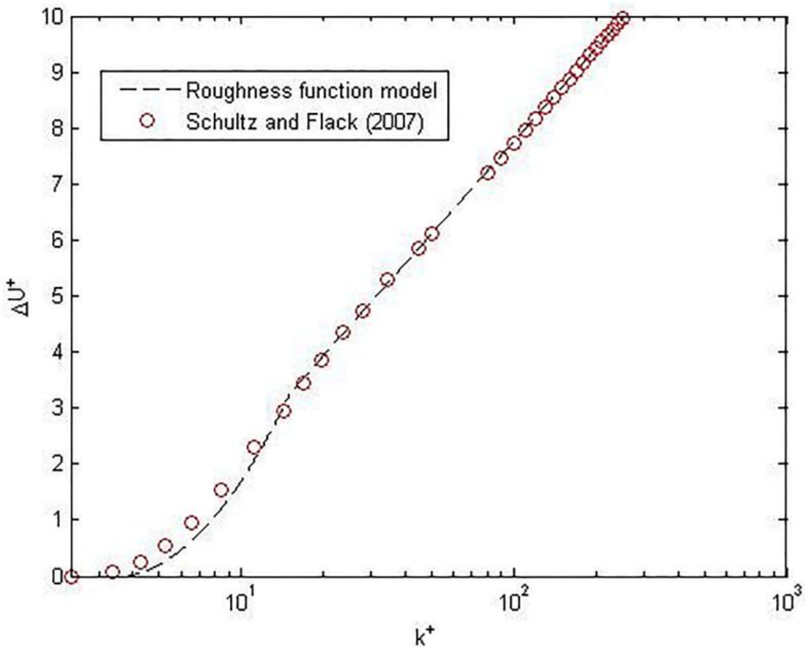


Fig. 15. The proposed CFD roughness function model for experimental Schultz & Flack (2007) roughness function data

IX. Having established the suitable wall-functions in the CFD code, next stage is the estimation of the hull resistance in full-scale which is a routine computation by applying suitable boundary conditions and meshing technique. At this stage, for practical reasons, the assumption of the hull form as a flat plate with no free surface may be preferred to reduce the computational time. Otherwise, the full 3D shape of the hull can be taken into account including the action of the propeller in the presence of the free surface to simulate the fully non-linear powering of the full-scale vessel by using unsteady RANS solver. Here, modeling of the propeller's action will require the experimental determination of the roughness functions and hence built-in CFD, for the representative propeller surfaces, similar to the hull surfaces (i.e. repeat of step I to VIII)

5. Application of the Approach

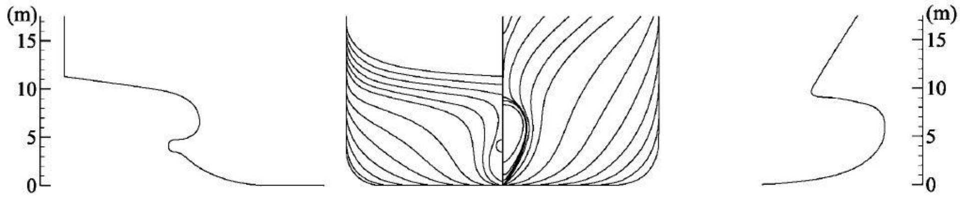
In this section, the above-described approach is applied to a benchmark container vessel, which is known to be *KRISO Container Ship (KCS)*, to demonstrate the effect of:

a. different types of coating systems (FR, SPC and CDP systems) by using Granville's extrapolation;
b. simulated hull roughness and FR coating system by using Granville's extrapolation;
c. biofilm (slime) with the combined effect of the simulated hull roughness and FR coating system by using Granville's extrapolation;
d. using different procedures to estimate the hull skin friction due to Granville's extrapolation, CFD-Flat plate and CFD-3D hull procedures.

Table 2 presents the main particulars of KRISO Container ship given by (Kim et al., 2011). The estimations are made for the powering characteristics of this vessel for the above-described cases of (a), (b) and (c) and results are presented in Table 3 for two different speeds which are 24 knots of original design speed and 19 knots of slow steaming speed.

Table 2. Main particulars of 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 (▯)	52030 m^3
Block coefficient (C_B)	0.6505
Design Speed	24 knots
Froude number (Fr)	0.26



As shown in Table 3 the results in row (a) presents the percent increase in frictional drag coefficient, ΔC_F (%) and effective power ΔP_E (%) resulted for the FR, SPC and CPD coating types when these coating systems were applied using standard application procedures or "normal" finish to represent the relatively smooth application of coatings. Whereas the results in row (b) of Table 3 presents ΔC_F (%) and ΔP_E (%) due to the effect of "mimicked hull" roughness ranges at "low" and "high" density for the same coating types. In addition, Table 3, also presents ΔC_F (%) and ΔP_E (%) values for the FR coating system with "low" and "high" density hull roughness range including the effect of biofilm.

According to the results presented in Table 3, only a small frictional drag/power increase are predicted on the KCS hull from the application of typical FR, SPC and CDP type coatings with "normal" finish applications carried out under idealised laboratory conditions. However, with 'in-service' surface conditions described in b) and c) cases, the drag penalty becomes quite significant.

Table 3. Increase in frictional resistance coefficient, $\%\Delta C_F$ and effective power, $\%\Delta P_E$ for the KRISO Container Ship (KCS) at slow steaming speed of 19 knots and design speed of 24 knots for different hull surface conditions. Predictions are made by using Granville's extrapolation method

Ship type		*KCS* (L=232.5m)			
Ship speed		(19knots)		(24knots)	
Description of condition		$\%\Delta \boldsymbol{C_F}$	$\%\Delta \boldsymbol{P_E}$	$\%\Delta \boldsymbol{C_F}$	$\%\Delta \boldsymbol{P_E}$
a) Coatings with "normal" application	FR type	1.59	1.25	2.60	1.78
	SPC type	4.48	3.54	5.69	3.91
	CDP type	6.96	5.50	8.83	6.07
b) Coatings with mimicked hull roughness	FR, 'low' hull roughness	5.95	4.70	6.80	4.68
	FR, 'high' hull roughness	7.65	6.05	9.17	6.31
	SPC, 'low' hull roughness	14.43	11.41	14.88	10.23
	SPC, 'high' hull roughness	15.86	12.54	16.15	11.08
	CDP, 'low' hull roughness	17.16	13.56	17.50	12.03
	CDP, 'high' hull roughness	18.75	14.82	18.80	12.92
c) FR type coated panels with biofilms	FR, 'low' +biofilms	16.32	12.90	16.05	11.03
	FR, 'high' +biofilms	14.34	11.33	14.00	9.63

Figure 16 and 17 are added for graphical display of the tabulated results in Table 3 for easier comparison of the results at 19 knots and 24 knots for the slow steaming and design speeds, respectively. In the figures, FR, SPC and CDP coatings with "normal" surface finish or relatively smooth roughness conditions are represented by the solid blue bars, whilst the mimicked "hull" roughness applications, at "low" and "high", levels are represented by the dotted blue and patterned blue bars, respectively. The combined effect of FR type coatings with mimicked “low” and “high” levels are shown in dotted brown and patterned brown bars, respectively.

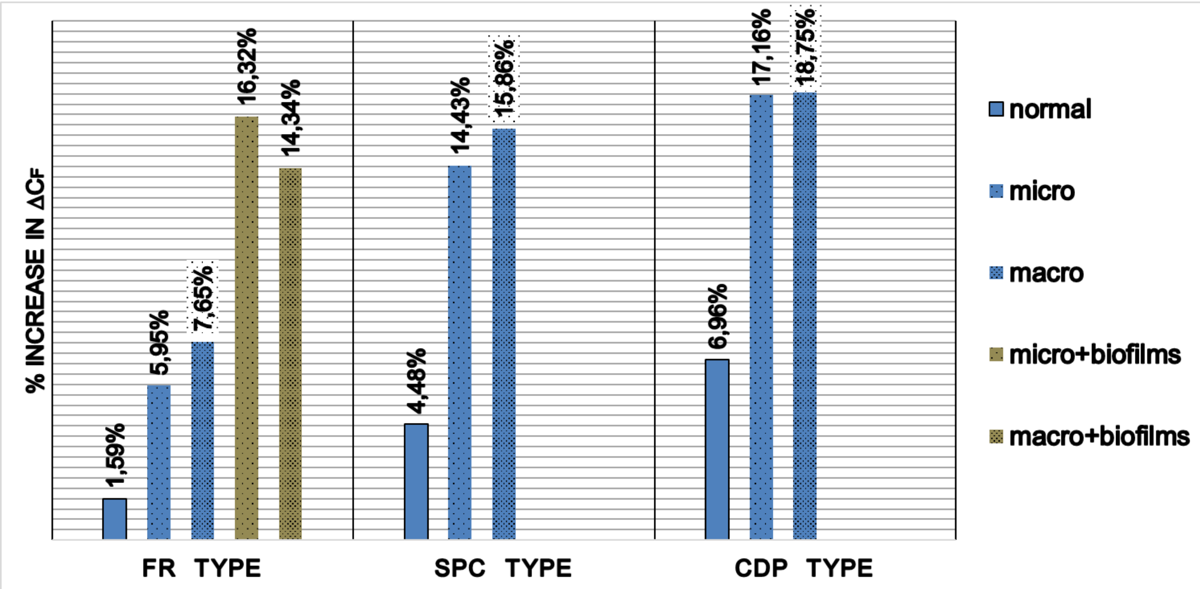


Fig.16. Estimation of percent increase in frictional resistance, $\%\Delta C_F$ for KRISO Container Ship for three different coatings types (FR, SPC and CDP) and hull surface conditions (condition a, b, c of Table 3) at 19 knots slow steaming speed. Estimation was based on Granville’s extrapolation method.

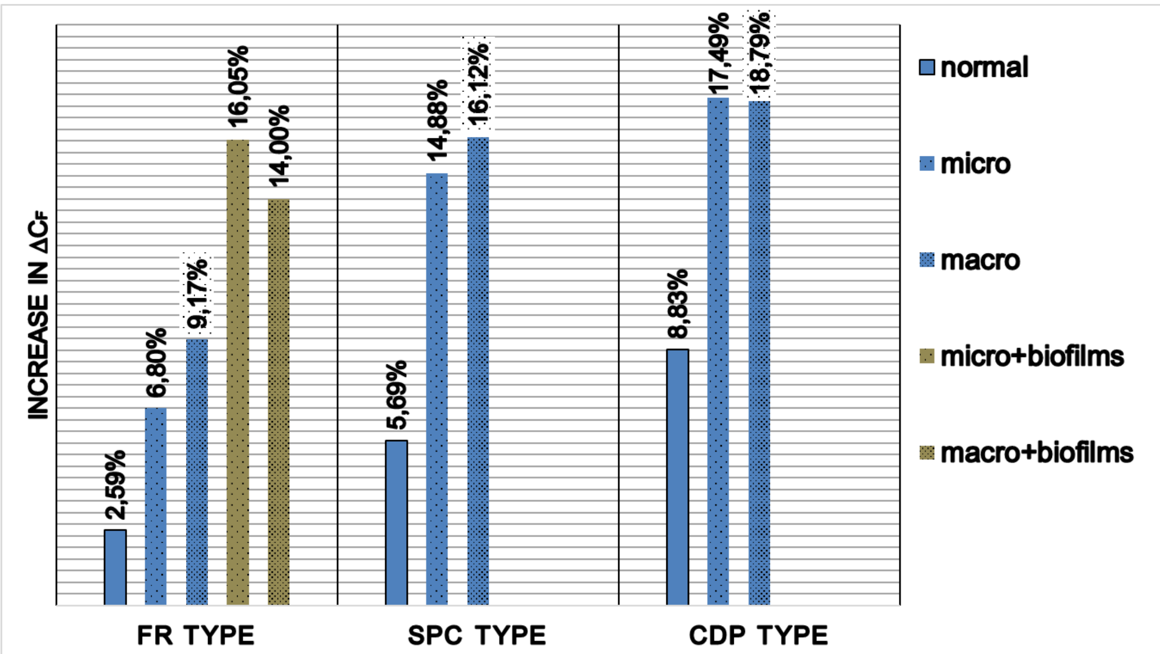


Fig. 17. Estimation of percent increase in frictional resistance, $\%\Delta C_F$ for KRISO Container Ship for three different coatings types (FR, SPC and CDP) and hull surface conditions (condition a, b, c of Table 3) at 24 knots design speed. Estimation was based on Granville’s extrapolation method.

The results presented in Table 3 as well as in Figure 16 and 17 are based on the Granville's extrapolation method. In the following the results of the Granville method are compared with the CFD based procedures as applied on the KCS vessel for the same speeds (i.e. 24 knots and 19 knots). Since the Granville's extrapolation procedure makes use of the flat plate assumption, the same assumption was also made for the full-scale KCS vessel in one of the CFD based prediction methods used while in the other procedure the 3D geometry of the full-scale KCS hull is used. The results of these three methods are referred by using the following legends: "Granville" for the Granville extrapolation method; "CFD-Flat plate" for the CFD prediction for the flat plate case; and "CFD-KCS hull" for the CFD prediction for the actual 3D hull case, respectively.

Table 4 and 5 display the results of these three different procedures for the full-scale KCS hull at 24 knots and 19 knots, respectively and for different hull surface conditions, which are based on Schultz's different coating and fouling conditions as given in Table 1. The increase in the frictional resistance coefficient, ΔC_F (%) of the KCS due to seven different surface conditions with respect to those of a hydraulically smooth surface, was predicted by using the earlier mention three different methods and presented in Table 4 and Figure 18 for 24 knots design speed of the KCS and in Table 5 and Figure 19 for 19 knots slow steaming speed of the KCS, respectively.

Table 4. Comparison of the computed (%ΔCF) values using different methods at full scale at 24 knots

	(%ΔC_F)		
Description of condition	**CFD-KCS hull**	**CFD-Flat plate**	**Granville**
Hydraulically smooth surface	-	-	-
Typical as applied AF coating	10.9	10.7	9
Deteriorated coating or light slime	29.4	29.5	30
Heavy slime	49.2	49.7	51.8
Small calcareous fouling or weed	76.9	77.7	82.2
Medium calcareous fouling	112.1	113.6	118.3
Heavy calcareous fouling	163.2	164.3	171.0

Table 5. Comparison of the computed (%ΔCF) values using different methods at full scale at 19 knots

	(%ΔC_F)		
Description of condition	**CFD-KCS hull**	**CFD-Flat plate**	**Granville**
Hydraulically smooth surface	-	-	-
Typical as applied AF coating	7.4	7.1	6.3
Deteriorated coating or light slime	26.3	26.2	26.6
Heavy slime	45.6	45.9	47.8
Small calcareous fouling or weed	72.8	73.3	77.4
Medium calcareous fouling	107.1	108.2	118.3
Heavy calcareous fouling	157.1	158.2	163.9

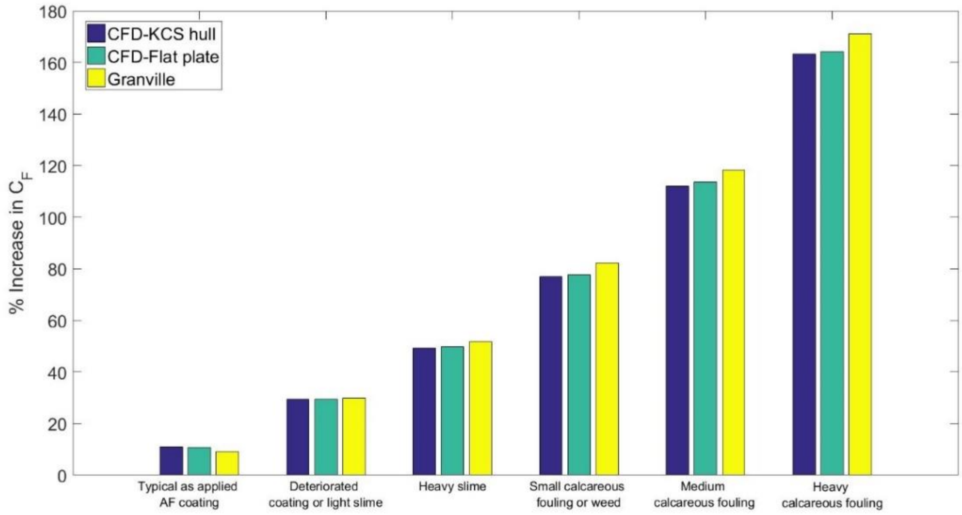


Fig. 18. Estimation of the percentage increase in the frictional resistance of the KCS due to different surface conditions at 24 knots (Re=2.89 x 109).

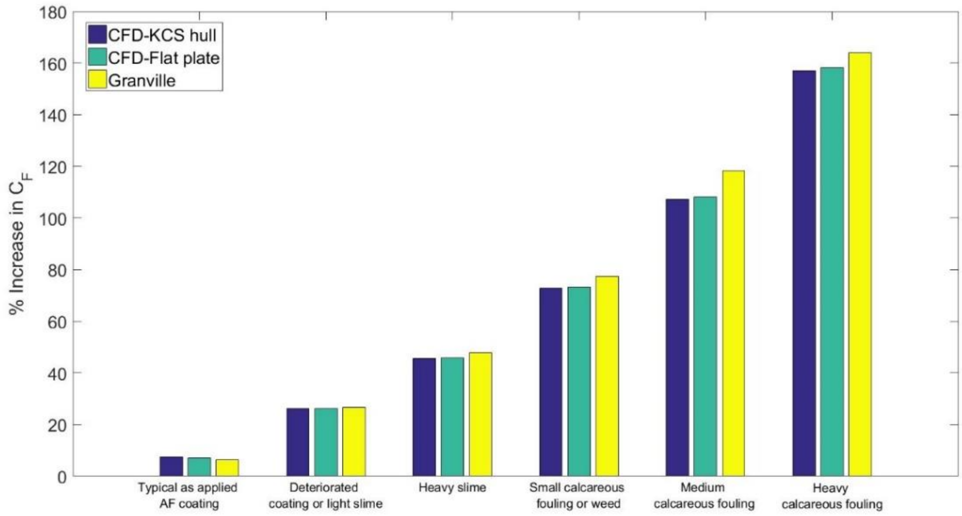


Fig.19. Estimation of the percentage increase in the frictional resistance of the KCS due to different surface conditions at 19 knots (Re=2.29 x 109).

As it can be seen in Table 5 & 6 as well as in Figure 18 & 19 the difference in the results due to the Granville and CFD procedures are negligibly small for the flat plate representation of the KCS hullform. However, this trend is changing when the 3D hull shape was taken into account as such the differences between the CFD-Flat plate, Granville and CFD-KCS (3D hull) predictions, become more noticeable as the hull surface conditions deteriorated.

Figure 20 demonstrates the percent increase in the total resistance coefficient, C_T (%) and hence in the effective power, P_E (%)of the KCS due to different surface conditions relative to the smooth condition at a design speed of 24 knots and at a slow steaming speed of 19 knots, respectively.

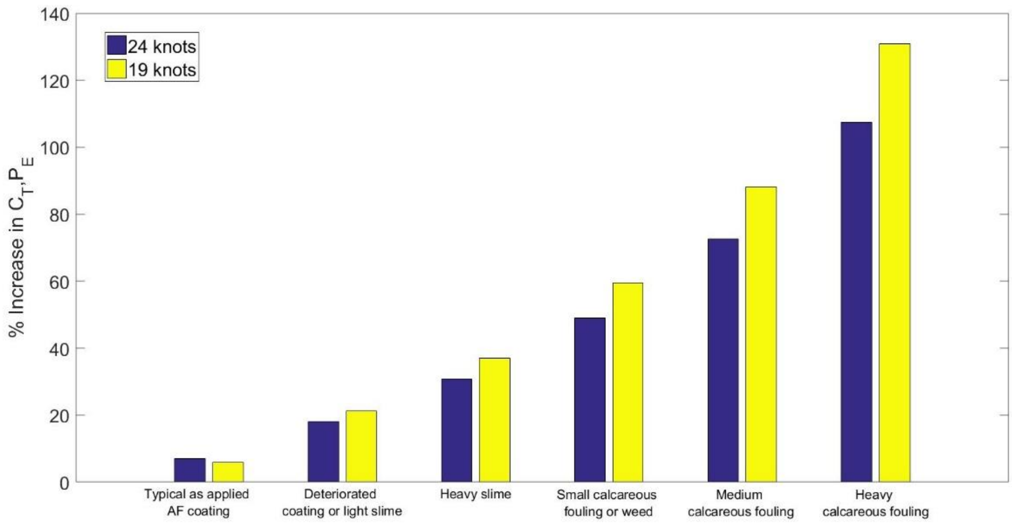


Fig. 20. Estimation of the percentage increase in the total resistance coefficient CT (%) and effective power, PE (%) of the KCS due to different surface conditions at two different speeds, 24 knots and 19 knots.

The results presented in Figure 20 indicate that the increase in the C_T and P_E of the KCS due to a typical newly applied fouling control system (with normal finish) were predicted to be 7.1% and 5.9% whereas those due to a deteriorated coating or with light slime may increase to 18.1% and 21.2% at ship speeds of 24 knots and 19 knots, respectively. The effect of heavy slime on the KCS hull was calculated to cause an increase in the C_T and P_E of 30.8% at 24 knots and 37% at 19 knots. The calcareous fouling would increase P_E by up to 107.5% at 24 knots and 130.9% at 19 knots. An interesting point to note is that the effect of a particular fouling condition on the effective power of the KCS is more dominant at lower speeds (i.e. at 19 knots slow steaming speed). This can be attributed to the fact that the contribution of the frictional resistance becomes more important than the residuary component of the total resistance at lower speeds. In other words, at higher speeds, the wave-making resistance component becomes dominant due to wave generation. Therefore, the effect of a given fouling condition on the total resistance of a ship is greater at low to moderate speeds than at higher speeds.

6. Validation of the Approach

A rational validation of the above-described approach in a real scenario, ideally, must be provided by the full-scale estimation of the changes in hull and propeller frictional drag caused by the application of different fouling control system or the growth of natural biofouling on the ship's wetted surfaces. Not being directly observable, this must be indirectly derived from other measurable quantities, the closest one being a speed-power relationship. The most important measurements to be carried out onboard a ship are therefore her speed through the water and the power needed to push her at that speed. Nonetheless, the complex environment and operational profile of a seagoing vessel contaminates the speed-power relationship by introducing other external resistance components. Factors of the like of winds, waves, ocean currents, vessel loading conditions affect the ship speed through water, her powering or both and these effects need to be accounted for in the estimation of the hull/propeller drag changes. Thus, other so-called "secondary" parameters need to be measured, for example, wind speed and direction or vessel draft.

Modern Ship Performance Monitoring Systems (SPMS) are mostly based on the earlier described set of measurements, their diversity stemming from the adopted data collection process, analysis method and scope of work. The SPMS installed on UNEW's *The Princess Royal* was conceived for the detection of changes in hull and propeller drag caused by alterations in their wetted surface roughness, whatever the cause, simultaneously targeting the smallest achievable uncertainty levels. The system, although developed on a small research vessel, can be applied to any vessel whose operator's intention would be to assess the effect of a fouling control system application or of biofouling build-up on the ship's wetted surface. The following sections aim at providing a concise description of the system in its main data treatment parts, namely *(i) Measurement, (ii) Filtering, (iii) Correction and (iv) Analysis.* Uncertainty of the system is then discussed.

(i) Measurements

As thoroughly shown by recent work, e.g. (Carchen et al., 2017), the primary feature of a competitively accurate SPMS stands in its measurement system. This should be completely automated and encompass a range of quality sensors. As shown in Figure 8, UNEW's RV *"The Princess Royal"* was therefore equipped with a new-generation Doppler Speed Log for the measurement of speed through water outside the ship's boundary layer and a pair of purpose-built instrumented shafts for the measurement of propeller power and thrust. These are complemented by complete navigational data, rudder angle potentiometers, an onboard weather station for the measurement of wind characteristics (speed, direction, temperature, and humidity), a wave radar (true wave height), two fuel flow meters (fuel consumption) and a water quality sensor. An in-house built Performance Monitoring software collects all the different signals and allows logging and displaying of relevant data to the crew.

(ii) Filtering

Raw measured data is always spurious for an immediate analysis, in that ship maneuvers (accelerations, course changes, etc.) and extreme conditions encountered (e.g. weather) alter the speed-power relationships and cannot be accurately corrected for. To exclude these and the random outliers from the dataset, situational, transient and statistical filters were implemented with the secondary aim of applying the least modifications to the raw data (Figure 21).

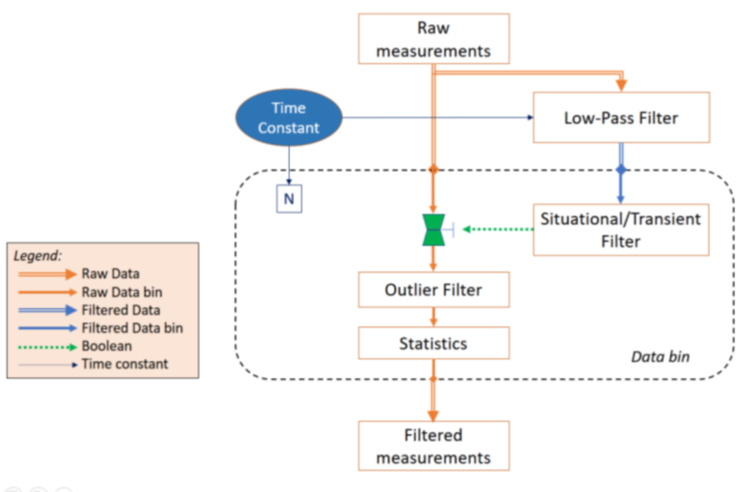


Fig. 21. Data flow through the filtering procedures

(iii) <u>Correction</u>

A deterministic approach to the data is one based on physical relationships between variables and it embraces the traditional naval architecture knowledge. Fundamentally, the total in-service ship resistance may be described as:

$$R_T = R_V + R_W + R_{add} \tag{4}$$

Where R_V is the viscous resistance, R_W is the wave making resistance and R_{add} the added resistance caused by factors intrinsic (e.g. loading condition) and extrinsic (e.g. wind, waves etc.) the ship. The purpose of the correction is the *a posteriori* determination and subtraction of R_{add} from the equation to allow a clearer observation of the change of R_V caused by a change of the coating system or biofouling growth. Because of its transparency and ease of obtaining different parameters to scrutinise, this approach was chosen to correct the data obtained in *(ii)* as shown schematically in Figure 22 and from full-scale measurements in Figure 23.

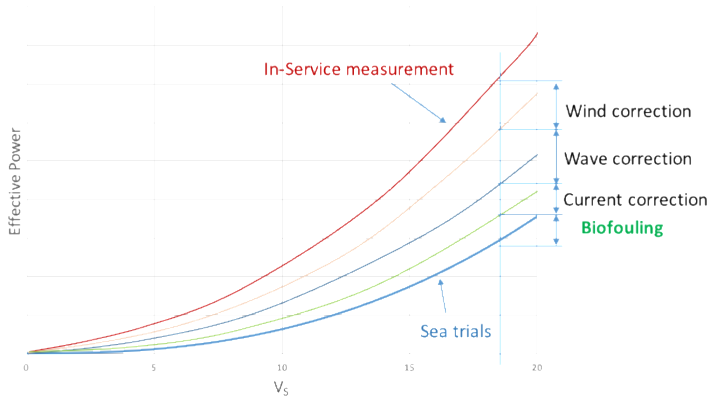


Fig. 22. Schematic representation of deterministic corrections for external disturbances

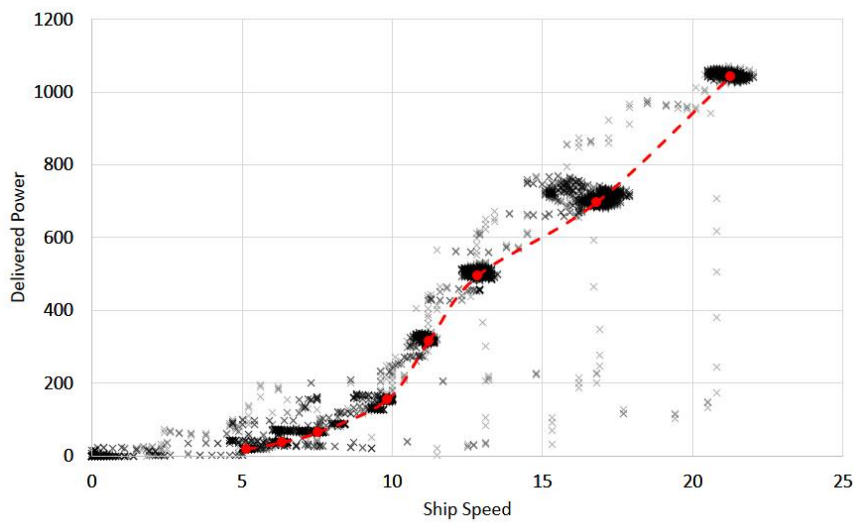


Fig. 23. Raw (blue markers) and corrected (red line and markers) performance measurements on the Princess Royal

The filtered data are corrected to represent the calm weather behavior of the ship according to a modified Taniguchi-Tamura method, (Taniguchi and Tamura, 1966), which makes use of propeller characteristics and vessel geometry. Corrections are applied for wind, head waves and water density using benchmarked data obtained from model tests or numerical simulations following relevant established methods (e.g. ITTC, 2014). The change in loading is negligible on this vessel, but a suitable correction can be applied in general. Figure 24 below shows the consistency of UNEW's SPMS in different trials with similar hull and propeller roughness.

(iv) <u>Analysis</u>

The long-term analysis of the corrected data obtained in *(iii)* allows thus to assess the change in calm water power due to alterations in the wetted surface roughness. From it, the propeller only feels a change in the loading condition, or in other words a change in the water inflow at a same rotational speed. Its usual definition as:

$$V_a = V_S(1 - w) \tag{5}$$

implies that the propeller perceives a change in ship speed V_S (increased ship resistance) and in effective wake fraction w (increased hull surface boundary layer). Moreover, if the propeller blades are also fouled, for the same condition earlier defined the propeller will also register a higher torque due to its own fouling. Long term monitoring of the effective wake obtained from the propeller torque is thus a powerful measure of the change in roughness of jointly hull and propeller, in that it shows the real increase of boundary layer on the hull surface and the effect of propeller fouling on the propeller performance. When the propeller thrust is measured and propeller open water curves are available, the comparison of the wake fraction as derived from torque and thrust allows to evaluate the change in frictional drag of the hull alone, as thrust is affected but negligibly by blade fouling. In addition, considering that, in nondimensional form, the corrected total ship resistance can be written:

$$C_T = C_F(1 + k) + C_W \tag{6}$$

and knowing the viscous form factor $(1 + k)$, the wave making coefficient C_W can be calculated for a clean hull condition. The later changes in the viscous coefficient $C_F(1 + k)$ can be estimated due to change in fouling control system and biofouling growth. This would eventually allow direct validation of the earlier explained procedures.

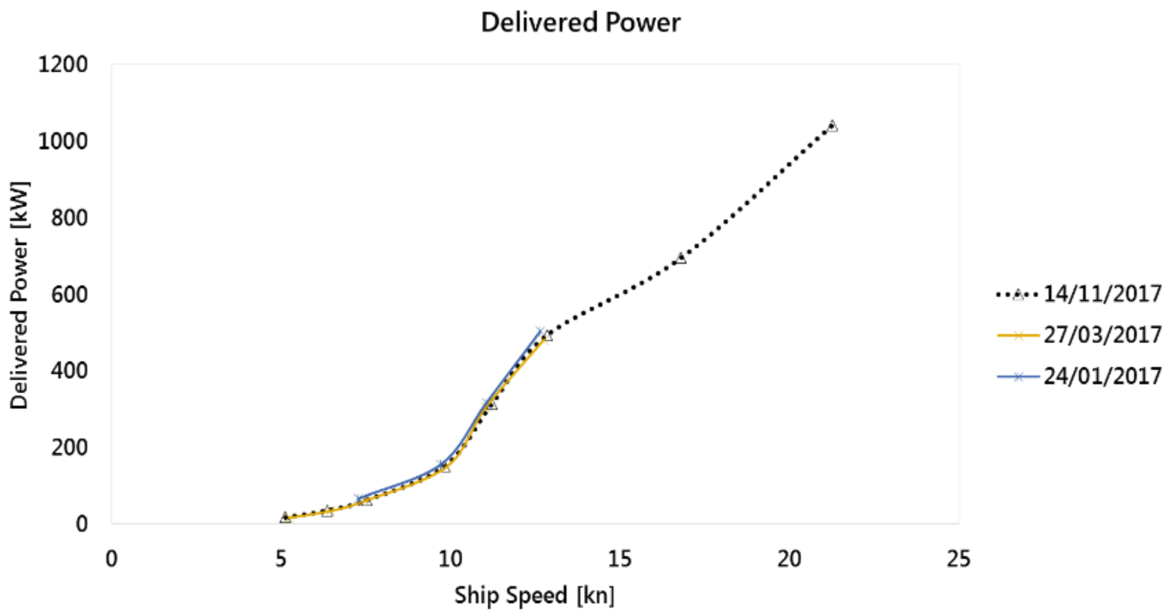


Fig. 24. In service Speed-Power curves of UNEW's research vessel "The Princess Royal"

Uncertainty analysis of the whole process presented above showed that the uncertainty caused by the monitoring and analysis system alone accounts for a maximum of about ±3% in shaft power at the 95% Confidence Interval, (Carchen et al., 2017b). This uncertainty level can be only reduced improving the quality of the sensors, the filtering techniques, and the analysis method. The variability of the weather, even when applying corrections, brings further uncertainty in the system, with total values being about ±4% to ±9% in shaft power at the 95% confidence interval (depending on ship speed). These results are supported also by previous findings in the literature. The contribution of weather to the uncertainty can be reduced by applying stricter filtering for the "non-extreme" weather conditions used for the analysis and by improving the corrections methods. As bigger vessels are less affected by weather the uncertainty contribution due to weather will be smaller in relation to the same filtering criteria.

7. Concluding Remarks

Based on two decades of bridging the gap between laboratory measurements and predicting the performance of commercial maritime vessels, in this paper, a rational approach to predicting the effects of modern-day fouling control systems on "in-service" ship performance is presented. This is further supported by a validation approach that involves the development of a dedicated performance monitoring and analysis systems on-board a full-scale research vessel which is currently underway

1. The proposed approach is generic and can be applied to any ship type and hull coating system in the presence of biofouling and it may even be combined with passive drag reduction systems.

2. The approach involves both the combination of experimental data from flat test panels treated with representative surface finishes and extrapolation of this data to full-scale. However, for more accurate and direct estimation of performance prediction at full-scale, the extrapolation

procedure needs to be replaced with Computational Fluid Dynamics (CFD) methods, especially for deteriorated hull surfaces due to fouling; at present, such experimental data are still required.

3. The rational nature and hence strength of the proposed approach is to represent the effect of the actual hull surfaces “in-service” by using state-of-the art experimental methods and data. This provides the option of an extrapolation procedure for practical performance estimations and also enables the use of CFD methods by avoiding the most difficult barrier of describing the actual hull surface numerically in CFD.

4. Validation of the proposed approach requires full-scale data to be collected using a bespoke ship performance monitoring and analysis system which is dedicated to assessing the effect of coating systems in the presence of fouling. Such a system is under development as reported in the paper.

5. Currently a new FTFC has been designed and is to be commissioned at the Kelvin Hydrodynamics Laboratory of the University of Strathclyde in September 2018. The new channel will have a special testing section, which will allow to test surfaces not only with coating and light biofouling (i.e. slime) but also with macro-scale (e.g. calcareous) fouling and passive drag reduction systems to support the ongoing research on biofouling hydrodynamics and drag reduction systems.

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