MANAGING INTERNATIONAL COLLABORATIVE RESEARCH BETWEEN ACADEMICS, INDUSTRIES, AND POLICY MAKERS IN UNDERSTANDING THE EFFECTS OF BIOFOULING IN SHIP HULL TURBULENT BOUNDARY LAYERS

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SUMMARY

This report documents a large scale joint research project with the aim of improving the efficiency of ship operations and management by providing a methodology and technology that can quantify the emission and fuel usage penalty due to bio-fouling on ship hull. This can be obtained through better understanding of turbulent boundary layer flows over rough surfaces that cause skin friction drag. Here six different institutions from four countries (Australia, Denmark, Indonesia, and UK) that consist of universities, a passenger ship company, a manufacturer of anti-fouling coatings, and the Indonesian Classification Society are formed. They represent three fields, namely: academic, industrial, and an independent party that supports policy makers. Each of them has different objectives and interests that are interconnected. The research collaboration uses an *in-situ* laser-based measurement technique of the water flow over the hull of an operating ship combined with under-water image-based surface scanning techniques. The shipboard experiments are accompanied by detailed laboratory experiments to provide further validation. This paper will discuss the importance and challenges of managing such collaboration and the significance of satisfying individual objectives from each three fields in order to achieve the overarching aim.

NOMENCLATURE

[Symbol]	[Definition] [(unit)]
ν	Kinematic viscosity (N s m^{-2})
ρ	Density of water (kg m^{-3})
U	Mean velocity (m s^{-1})
U_τ	Skin friction velocity (m s^{-1})
L	Characteristic length scale (m)
δ	Boundary layer thickness (m)
k	Roughness height (m)
k_s	Sand grain equivalent roughness height (m)
k_a	Average roughness height (m)
e	Roughness offset (m)
z	Wall normal distance (m)
ES_x	Effective slope

1. INTRODUCTION

There are approximately more than 100,000 ships (including cargo, military, tanker, and passengers) operating worldwide, together consuming around 200 – 300 million metric tons of fuel per year (Corbett et al 1999, Erying *et al*, 2010). To put it into perspective, this is equivalent to 5% - 8% of world's oil production in 2015. Much of the oil that is consumed by these ships is low grade and contains harmful materials such as: sulphur, asphaltenes, leads, various metals, and ash (Corbett *et al*, 1999, Winebrake *et al*, 2009). When this type of oil is fed into a ship's internal combustion engine, its by-product is gas emission that contains particulate matter (PM), sulphur oxides (SOx), nitrogen oxides (NOx), black carbon (BC), carbon dioxide (CO_2), carbon monoxide (CO), and other harmful properties. The air pollution from ship-related emission has direct impact to human's health and well-being. Recent studies indicate that around 60,000 – 90,000 premature death annually are caused by shipping air pollution, particularly at the coastal area of Europe, East Asia, and South Asia (Corbett *et al*, 2007, Winebrake *et al*, 2009). Further studies by Erying *et al*, (2010) show that aerosol pollution and their derivative species from ships combustion can be transported high in the atmosphere and carried further inland by airstreams, resulting in increased pollution in locations that are far from coastal areas. Therefore, the exact number of mortality caused by ships emission may be even higher. Furthermore, many studies also show that the global shipping industries contribute towards climate change. Hence this industry has a large economic, environmental, and health footprint (see Erying *et al* 2010 and Miola and Ciuffo 2011 for recent reviews on ship impacts on climate).

The issue of health, global warming, and energy crisis have prompted efforts by policy makers, academics, and industries representative to find new ways to reduce energy consumption in the shipping industries (Davies, 2006; Longva *et al*., 2010, Molland *et al*. 2014). This is particularly crucial for countries that rely heavily on ships, such as archipelagic countries (Indonesia, Japan, Malaysia, Philippines, UK, Pacific nations), and countries that are geographically isolated from major trading partners (Australia, New Zealand). From the listed countries, it is clear that the issue affects both developing and developed countries. This is even more important for countries that subsidise fossil fuel. A recent report by Coady *et al* (2015) from the IMF (International

Monetary Fund) reveals that global petroleum subsidies amount to \$1.6 trillion (2.2 percent of global GDP) in 2013. Many marine dependant developing countries such as Indonesia provide subsidies for passenger ships and ferries. Such subsidiaries burden the country's budget and slow the growth of other infrastructure.

Hull roughness due to biofouling (marine organisms that settle on the ship's hull) is an important, but largely unquantifiable contributor to the overall energy expenditure, emissions, and pollution from the shipping industry. Many studies have shown that biofouling contributes significantly to the ship's overall drag resulting in excess use of fuel to propel the ship forward (see Schultz *et al* (2004, 2007, 2011) and Monty *et al* (2016) for recent studies). Unfortunately, currently there are no reliable techniques that allow ship owners and operators to quantify a ship's drag penalty due to biofouling accurately.

In an effort to understand the skin friction drag on ship hulls due to biofouling and to improve the efficiency of ship operations by providing a methodology and technology that can accurately quantify the emission and fuel usage penalty, a large-scale research collaboration is currently underway. The research involves an in-situ laser-based measurement of the water flow over the hull of a ship coupled with a detailed under-water image-based surface scanning techniques. These techniques allow direct measurement of the increase in drag experienced by the ship under different fouling conditions. The two novel shipboard experiments are accompanied by detailed laboratory investigation to provide further validation. The outcome of the study will allow policy makers and ship industries to make more informed decisions in terms of operations at operational or regulatory level.

The project involves six institutions from four different countries, namely: Institute of Technology Sepuluh Nopember, Biro Klasifikasi Indonesia (Indonesian classification society), and Dharma Lautan Utama passenger ship company from Indonesia; the University of Melbourne from Australia; the University of Southampton from the United Kingdom (UK); and Hempel A/S an anti-fouling paint company from Denmark.

In general the six institutions can be categorized into <u>*three major fields*</u>, namely: academic, industry, and classification society to support policy maker. Each of these three fields has different interests and expected outcomes that form the base of the overall main objective of the research collaboration. To accomplish the challenging objectives, the six different participants need to collaborate closely and effectively, particularly because each of them has a different role and unique set of expertise for the project.

In this paper, we discuss the importance of collaborative research in tackling biofouling, which is one of the most challenging issues in the shipping industry. This includes the motives and details of the joint research, the role of each institution, the expected outcome or results from individual fields, and how these individual field's objectives are correlated and satisfied to achieve the overarching goal. This paper will also discuss some challenges that we have experienced. Note that the current report is based on, and also serves as an extension of our recent conference paper (Utama *et al*, 2016) that was presented at the RINA International Conference on the Education and Professional Development of Engineers in the Maritime Industry (Singapore 20-21 September 2016).

2. RESEARCH GROUP FORMATION AND ROLE

Research collaboration is an essential part of any modern scientific endeavour, particularly for complex and large-scale projects. With the ever increasing cost of scientific apparatus and materials, lower cost of travel and communication (internet and telephone), and the need for division of work in interdisciplinary research, it is only natural that many scientists resort to collaboration, both nationally or internationally (Katz and Martin, 1997; Subramanyam, 1982; Melin and Persson, 1996). Our proposed research project requires a large quantity of resources such as: lab facilities, field experiment equipment, travel funds, and personnel salary. To the best of our knowledge there have not been many attempts for this type of research. One such study is by Lewthwaite *et al*. (1984) where it also involved several different institutions. Learning from their previous experience, we have assembled a likeminded group of institutions to tackle the issue of biofouling.

The large scale research collaboration is initiated by the University of Melbourne and Institute of Technology Sepuluh Nopember (ITS), in response to the newly formed Australian-Indonesian Centre (AIC) program aimed to strengthen collaboration between Australian and Indonesian universities. The University of Melbourne approached ITS in the late 2014 to propose novel boundary layer study that involves access to an operational ship. The research idea has been formulated by academics in Melbourne over the last decades or so, however the difficulty in obtaining access to an operational ship in Australia hindered realisation of the concept. From several formal and informal meetings between the academics from the University of Melbourne and ITS, a collaboration plan finally materialized.

For this research, the University of Melbourne is responsible for the management of the overall research plan and contributes in the form of field research equipment, such as the LDA, surface scanner, and other supporting research apparatus. Furthermore, the University has a very strong fluid mechanics background and extensive laboratory facilities, therefore it is an ideal place for the laboratory experiment. The relatively short distance between Indonesia and Australia is another reason for the University of Melbourne to host the laboratory experiment.

As one of Indonesia's leading marine research universities, ITS has a very strong marine faculty and is well-linked to various Indonesian marine intuitions (both in industry and government). The main role of ITS is to host the field experiment and use their extensive contacts in the Indonesian maritime industry to assist with the import of various scientific apparatus from overseas, and liaise with local government representatives. The university is also responsible in providing Masters and final year Undergraduate students to assist in this project.

With its strong alumni connection, ITS has invited PT Dharma Lautan Utama (DLU), an Indonesian passenger ship and ferry company, to be involved in the research project. PT DLU is one of the largest passenger ship operator companies in Indonesia and is actively involved in many ITS activities. The company has agreed to lend the all-important ship as test bed. The ship is a RO/RO passenger ferry called Dharma Kencana IX (figure 1) that serves between Merak (Java island) and Bakaehuni (Sumatra island), Indonesia's busiest lines. The two islands are the most densely populated in Indonesia (note that Indonesia is the 4th largest country in the world in term of population - approximately 250 million people).

Figure 1 : Dharma Kencana IX ferry from PT Dharma Lautan Utama (PT DLU)

Field experiments in an operational ship pose certain risks, particularly for our proposed experiment where there will be an optical access at the bottom of ship. Therefore, to ensure the safety of the scientists (and ship) for the entire duration of the investigation, ITS has invited Biro Klasifikasi Indonesia (BKI), Indonesian classification society, to be part of the research team. BKI is a recognized organization by the Indonesian Government that is tasked to classify any Indonesian flagged marine transport both domestic and international that operates in Indonesian water and/or world wide voyage [DJPL, 2016]. BKI assist the research collaboration via technical evaluation regarding ship design, building, reconstruction, maintenance, modification, and other dry-docking activities as well as periodical survey, in accordance with BKI technical standards (rules and regulations).

The field experiment involves a laser-based velocity measurement (laser Doppler anemometery). Two crossed lasers shine through an optical access on the bottom of the hull and measure the velocity gradient in the turbulent boundary layer formed over the ships hull. Because such method is novel and un-proven it requires repeated test under constant environment, i.e. constant hull condition over a period of time. Therefore, the University of Melbourne invited Hempel A/S, a multinational antifouling company to be part of the research collaboration. They contribute in the form of antifouling paint that is applied on the hull of Dharma Kencana IX during dry docking when the hull is in clean state. The paint allows the ship hull to remain clean for longer period of time permitting the field researchers to test the LDA during the initial stages of this project.

Although the University of Melbourne and ITS have secured the necessary lab and field facilities and equipment, they still lacked the necessary personnel to perform the experiments and guide the ITS Undergraduate and Masters students. Therefore, the two universities invited the University of Southampton as part of the research team. ITS and the University of Southampton have a long history in academic cooperation, particularly in naval research. Many senior ITS academics have received higher education from the University of Southampton. Furthermore, the University of Melbourne and the University of Southampton have previously performed similar collaborative laboratory experiments, where they scanned a sample of tubeworm type fouling and characterised the drag using a wind tunnel (see Monty *et al*, 2016).

In early 2015 ITS and the University of Southampton secured funding from the British Council via the Newton Fund program, leveraging the previous subsidy from the Australian-Indonesian Centre. This cooperation also acts as a realisation of the cooperation between the government of Indonesia and UK that was signed on 1st November 2012 at 10 Downing St, London, and witnessed by the then Indonesian President and The Prime Minister of England. This funding allows the University of Southampton to recruit a Postdoctoral research fellow (Post-doc) to perform the field and laboratory experiment, and train the Undergraduate and Masters students from ITS.

There are two crucial lessons arising from the research group formation. The first is the importance of networking, where it allows scientists to learn about each other's research, facilities, etc, particularly in many different channels/levels. Without proper networking, such large international research would not materialize. The second is inter-government cooperation. Without close relationship between the Indonesian-Australian and Indonesian-UK governments, such funding would not exist. It is an evidence that proper international relationship and policy between governments can influence the more grass root level, i.e. people-to-people engagement.

3. CORRELATION BETWEEN INDIVIDUAL FIELD OBJECTIVES

From the previous section it is clear that this research project involves many different institutions that can be grouped into three different fields. Each of these fields has their own individual objectives that together form the overarching goal. The challenge for this collaboration is to satisfy each field's individual objective without sacrificing the overall goal. This section will discuss each individual field's objective and how they correlate with each other.

3.1 ACADEMIC FIELD OBJECTIVES

The three academic institutions: ITS, the University of Melbourne, and the University of Southampton have two main objectives, the first is to obtain further understanding about turbulent boundary layer flows over rough surfaces that cause skin friction drag. The expected outcome from the project is a database with high research value. These results will be published in peer-reviewed journals and conference papers, allowing the three academic institutions to communicate their results to the scientific communities and wider audiences.

Figure 2: One of ITS Masters student examining fouled ship hull

The second objective is to educate and train higher degree students via this international research. The University of Melbourne uses this research opportunity to construct a capstone/final year project for Master students. The project is to perform an initial study and design for the image based surface scanner, allowing the students to learn digital image reconstruction techniques. The project also serves as an initial study for the Postdocs from the University of Southampton to continue and expand. These objectives are similar with Bruneel *et al* (2010) and Dasgupta and David's (1994) arguments that university is mostly driven with scientific and academic excellence.

For ITS, the funding from AIC and Newton fund is particularly beneficial. The research collaboration allows their two Masters students to experience international research collaboration and broaden their view. The two students are from the "Pre to Post MSc" program which is funded by the Indonesian Ministry of Research, Technology and Higher Education. Figure 2 shows one of the Masters students examining a fouled ship hull (note that this particular fouled hull is not from our test bed ship). The program is aimed at training and educating high achieving students, that originate from other smaller or younger Universities that are located in the eastern part of Indonesia, at ITS. In developing countries such as Indonesia there is a considerable gap in education quality between different areas. The program is aimed to reduce such gap. The two Master students are expected to return to their respective universities and work as university lecturers. The international collaboration project also paves ways for ITS to allow more Undergraduates and Masters students to be involved, particularly those aiming to continue their study in PhD at The University of Melbourne and The University of Southampton, and expected to return to ITS as lecturers. This is part of the effort by ITS to be a world-class research university. Furthermore, it also strengthens the relationship between the three universities beyond the current joint research.

Finally, for ITS the collaborative project also represents the three core roles for higher education in Indonesia, namely: (1) education and teaching, (2) research and development of science, technology and arts, (3) community service. The three philosophies are more commonly known as TRI DHARMA PERGURUAN TINGGI (Utama and Pribadi, 2011).

3.2 INDUSTRIAL FIELD OBJECTIVES

The two industrial representatives, namely: PT DLU (passenger ship company) and Hempel A/S (manufacturer of antifouling coatings) are from different industries that complement each other. For passenger ship companies such as PT DLU their fixed costs are crew and staff salary, fuel, and maintenance (including dry docking and anti-fouling paint). To improve earnings, many shipping companies require effective and efficient operation management. Fouled hulls are one of the main sources of expenses for PT DLU. Apart from causing excess fuel usage during operations, it forces the ship to undergo a relatively expensive dry docking process, during which it is unable to generate revenues. The passenger ships are required to perform dry docking once a year (DJPL, 2014; BKI, 2016).

For PT DLU, having a more informed decision in terms of operations (particularly related to dry docking) will be economically beneficial. The LDA measurement technique also has the potential to be developed and downsized to be part of the standard sensor suite on a modern ship, providing a constantly updating report on the health of the hull. The surface scanner data when considered together with the LDA results can potentially form a single system to predict a ship's excess fuel usage.

For anti-fouling companies (i.e. Hempel A/S), the prospect of the availability of a workable correlation/equation that allows the hull fouling penalty to be calculated directly from surface scan information is desirable. It provides them information as a basis for the maximum allowed fouling properties (height, effective slopes, sand grain equivalent roughness) over a certain period from their anti-fouling technology. Hence it allows anti-fouling producers to provide more precise information regarding their product performance to their customers.

3.3 POLICYMAKER FIELD OBJECTIVES

Biro Klasifikasi Indonesia (BKI) is an institution that is tasked by the Indonesian Government to classify any Indonesian flagged marine transport that operates both in Indonesian and International waters. The institution has an important role in advising the Indonesian Government regarding various marine safety, environmental protection, and procedures. Various marine rules and codes including docking schedules are governed by BKI and Ministry of Transportation, many of which are also based from the International Maritime Organization (IMO) regulations.

One of the major outcomes from this research collaboration is more detailed information regarding the energy and economic ramifications of a fouled ship hull. Such information can be used by BKI as a scientific basis to review Government policy regarding the management of biofouling treatment procedure. For example, modifying regulations regarding the periodical inspection of antifouling application during scheduled dry docking for passenger ships or other types of ship. The timeline should be based more on the proper calculation of hull roughness condition. Hence it will benefit ship operators that adhere to the regulation of using proper anti-fouling technology and prevent heavily fouled ships from using excess fuel. In short, it would allow more economical and efficient ship operations. This is particularly important for Indonesia because the country is still subsidising fuel for passenger ships and ferries. Such research intensive based policy is difficult to perform in developing countries due to the low national research budget. Hence this research is an excellent opportunity for BKI to implement such research results into policy. Furthermore, the policy can also be submitted internationally through IMO, allowing other IMO member states or flag administrators to study and implement it for their respective countries.

4. TURBULENT BOUNDARY LAYERS

In order to understand the reason behind the proposed research, this section will provide a short background on turbulent boundary layers, particularly over rough surfaces.

As a ship moves through the water, the no-slip condition at the solid boundary will generate a thin region of shear close to the hull boundary where the fluid is pulled along with the ship. The velocity gradients within this region give rise to tangential stresses or skin friction drag which provides a major component of the total drag or resistive force that the ship propulsion systems must overcome. The energy consumption to overcome skin friction drag is relatively costly. For example, for a large ship such as a Very Large Crude Carriers (VLCC) up to 80%-90% of the total drag is due to skin friction (Lackenby, 1962). Hence a large amount (or in many cases the majority) of the fuel which is used to propel the vehicle is expended purely to overcome skin-friction drag. The motions within the thin shear layer, particularly in large engineering applications such as ships, are highly turbulent, hence it is generally described as a turbulent boundary layer. If one considers the large contribution that sea transportation makes to global emissions, it is easy to see that drag from turbulent boundary layers constitutes a very pressing engineering and societal problem.

4.1 REYNOLDS NUMBER

The study of turbulent boundary layers is closely related to Reynolds number,

$$Re = UL/v \tag{1}$$

where U is mean velocity, L is a characteristic length scale, and v is kinematic viscosity. For the hull of moving ship, with hull lengths of 100 to 250 m and cruising speed of 5 – 10 m/s, Reynolds numbers on the order of 10^9 can result. With the high Reynolds numbers such as this, turbulent boundary layers are unavoidable.

For canonical wall bounded turbulent flow (i.e. pipe flow, channel flow, and turbulent boundary layer flow), it is desirable to use Friction Reynolds number

$$Re_\tau = U_\tau \delta / v \tag{2}$$

where U_τ is skin friction velocity, and δ is boundary layer thickness. The skin-friction velocity U_τ is proportional to the skin-friction drag, hence higher skin-friction velocity translates to higher skin-friction drag.

Adding to the complexity of the problem, the already high contribution of skin friction drag due to high Reynolds number flow in large ships is exacerbated by the issue of surface roughness. Although the hull of a large ship can often seem relatively smooth, particularly when it is just recently cleaned and painted, it is generally not so from the perspective of the flow. When the height of surface irregularities become appreciable in term of viscous length scale (v/U_τ), the flow will "see" the roughness and start to interact with it. Nikuradse (1932) considers that a surface is "smooth" when the viscous scaled roughness height $k^+ < 5$, where

$$k^+ = U_\tau k / v. \tag{3}$$

here k is roughness height. Hence this translates to a maximum permissible physical roughness for ship moving at cruising speed of 5 – 10 m/s to be around 20 – 50 μm, which is exceedingly small. Therefore, the seemingly smooth ship hull is in fact dynamically rough (from the perspective of the flow). When we take biofouling, which have roughness heights orders of magnitude greater into consideration, it is clear that the drag will be much higher.

5.2 ESTIMATING SKIN FRICTION VELOCITY (U_τ) AND SAND GRAIN EQUIVALENT ROUGHNESS (k_s)

In canonical wall bounded turbulent flow, skin friction velocity U_τ can be estimated from a measured velocity distribution over some wall normal distance z (using either hot-wire, Pitot-tube or Laser Doppler Anemometer) by fitting the mean velocity profile to a logarithmic law:

$$\frac{U}{U_\tau} = \frac{1}{\kappa} log\left(\frac{z\, U_\tau}{\nu}\right) + A \quad (4)$$

where κ is the Karman constant and A is the wall intercept (both considered to be universal constants). However, due to the non-smooth nature of the surface, the entire profile will be shifted downwards by the Hama roughness function $\Delta(U/U_\tau)$. Hence equation 4 will become:

$$\frac{U}{U_\tau} = \frac{1}{\kappa} log\left(\frac{(z+e)\, U_\tau}{\nu}\right) + A - \Delta\left(\frac{U}{U_\tau}\right) \quad (5)$$

here e is the necessary roughness offset (see Clauser, 1954, 1956 for further reading regarding the estimation method).

An important component in estimating drag is the sand grain equivalent roughness height k_s, first introduced by Nikuradse (1932). Although both k_s and k have dimensions (in meter), unlike k that is directly measurable from the surface topography, k_s can only be estimated by exposing the rough surface to turbulent flow at various different free-stream velocities (because k_s is a measure of the influence a surface has on the flow). Currently, the most common technique to estimate k_s is through laboratory testing (in wind tunnels, water channels etc), where k_s can be determined by assuming "fully rough" conditions of the form:

$$\Delta\left(\frac{U}{U_\tau}\right) = \frac{1}{\kappa} log\left(\frac{k_s\, U_\tau}{\nu}\right) + A - B \quad (6)$$

The issue with this technique to determine k_s is the cost. One would need to perform many rough surface wall-normal measurements at different Reynolds number in the laboratory facility to obtain various $\Delta(U/U_\tau)$ values. For realistic roughness such as the "orange peel" pattern of a freshly cleaned and painted ship hull or the complex surface topography of a bio-fouled hull, one would need to scan or imprint the surface, replicate it (through 3D printing or CNC machine), and lay it in the wind tunnel or water channel. This manufacturing process itself is time consuming. Furthermore, it is important to scale the roughness dimension, to account for the difference in Reynolds number between the flow of a ship and the fluid flow in a laboratory wind tunnel or water tunnel (see Monty *et al*, 2016).

Apart from the manufacturing process, the time required to complete rough surface boundary layer experiments is also relatively costly. For illustration, a typical wall-normal experiment in a wind tunnel over a rough surface (such as sand paper or replica of ship hull roughness) at a respectable $Re_\tau \approx 1500$ will take around three hours to measure using hot-wire. From this experiment we can obtain one value of $\Delta(U/U_\tau)$. In order to obtain sufficient values of $\Delta(U/U_\tau)$ to estimate k_s via equation (6), more wall-normal measurements at higher Re_τ are required. The required rule to accurately estimate k_s is the need to attain "fully-rough" condition where ${k_s}^+$ has to be in the order of 70 – 100. Furthermore, δ/k has to be greater than 40 in order to minimise the effect of blockage (Jimenez, 2004). Hence the range of Reynolds numbers required is considerable high. Therefore, one would need to have access to large and costly wind-tunnel/water channel facilities to perform the investigation. Considering the challenge in measuring U_τ and k_s from laboratory activities, it is desirable to develop techniques and methodology that by-pass this need.

5. THE COLLABORATIVE RESEARCH METHODOLOGY

To meet the overarching aims of the research collaboration, the research methodologies are divided into four research strands.

5.1 RESEARCH STRAND 1: LASER DOPPLER ANEMOMETER (LDA) MEASUREMENT

Here we intend to directly measure the boundary layer development over a ship's hull under sailing conditions to monitor the influence of the accumulation of bio-fouling on the skin friction drag. The flow measurement will be made using a Laser Doppler Anemometer (LDA), which is a non-intrusive measurement technique that requires only optical access and does not require a full hull-penetration (see Tropea 1995 for further reading regarding LDA). Lewthwaite *et al*. (1984) attempted a similar study using pitot tubes.

Figure 3 shows the schematic of the experiment, where a small glass window is placed on the double-bottom hull of an operating ship. The actual set up can be seen in figure 4. The LDA measures the velocity gradient in the turbulent boundary layer formed over the ship's hull (during steady sailing) across some traversable distance from close to the hull surface, to at least the end of the logarithmic region. From the velocity gradient and traverse distance we can estimate the skin friction velocity U_τ and Hama function various $\Delta(U/U_\tau)$, allowing a direct measure of local skin friction coefficient on the operating ship. The flow over the ship hull will be monitored (along with other key data - GPS coordinates, fuel data, etc) during the entire inter dry-docking period.

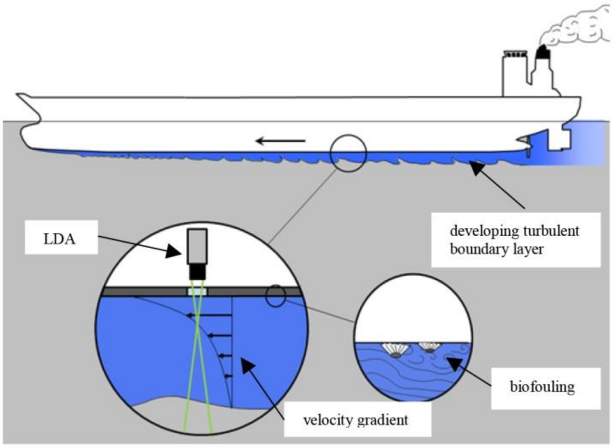

Figure 3: Illustration of the LDA with turbulent boundary layer and surface roughness in ships

Figure 4: LDA experiment set up

5.2 RESEARCH STRAND 2: IMAGE BASED SURFACE SCANNER

The pioneering work of Lewthwaite *et al* (1984) demonstrated for the first time, a successful attempt in studying the skin friction drag of an operational ship under the influence of bio-fouling. The results confirm the challenges faced by the naval industry in overcoming the deleterious effects of bio-fouling. However, one thing that was lacking in Lewthwaite *et al.*'s (1984) work is the absence of the hull-condition record.

To avoid similar drawbacks, here we propose an image-based surface scanner (via digital camera) to monitor the state of the hull surface finish (figure 5). The surface scanner is made of four digital underwater cameras that are attached to a frame. Photos taken by the cameras can be used to reconstruct the 3D topology, allowing us to investigate the roughness in detail. Figure 6 shows sample of biofouling reconstruction.

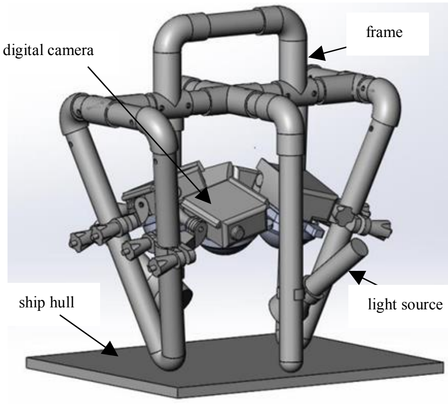

Figure 5: Surface scanner

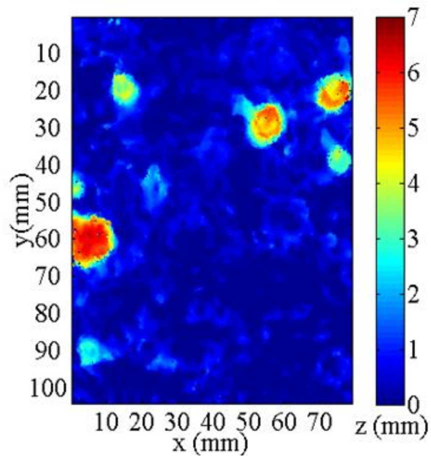

Figure 6: Digitally reconstructed biofouling from image based surface scanner

The surface scanner will record the hull condition regularly, starting during dry-docking and continuing (via dive inspections) until the following scheduled dry-docking (typically a period of one year). This allows a direct comparison between the physical dimension of the biofouling and its effect on the ship skin-friction drag. The scan data can be used to predict the Hama Roughness $\Delta(U/U_\tau)$ from the known average roughness height k_a and effective slope ES_x (Chan *et al*, 2015). Hence the prediction of Hama roughness from this surface scanning can be compared with the estimation from the LDA experiment. Furthermore, the scanned data will later be used in the third and fourth strands of this research.

5.3 RESEARCH STRAND 3: AERODYNAMICS TESTING

Here we intend to validate the efficacy of the LDA measurement technique under controlled laboratory conditions. As previously discussed, generally to predict the drag caused by biofouling, one needs to perform experiments on the surface roughness using a laboratory wind tunnel/water channel at various Reynolds numbers.

From the wind tunnel experiment we can obtain the skin friction velocity U_τ and the Hama roughness function $\Delta(U/U_\tau)$, that can lead to the determination of k_s.

There are two common methods to investigate the effects of biofouling on turbulent boundary layers using wind tunnels. The first forms a test surface from the actual bio-fouling that has been grown in their natural habitat and then removed to a laboratory for experiment (Walker *et al*, 2013). However, this technique is relatively difficult to perform due to the challenges in preserving them for lab environments, particularly the effect of change from their natural habitat, such as from sea, river or lake to lab water tunnel or channel. The second method involves replicating the bio-fouling through casting, machining, rapid-prototyping or combinations of the three (see section 3.2). The second method is often desirable because we can rescale the surface to perform tests under more convenient fluid conditions (i.e in air rather than sea-water), and it also avoids the need to introduce fouling (marine organisms) into expensive laboratory facilities.

Figure 7: Scaled replica of “orange-peel” pattern from freshly cleaned and painted Dharma Kencana IX ship hull inside a wind tunnel

Using the digitally reconstructed and scaled biofouling data from the surface scanner (from strand 2), a detailed master model is manufactured and replicated using a CNC-Machine, the material can be from plastic, engineering wax, or aluminium. From the master model, a moulding from silicone rubber is made and can be used to produce multiple epoxy casts that are identical with the master model. A similar manufacturing method was used by Nugroho *et al* (2013, 2014) and Monty *et al* (2016) for their surface roughness experiment.

Figure 7 shows epoxy casts of “orange-peel” pattern from freshly cleaned and painted Dharma Kencana IX ship hull inside a wind tunnel at the University of Melbourne. Note that the orange peel pattern was obtained via imprint from silicone rubber during dry dock, and then scanned using triangulation laser scanner. We did not use the image based surface scanner, as the apparatus was still under development in Melbourne during that period.

5.4 RESEARCH STRAND 4: DATA CORRELATION

The information from the LDA, surface scanner, and wind tunnel can be used to predict the drag of the entire ship. A recent report by Monty *et al* (2016) shows that by using information such as k_s, ship speed, kinematic viscosity, and hull length (or boundary layer length), one could numerically predict the drag on a fouled full scale ship. When combined with ship-board data such as GPS coordinates, velocity, sea-state, fuel usage, draft, this will allow us to produce a full scale prediction of the fuel drag penalty. The end result of this planned project is a catalogue of data taken over a certain period of time that will help us to produce a workable correlation/equation that will ultimately enable the hull fouling penalty to be calculated directly from just surface scan information.

From the above discussion, it is clear that this project requires substantial logistic and monetary resources. The situation is the reflection of the earlier argument by Katz and Martin (1997) regarding the need of collaboration to combine resources. Our research endeavour is currently still on its early phase. We expect further results from the LDA and wind tunnel experiment to be available in the next available report. This includes the development of the image based surface scanner.

6. CONCLUSIONS

A large scale international research collaboration with an overarching aim to understand the negative effect of biofouling on the turbulent boundary layers of ship’s hull and to improve the productivity of ship operations by providing a technique and technology that can measure the emission and fuel usage penalty more precise is currently underway. The research involves six institutions from four different countries that represent academic, industry and policy maker fields. Each of them has different and specific roles that complement each other. The three universities act as initiator and provide the necessary scientific expertise, research personnel, and equipment. The ship company provides the ship as an experimental test bed and the anti-fouling producers provide the necessary technology to repel biofouling on the ship’s hull. Finally, the classification society provides technical advice, ensures the safety of the project, and provides avenues for the research to impact government policy.

In this report we have shown that it is possible to form a large scale international collaboration despite the differences in interest and expected results for each of the three fields. The three academic institutions are interested to obtain better understanding in rough wall turbulent boundary layers, to educate higher degree students, and to have their research exposed to the broader community. The two industrial firms are interested with the possibility of having more efficient ship operation management and new technology that can be applied. Finally, the Classification Society is interested to have a better government policy based on the research outcomes. From the individual objectives of each field, one can see immediately that they are complementary and synergistic, making this a well-structured project. By satisfying the requirements and objectives of each field, the overall aims of this project can be attained.

There are four important research strands that form the pillars of the research collaboration. The first strand is to measure the effect of roughness on ship's hull in-situ using the Laser Doppler Anemometer (LDA). The second strand is to develop an image based surface scanner that allows divers to record the development of biofouling on the ship's hull. The proposed LDA experiment from the first strand is novel and un-tested, therefore to validate the technique a wind tunnel experiment is needed. The wind tunnel validation will form the third research strand. Finally for the fourth research strand we are interested to correlate the data from strand one-to-three with ship performance data (GPS coordinates, ship velocity, fuel usage, etc). This will ultimately allow us to provide a correlation that enables the hull fouling penalty to be calculated directly from just surface scan information. The research collaboration is currently underway and still on its early stage. Initial results will be available in the next round of publication.

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