IN-SITU TURBULENT BOUNDARY LAYER MEASUREMENTS OVER FRESHLY CLEANED SHIP-HULL UNDER STEADY CRUISING

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SUMMARY

A novel study on assessing the drag penalty due to hull roughness from a recently cleaned and painted ship hull is reported. Here we estimate the rough surface drag penalty by measuring the velocity profile directly over the hull of an operating ship under steady cruising using a Laser Doppler Anemometer (LDA). The novel technique is non-intrusive and requires only optical access and does not require a full hull-penetration. For this experiment a small glass window is placed on the double-bottom hull of an operating ship, allowing the LDA to measure the velocity gradient in the turbulent boundary layer formed over the hull (during steady sailing) across some traversable distance from close to the hull surface, to at least the end of the logarithmic region. Preliminary initial results show that there is an approximate 37% increase in skin-friction drag for a recently cleaned ship-hull compared to the hydrodynamically smooth surface.

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NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
ν	Kinematic viscosity (N s m^{-2})
U	Mean velocity (m s^{-1})
U_τ	Skin friction velocity (m s^{-1})
U_∞	Free stream velocity (m s^{-1})
L	Characteristic length scale (m)
δ	Boundary layer thickness (m)
z	Wall normal distance (m)
κ	Karman constant
A	wall intercept
Re_x	Reynolds number
C_f	Coefficient of friction
δ	Boundary layer thickness (m)

1. INTRODUCTION

Skin-friction drag that arises from turbulent boundary layers formed over the ship hull is one of the primary sources of energy consumption in the maritime sector. Lackenby [1] and Kodama [2] estimate that around 80%-90% of the total drag experienced by a large bulk carrier is due to skin-friction drag. If we combine it with the fact that the shipping industry is one of the major energy users in the world, with estimated 200–300 million metric tonnes of fuel consumed by more than 100,000 ships annually [3-5], it is easy to see that the a large proportion of the industry's fuel usage is to overcome the skin-friction drag. Furthermore, the oil that these ships burn is mostly of a low grade, with sulphur content that can be many times more than is permitted in diesel fuel. Hence, beyond the large energy and economic footprint, skin-friction drag also directly contributes to air pollution and health problem [3-6].

The negative energy, health, environmental, and economic impacts of skin-friction drag is further exacerbated by the presence of surface roughness [2, 7-18]. Hull surface roughness is an important, but largely unquantifiable contributor to the overall energy expenditure, emissions, and pollution from the shipping industry. These hull roughnesses are generally in the form of mechanical defects or biofoulings (the settlement of marine organisms on a surface in an aquatic environment). From a non-hydrodynamic perspective, a ship hull can often seem relatively smooth, particularly when it has just recently experienced dry-dock, where the hull is cleaned, sand-blasted, water-blasted, and repainted with anti-corrosion and anti-fouling paints. However, close inspections reveal that the hull can exhibit an "orange peel" roughness pattern that is above the ideal smooth state. Reports by Schultz [13,14] show that a plate in towing tank which is covered by biofouling and later cleaned, exhibit a higher skin-friction drag than a fresh new plate. The higher drag may arise from defects that come from the cleaning process. For a real case scenario, such as operating ship, the hull imperfection from repeated cleaning and painting process may be even more severe.

Considering the issues caused by ship hull roughness, it is imperative for naval architects and fluid dynamicists to characterise it and estimate the full-scale ship drag penalty. This would allow ship operators to estimate fuel usage and schedule the appropriate time for cleaning. Currently, the most accurate methods in estimating the drag penalty from ship hull roughness are via laboratory replication and experiment [8-18]. This method generally involves imprint and scanning of the hull roughness. The digital data is then scaled (to match the laboratory's Reynolds number) and replicated via CNC, 3D-Printing, or casting. The replicated roughness is then laid inside a wind tunnel, water tunnel, or towing tank and the flow over the roughness is measured via hot-wire anemometer, LDA, force balance, or Particle Image Velocimetry (PIV). Some studies use rotating disk or rotating cylinder apparatus to characterise the roughness (see Lindholdt et al [17] for further review). The main issue with these techniques is the cost, both in time and laboratory facility [17-19]. Furthermore, the scanning from the actual hull-roughness is generally performed over a small area, and we assume that it represents the entire ship hull (i.e. the entire hull surface roughness is homogeneous). Hence the laboratory measurement may not be able to capture the actual roughness surface flow over the hull. Another major challenge in performing laboratory experiment is the difficulty to match a real-world Reynolds number (i.e. flow over ship hull).

One method to overcome the laboratory experiment issue is to perform the measurement in-situ over a ship hull. This type of measurement technique generally uses Pitot tube that is attached under the hull of operating ship and [20-22]. The Pitot tube can be in a form of a Pitot tube rake [21] or a single Pitot tube attached to a traverse system that can move vertically in the hull-normal direction z [20,22]. These techniques allow one to measure the velocity profile over ship hull and estimate the skin friction velocity U_τ via the logarithmic -law of the wall. Lewthwaite et al [22] measured the mean velocity of a 23 m long ship hull over a two year period to monitor the effect of biofouling on the skin friction drag. Their result reveals an approximately 80% increase in skin friction which corresponds to a 15% loss in ship velocity at a matched fuel usage. Although this technique allows Lewthwaite et al [22] to measure the mean velocity U, the use of a manometer prevented them from obtaining the turbulence intensity or other higher order statistics. Furthermore, the use of a large Pitot tube may disturb the flow due to its intrusive nature and is also prone to blockage by fouling.

In order to obtain higher statistical reading without perturbing the flow over the ship hull, it is necessary to use a high-speed non-intrusive measurement technique. One such technique is via Laser Doppler Anemometer (LDA). In this study we report preliminary measurements with an LDA where we measure the mean velocity profile over a recently cleaned and painted ship hull under sailing conditions.

2. EXPERIMENT SET-UP

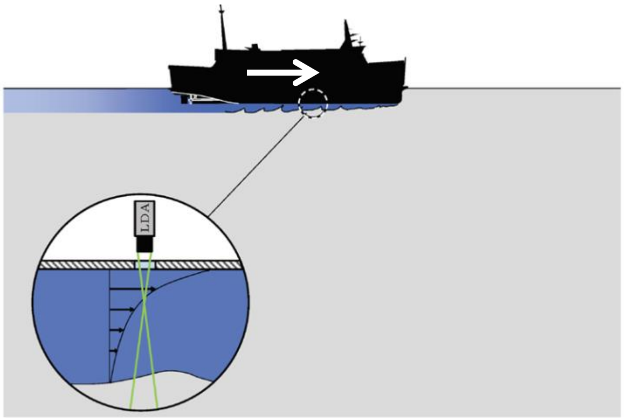

Figure 1: Illustration of the LDA set-up that measure the mean velocity profile inside the turbulent boundary layer that develop over ship's hull.

The experiment here is to use an LDA that is looking outwards via a small window/optical access installed in the bottom of the hull of a ship. The LDA is attached to a traverse system that measures the mean velocity profile inside the turbulent boundary layer (figure 1).

2.1 TEST BED SHIP DETAILS

Figure 2 : Dharma Kencana IX ferry from PT Dharma Lautan Utama (PT DLU)

The ship that is used for the experiment trial is a 70 m Roll-on/roll-off ferry Dharma Kencana IX that belong to PT Dharma Lautan Utama (figure 2). The ship operates daily serving Merak-Bakauheni line in Sunda Strait, Indonesia. The route is the busiest in Indonesia connecting the island of Java and Sumatera. The ship cruising velocity is around 9-10 knots (depending on weather), which translates to approximately 4.5 – 5 m/s. The constant velocity cruise time between the two islands is approximately one hour and fifteen minutes. The regular route allows us to perform repeatable measurement over a relatively consistent environment.

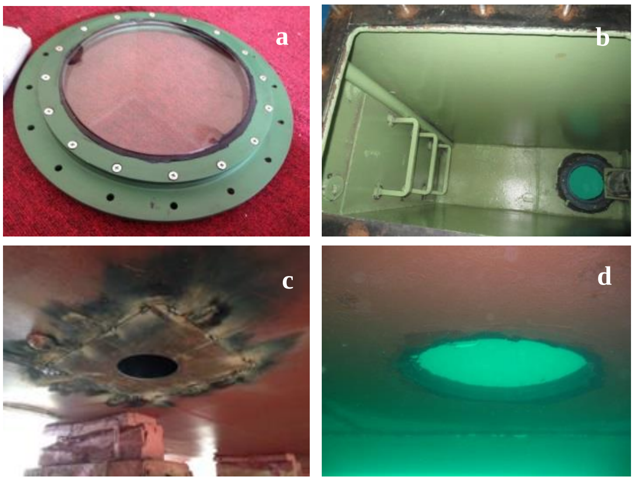

Figure 3: The water tight enclosure and window access at the double bottom hulls. (a) The optical access frame and glass, (b) Water tight enclosure inside double bottom hull with the optical access attached, (c) The circular cut for the optical access viewed from outside during dry docking, (d) The optical access viewed from underwater outside the ship's hull

A window was installed on the underside of the hull, located approximately 25.5 m downstream of the bow of the ship during its annual dry-docking and hull cleaning. The window is enclosed within a water-tight enclosure that is constructed between the double bottom hulls which also houses the LDA and computer controlled traversing rail. This enclosure ensures the safety of the ship in the unlikely event of a window failure. Figure 3 shows the enclosure and window access at the double bottom hulls. The window has a diameter of 300 mm and it is made of two tempered glass discs (with thickness of 10 mm and 12 mm) laminated with Polyvinyl butyral/PVB (with thickness of 1.52 mm) to ensure integrity.

2.2 HULL CONDITION

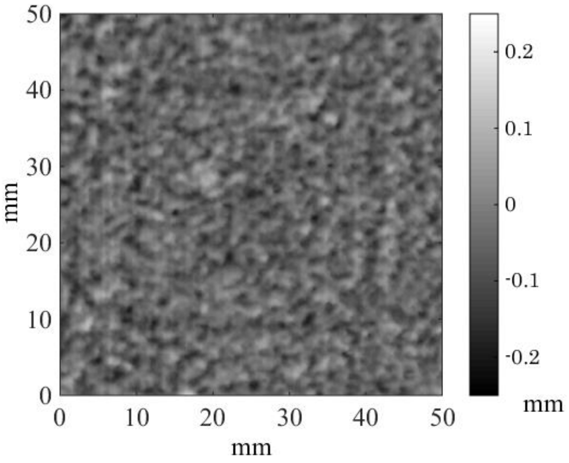

Figure 4: Lase scanner scan from a recently cleaned and painted ship hull.

During the annual dry docking, the Dharma Kencana IX ship hull is cleaned via sand and water blasting and then protected with anti-fouling paint under the supervision of anti-fouling paint producer. Figure 4 shows the laser scanning result from the "clean-hull". It has an "orange peel" pattern with roughness of ranging from 0.1-0.5 mm. Based on our personal communication with anti-fouling producer representatives, this type of hull-roughness can be found in many recently dry-docked ships, and it is relatively common. A much more severe "orange peel" pattern is even regularly found on many recently dry –docked ships.

2.3 LDA SYSTEM

The LDA system used is a Dantec two-component FlowExplorer Laser Doppler Anemometer that is attached to a Velmex computer controlled traverse system (see figure 5). The LDA consists of two cross beams at the wavelength range of 650 – 670 nm (red) and 770 – 810 nm (near infra-red). The LDA is only used to acquire the instantaneous velocity in the boundary layer when the ship is operating at cruise speed and hence maintaining a constant free stream velocity.

Figure 5: LDA system set up inside the water tight enclosure.

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In this experiment no artificial seeding in the flow is introduced, instead, the LDA relies on the natural small particles in the sea-water. The use of artificial seeding, such as glass particles is a safety hazard and can contaminate the port and sea, endangering the marine life and human alike, particularly the traditional fisherman. In this LDA experiment we use a lens with a standoff range of 500 mm.

2.4 FREE STREAM VELOCITY

Figure 6 shows the free stream velocity/cruise velocity of the ship during the LDA data acquisition. The velocities are obtained through the on board GPS system. The data shows that the ship's velocity is approximately 4.5 m/s. Note that there are slight velocity variations during data acquisition. This is due to external effects such as wind, current, and wave. The free stream velocity variation will affect the hull's mean velocity profile measured by the LDA. However, for this type of field study, this variation is considered acceptable.

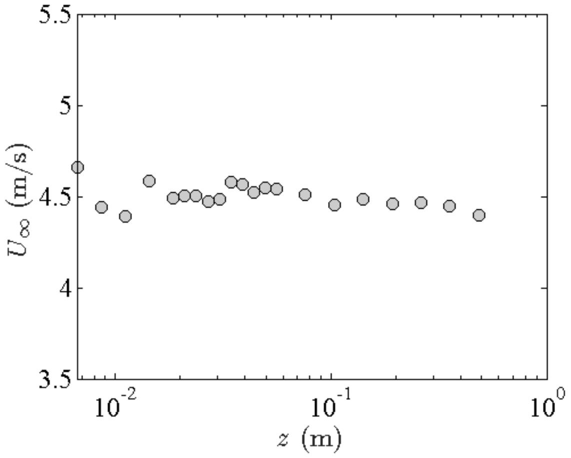

Figure 6: Free stream velocity/cruise velocity measured for each wall-normal position

3. RESULTS AND DISCUSSIONS

3.1 MEAN VELOCITY PROFILE

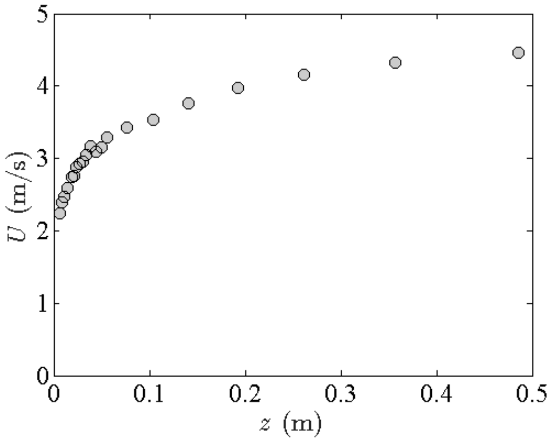

Figure 7: Mean velocity profile of the LDA reading, where U is mean velocity profile and z is wall normal distance.

Figure 7 shows the mean velocity profile of the LDA measurement over the ship hull. Here the LDA measures from a hull normal position of 6.7 mm to 485 mm with 21 logarithmically spaced positions. In this experiment, the initial measurement is located relatively far from the wall due to the difficulty in measuring the near wall flow. This is mostly due to the wall presence that changes the laser optical path and causes a shift in the measurement volume [23]. This issue is exacerbated by inconsistency in the size of natural seeding. LDA works by detecting Doppler shift from the laser that is scattered by particles (seeding) that move with the flow. The seeding particles are generally in the order of microns [24]. However, due to the lack of artificial seeding with constant size this may lead to difficulty in detecting instantaneous velocity.

The LDA starts to lose its data rate reading as we traverse further from the surface and approach the edge of the boundary layer. This may due to the laser wavelengths (red and near infra-red) that are severely attenuated in water. Hence, this has prevented us from measuring the flow velocity further from the wall. Furthermore, here we are also limited to use only 500 mm lens, as other longer range lenses cause further reductions in the obtainable data rate. Despite these issues, we have managed to acquire enough data samples to obtain the mean velocity profile.

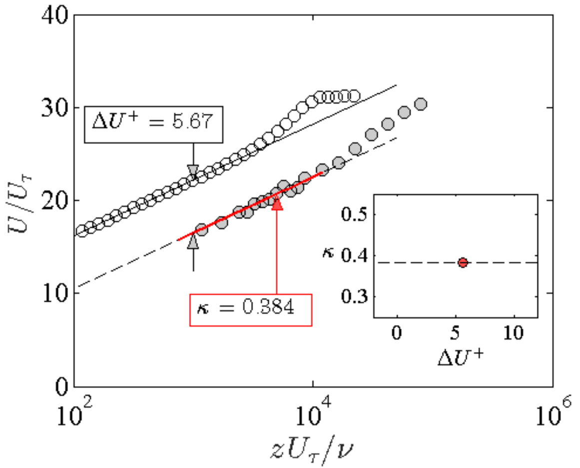

Figure 8: Mean velocity profile of smooth wall (from Marusic et al [27]), marked with open circles; and the rough ship hull, marked with grey circles. The inset figure shows the value of Hama roughness function against κ.

From the mean velocity profile, we are able to determine the skin friction velocity U_τ via a modified Clauser method [25, 26], by fitting the mean velocity profile to the logarithmic law:

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

where κ = 0.384 is the Karman constant, A = 4.2 is the wall intercept, and ν is kinematic viscosity of water. Due to the non-smooth nature of the hull surface, the entire profile will be shifted downwards by the Hama roughness function $\Delta(U/U_\tau)$. In the smooth wall case, the Hama roughness function is zero, i.e. no vertical shift in the mean velocity profile.

Figure 8 shows the mean velocity profile of a smooth wall reference (open circles), taken from Marusic et al [27]; and the rough ship hull measurement from the LDA reading (grey circles). The straight dark line is the log law over the smooth wall with Hama roughness equal to zero, and the dashed black line is the logarithmic law over the rough surface (equation 1). The figure clearly shows the a downward shift of the LDA measurement when compared to the smooth wall, with Hama roughness function $\Delta(U/U_\tau)$ around 5.67, which indicates an increase in drag penalty.

3.2 INCREASE OF SKIN FRICTION COEFFICIENT C_f

Using the mean velocity profile of turbulent boundary layer over the smooth and rough wall (see figure 8), and the mean momentum integral equation, the local skin friction coefficient C_f as a function of distance over a flat plate can be obtained. Here we follow the methods of Monty et al [18] m to estimate it numerically. Figure 9 shows the predicted average skin friction coefficient for the smooth surface (open circles) and the rough hull (grey circles) for ranges of Reynolds number,

$$Re_x = U_\infty \, L/\nu \ . \tag{2}$$

Here U_∞ is the ship free stream velocity/cruising velocity, L is characteristic length scale (or in here represents the distance from the front of the ship to the optical access). The vertical dashed black line represents the ship hull at a downstream location of 25.5 m, where the optical access located, and a cruise speed of 5 m/s.

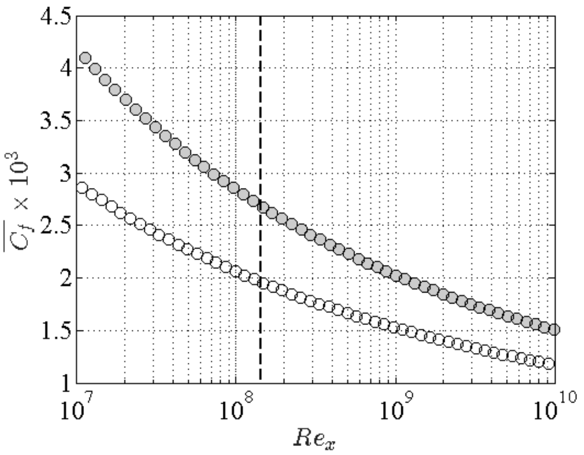

Figure 9: Average skin friction coefficient against Reynolds number for the (black circles) smooth surface and (grey circles) for the rough surface. The vertical dashed black line is the Reynolds number of the ship at downstream location of 25.5 m (optical access location) and cruise speed of 5 m/s.

From figure 9, the coefficient of friction for the hydrodynamically smooth wall at $Re_x = 1.4 \times 10^8$ is 1.96×10^{-3} (at the cross of vertical dashed line and open circle), while for the rough surface the coefficient of friction is 2.69×10^{-3} (at the cross of vertical dashed line and grey circle). From this calculation, we found that there is an increase of drag by almost 37% when it is compared to a hydrodynamically smooth wall. Such an increase is relatively significant. This result shows that even a freshly cleaned and painted ship hull, may already suffer from 37% increase of drag penalty.

Note however, that the result still needs further analysis and validation using other LDA system. Our LDA system uses red and infra-red lasers that suffer from attenuation when it measures velocity of liquid (sea water). Hence there is a possibility that we did not capture the entire flow dynamics. Further studies using an LDA that uses a blue and green laser, which will suffer less from attenuation would be desirable and would allow us to obtain a higher data rate, and hence obtain additional turbulence statistics.

3.3 POSSIBLE EFFECT FROM ROUGHNESS HETEROGENEITY AND WELDING SEAM

Beyond the “orange peel” pattern such as in figure 4, there are other possible causes of the drag penalty. Two of which that we believe have the highest impacts are biofouling heterogeneity and welding seam.

Welding seam is a common feature in ship hull that connects panels that form the hull profile. Many of these seams have significant thickness, around 2 - 10 mm. These features can act as additional trips that cause internal boundary layers that affect our reading. Moreover, it may also act as a blockage in the flow. Figure 10 shows one such seam that is located a few meters upstream of our optical access. Removing these seams would result in additional cost for the ship manufacturer and operator, hence they are rarely removed, but will reduce drag which may eventually yield net savings over the operating life of the ship.

Figure 10: Biofoulings from previous dry-docking cycle that were not cleaned due to inaccessible caused by the docking blocks and welding seam.

The drag penalty experienced by mechanical defects on ship hull is further exacerbated by the roughness heterogeneity. This heterogeneity is mostly caused by the patches of biofouling that remain from the previous cycle of dry-docking. These inaccessible patches are mostly caused by the docking blocks (see figure 10). From private communication with ship operator representatives and anti-fouling producers, it is very common to have such heterogeneity. This is due to the high cost of the dry-docking process. Removing the biofouling that is covered by the docking blocks will require an extra cycle of an expensive dry docking process (requiring a refloat).

Such heterogeneity and additional `trips' due to weld seams are believed to affect the ship's skin friction drag. Our LDA measurement may also pick up the secondary flow and internal boundary layer that is generated by the biofouling heterogeneity and welding seam located upstream of the optical access. This could also shift the Hama roughness function lower in the mean velocity profile, resulting in higher drag penalty. In the future the upstream fetch between the optical access and the front of the ship will be more thoroughly surveyed, and monitored during the experiment.

Persuading ship operators to remove such welding seam and biofouling heterogeneity would require a good economic reason. In order to provide a better argument, it is desirable to perform another measurement on the same ship where its welding seam and biofouling heterogeneity are removed. This would reduce the additional drag penalty and improve ship's efficiency. From the turbulent flow study perspective, this will also provide us with a more controlled experiment.

4. CONCLUSIONS

A study of in-situ turbulent boundary layer measurement from a recently cleaned and painted ship hull via LDA is reported. The result from this investigation shows that even a "clean" hull may already suffer from a substantial drag penalty increase compared to the theoretically ideal hydrodynamically smooth surface. Our data shows that the increase may up to 37%. The study shows the sobering challenges facing the shipping industry in dealing with surface roughness.

The results presented here reflect a preliminary investigation. Further studies using a more powerful LDA (with blue and green laser) are needed to provide better turbulence statistics. Furthermore, this also would allow us to measure further from the wall, up to boundary layer thickness δ, increasing the accuracy with which local C_f can be determined

The hull roughness drag penalty is exacerbated by the welding seam and heterogeneity that arises from biofouling that was not cleaned in the previous dry-docking cycle (due to coverage by the dock blocks). Hence there is a need to investigate this type of roughness in more detail. This includes a direct drag penalty comparison between a ship that has welding seam and biofouling heterogeneity, and the same ship that has those roughness removed.

5. ACKNOWLEDGEMENTS

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Nick Hutchins has been an ARC Future Fellow and is a Professor in Mechanical Engineering at The University of Melbourne. Prof Hutchins is an experimental researcher in Fluid Mechanics, specialising in turbulent boundary layers, rough wall flows, flow control of turbulent boundary layers, drag reduction and advanced flow diagnostics. His major contributions have been in the classification of large-scale structures in turbulent boundary layers, and also in quantifying errors in fluid measurement techniques.

Prof Bharathram Ganapathisubramani
Bharathram Ganapathisubramani is a Professor of Experimental Fluid Mechanics in the Aerodynamics and Flight Mechanics Research Group at the University of Southampton. He was previously a Senior Lecturer at Southampton (2010-2012) and a Lecturer at Imperial College London (2007-2010). There are three major strands in BG's research and he has made several unique contributions in each of them. The first strand is aimed at physics and control of turbulent flows in aero-/hydro-dynamic applications. Examples include quantifying the effects of scale interactions in turbulent shear flows, isolating large-scale mechanisms responsible for skin-friction drag and scaling of large-scale energy containing motions in smooth-wall turbulent boundary layers, effects of geometric modifications of bluff bodies on dynamics of turbulence and established scaling laws and using multi-scale geometries for flow control. The second strand is focussed on fluid dynamics of biological/bio-inspired systems. Work in this area includes CT-scan based simulation of fluid flow through lymphatic node, aeromechanics of active and passive membrane wings, evolution of flight and swimming performance of marine reptiles. The final strand, which serves as the link between the other strands of my research, is on development of new experimental and data reduction methods including pressure determination using planar and volumetric velocimetry data, temperature measurements in high-speed flows and innovative ways of examining the data.