High Performance Sailing in Olympic Classes - a Research Outlook and Proposed Directions

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HIGH PERFORMANCE SAILING IN OLYMPIC CLASSES – A RESEARCH OUTLOOK AND PROPOSED DIRECTIONS

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Abstract. The purpose of this paper is to explore research opportunities in Olympic sailing classes. Olympic classes provide high-performance sailing using a diversity of equipment, with the understanding that the equipment, individual athletes, and the knowledge relating to those two factors impacts performance. Thus, the Olympic motto, "*Citius, Altius, Fortius*" (Latin for "Faster, Higher, Stronger"), governs everyday life for many engineers. During the last few years, Chalmers has supported a project that focuses on the possibilities and challenges for research combined with engineering knowledge in the area of sports. The initiative has generated external funding and gained great acclaim within Chalmers, among staff and students, in the Swedish sports movement, and in large companies, as well as within small and medium sized enterprises. The project focuses on five sports: swimming, equestrian events, floorball, athletics, and sailing. The contribution from this paper describes an outlook identifying eight areas containing research opportunities: sailing dynamics, how to sail in Olympic classes, fluid structure interaction, surface structures, turbulence induction on the rig, equipment in Olympic classes, and applying game theory to sailing.

1. INTRODUCTION

The Olympic motto, "*Citius, Altius, Fortius*" (Latin for "Faster, Higher, Stronger"), governs everyday life for many engineers. During the past few years, Chalmers has supported a project that focuses on the possibilities and challenges for research combined with engineering knowledge in the area of sports. The initiative has generated external funding and gained great acclaim within Chalmers, among staff and students, in the Swedish sports movement, and in large companies as well as within small and medium size enterprises (SMEs). The project focuses on five sports: swimming, equestrian events, floorball, athletics, and sailing.

1.1 Purpose

The purpose of this paper is to explore research opportunities in Olympic sailing classes. Olympic classes provide high-performance sailing using a diversity of equipment, with the understanding that the equipment, individual athletes, and knowledge relating to these two factors impacts performance.

1.2 Outline of the paper

The paper describes an outlook identifying researchable problems related to high-performance sailing in Olympic classes. The paper is divided according to five directions proposed for further research. Section 2 covers sailing dynamics and Section 3 how Olympic classes should be sailed. Section 4 then explores opportunities linked to fluid structure interaction (FSI), followed by Section 5, which addresses surface structures. Section 6 progresses into turbulence induction in the rig, while Section 7 concerns one-design equipment in Olympic classes. Finally, Section 8 will articulate a new direction for research in sailing that applies game theory to sailing tactics and strategy.

2. SAILING DYNAMICS

Sailing dynamics is a research area yet to be explored. On a larger scale, ship propulsion in waves is an emerging area of study, with a focus on energy consumption. The analogy to sailing in smaller boats differs, as high-performance yachts use waves for their propulsion; this is increasingly the case in several Olympic classes by the use of pumping. The induced unsteady flows are of special interest for further research and theory, as well as in practice for sailors. Pumping can be both muscularly induced and/or induced by bodily movement, thereby presenting an array of scientific challenges.

The physics of sailing contain a number of research areas with a multitude of academic and practical interests.
As all surface vessels, a sailing yacht travels in the intersection between two media. Its difference from, for instance, a cargo ship is that the two media are of equal importance. Aerodynamic forces cause propulsion, while the resistance that it is to balance is decided by the hydrodynamics of the underwater shape. For most ships, aerodynamics is of little importance.

Especially interesting are the physics of sailing in waves, which presents a very dynamic problem. The hull must be propelled optimally in the wave in both head and

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following seas. The aerodynamics is complicated by the often sudden motions of the mast.

The competitive high-level dinghy sailor continuously changes the boat's heading, while at the same time works by moving his or her body to attain the correct heel and trim corresponding to the wave. As a trend, in several classes, it is nowadays allowed to induce planing by sudden body movements and rapid changes in the angle of attack of the sails (e.g., by sheeting rapidly, or pumping).

Little research is available about sailing dynamics. We estimate that current research efforts in this area will contribute to exploring and explaining recent developments in high-level performance in today's Olympic classes, in which athletes' fitness and strength are evolving due to the dynamic parts of sailing an Olympic dinghy. Academic endeavours in this area will be appreciated, by athletes and coaches, who will become able to adopt a more sustainable way of sailing boats closer to their performance potential.

Research in sailing dynamics will equally make scientific contributions, as well as provide spin-off effects in several areas of ship design. Propulsion in waves is a relatively new research area and, lately, of increased importance, given new requirements by energy declarations or the Energy Efficiency Design Index (EEDI). The vessels' movements in waves and increased resistance in waves are thereby of great importance and have emerged as a new focus area in research settings.

Floating offshore constructions are also influenced by waves. An adjacent area is research on waves connected to energy converting devices that transfer the motion of waves to electrical energy.

Computational methods used until now are based on the potential flow theory that neglects viscosity. This approach provides adequate results for some motions, while inadequate and generally poor results in others.

The added resistance in waves is an area in which potential flow can be used for approximations only. As aforementioned, for newly constructed vessels, international regulations will necessitate accurate predictions of vessel resistance in waves.
By using emerging computational capabilities, it is now possible to use the Reynolds-Averaged Navier–Stokes (RANS) type of methods to simulate motions in waves in viscous flows.

Contributions made in the area concerning sailing yachts, by the use of advanced RANS methodologies, can be translated into increased knowledge about the motions of ships in waves.

2.1 Sailing dynamics for a Laser dinghy

During 2014, SSPA (SSPA Sweden AB, for more information refer to www.sspa.se) has performed a series of tests with a full scale Olympic-class Laser dinghy (for a more detailed description refer to Section 3.2 or [1]). Though results from all tests are currently unavailable, a few indications of further research are indicated in this outlook. Trim and heel were systematically varied at different boat velocities. A similar investigation of a Laser hull was carried out at the University of Strathclyde [2]. However, this was done with a scale model including turbulence stimulators and the heel angle was not varied. The approach to study an Olympic class dinghy in a towing tank deviates from previous research, that for instance focuses on method development [3] or accuracy and repeatability of tank testing [4] using America's cup Class Yachts.

Due to economic constraints, tests were limited to still water without leeway, corresponding to downwind sailing in relatively calm weather.

To study leeway and the effect of the rudder and centreboard, computational fluid dynamics (CFD) was used in a master's thesis. Due to limitations in adapting the software used, the master's thesis was directed toward verification and validation of the program instead of toward obtaining new data.

An extension of the study would be to conduct the desired calculations for upwind sailing and to use measured and calculated numbers in a velocity prediction program (VPP) to optimise heel and trim depending on boat velocity (i.e., not only resistance), since aerodynamic forces are effected by the heel.

However, the major challenge lies in waves, as omitted in tests performed at SSPA, again due to financial constraints.

Both upwind and downwind, the interaction with waves can affect the optimal position of the centre of gravity. By using modern CFD methodologies combined with measured values, these issues could be addressed by using unsteady methods for both water flow and airflow.

2.2 Pumping

The next step following the above described trajectory would be to study pumping: the rapid pulling of the sail at the right time to increase boat speed and induce planing.

As described previously in this paper, the pumping technique and its use are evolving and have recently been allowed in racing.

Studies of pumping should challenge available CFD capabilities and therefore provide ample opportunities for considerable contributions.

For a Laser dinghy, we envisage the following steps:

1. Optimisation of the centre of gravity going upwind in still water.
2. Sailing in head seas, with estimated forward propelling force.
3. Sailing in following seas, with estimated forward propelling force.
4. Unsteady computation of aerodynamic forces in waves upwind.
5. Unsteady computation of aerodynamic forces in waves downwind.
6. Improvements of Steps 2 and 3, with derived forces uncoupled.
7. Unsteady computation of aerodynamic forces when pumping in still water and following seas (according to Step 5).
8. The effect of pumping and sailing in still water and following seas (uncoupled, with forces from Step 7). If this step were to couple the aerodynamics and hydrodynamics, it might become unobtainable.

The proposed actions will provide contributions to the scientific community, ship designers, and dinghy sailors.

3. HOW TO SAIL OLYMPIC CLASSES

3.1 Background

SSPA has performed tow tank testing on a Laser-class dinghy to show very interesting results on how to sail the vessel [1]. Though not presented in full in this paper, results show the necessity of more testing to achieve higher performance in Olympic sailing classes, as well as to indicate the potential benefits for sailors of the dinghies.

We have outlined proposed research directions for the Laser, the Nacra 17, the 49'er & 49'er FX, and the Finn Class.

For the 470 and RX classes, we have nothing planned although we anticipate research challenges in the area. Contributions will for the time being, be made by others.

3.2 Laser

The Laser dinghy (see www.laserinternational.org for a description) is a four-metere-long dinghy for one sailor. The Laser class has been an Olympic discipline since the 1996 Summer Olympics in Atlanta. The boat is a strict one-design class, which means that design alterations or additions of any kind are prohibited. Therefore, how the dinghy is sailed becomes ever more important, and any improvements in sailing practice will consequently improve performance in competitive situations at any level of competition.

As a result of the hull's three-dimensional shape, the flow around the dinghy differs for different attitudes to the direction of motion. This implies the possibility of locating a minimum of hydrodynamic resistance by sailing at a specific angle of trim and heel.

Hydrodynamic resistance is not the only effect that must be considered when altering the angle of heel and trim. The projected area for the centreboard and rudder is decreased when the dinghy is heeled, as is the case for the sail. Stability can decrease when trimming on the bow.

Since the weight of the sailor represents more than half of the displacement, angles of heel and trim are changed by positioning the sailor in certain positions.

At the professional level, sailors perform similarly, perhaps by having coaches providing insight into how leading performers drive their boats, and thus possibilities like sailor position must be exploited in order to gain advantage on the racecourse. There is little evidence in the literature that investigations along these lines have been undertaken elsewhere.

The governing equations for the dynamics of a fluid are the Navier–Stokes equation and the continuity equation. However, it is impossible to fully resolve the flow around a ship, yacht, or dinghy with these equations (Larsson and Raven, [5], section: 9.7.1), due to the large separation of scales in the domain and the computational effort required to handle such a separation. Since the Laser dinghy is four meters long, the smallest scales in the flow—the Kolmogorov scales—are a mere fraction of a millimetre (Larsson and Raven [5]). As a result, the resolution of the discretised domain must be incredibly fine in order to fully resolve the flow (Feymark [6]). Resolving one of the smallest turbulent scales requires approximately four cells in each spatial direction.

In this study, preparing the dinghy for tow tank testing necessitated modifications. An aluminium frame was fitted to the deck around the cockpit. This frame provided a point at which to attach the towing device and also served to accommodate the weights used to position the dinghy at the desired attitude.

The appendages were also removed in order to facilitate what is a bare hull case.

The final modification consisted of adding points at which to attach string connected to the measuring devices used to accurately measure heel and trim during speed tests. Figure 1 displays the test frame on the deck, and Figure 2 the test setup during a run.

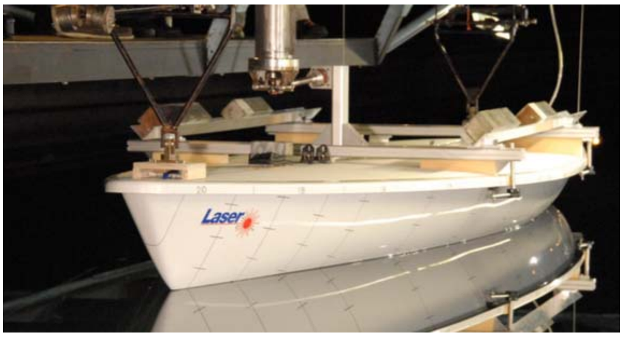

Figure 1. Photo by SSPA, showing the test-rig towing attachment and weights

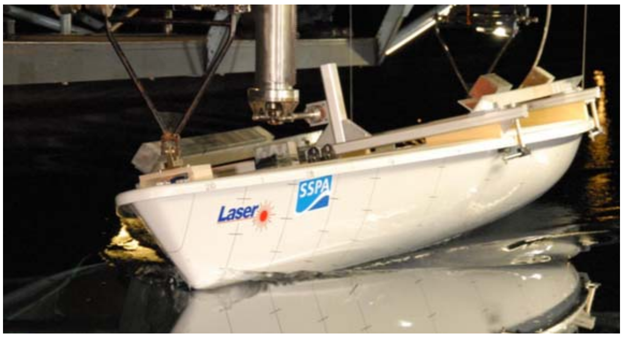

Figure 2. Photo by SSPA, showing the Laser dinghy during a run

The dinghy was towed with a rod connected to a dynamometer close to the mast position about 20 cm above the deck. The actual towing point in this study was not important since the study aimed for the actual sailing conditions regardless of how the trim and heel was achieved. In a small boat like this the person sailing it will be able to adjust position by moving forward, aft or sideways to heel or trim the dinghy to the desired condition.

The set up to the carriage allowed the hull to move freely in heave, pitch and roll but was restricted in surge, sway and yaw.

Due to limited testing time, the heel tests were only performed as heel-to-starboard tests.

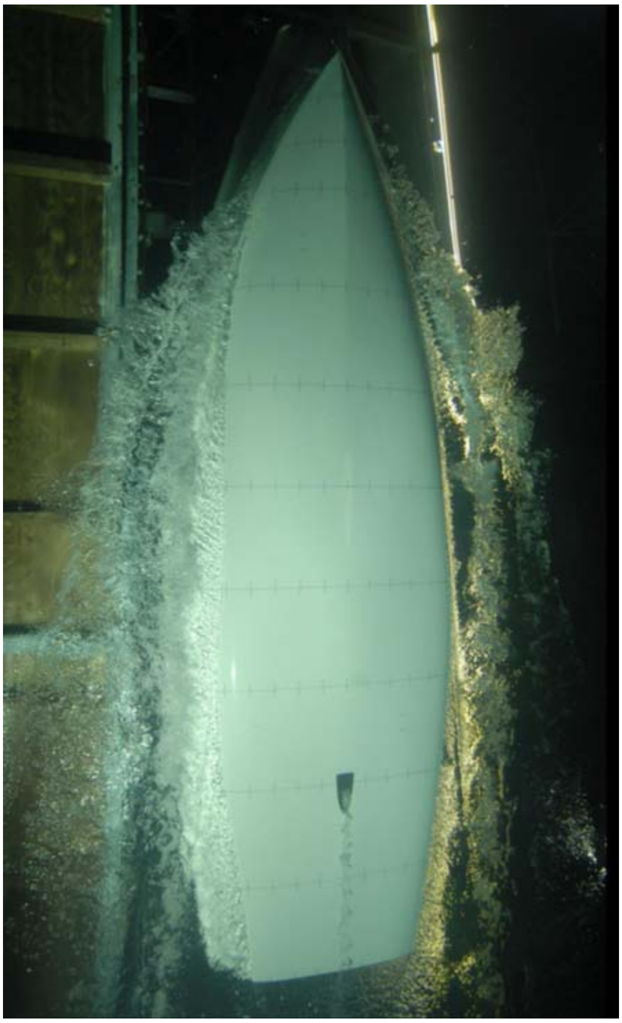

Figure 3. Photo by SSPA, showing the figure shows a test run with open self-bailer at 6 knots boat speed

The self-bailing test was successful, with a measureable difference in hydrodynamic resistance, as depicted in Figure 3. A discussion of results are beyond the scope of this paper; however, in the run at 6 knots depicted in Figure 3, the resistance with closed self-bailer was 113,228 N and with the self-bailer open 112,637 N, for a difference of 0.52%.

Studies conducted thus far have indicated interesting opportunities for future research. Sailing recommendations based on results can be provided, including adjustments to suit different crew weights. The latter can be exceedingly desirable for sailing venues with deviating meteorological conditions (i.e., high- and low-wind speeds). Also, a VPP study should be conducted.

3.3 Nacra 17

The Nacra 17 is a new addition to Olympic classes. Apart from being new among Olympic classes, the boat itself is newly constructed.

Therefore, we foresee that diverse research is available to pursue.
However, as a first step, we suggest studies of the foils and hulls in combination. Discussions with two national sailing federations have indicated the need to study the lifting force from the foils in combination with foil setup.

3.4 49'er and 49'er FX

The 49'er is a more established high-performance skiff. Apart from sharing more general questions addressed in Sections 2, 5, 6, and 8, two aspects could be investigated further, including the similarity between hull and masts from boat to boat, as addressed in Section 7. As for the others, a contribution can be made concerning the trim of the boat (i.e., crew position) downwind. Tow tank testing in full scale can indicate differences in hydrodynamic resistance for different trim angles.

3.5 Finn

The Finn dinghy is the men's single-handed, cat-rigged Olympic class for sailing. A Swedish canoe designer, Rickard Sarby, designed it in 1949 for the 1952 Summer Olympics in Helsinki. Since the 1952 debut of the boat, the design has been in every summer Olympics, making it one of the most prolific Olympic sailboats, as it is the longest serving dinghy in the Olympic Regatta. It currently fills the slot for the Heavyweight Dinghy at the Olympic Games.

The Finn is a one-design class with strict rules for the hull shape. There are a variety of builders around the world, but there seems to be no competition in using the tolerances for optimising the hull shape. The discussions are instead focused on a feature that claims to give a more competitive boat. That is, to build in a certain amount of flexibility in the forward part of the hull, which recently also has been introduced on the aft body. The flexibility in the forward part is claimed to give more speed upwind by reducing hard wave collisions, and the suggestion is that a flexible aft part could offer the adverse effect on downwind legs.

A suggested test program for tow tank testing focuses on the possibility of capturing this claimed performance edge. The test program is rather comprehensive since the effect is probably quite time-consuming to detect and verify.

The test will be performed in full-scale with hulls coming from the production lines of the boat manufacturers. It will include one model that is conventional (even stiffness) used as reference, one hull with forward part flexible and one with both forward and aft body flexible.
The explanations available for this practical phenomenon can be found in the next section about FSI.

4. FLUID STRUCTURE INTERACTION

The flow around a sail is a clear example of a Fluid-Structure Interaction, with the shape to a large extent being dependent on the pressure distribution, which is dependent on the design of the shape of the sail. In Olympic classes the hull can be designed using FSI, as previously described in section 3.5, with soft and flexible hulls to reduce resistance sailing towards waves, gaining forward motion sailing downwind from waves. The established practice requires considerable theoretical challenges in describing the phenomenon.

FSI is currently studied at our institutions, for instance in developing flexible composite propellers, which adapt to the flow around the aft of the ship. Equally, FSI emerges in importance in wave-energy and tidal-energy research. As a research area, FSI is connected to research on structures, and hydrodynamics research is an excellent example of fruitful multi-disciplinary research, see Feymark [6].

5. SURFACE STRUCTURES

Ways of reducing the resistance of ships and sail boats in motion can be further explored, and special considerations for Olympic classes are a necessity. Surface structures offer an opportunity for research in this area. It has been known for some time, Bechert and Hoppe [7], that the texture of the sharkskin reduces drag. This has been exploited in several applications, the Speedo swimsuit being perhaps the most well-known example. 3M developed a special film with longitudinal grooves, called riblets, used in the America's Cup in the 1980's. One of the authors, Larsson (and co-workers), patented a surface texture, which had both drag reduction and anti-fouling properties, Berntsson et al. [8]. For a recent review of drag reduction using riblets, see Dean and Bhushan [9].

However, the Racing Rules of Sailing, rule 53, affects surface structures, and Class Rules for each individual class can further impact manufacturing or later applications of surface structures.

6. TURBULENCE INDUCTION ON THE RIG

6.1 Introduction

By inducing turbulence on a sailing mast, the air-flow can stay attached to the mast/sail profile better than otherwise possible, thereby reducing the drag and improving the efficiency. The principle is well known in fluid dynamics and it has been explored for a mast in previous research at Chalmers, with very promising results. However, the project was halted when it was considered that it might be in conflict with class rules for the Star class before the 1984 Olympics in Los Angeles. The idea to reduce the energy needed to propel a sailboat forward is not forgotten, however, and the idea can now be explored for the Olympic Finn class. Equally interesting is the use for leisure yachts, being applicable both to furling headstays and masts.

6.2 Inducing turbulence

In fluid dynamics it is a well-known fact that roughness on the surface of a cylinder or ball can reduce the drag. For a detailed explanation of the effect, see for instance Larsson et al. [10] The reduction is achievable only for a certain range of Reynolds numbers of the order of 100 000. This number is defined as the flow velocity times the diameter divided by the kinematic viscosity of the fluid. Objects in the interesting range are, for example, golf balls and sailing yacht masts, where the fluid is air. For the golf ball the effect is exploited through dimples, which reduce the drag and make the ball fly further. For the mast there would be a double effect, since not only will the drag of the mast be reduced, there will also be a reduction in the disturbance of the flow around the sail, thus making it more effective. Surprisingly, this effect is not generally exploited by sailors.

In two Master's thesis projects at Chalmers in the 1980's, supervised by one of the authors, experiments were carried out in a small-scale wind tunnel with different mast sections with roughness, also called turbulence stimulators, with a small plate sail behind the masts. It was shown that the flow behind the sail was significantly improved by the roughness for all sections. It was also shown that the roughness elements could be made very small and concentrated at the leading edge of the mast. In the second project, a turbulence stimulator (a small ridge on the symmetry plane) was developed for the Star boat mast to be used in the 1984 Olympics. Due to some uncertainty regarding the rules for the Star boat mast the invention was not used, however. To the knowledge of the authors, the idea has neither been further developed nor used in practice. (There are rumors that a tape with some roughness elements to put on the mast was commercially available in the 1970's, but that does not seem to have been effective).

6.3 Turbulence induction for the Finn class and the Furlex profile

In a current project turbulence stimulators are being optimized for two commercially available products: the Finn Dinghy mast (Wilke) and the Furlex jib roller (Seldén). The Furlex system is used on all kinds of yachts except the smallest ones. In neither case will there be a problem with class rules. Note that the optimum stimulator size depends on the Reynolds number, i.e. both on the mean diameter and on the wind speed. The optimum will thus be quite different for the two cases and it will have to be optimized for a certain wind speed. The stimulator will also work for other speeds, but not as well as for the optimum speed.

The optimization of the stimulators will be carried out through wind tunnel measurements of the mast and roller sections with a plate sail behind them. Different stimulators will be applied and the flow measured on the leeward side of the sail. The configuration with the smallest disturbance from the mast/roller will be selected. An estimate of the achievable speed increase of the yacht due to the stimulator will be made. Note that even very small speed increases (less than one per cent) are decisive for the outcome of a yacht race.

Wilke has had a continuous development of their Finn masts for more than 15 year, albeit the aerodynamic profile of the mast has remained relatively the same, as the investment in testing an aerodynamic profile usually lies outside the budget for small- and medium sized enterprises. The profile of the mast is allowed to be changed with regard to class rules. However, since each mast is tailored to specifications of the customer regarding bend-characteristics, a change in the profile will require adjustments to moulds and lay-up of the carbon fibre in the masts.

For Selden, the situation is different. Since autumn 2013 Seldén Mast had "aero grooves" implemented in their furling jib systems. A complete range of the system is in progress, covering boat sizes from 8m to 20m, with the Furlex model series 100, 200, 300, 400 and 500.

So far Seldén mast has spent hours on product design and aerodynamic investigations and on test sailing. These changes to their design were made on the assumption that any change in the design might have this effect, since knowing of the idea in principle. Thus Selden has a product in place and could verify the concept, as well as getting research done in showing what the design should look like.

7. ONE-DESIGN EQUIPMENT IN THE OLYMPIC CLASSES

All Olympic classes are one-design classes, albeit with different rules. The concept of one-design is that the race results should be adhered to by the individual performance and capability of the athlete – not the material that each athlete uses. In a one-design class there should be equality in the equipment used.

The opposite is presented, for instance, in the America's Cup, with the development on new designs that can have a decisive impact of the outcomes of races and overall results in a series of races.

Inside the Olympic one-design classes, there are different strategies for the one-design concept. On one end of the scale, there is the Laser, with the entire boat and equipment being supplied to the athletes (with small exceptions due to personal preferences). At the other end there is the Finn class with extensive development of masts, sails and hulls, both in materials (mast and sails) and regarding shape (sails, hulls) and structural properties (hulls). And in between these two, the other classes have to select equipment from a few accredited suppliers and shapes.

The differences that might occur in the equipment are spurred by gossip and scuttlebutt amongst sailors, coaches and manufacturers, which leads us to stipulate the following research statement:

> *"How different is equal? One-design equipment in the Olympic classes."*

Initial tests of equipment show that there is a divergence in similarity. How equal are 49'ers manufactured from different moulds? How equal are two sets of foils for a Laser dinghy? How stiff is this top-mast for my Laser? Will I be affected by repairs on my foils, or should I just purchase another set and sell these to a master sailor? A researcher being close to elite sailors will, after a while, get used to these questions. Figures 4, 5, 6 and 7 illustrate a few initial efforts from our research group, scanning a Laser hull, and rudders and centreboards from several boats in varying conditions and ages. The surfaces were analysed, and for the rudders the surface roughness was measured. Alas, these interesting results are outside of the scope of this paper, they only indicate the need for further investigations.

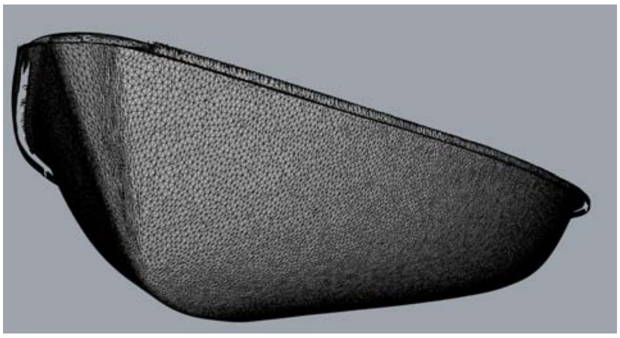

Figure 4. The figure shows the results from the scanning of a Laser dinghy.

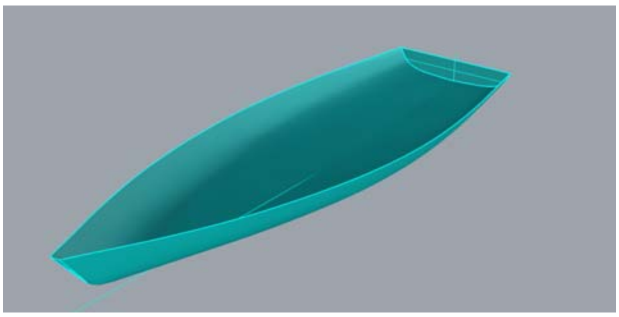

Figure 5. A recreated CAD file for the measured Laser.

The area requires more research into causes and effects on performance.

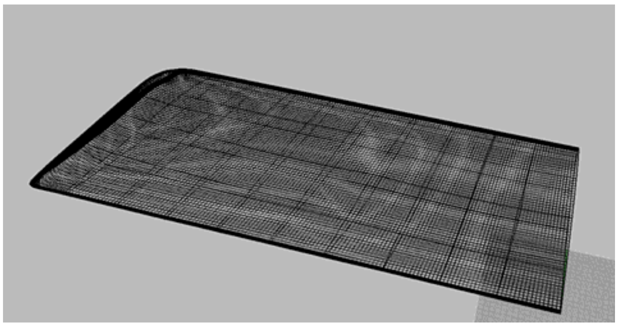

Figure 6. The figure shows the results from the scanning of a Laser rudder.

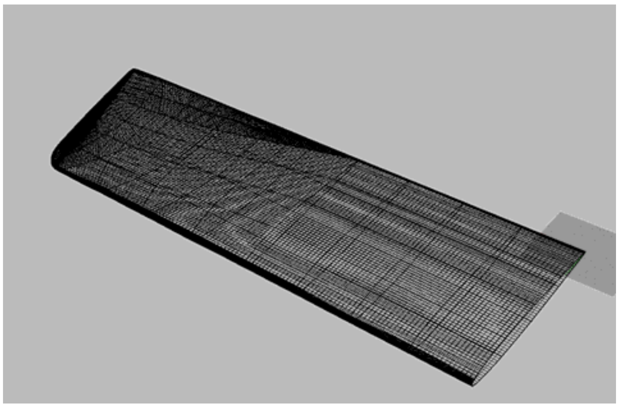

Figure 7. The figure shows the results from the scanning of a Laser centerboard.

In other sports, these issues relating to equipment have been regulated, either by international federations or by certified research institutions testing the equipment. We suggest a similar approach for the sailing sport.

8. APPLYING GAME THEORY TO SAILING TACTICS AND STRATEGY

Modern era game theory started in the 1920s in Princeton, with John von Neumann [11] taking the lead. Later, another Princeton-John followed. John Nash [12], whose life was portrayed loosely in the motion picture "A Beautiful Mind" [13]. The scientific areas that today apply mathematical game theory are Economics, Ecology and Peace and Conflict research.

Game theory fills a void in the world of sailing. Sailing as a sport contains many variables to consider for the individual athlete. These variables are considered by the athlete, and as the play during a race evolves, new situations and decisions have to be made continuously, all favoring the use of game theory to reduce risk or increase chances of success. And any facilitation in the constant decision making is favored by the sailor.

Up until this day, we have a few well-defined problems identified, showing the potential, and indicating how very different areas can be mathematised in this way. To illustrate the use of game theory, we propose studies of two situations: The start of a sailing race, and the rounding of a windward mark.

8.1 Two practical examples of game theory in sailing

The start of a sailing race can for the uninformed look like a collection of boats collectively sailing in somewhat orderly shape in the same way. Or, for the initiated, as a very intense, physically and mentally demanding situation, making or breaking your day, week or sailing career.

The start involves summarizing your entire experience and knowledge in diverse areas such as meteorology, competitors, your equipment, and your own abilities. All evolve into how you start that very specific race.

One of the hottest areas in game theory could be applicable in this situation - mean-field-theory [14]. To offer a practical example of the problem in a sailboat race, suppose that the number of tactics in the start could be simplified into 5 different tactics (which might not deviate much from how an elite racer might structure his or her options). The five tactics could be windward start, leeward start, starting on a port tack, starting in the middle or starting between the middle of the line and the windward end.

Suppose also that there is a large number of competitors, and that the sailor keeps track of how the successful competitors started. By mimicking their tactics for the next start of a race in the regatta, we get an evolutionary process. However, this also implies that the preconditions are radically affected by the actions of other sailors. The desired starting position is where few others are to attain as much free wind as possible, which will be in conflict with the preferred starting position from the previous race.

It is this conflict that drives the game theoretical problem. One research question could be if there is one evolutionary stable tactic.

8.2 The windward mark rounding

If the sailing race is allowed to proceed, the sailors will eventually be encountering the problem of the windward mark rounding – exiting as well. But, in the context of game theory, the decisions that need to be made by the athletes are once again interesting to study. Bare-away or gybe set? I.e., continue to sail on the same tack, or immediately gybe after the mark? Once again, this would be an area benefiting from game theory.

Both problems described above could be studied in theory alone, as well as being aided by large agent-based simulations.

9. CONCLUSIONS

This paper has presented a multitude of research challenges related to high-performance sailing in the olympic classes. Sailing provides the practical problem motivation for these research areas, that provide excellent research opportunities and prerequisites for excellent world class research within their respective fields.

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