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EXPERIMENTAL INVESTIGATIONS ON CONVENTIONAL AND UNCONVENTIONAL BOOST SYSTEMS TO ASSIST TAKE-OFF OF HYDROFOIL CRAFTS

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Abstract. In 2020, a dedicated research regarding the take-off was granted. The objective was to investigate experimentally unconventional solutions to overcome the take-off hump; this challenge implies the risk to identify also not successful solutions but, at the same time, to dare looking beyond the current state of art. Inspired by nature, an impulsive boost could be used to overcome the take-off hump of the hydrofoil craft's resistance: the modelled mechanics were inspired to the impulsive boost thrust generated by the ink fishes or by a rapidly flapping hydrofoil. Together with the experiments of physical unconventional boost systems, a systematic investigation on the required boost thrust, energy and power was also carried out by means of a dedicated model test set-up. Objective was to answer questions such as: What kind and how much of boost is needed to let the craft take off? For how long is this boost needed? Which solutions are more promising for further development?

1. INTRODUCTION AND OBJECTIVES

When thinking about high speed crafts and application of hydrofoils in the maritime world, the imagination of most goes to the sailing boats of the Americas cup AC75 class or high performance passenger or recreation vessels. These applications are typically characterised by light displacements. Foils for larger displacements are challenging to apply due to limitations such as the excessive power demand, in first instance, at the take-off. However the possible economic and emissions-related advantages to operate in foil-borne mode triggered the interest to explore new ways to assist the take-off phase, also for relatively "heavy" payloads.

In 2020, a research project was granted with the objective to investigate experimentally unconventional and innovative solutions to assist the take-off. This challenge implied the risk to identify also not successful solutions but, at the same time, to dare looking beyond the current state of art. The investigation of "out of the box" solutions implied that the required level of detail at this stage was low: the primary interest was to evaluate multiple promising solutions rather than focusing only on one case, with the knowledge that success was not guaranteed for any of the tested alternatives.

2. APPROACH

The main focus of the research was on solutions to develop an impulsive boost thrust to assist the take-off in calm water. An example of typical (but not general) relation between steady resistance in calm water and speed for a craft with hydrofoils is presented in Figure 1. Prior to take-off, the resistance has a peak ("take-off hump") to overcome. In that respect, from an ideal point of view, there are two options: one is an "oversized" standard propulsion system in order to generate the entire required thrust; another one is the integration of a boost system that provides only part of the total required thrust.

The last alternative appears to be more promising if:

- The standard propulsion system is capable to generate propulsive thrust for the speeds before and, especially, after the take-off hump (otherwise the craft will revert to the less efficient hull borne condition)
- The system to generate the required boost thrust should not take a too large percentage of the total displacement (at cost of the available payload on board)
- It should be practical to integrate such a boost system in the ship design.
- The overall life-time cost (in economic and environmental terms) should be lower than an equivalent vessel with a larger main propulsion unit.

The first priority of the experimental campaign was to answer questions such as: What kind and how much of boost thrust is needed to let the craft take off? For how long is this boost needed?

The energy/power demands to provide this required boost thrust were only briefly investigated in the this research campaign. Their role is absolutely fundamental to further advance the feasibility of solutions and to evaluate the impact on the total weight of the craft.

2.1. Take-off hump

Figure 1 shows a resistance curve with a pronounced take-off hump. If this hump were not very high, almost flat, the boost force required to take-off would be very small and, in general, the application of a dedicated boost system might be not so advantageous.

The take-off hump depends on multiple factors:

- Hull displacement
- Hull form

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- Hydrofoils and their eventual surface control (such as flaps) design
- Sea state
- Design take-off and cruising speed

Once all of these factors are evaluated for a specific design, further studies can be performed to finalize a boost system for the take-off. As a consequence of this, the results of this research cannot be generalized to all hydrofoil crafts but only used as a first reference for feasibility studies in early design phase.

3. MODEL SET-UP

The following key elements are discussed in the next sub-sections with respect to the model test set-up:

- Hull form and hydrofoils
- Captive and semi-free sailing set-up
- Boost systems (virtual and physical)

3.1. Hull form and hydrofoils

The objective behind the selection of the hull form and hydrofoil was to have a representative demonstrator for the application of the different boost systems. Thus, there was no need for an in-depth optimisation as long as the complete package (hull plus hydrofoil) had a clear take-off resistance hump and the hydrofoils were delivering enough lift for take-off (and steady foil-borne condition).

The shape and main dimensions of the hull were chosen based on considering a selection from MARIN's database of planing crafts with (and without) hydrofoils. Figure 2 shows the body plan: a typical form for high speed hull (and foil)-borne applications. Figure 3 shows the main particulars of the selected hull compared with database values. Table 1 present the main characteristics of the hull on model and full scale (for the chosen scaling factor of 10).

The hull was equipped with two sets of hydrofoils: the front set consisted of surface piercing J-hydrofoils while the aft set consisted of one deeply submerged inverted π hydrofoil. Figure 4 shows an overview of the hull model with the hydrofoils.

The configuration with surface piercing hydrofoils was chosen in order to have a self-stabilizing platform, with no need for a dynamic lift control system.

The main dimensions and location of the hydrofoils were designed for stability in foil-borne condition. The design alternatives were evaluated by means of MARIN's in-house codes Hydsim and Hydres (based on simple lifting line theory and vortex lattice method). The resulting configuration was the well-known "airplane" with the largest percentage of lift allocated to the front foil (while the aft foil working mainly as a pitch stabiliser).

The design angle of attack of the foils was estimated in the design phase and further fine-tuned manually in the tank, to allow for scale effects compensation.

Figure 4 shows also anti-ventilation plates applied to the front foil. This was necessary due to frequent instability caused by random ventilation events.

3.2. Captive and semi-free sailing set-up

Two model test set-ups were used for the experimental campaign: captive and semi-free sailing.
The captive set-up consisted of a traditional system for towing tests: the hull was towed by the carriage via a six-component force frame; pitch and heave were free but not roll and yaw. The towing force, pitch and heave were measured. This set-up allowed to measure the steady resistance curve of the craft as well as static sink and trim as a function of speed, which represented the basic input information for the campaign with the second test set-up. In fact, recalling Figure 1, with the knowledge of the total resistance at the take-off hump it was possible:

- to identify the speeds in hull-borne and foil-borne condition and their correspondent resistance demands;
- to identify the thrust force needed for take-off and for steady foil-borne cruising;
- to identify the minimum boost force in order to reach the take-off speed.

The semi-free sailing set-up was meant to allow the craft to be accelerated by the combined action of main and boost thrust forces, to reach the take-off speed and overcome the take-off hump (if the boost impulse is sufficient) and then to keep flying (by means of only the main thrust force). Normally a completely free sailing and self-propelled model could have been also considered, despite for example the additional complications of the installation of a dynamic control for the course. For this experimental campaign a different approach was chosen:

- to simplify the model test set-up from the dynamic control aspects;
- to have a controllable towing force resembling the thrust action of the propulsors;
- to have a controllable boost force (in magnitude and release time) to superimpose to the aforementioned force;

Figure 5 shows photos of the semi-free sailing set-up and its schematic working principle. The hull was connected to the carriage via two longitudinal lines controlled by electrically driven winches and four transversal lines connected directly to the carriage with springs. The role of the transversal lines was to restrain the model from uncontrolled yaw motions. The longitudinal lines had two main tasks: to apply a controlled propulsive (and eventually boost) force and to control the position of the model. In fact the model was not towed by the carriage but freely accelerated thanks to the forces exerted by the winches. The carriage control was all the time following the virtually self-propelled model based on the input given by the winch position (and consequently) the relative position of the model respect to the carriage. Force transducers were applied to the front and aft winch lines in order to monitor the applied longitudinal force. The semi-free sailing set-up was also used in "towing" mode to measure the towing force. However in this mode the accuracy of the measured resistance was lower because the model was relatively free to yaw (implying extra additional drag) when advancing.

3.3. Boost systems

In this section, only the description of the boost systems is presented together with their working principle. In the discussion of the results, a more detailed analysis is given about their effectiveness and eventual improvements.

The previously described semi-free sailing set-up allowed to perform systematic investigations on the required boost thrust and release time in order to attain the take-off speed and then steadily remain in foil-borne condition. Therefore this was considered as a first "virtual booster" (also named Booster 1). The advantage was the possibility to derive some preliminary indication of the required boost energy and power for the take-off. The input parameters for the control of the winch force were defined as follows:

Name	Description
F_main	Main propulsion force to drive the boat to a higher constant speed once foil-borne
F_boost	Additional boost force exerted to reach the take-off speed
t_up	Time to sum the F_boost to F_main
t_boost	Release time of the boost force
t_down	Time to remove the boost force

This type of set-up could be generally applicable for any hull-hydrofoil design case, where the demand of thrust, energy and power could be investigated in order to identify the most suitable boost system .

In parallel, physical boost systems were developed based on nature concepts, such as the one generated by the ink fishes or by a rapidly flapping fin. The complexity of the engineered systems was kept simple, since the first objective was to evaluate how promising such concepts could be. Further design loops and refinements would be required for actual implementation.
The physical booster systems were tested with the semi-free sailing set-up. In this case only the main propulsion force (F_main) was constantly applied to steadily sail the boat before and, eventually, after the take-off.

The first physical system considered was the Flapping aft foil-Booster 2. Figure 6 shows a photo of this system: the aft foil was connected to a pneumatic linear actuator (manually driven for multiple actuations) pushing the foil vertically downwards (from a higher position to the one designed for the steady flight). The speed of actuation could be varied by changing the air pressure in the actuator, while the angle of attack of the aft foil remained fixed.

Impulsive lifting vertical and propulsive horizontal force were produced when the foil was pushed vertically downwards and advancing at speed, thanks to the instantaneously variation of the inflow conditions (effective angle of attack and velocity) to the foil.

The second physical system considered was the "Waterjet-Booster 3". Figure 7 shows an overview of the system and its installation on board of the model. The inspiration comes from the squid ability to generate an impulsive force by jettison water at high speed. The physical principle is the change in water momentum thanks to the conversion of pressure energy into kinetic energy. This principle is common in the maritime sector when thinking, for example, of the propulsion waterjets. However, unlike a normal waterjet, the adopted one was a closed system with a limited capacity of stored water. Quantity of water in the cylinder, water pressure and nozzle diameter were varied to control intensity and duration of the boost force.

In line with spirit of this research campaign for high risk (of failure) innovative solutions, an additional system, still inspired by the squid, was tested with a dedicated set-up in bollard pull condition. Figure 8 shows an overview of this concept booster, named "Squid concept – Booster 5": two elastic and strong bags were in contact with each other; one bag was filled with (variable) pressurised air and pressing the second bag (filled with water and connected to a nozzle variable in diameter). This booster represented a further step into the biomimetic, attempting to reproduce closely the squid mechanism (a water-inflated elastic membrane capable to release quickly water at high speed and consequent large developed boost thrust). The controllable parameters were the pressure (in this case only the air bag), quantity of water and nozzle diameter.

The last physical booster system mounted in the model (precisely on top of the hull deck at the stern) consisted of one high power air turbine (named "Air turbine jet – Booster 4). Figure 9 shows a photo of the system. By varying the revolution rate of the turbine different horizontal thrust force (or eventually a combination of vertical and horizontal) could be generated to provide the boost and to reach the foil-borne condition.

4. DISCUSSION OF RESULTS

The results are first discussed on model scale followed by considerations on full scale (when applicable). For simplicity, only tables of extrapolated results are presented in this paper.

4.1. Model scale

4.1(a) Captive set-up

The first step of the model test campaign was to determine the steady resistance curve, shown in Figure 10, in order to:

- Identify the take-off speed (around 5 m/s);

- Fix the minimum main propulsive force (around 101 N) to have the boat steadily sail in foil-borne condition at speeds beyond the hump;
- Identify the minimum boost force (about 4 N) to reach the take-off.

With the minimum boost force, time and distance for take-off were on the limit of the testing conditions (maximum length of the basin). Therefore the choice of the boost force input for the virtual system was set for values at least three times the minimum one so that take off could be achieved within the available basin length. For the physical boosters, it was not known in advance how much boost force and release time would have been deployed. It was directly found out during the experiments with the maximum available basin length.

From the captive set-up, the boost force and release time developed by the Flapping aft foil-Booster 2 and the Waterjet-Booster 3 were also preliminarily measured for some combinations of their input parameters.

In terms of deployed horizontal boost force, the "Flapping aft foil-Booster 2" was capable to generate enough force to push the craft beyond the take-off hump but the release time was very short (less than 1 second). In this experimental campaign a simplified set-up was chosen in the spirit of a preliminary investigation: both parameters, speed of actuation and angle of attack, were kept constant. The action of boost force (and consequent acceleration when in semi-free sailing set-up), obtained when kicking downwards, were unfortunately cancelled by the motion upwards. Both aspects are shown in Figure 11.

4.1(b) Semi-free sailing set-up

The second step of the model test campaign, in semi-free sailing set-up, investigated which systems (and their combination of parameters) could provide enough boost for the take-off and maintain a steady foil-borne condition. For all the tests, the testing sequence was as follows:

- A constant propulsive force "F_main" of 101 N was applied mimicking the action of a main propulsion system. Given the steady relation between resistance and speed, this force was capable to maintain a speed of about 4.6 m/s before take-off (and about 5.5 m/s once in foil-borne condition);
- Initial acceleration up to 4.47 m/s by means of towing action of the carriage via the winch system;
- Switch from "towing mode" to "following mode", where the model is free to sail and accelerate in response to the applied propulsive forces (F_main and F_boost);
- End of the run with deceleration controlled in "towing mode".

The tested physical systems, excluding the flapping aft foil-Booster 2, gave enough boost force to reach a stable flight, provided that the combination of booster force and release time was sufficient. The cases where take-off was not successfully reached are specifically mentioned in the tables introduced along the discussion.

4.1(c) Virtual booster

The first tested booster was the virtual one. Figure 12 shows the applied boost profiles in terms of force and release time.

A successful boost action was identified by take-off and steady sailing at speeds above 5 m/s (which corresponded to a full foiling condition). In that respect, only one combination of booster input (15 N force applied only for 1 sec) resulted insufficient to reach a steady flight.

The results for the virtual booster clearly indicated that, with the same booster force, release times shorter than 2 seconds were likely not enough to reach a steady full foiling condition.

4.1(d) Physical boosters

For the Flapping aft foil-Booster 2 the release time was very short (about half second): a longer actuation (and acceleration) time was needed by means of multiple kicks. However to be efficient and effective, these kicks demand necessarily a variable vertical speed of actuation combined eventually with a variable angle of attack so that no increase in the resistance is experience during the upwards motion. As said before both parameters were kept constant with the consequent continuous cancelling of the propulsive action (kicking downwards) by the upward actuation of the foil. Figure 13 shows an example of the model speed behaviour combined with the multiple kicks. Further development and optimisation in the biomimetic aspects of this mechanism could improve the effectiveness of the system.

For the waterjet-booster 3 some of the conditions (pressure and nozzle dimeter) tested in captive set-up were investigated to evaluate whether the take-off and steady flight were effectively reached or not.

The Air turbine jet – Booster 4 was tested only with the orientation to generate only horizontal boost force (measured at the location of the turbine).

For "Squid concept – Booster 5", Figure 14 indicates the possibility to eventually generate comparable booster force although the challenge (similarly to the Booster 2) lays in the release time: for Booster 2 the release time depends on factors such as the vertical length of the actuation motion and the possibility to perform multiple kicks to generate efficiently enough vertical and horizontal boost force; for Booster 4, the capacity of the "water bag" can represent the biggest challenge (with the same input pressure and nozzle diameter).

The working principle of the Waterjet-Booster 3 and Squid concept – Booster 5 are the same (impulsive force generated by change in momentum of water ejected at high speed). The mechanism is very different but both systems on model scale were capable to develop similar boost force. This comparison is however approximated and not entirely fair because the Squid concept – Booster 5 was tested only in bollard pull condition. Nonetheless it remains an interesting exercise to explore alternative ways to generate a boost force.

4.2. Full scale considerations

Table 3, Table 4and Table 5 shows the relevant parameters for the take-off extrapolated to full scale (especially concerning the boost force, release time, attained speeds, take-off distance). For the test with the virtual booster, there are additional output values discussed in the next subsection. Some considerations about the extrapolation procedure and possible scale effects are treated in subsection 4.2(b).

The ensemble of investigated booster forces and release times gave a reference for the testing of the physical systems in terms of required conditions for successful take-off. In that respect Figure 15 shows a correlation between these two factors (booster thrust and release time) and the successful (or not) take-off (which includes a reached stable flight). It is important to realize that such a figure is not general applicable because the trends can differ in relation to different hull form, hydrofoils, displacement etc. However, as initially said about the representability of the hull model, this investigation can set some initial boundaries about feasibility and promising level of new ideas.

4.2(a) Power/energy requirements and impact on displacement

An additional analysis of the tests with the virtual booster was performed to evaluate the boost demands in terms of energy/power and the impact on the additional weight when existing systems are integrated to the standard propulsion system (battery or supercapacitors packs).

For each test, the booster thrust was constantly applied for the chosen release time. The speed before and after the boost is constant, steadily increasing during the release of the boost force. The total and boost power can be derived as the product of respectively the total thrust force and boost force with the instantaneous speed. Furthermore the integration of the power over time gives respectively the total and boost energy. As an example of this analysis on model scale, Figure 16 shows the model speed and the total power in function of time.

It was also considered to use modern electric drive systems to provide the boost power. Systems like batteries and supercapacitors are now used in various applications to provide high peak powers during short timeframes. These systems have higher power densities than conventional combustion engines, and thus are interesting to consider for the boost power. Table 3 shows the extrapolated booster power and energy together with the estimated weight of battery or supercapacitor packs.

The weight estimation of battery and supercapacitors is derived from the Ragone chart plotted in Figure 17: in correspondence of release times close to the measured ones (10 or 20 seconds) there are different effective power density values for batteries and supercapacitors. From the power density, energy density and the boost power, the system weight is calculated. In case of the battery package the impact of the discharge rating on the weight is also taken into account (batteries need to be of a certain size to be able to discharge an amount of power greater than their energy capacity). In the computation of the weight a conservative factor of 5 kg/kW was considered to include the additional weight of all the other systems integrated, like electric drives, converters. These considerations about weight are clearly preliminary and they can change based on the required power and actuation time. For example, longer actuations (in the order of 2-5 minutes) can invert the rank of the lightest solution between battery and supercapacitors.

The importance of the weight estimation of the booster systems is crucial to judge their feasibility (and worthiness): for a given total displacement, an excessive weight might lead to a not economically acceptable reduction of transported payload; furthermore the initial investment cost for a more complex design might not be justified economically.

Figure 18 shows some historical data [1] about the typical weight distribution of hydrofoil craft. The source of data is quite old (1954). It is reasonable to expect that with the current technology some weight components (such as hull and hydrofoil structures or machinery) could be reduced, but not drastically. However this figure provides a reasonable picture to derive initial feasibility considerations. In a range of displacement between 30 and 100 tons, the available payload (in percentage of total displacement) is about 30% and the presence of the boost systems (battery or supercapacitors) would reduce if by a range between 2 and 10%, depending on the take-off requirements (power, boost thrust, release time and acceleration).

For the tested physical boost systems, an estimation of their impact on the weight would require a more in depth analysis and design refinement.

4.2(b) Extrapolation and scale effects

The results of the measurements were scaled up to full size values according to Froude's law of similitude. The scale considered was 10 and in Table 2 the scaling factors as applied are shown.

No dedicated extrapolation procedures were adopted considering that this research belongs to a very preliminary design phase, where the focus was to derive trends and orders of magnitudes.

In a more advanced design stage, the boost system mechanisms described in Section 3.3 should be subject of additional in depth investigations. For their experimental assessment, scale effects can affect the performance as follows:

Boost system	Factors scale affected
Flapping aft foil-Booster 2	Viscous effects on angle of attack Viscous drag Actuation speed
Waterjet-Booster 3	Weight of the system Local headloss at nozzle
Air turbine jet–Booster 4	Turbine mechanisms and weight
Squid concept–Booster 5	Elastic response of the air and water bags Viscous flow in the bags Local headloss at nozzle

The above table is meant as an overview of the main scaling issues but, once identified a promising system, more in-depth studies are necessary.

Beyond the scale effects on the single booster mechanisms, it is worthy to remind other relevant aspects to take into considerations when testing a full foiling craft:

- Scale effects on the free surface (especially in relation to ventilation issues in case of surface piercing hydrofoils)
- Position of the towing point (unless a full self-propelled free sailing set-up is used).

5. CONCLUSIONS

An experimental model test campaign was carried out to investigate unconventional and innovative solutions to assist the take-off of hydrofoil crafts. The primary objective was to evaluate new "out of the box" ideas rather than performing a complete design loop for one system. This challenge implied the risk to identify also not successful solutions and/or to realize the steps to be taken for further development and optimisation.

The hull form was meant to be as representative as possible with respect to the main dimensions and displacement. The hydrofoil configuration was treated only as a "lift generator" for the take-off and not optimised.

One "virtual booster" system allowed to explore systematically the correlation between the boost force and release time to successfully take-off and to reach a steady foil-borne condition.

Four physical booster systems were experimentally tested. They were inspired to the impulsive boost thrust found in nature. Among them, the waterjet-Booster 3 proved to provide enough boost thrust and release time; similarly the Air turbine jet – Booster 4. The Flapping aft foil – Booster 2 did not succeed to reach take-off but it could be promising with further development and optimisation into a more elaborate motion pattern during the kick (including variable angle of attack).

A correlation between inputs (booster thrust and release time) and the successful (or not) take-off was estimated to provide a preliminary feasibility tool on the feasibility and on the promising level of these unconventional possible installations.
The impact on the total weight of the craft was estimated when using other new boost systems (such as battery or supercapacitors drive systems).

The investigations and results presented in this paper represent only a first step after which a more in depth research and design are required from the industry for those systems considered most promising (and suitable for any given strategic and design objectives).

Acknowledgements
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Reference

1. Hoerner, S.F., Michel W.H. et. al., (1954), *Hydrofoil Handbook*, Volume 1 Design of hydrofoil craft Unclassified document from Gibbs&Cox, Inc., US.

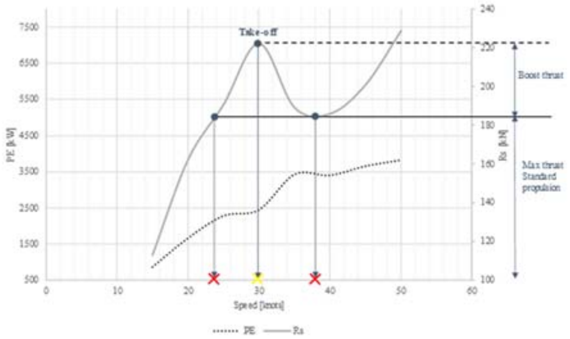

Figure 1. Example of resistance (and power) curve for a craft with hydrofoils

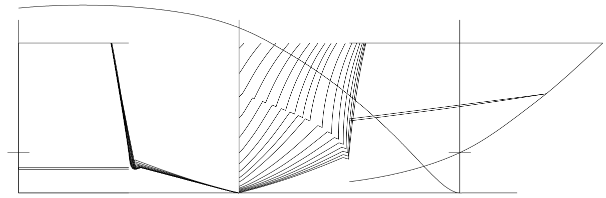

Figure 2. Body plan of hull M10185A

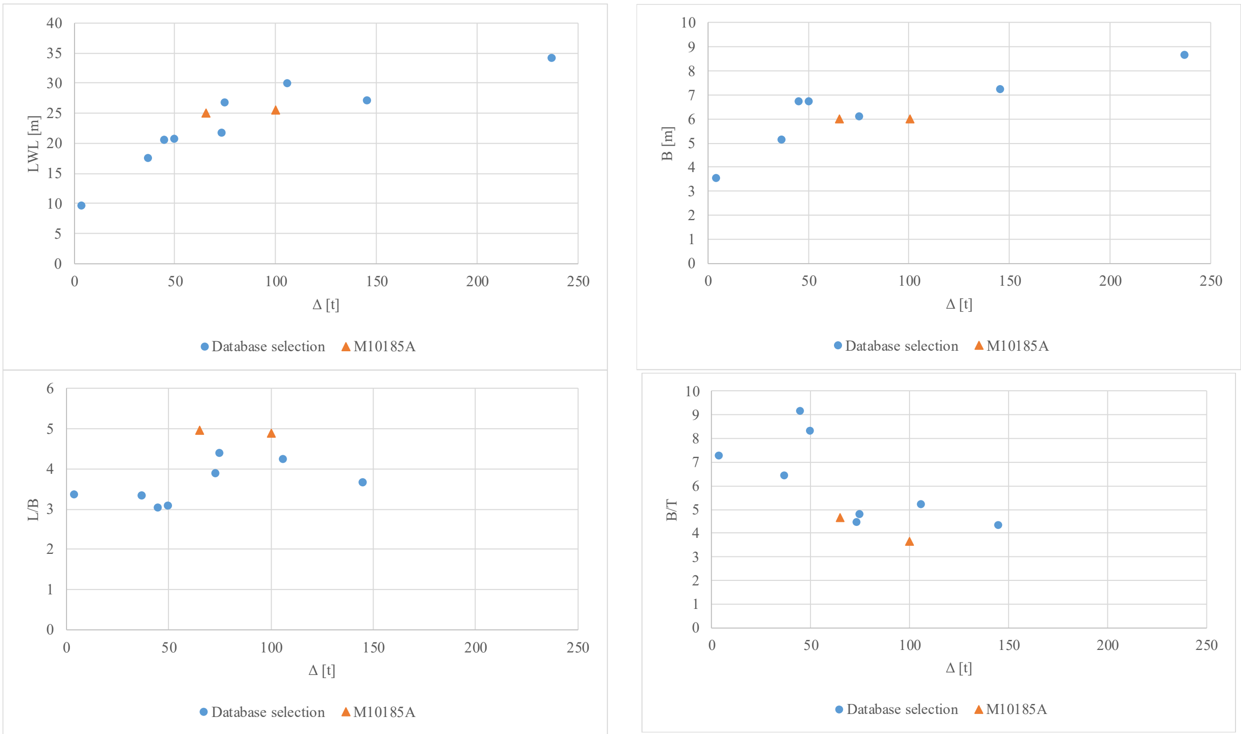

Figure 3. Parameters values of hull M10185A and database selection

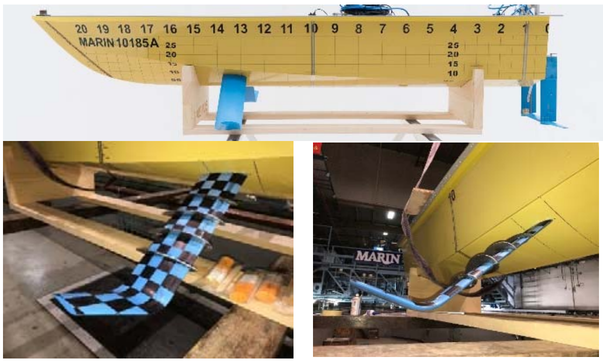

Figure 4. Photo of hull model M10185A equipped with designed hydrofoils (before application of anti-ventilation plates) (top); details of front hydrofoils and anti-ventilation plates mounted on the front foils (bottom)

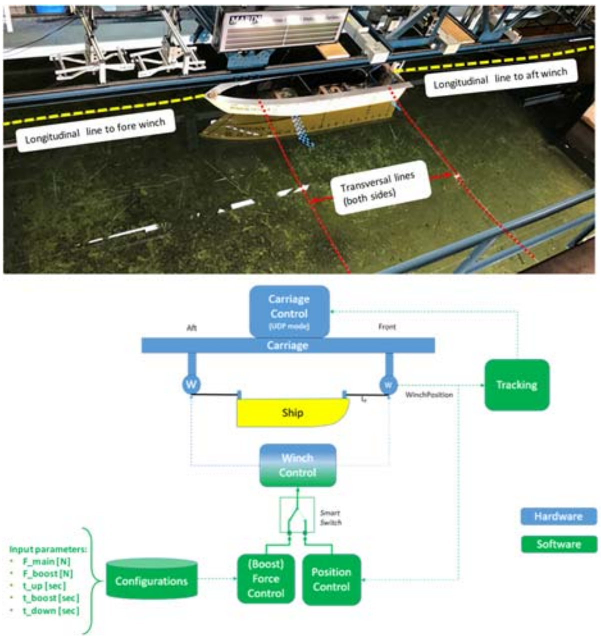

Figure 5. Overview (top) and working schematic (bottom) of semi-free sailing set-up

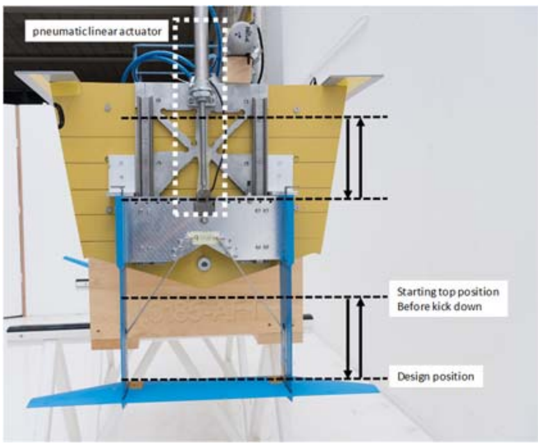

Figure 6. Flapping aft foil-Booster 2

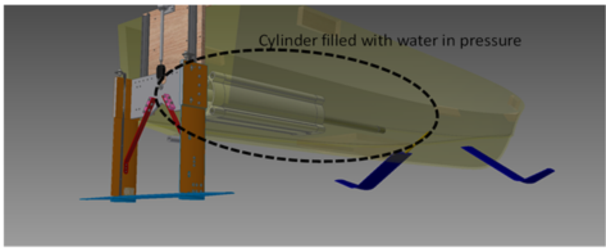

Figure 7. Waterjet-Booster 3

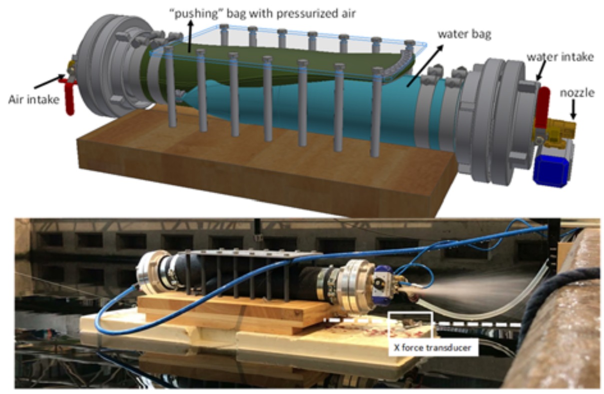

Figure 8. Squid concept – Booster 5; CAD drawing (top) and set-up photo (bottom)

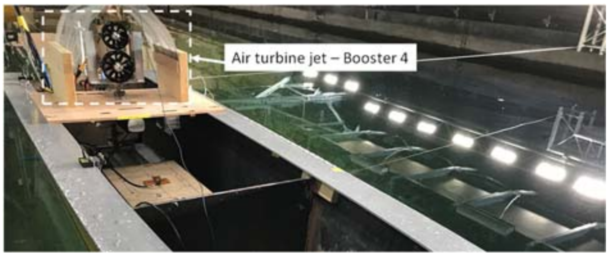

Figure 9. Air turbine jet-Booster 4;

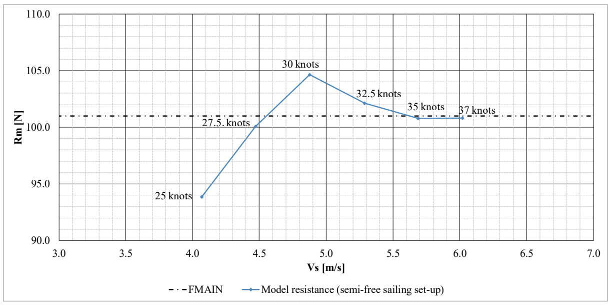

Figure 10. Resistance curve (model scale) with indication of speeds (in knots) at full scale

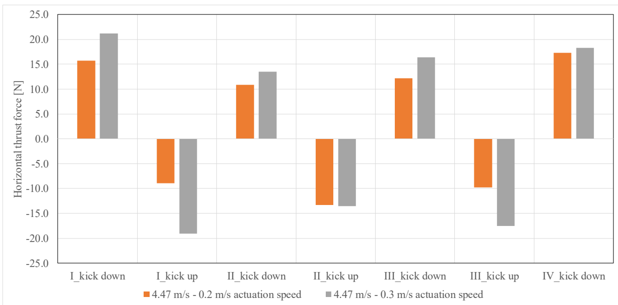

Figure 11. Flapping aft foil-Booster 2 (captive set-up) – Horizontal boost force during actuation

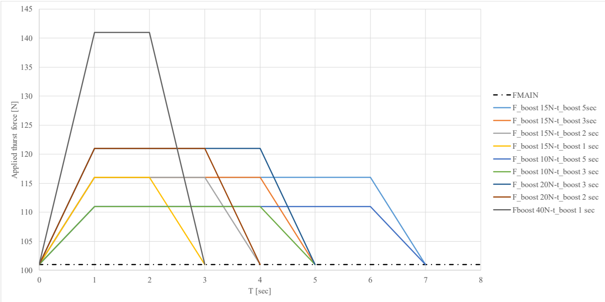

Figure 12. Boost profiles applied for virtual booster tests

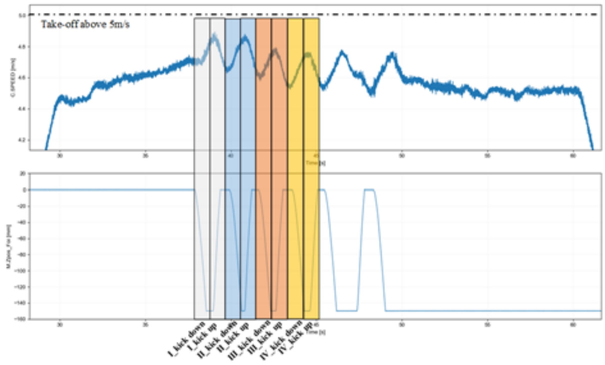

Figure 13. Flapping aft foil-Booster 2 (semi-free sailing set-up); example of model speed combined with indication of actuated kicks (down and up)

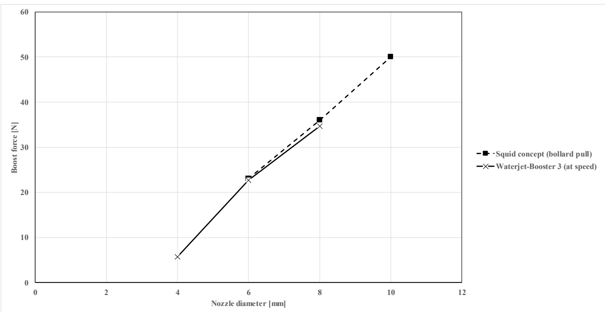

Figure 14. Comparison of boost force generated by Squid Concept-Booster 5 (in bollard pull) and Waterjet-Booster 3 (at speed)

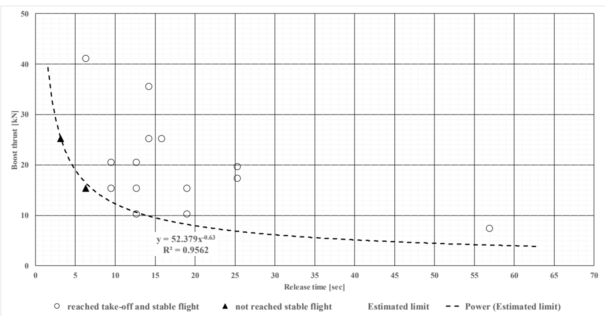

Figure 15. Correlation between booster thrust and release time for successful take-off

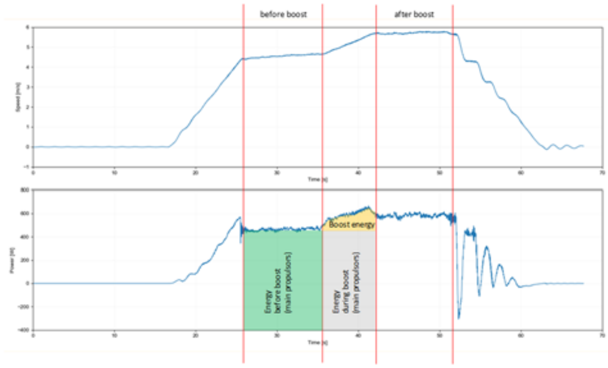

Figure 16. Example of computed model speed and instantaneous total power in function of time

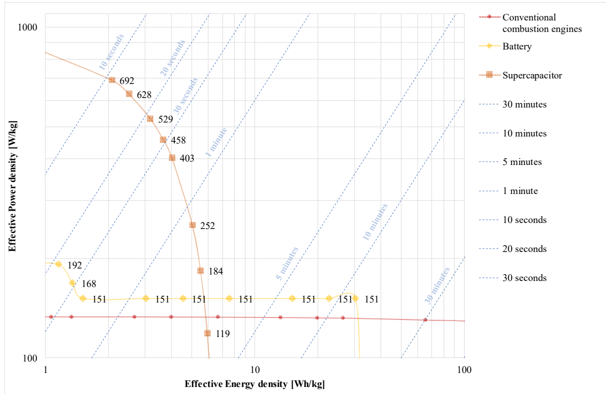

Figure 17. Effective Power and energy density for different systems and release times

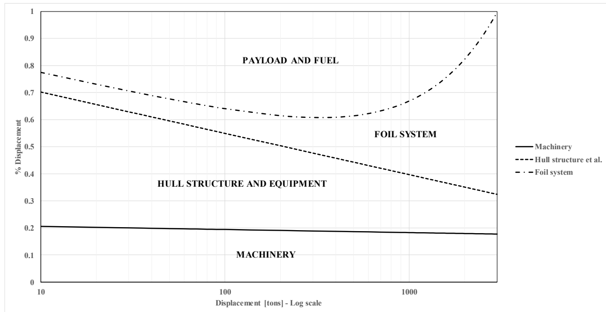

Figure 18. Weight distribution of hydrofoil craft (graph derived from information of [1])

Table 1: Hull form main characteristics

Symbol	Value	Unit	Description
L_{PP}	25.000	[m]	Length between perpendiculars
L_{WL}	24.995	[m]	Length on waterline
B	6.000	[m]	Breadth max. moulded
B_{WL}	5.013	[m]	Breadth max. moulded on waterline
TF	1.074	[m]	Draught moulded fore
TA	1.074	[m]	Draught moulded aft
DISV	63.401	[m^3]	Displacement volume moulded
Δ	65.050	[t]	Displacement mass [water density = 1026.0 kg/m³]
FB	15.380	[m]	Position centre of buoyancy aft of FP
CB	0.471	[-]	Block coefficient
CP	0.719	[-]	Prismatic coefficient
L/B	4.987	[-]	Length-Breadth ratio
B/T	4.667	[-]	Breadth-Draught ratio

Table 2: Data scaling table

Quantity	Scaling factor
Linear	$\lambda = 10$
Volume	$\lambda^3 = 1000$
Force	$\lambda^3\gamma = 1027$
Pressure	$\lambda\gamma = 10.27$
Linear velocity	$\lambda^{0.5} = 3.162$
Time	$\lambda^{0.5} = 3.162$
Power	$\lambda^{3.5}\gamma = 3247$
Energy	$\lambda^4\gamma = 10269$
Note: γ is the ratio of the specific mass of seawater to that of the fresh water in the basin, with γ = 1.027	

Table 3: Virtual Booster tests input and output (full scale)

Test No.	Run No.	F_main	F_boost = Boost thrust	t_up	t_boost	t_down	Average speed before boost	Average speed after boost	Distance to take-off
		[kN]	[kN]	[sec]	[sec]	[sec]	[knots]	[knots]	[m]
0104015	011-03	104	15	3	16	3	28.3	35.2	310
0104015	011-04	104	15	3	9	3	28.3	33.8	202
0104015	011-05	104	15	3	6	3	28.3	31.3	146
0104015	011-06	104	15	3	3	3	28.3	30.1*	95
0104015	013-02	104	10	3	16	3	28.3	32.6	297
0104015	013-03	104	10	3	9	3	28.3	32.0	196
0104015	015-01	104	21	3	9	3	28.3	34.4	204
0104015	015-02	104	21	3	6	3	28.3	33.8	152
0104015	017-02	104	41	3	3	3	28.3	33.8	101
*Take-off not successful									

					Estimated booster weight			
Test No.	Run No.	Average speed after boost	Average boost power	Average boost energy	Battery drive system		Supercapacitors drive system	
		[knots]	[kW]	[kJ]	[kg]	%Δ	[kg]	%Δ
0104015	011-03	35.2	251	4755	2212	3.4	1727	2.7
0104015	011-04	33.8	202	2557	1785	2.7	1393	2.1
0104015	011-05	31.3	238	2259	2090	3.2	1535	2.4
0104015	011-06	30.1*	235	1489	2067	3.2	1517	2.3
0104015	013-02	32.6	185	3512	1634	2.5	1275	2.0
0104015	013-03	32.0	166	2095	1462	2.2	1141	1.8
0104015	015-01	34.4	325	4108	2867	4.4	2238	3.4
0104015	015-02	33.8	314	2978	2755	4.2	2023	3.1
0104015	017-02	33.8	649	4108	5701	8.8	4186	6.4
*Take-off not successful								

Table 4: Waterjet-Booster 3 tests input and output (full scale)

Test No.	Run No.	Water volume	Water pressure	Nozzle diam.	Boost thrust	Release time	Average speed before boost	Average speed after boost	Distance to take-off
		[L]	[bar]	[mm]	[kN]	[sec]	[knots]	[knots]	[m]
0104017	002-01	5000.0	43.2	60.0		34.8	26.6	33.1	534
0104017	006-01	5000.0	72.2	60.0	*20*	25.3	26.6	37.5	443
0104017	012-01	5000.0	43.2	80.0		19.0	25.8	32.1	283
0104017	016-01	5000.0	70.1	80.0	*36*	14.2	25.6	34.4	269
0104017	018-01	5000.0	73.7	40.0	*7*	56.9	26.2	33.2	870
0104017	020-01	5000.0	87.2	40.0		50.6	26.2	33.8	780
0104017	024-01	5000.0	87.3	60.0		25.3	26.0	36.7	408
0104017	026-01	5000.0	92.4	60.0		23.7	25.8	35.4	373

Table 5: Air turbine jet-Booster 4 tests input and output (full scale)

Test No.	Run No.	Turbine RPM*	Force at turbine	Release time	Average speed before boost	Average speed after boost	Distance to take-off
		[RPM]	[kN]	[sec]	[knots]	[knots]	[m]
0104018	010-04	-	19	25	27.4	35.2	458
0104018	012-02	-	29	16	27.4	36.3	311
0104018	012-04	-	29	3	27.8	29.1**	102
*Extrapolation not applied because depending on the specific turbine installed ** Take-off not successful							