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Digitalization of High Speed Craft Design and Operation Challenges and Opportunities

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Abstract

In recent years, global demands for safe and sustainable ships led to dramatic changes in maritime industry. Digitalization is expected to play important part in the future. This is supported by analysis of the autonomous ships market which shows that digitalization of large ship types such as tankers and container ships is well on track. Although to date designs of autonomous High Speed Craft (HSC) have been developed, there are only a few studies on the impact of digitalization on design and operations. This is because of the challenging operational profile of these assets across a spread of waterborne activities namely fishing, leisure, patrolling and rescuing. This paper reviews literature of relevance on the potential of digitalization of the HSC sector in the Baltic. An overview of the systems that could be partly digitalized and how technology developments may influence operations are also outlined.

Keywords: High Speed Craft (HSC); Design and Operation; Digitalization; Green Small Craft.

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1. Introduction

1.1. Importance of digitalization in marine industries

In today's environmentally conscious world maritime innovation is expected to reflect the increasing societal demands to minimize the impact of shipping on the environment [1]. Accordingly, current and future ship designs are expected to comply against demanding environmental standards, requirements for new equipment and for sustainability within the context of lifecycle performance. Recent advances in technology and innovation means that modern digital simulation tools may be further developed and utilized for use in ship design and waterborne operations. This is because cutting-edge digital solutions could make the evaluation of new design concepts easier and faster. They could also promote design innovation and performance.

1.2. Small craft as part of the Baltic marine transportation system

In recent years the numbers of high-speed craft (HSC) in the Baltic Sea increased. According to HELCOM [2], Sweden, Denmark and Finland belong to the countries with the highest per capita boat ownership in the world. Generally, about 3.5 million leisure boats are active in the Baltic Sea today [3]. Those mainly operate close to the coastal areas and are used for recreational boating. In 2015 the Finnish Transport Safety Agency reported that their national small boat registry listed over 195,000 small boats powered by classic combustion engines. A detailed questionnaire survey conducted by the Swedish Transport Agency included qualitative information on the activities of 881,000 leisure boats in Sweden, including fuel consumption [3].

1.3. The digitalization of small HSC

In contrast to conventional recreational boats, small HSCs are produced and operated in a large numbers and have wide span of price and specialist operational profile. In recent years, emissions of these vessels in way of coastal areas raised environmental concerns. Improving the energy efficiency of these vessels requires optimization of their hull, propulsion systems and operational performance by integrated and advanced control systems. The latter implies high operational and manufacturing costs. A life-cycle approach that accounts for environmental sustainability (optimized Operational Expenditure – OPEX and low emissions) requires digitalization from concept design to manufacturing, operations and eventually recycling. As a first step on the way forward the main focus of this article is on state-of-the-art progress, challenges and opportunities of relevance to the digitalization of small HSC at concept design stage. Special emphasis is attributed on the potential of digitizing solutions of relevance to hydrodynamic design, propulsion system design and onboard control systems and their components.

2. Literature Survey

The literature survey has been performed based on the evidence-based approach. A five-step process that is shown in the Figure 1 has been followed and various scientific databases including Web of Science, Google Scholar and Scopus have been used for a detailed literature survey. Keywords included marine hydrodynamics, hull design, propulsion system, propeller design and automation and digitalization of relevance to small HSC. A detailed survey of previous EU project was also carried out.

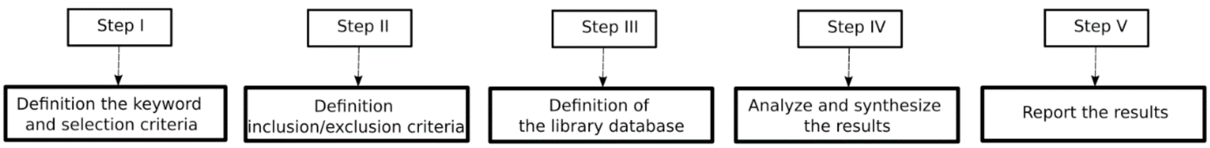

Fig. 1. Research Methodology.

The literature survey focused on three categories:

- *Hydrodynamic hull design of small HSC.* The hydrodynamic design of conventional ships and recreational vessels involves various design aspects including resistance, seakeeping and maneuvering. Whereas the literature on these topics is broad the hydrodynamic design of small HSC by considering seakeeping and manoeuvring behaviour as well as advanced hull forms is generally limited [4, 5, 6].
- *Propulsion system design for better energy efficiency and lower noise emission.* Fully electric outboard, inboard and pod propulsion units for potential use in small HSC emerged only recently [7, 8, 9]. They are still not widely adopted, partly due to power limitations. Whereas research on Underwater Radiated Noise (URN) becomes increasingly important for commercial shipping [10, 11], there is a lack of investigation about URN of practical to small HSC operations in semi-open seas or coastal regions.
- *Automation and digitalization of onboard systems.* The need of optimization and integration of onboard systems demands suitable appreciation and eventually application of modern technologies such as artificial intelligence, big data analysis, virtual reality tools, augmented and mixed reality, cloud computing, cyber-security, 3D printing and predictive maintenance systems.

2.1. Advances in hydrodynamic hull design

Today the European boat industry owns 26% of the world small HSC market [12]. Notwithstanding this, in recent years the growing competition from Asia and North America is threatening Europe's future market share. Since foreign competitors adapt their products more closely to consumer demands accelerating innovation in design is essential to maintain the competitiveness of the EU boat industry. Existing software products for HSC design (e.g. Maxsurf, Orca3D, DELFTship, FastShip, Freeship, etc.) are unable to predict the influence of advanced system characteristics (e.g. hull form and appendages) or operational characteristics (e.g. speed and environmental conditions) on small HSC. Therefore, most of current design tools are based on empirical formulas with limited range of applicability and simplified methods such as potential theory or Savitsky Method [13, 6, 5, 14].

Traditionally, the hydrodynamic theories for use in maneuvering and seakeeping of small HSC in waves tend to neglect interactions between motions in various degrees of freedom [15, 16]. Recently a novel mathematical model that may be used for the prediction of steady performance of heeled planing boats was introduced [17]. Using this model as a basis, a procedure for time domain simulation of roll motion of the warped planing hulls [18], coupled heave and pitch motions of planing hulls at non-zero heel angle [19] and a nonlinear mathematical model for coupled heave, pitch, and roll motions of high-speed planing hull dynamics [20] were developed. Consequently, mathematical models that accounts for sway, dynamic sinkage and trim as well as roll and yaw motions of planing hulls have been developed [21, 22, 23] and an oblique-asymmetric 2D+t theory was introduced [24]. Parametric studies and comparisons against experiments demonstrated that this approach could be used as the basis of a digital tool for the evaluation of dynamics of small HSC in waves [23, 24, 25, 26]. Studies on the influence of advanced hull features (e.g. two step planing, catamaran designs, etc.) are still limited to calm water conditions [27, 28, 29, 30, 31, 32].

Innovation could accelerate via the use of new generation Smart Computational Tools (SMT) for use in early-stage small HSC design [33]. Ship dynamics methods using advanced nonlinear hydrodynamic theories, Machine Leaning (ML) and Artificial Intelligence (AI) methods if properly understood and validated could help in the development of competitive purpose specific products [34, 35, 36].

2.2. Advances in digital propulsion systems

Outboard or stern drive propulsion units used in small HSC are made of propellers of submerged or surface-piercing specification. For larger working boats with speed less than 20 kn, inboard or pod propulsion units with controlled or fixed pitch propeller are commonly used. For HSC cruising faster than 30kn, waterjet propulsion systems are the best choice. Contra-rotating propellers are adopted sometimes for higher efficiency. In this section, the digital design and analysis of each propulsion type are reviewed, as well as the digital analysis of energy saving devices and propeller’s underwater radiated noise (see Figs. 2, and 3).

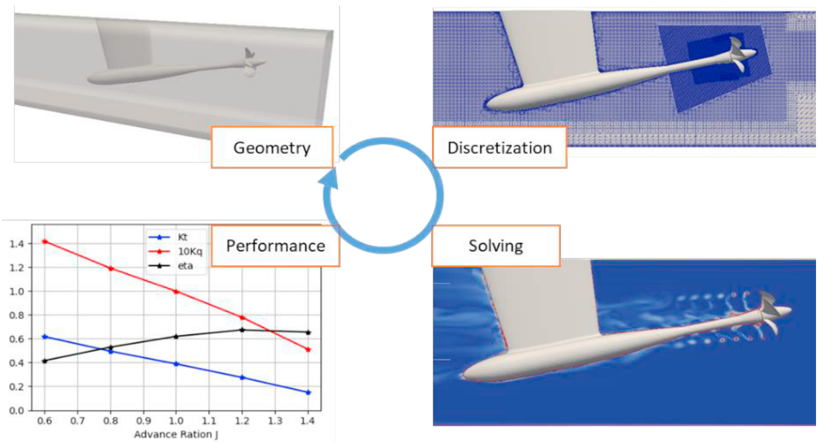

Fig. 2. Digital analysis and design of the propulsion system.

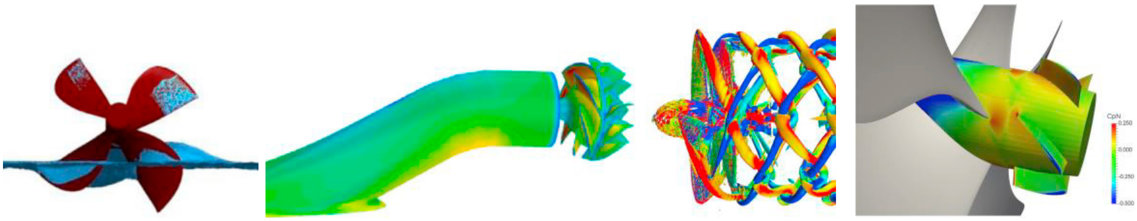

Fig. 3. Digital analysis of different kinds of propellers and devices. From left to right: surface-piercing propeller [37], waterjet [38], contra-rotating propeller [39], and propeller boss cap fin [40].

2.2.1 Surface-piercing propellers (SPP)

In literature, digital analyses of SPP are mainly realized by Boundary Element Methods (BEM) and Unsteady Reynolds-averaged Navier–Stokes (URANS) approaches. For example, Young and Kinnas [41, 42] presented a low-order potential based 3D BEM for the analysis of surface piercing propellers. Their method can predict dynamic blade loads of SPP in partially ventilated, transition, and fully ventilated flow conditions. Alimirzazadeh et al. [43] analyzed SPP performance in several immersion ratios and maneuvering conditions by a URANS method. The authors demonstrate that the maneuver condition may lead to increase the thrust and torque coefficient. Using RANS, sliding mesh technique and VOF method, Ganji Rad et al. [44] demonstrated that the maximum thrust and torque coefficient of SPP may mostly occur at 70% immersion ratios. However, maximum propeller efficiency occurs at immersion ratio of the order of 33%. Nouroozi and Zeraatgar [45] explained that the numerical grid should be fine enough to idealize the flow pattern and turbulence modelling parameters in regions near the blade's tip, trailing and leading edges and over the suction side. Ren et al. [46] compared the performance of SPP in horizontal and oblique flow conditions by URANS. Their study confirms that the volume of ventilation increases dramatically in oblique flow.

2.2.2 Waterjet propulsion systems

To date knowledge from digital waterjet model simulations has been exploited to understand waterjet-hull interactions, loads due to non-uniform flow field variations and the potential of associated improvements in waterjet efficiency. For example, Eslamdoost [47] investigated waterjet-hull interactions by employing numerical simulations of the flow around a planing waterjet-propelled hull. This research suggests that the jet thrust deduction fraction, which measures the difference between the net and gross thrust, may be large when the waterjet nozzle exit is not ventilated. Gong et al. [48] carried out unsteady numerical simulations of a four-waterjet-propelled ship. Their results indicated that the flow rates and gross thrust of inner waterjets may be greater than those of the outer waterjets due to waterjet-hull interactions. Zhang et al. [49] investigated the stern flap and waterjet-hull interaction with URANS simulations for a waterjet-propelled trimaran. They suggest that a stern flap may effectively reduce trim, the resistance acting on the hull and the waterjet thrust deduction. Motley et al. [50] carried out transient fluid dynamic simulations of a waterjet-propelled surface effect ship. Their results show that the ingested boundary layer from the bottom of the side hulls can become increasingly nonuniform as the flow advances through the pump. Park et al. [51] employed RANS and multi-blocked grid to simulate the flow in a waterjet with the flush type intake duct. They stated that approximately 7–9% of the total power is lost in intake duct due to flow separation, nonuniformity, etc. Yang et al [52] carried out experiments and simulations to investigate the reactive thrust and the conversion efficiency of cylinder, conical and optimized streamline nozzles. Their results show that an optimized streamlined nozzle performs the best. Huang et al. [53] proposed a multi-objective optimization system to optimize the flush-type intake duct of waterjet. RANS CFD was used to analyze the flow field in the waterjet. The nonuniformity and perpendicularity of outflow, and hydraulic efficiency for the intake duct were treated as the optimization objectives with four geometrical parameters as the design variables.

2.2.3 Contra-rotating propellers (CRP)

CRP configurations can improve hydrodynamic efficiency and therefore they have been used on small HSC for some time. Recently, Brizzolara et al. [54] presented a computational method developed for the design of CRP for HSC. Lifting-line methods of relevance has been developed in the open access software OpenProp [55, 56]. Schulze and Weber [57] presented an optimal design of a CRP at Z-drives. The differences in efficiencies between three types of arrangements (push-push, pull- pull and push-pull) were found to be small. Nouri et al. [58] investigated the optimization of a CRP using RANS, genetic algorithm and kriging method. The obtained results presented an acceptable efficiency for the utilized algorithm. Huang et al. [59] developed a design method of wake-adapted CRP with specified circulation distribution based on the vortex lattice method. The results of the RANS self-propulsion simulations indicated that the design product had approximately uniform pressure distributions on the blade surface and the hydrodynamic performance objective was obtained. Ghassemi [60] presented a CRP design procedure based on BEM. It was found that CRP had 2-3% larger efficiency. Su et al. [61] introduced a BEM/RANS interactive method to predict the pod CRP performance. In their scheme, the forward and aft propeller performances are handled by two separate BEM models while the interaction between them are achieved via coupling them with a RANS solver. Hou and Hu [62] investigated the energy saving performance of Contra Rotating Azimuth Propulsor (CRAP) based on BEM. The comparison showed that CRP had a decrease in delivered power by approximately 8% comparing with conventional propellers. Hu et al. [40] predicted the tip vortex of the DTMB 4-4 blade CRP by using large eddy simulation (LES) and the overset grid method. It was observed that the tip vortex of the forward propeller is cut by the blade tip of the aft propeller periodically, and its axial vorticity decreases suddenly after passing through the disk of the aft propeller. The tip vortex of the forward and the aft propellers intertwine with each other and move downstream in the wake flow.

2.2.4 Energy saving devices (ESD)

In recent years ESD gained a lot of interest due to environmental awareness, financial incentives and new regional and international rules. For HSC Propeller Boss Cap Fins (PBCF) are the most researched application. For example, Hsin et al. [63] and Xiong et al. [64] presented the design of a PBCF by CFD. These studies show that pitch angle and the angle of installed fins are important for design efficiency. The optimal radius of PBCF is 1.5 times of propeller hub. Hou et al. [65] used a BEM to demonstrate that a propeller-PBCF system may increase trust and propulsive efficiency by 8.7% and 8.3% respectively.

2.2.5 Underwater radiated noise (URN)

Validation methods and investigations on practical noise emigration measures for use in small HSC are very limited. This is because URN predictions become challenging due to the complex free surface shape around the propeller, the mixing of ventilation and cavitation, and the Lloyd's mirror effect caused by the HSC. The most popular numerical method is to couple hydrodynamic CFD with acoustic analogies. Recently, VTT adopted the Lighthill analogy for the model of propeller radiated noise in cavitation tunnels [66, 67, 68]. Some differences exist among the methods using the Ffowcs Williams-Hawkings (FWH) FWH analogy. For example, one needs to decide between two approaches named 'direct' and 'permeable' (or porous) FWH formulation. The direct FWH approach is based on the Farassat 1A formulation [69] for solid surface contributions and calculates the contribution of Lighthill tensor with volumetric integration [70, 71]. The permeable FWH approach uses a data surface named 'permeable surface' enveloping the main sound sources, and theoretically all the effect inside this surface can be included by considering only virtual sound sources on it. It is therefore preferred by most researcher because the direct FWH approach is deemed unfeasible for engineering problems [72, 73].

2.3. Digital Systems and Subsystems onboard HSC

Maritime transport and industry in comparison to other spheres is not developed enough in the context of digitalization. The systematic literature review presented in [74, 75] conveys that although maritime transport is the backbone of world commerce digitalization lags significantly behind. In addition the EU lacks a clear maritime digitalization strategy. Regulations for HSC [76, 77, 78, 79, 80, 81, 82] suggest that onboard systems to be considered are:

- Machinery, propulsion and auxiliary systems
- Control systems
- Navigational systems
- Radio-communication systems
- Stabilizing and positioning systems
- Anchoring, towing and berthing systems
- Alarms and fire safety systems
- Life-Saving appliances and arrangements

Today, vessels, their systems, equipment and components are increasingly linked to the internet, making them accessible from anywhere and part of a network of online maritime assets [81]. This presents the opportunity to access real-time data, enabling increased automation, decision support, remote monitoring. It also promotes HSC safe and sustainable operations. Digitalization of seagoing vessels under high dimensional data driven models is studied and discussed in. The following elements should be considered in the strategy phase [74, 83, 84]:

- *Management of resources and technological capabilities.* Those should account for organizational redesign and talent review, centralization and function allocation, adoption of new operating methods, internal development and skill building, acquiring new talent through hiring, outsourcing functions to external companies;
- *Integrated systems, tools, and connectivity* including IT and system integration, increased network and connectivity, automation, remote monitoring and control, data management and cyber security, data-collection, sharing, analysis and data standardization protocols;
- *Technology efficient solutions* with emphasis on automation, fuel /power system consumption optimization, waste-heat recovery and hybrid systems, etc.;
- *Energy-efficient and enhanced performance* with focus on reduced OPEX, fuel consumption and GHG emissions.

It should be added that big data, digitalization and the utilization of exponential technologies are more important now than ever before as the maritime industry recovers from the crippling effects of the COVID-19 pandemic [85]. The lack of standards and necessary rules imply the need to develop global digital ISO standards [86, 81]. Digitalization can have also a significant safety dimension, for example by automation of online risk analysis and risk assessment. As an example, in [87] a new environmental risk assessment tool in which environmental concentrations are predicted based on estimated release rates of biocides to the aquatic environment and risk characterization ratios are calculated using XRF (X-ray fluorescence) method. The assessment process is well digitalized and can be adapted for HSC.

To date, IMO defined 4 levels of maritime autonomy [80] and small HSC can be adjusted to fit in Levels 1,2. At Level 1, the vessel is equipped with automated processes and decision support, where seafarers (or operators or passengers) are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with people on board ready to take control. At the level 2, the vessel is remotely controlled with seafarers/operators/passengers on board. The vessel is controlled and operated from another location. Operators are available on board to take control and to operate the shipboard systems and functions. Higher levels are assumed to be out of scope of this paper.

3. Challenges and Opportunities

To make small HSC a popular choice for EU boat builders, designers and owners it is essential to develop digital green, safe and smart designs. This section summarizes challenges and opportunities for the digitalization of HSC with focus on hull and propulsion system design as well as digital onboard systems. Opportunities for hull digitalization can be divided into various categories including craft lines design, calm water performance prediction, prediction of seakeeping and maneuvering. All these have serious effects on performance of small HSC and boat fuel efficiency. They can be solved using smart and digital tools as follows:

- Design of innovative hull forms such as stepped hulls, tunneled boat and hydrofoil craft;
- Digital simulation of seakeeping and maneuvering performance in real conditions;
- Implementation of AI and optimization algorithms for use in concept design ;
- Combination of developed mathematical models with AI tools;

Propulsion system design research directions can be summarized as follows:

- Universal guidelines for the waterjet and hull design to achieve beneficial waterjet-hull interactions;
- Measures to improve the waterjet efficiency and mitigate the negative effect of non-uniform flows;
- Optimisation of noise and vibration of surface piercing propellers;
- Systematic comparison of the hydrodynamic characteristics of contra-rotating and conventional propellers (hydrodynamic efficiency, hull-propeller interaction, cavitation, noise, vibration, and cost);
- Assessment of the efficiency of auxiliary equipment (e.g. boss cap fins);
- Numerical prediction methods for the assessment of URN with application to different propulsion systems;
- Methods for the operational efficiency and URN emissions.

The challenges in the case of digitalization of vessel's onboard systems and operation are summarized and presented in Fig. 4. AI and optimized voyage planning are areas that should be considered for smart operation. For instance, AI-based predictive positioning systems can enable to monitor and predict future positions, movements and maneuvers of the vessel hours in advance, improve situational awareness, decision-making and ultimately safety. Fuel optimization systems that utilize AI can help reduce fuel consumption and emissions. Smart operations rely on automated data collection systems that use cloud-based technologies to analyse data in real time. On the other hand, ML can enhance performance analytics, passing on recommendations to humans who use their judgment to make operational decisions.

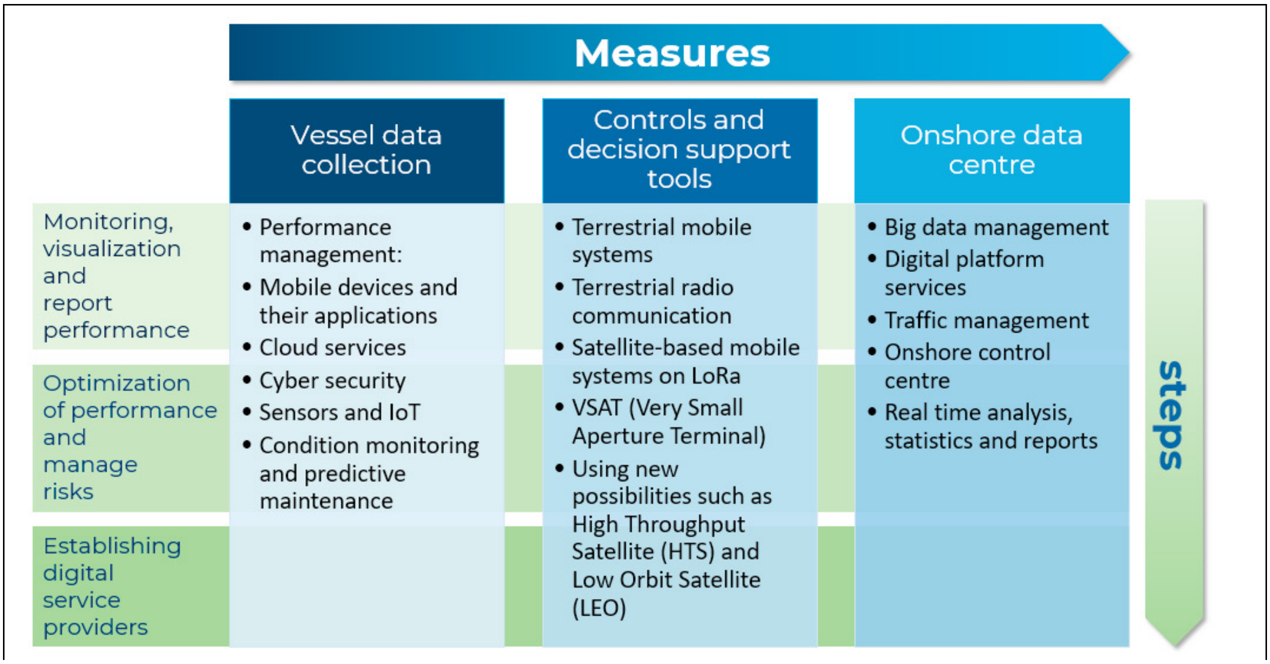

Fig. 4. The challenges in the case of digitalization of vessel's onboard systems and operation.

4. Conclusions

This paper reviewed challenges and opportunities of relevance to digital design and operation of small HSC. The study focused on aspects of functional ship hydrodynamics, design for green propulsion and digital onboard systems. The potential for digitalization of HSC that is green and efficient is significant. It was concluded that research of direct relevance to the digitalization of small HSC is either brief or outdated. Yet, the development of smart Computational Tools (SCT) for safe and sustainable design and operations is essential and remains at embryonic stage. In the future, emerging technologies such as AI and ML methods should be combined with state-of-the-art computational methods (e.g. nonlinear hydrodynamics and fluid dynamics) for hull form development, safety assessment (e.g. seakeeping and wave loads analysis) and performance monitoring (e.g. under water emissions monitoring and maneuvering optimization). The potential of digital on-board systems and higher level of monitoring can be realized by use of advanced and larger numbers of sensors, power system optimization, waste heat recovery, flexibility for working in hybrid modes, predictive positioning and maintenance, automatic data acquisition, cloud-based data processing and management, and real time data analysis shape the core of challenges in relation to the digitalization of maritime industry, and particularly HSC.

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