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HYDRO-STRUCTURAL ISSUES IN THE DESIGN OF ENERGY SAVING DEVICES FOR SHIPS

Andro Bakica, Nikola Vladimir, Ivo Senjanović

Summary

The shipping sector is currently under growing pressure concerning the GHGs emission restriction prescribed by the International Maritime Organization (IMO). Improving the efficiency of the fleet has always been an attractive subject to the shipowners, but with the new regulations, the reduction in fossil fuel consumption has switched from optional economic benefit to a rule. One of the ways for the ship to comply with the new regulations is by installing or retrofitting Energy Saving Devices (ESDs). The ESDs exploit the axial and rotational energy losses inevitably produced by the propeller operation. The ESDs differ in shape, position and kind of energy to be recovered. This article gives an overview of the current trends and practices in the field of the ESDs, along with their classification and type of operation. Furthermore, besides the hydrodynamic design, which still holds the primary importance, structural issues are also addressed, since this subject is rarely investigated in the literature. Given the complex flow field of the ESDs influenced by propeller, ship motions, wake field and waves, applicability of numerical models is described in detail, whereby the state-of-the-art approaches are clearly highlighted. Overall, the ESDs are expected to further mature in the future given the rigid rules, the promising potential of efficiency improvements they offer and the low-cost of installation.

Keywords: energy saving devices; hydrodynamic analysis; structural analysis; fuel savings; environmental impact.

1. INTRODUCTION

Nowadays, the ship efficiency of the merchant fleet is placed at the forefront of the industry primary goals for the near future. In an effort to reduce the GHGs emissions of the shipping sector, the International Maritime Organization (IMO) has imposed the regulations through Energy Efficiency Design Index (EEDI) for the newly built structures [1], and Energy Efficiency for eXisting Ships (EEXI) for the currently operating vessels [2]. The aforementioned rules initiated a series of technological and engineering improvements in the areas concerning reduction of fuel consumption for the standard two-stroke diesel main engines. This can be achieved in different ways, for example by using renewable energy for the crew hotel accommodation (solar cells, Flettner rotors), exploiting recirculating heat from the exhaust system, air lubrication [3], or by additional hydrodynamic improvements reducing the ship drag or improving the propeller efficiency. The last category has been significantly influenced by continuous improvement in the computational power and its accessibility. Complex numerical models are increasingly developed and validated, thus enabling engineers to optimize the flow beyond the trial-and-error practices often employed in the experimental basins.

Lately, in the field of propeller efficiency, Energy Saving Devices (ESDs) have gained a lot of popularity among the shipyards and shipowners, especially through retrofits when complying with the EEXI. There are various shapes and types of the ESDs, but all of them attempt to reduce the energy losses in the flow originating from the propeller operation. These losses can be divided in rotational and axial contribution. It is generally accepted that the rotational losses are on average about two times larger than the axial ones [4]. The formal classification of the ESDs follows the Carlton [5] proposal depending on the position of the device with respect to the propeller, as shown in Figure 1. Energy saving devices classification. Zone I devices are located before the propeller plane with the aim of creating an improved wake field, thus lowering the lost fluid energy in the propeller slipstream. Zone II devices are the non-conventional propeller designs, and Zone III devices are exploiting the post-swirl energy of the propeller.

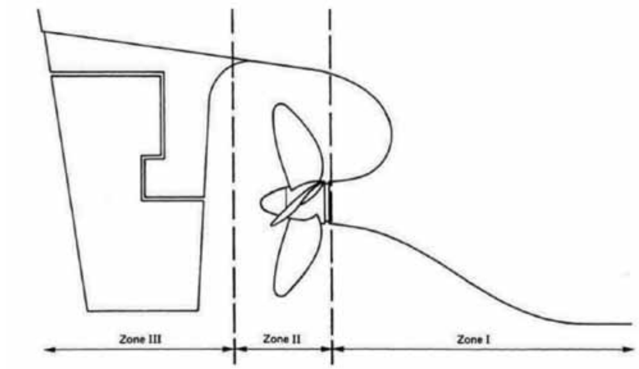

Figure 1. Energy saving devices classification [4]
Slika 1. Klasifikacija uređaja za uštedu energije na brodovima [4]

This paper addresses the current trends in the design of the ESDs from both hydrodynamic and structural perspectives. Although hydrodynamic evaluation is of crucial importance to justify the benefits of the ESD instalment, the structural design remains overlooked in the literature. When assessing the entire life cycle of the ESD, for the ship owner, the structural integrity is a vital issue since the failure of the structure would require costly repairs and unnecessary dry dockings. The article also focuses on the state-of-the-art numerical tools employed when analysing the ESDs, ranging from simpler to more complex levels of mathematical modelling and computational effort. The paper is divided into four sections: the second section gives a brief overview of the ESDs developed for ships and their appropriate hydrodynamic evaluation, the third section reviews the current procedures developed for the ESD structural design, and the fourth section concludes the study.

2. OVERVIEW OF ENERGY SAVING DEVICES

The ESDs are broadly divided by their position with respect to the propeller. A comprehensive review of available solutions for stern hydrodynamic ESDs, the working principles, the methods used for the design, optimization, and evaluation of the performance improvements, and the relevant issues of these specific ESDs is offered by Spinelli et al. [6]. It is fair to say that in this work, as in many other references, more attention is paid to hydrodynamic aspects compared to the structural ones. Currently most developed ESD types are placed before the propeller, in Zone I. The main goal is to alter the flow and enhance the propeller operation by either redistributing the radial axial velocities (duct type ESDs) or by introducing the additional rotational velocity component to the propeller plane, thus reducing the propeller post-swirl energy (fin type, pre-swirl devices). Currently, devices in this zone hold the majority of the commercially available and installed ESDs.

The idea of the duct type device is not new [7], but has significantly gained interest due to low emission requirements by the maritime sector and accurate viscous fluid models by the use of Computational Fluid Dynamics (CFD). The CFD has enabled an in-depth view of the flow pattern near the ESD, thus allowing extensive design optimization in a full-scale simulation environment, where different numerical schemes are nowadays investigated, as for instance reduced order models [8]. Furthermore, the CFD results concerning duct devices have shown good comparisons with experiment [9]. As for the Schneekluth duct or wake equalizing duct [10], the advertised savings are even up to 12%, with vibration reduction claimed up to

50%. On the other hand, regarding rotational energy losses, quite a lot of work has been employed on the Pre-Swirl Stator (PSS) device [11]. The PSS can differ in number of fins, position and inclined angle. Optimization and design approach to the PSS is presented by Furcas and Gaggero [12] using the genetic algorithm and simpler fluid model, while the most promising designs are further investigated with the full CFD approach. Maximum savings achieved from simulations results are near 8%. Another relatively popular ESD is the combination of duct and the PSS, called the Mewis duct [13], [14]. Saving from this ESD are also reported at maximum near 8%. All three ESDs concern only the full form slower vessels, such as bulk carriers or very large crude carrier, since this type of hull form enhances the bilge vortex creation, i.e. fluid energy losses and inadequate propeller inflow. The best improvement occurs where the propeller thrust coefficient is high and the speed relatively low. The ESDs mentioned previously are shown in Figure 2. Concerning experimental analysis, Dang et al. [15] introduced a new concept of ”smart ship model”, where the model hull is altered to induce a full scale wake in the experiment. The actual shape of the full-scale wake is computed using the CFD. The authors tested duct shaped device and asymmetric PSS fins to find out that the latter is much less sensitive to scale effects. Dang et al. [4] considered the energy losses and divided the kinetic energy losses in the slipstream on the axial and transversal losses. The following major findings are reported:

- Extra thrust generated by the ESD shape without the propeller is cancelled when the propeller is functional, raising the thrust deduction coefficient, thus producing the added resistance;
- In the propeller slipstream, the transverse kinetic energy is almost double of the axial kinetic energy;
- The aim of the ESD design should mainly focus on lowering the rotational losses;
- Flow separation (evident at the connections between the trailing edge of the duct and the stator) should be minimized on the ESD;
- Local forces on the ESD alone are internal forces of the propulsion systems and the shape should not be optimized for the maximum thrust output as it is often found in the literature, but for the interaction with both the propeller and the hull.

Figure 2. Mewis duct (top left), pre-swirl stator (top right), and Schneekluth duct (bottom)
Slika 2. Mewis vod (gore lijevo), predvrtložni stator (gore desno), Schneekluth vod (dolje)

Devices in Zone II concern the novel and unconventional propeller designs, as well as devices placed at the propeller itself. The first non-standard propeller design was introduced as early as in the 1970s, with the cylindrical end plates at the blade tip to alleviate the tip vortex common in cavitation inception. Lately, a lot of work has been put into the development of the Contracted and Loaded Tip (CLT) propeller with the end plate formed as part of the propeller geometry. Gaggero et al. [16] used a potential flow method extended with the possibility to model cavitation (only sheet cavitation at the blade tip) to reach a satisfactory design. The work is further elaborated in [17], where a new CLT propeller design is proposed. Apart from the optimization genetic algorithm, mentioned paper presents a full and detailed comparison between the CFD and the potential solution, with further insight into the physics of the CLT propellers. The main problem of such a design is the production of noise and vibration on the hull surface due to high pressure loadings on the propeller tips. As a non-standard design, scale effects can also be an issue [18]. Probably the most popular ESD in Zone II is the Propeller Boss Cap Fin (PBCF), which reduces the hub vortex [19]. Savings range from 1-2% with the number of fins usually equal to the number of propeller blades. Low-cost installation and maintenance, if designed properly from the hydrodynamic perspective, make this the most frequently employed ESD in this category. Work related to this ESD can be found in [20] and [21], with an example of the PBCF shown in Figure 3. Another ESD in Zone II is the Contra Rotating Propeller (CRP) [22], [23], but due to complexity in manufacturing (gearbox, shaft bearings) and high cost of maintenance for two propellers and equipment, the CRP is rarely the best choice in merchant shipbuilding. However, the energy saving effect of the CRP is known to be the largest among Zone II devices.

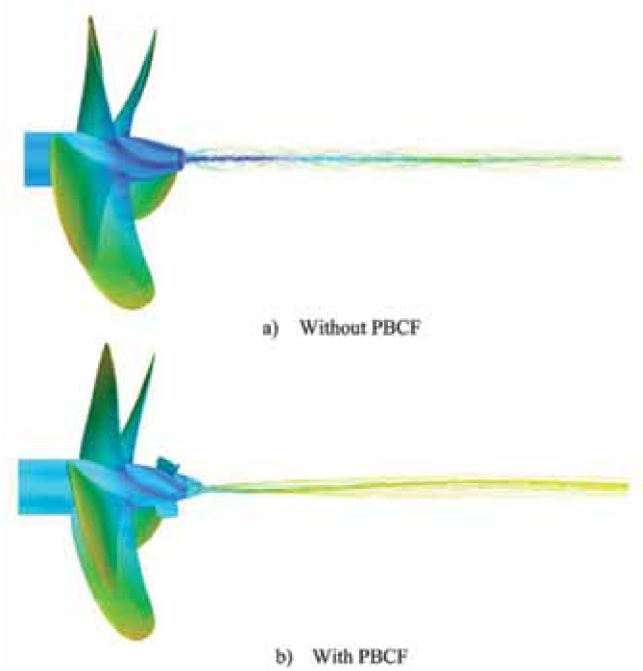

Figure 3. Propeller boss cap vortex [18]
Slika 3. Vrtlozi iza završetka vratila vijka [18]

The ESDs exploiting the energy in the propeller slipstream are positioned in Zone III. The majority of the devices in this zone currently in use are dedicated to altering the rudder configuration and either producing additional thrust or attempting to cancel the unfavourable rotational swirl in the flow after the propeller. Some of rudder modifications are the so-called twisted rudders, such as Z-twisted rudder [24], X-twisted rudder [25], twisted rudder [26], rudder bulb [27], and even wavy rudder [28] bio-mimicking the whale fin. Besides the rudder modifications, another type of the ESD in Zone III is the Vane Wheel (VW). The VW is a freely rotating wheel with the blade geometry half turbine and half propeller thrust giving shape. Although the original idea never went to wide scale practical use, the new approach is to remove the thrust part and simply extract the energy by powering the ship generator. In the given context, Lee et al. [29] developed a new type of the VW without the thrust generating part of the blade tips, reducing its diameter to 80% of the propeller. There are several advantages: interference with the propeller is minimized; the weight of the turbine is lowered (stable structural design); and the unavoidable propeller tip vortex impact on the turbine is removed. Therefore, this kind of turbine only powers the generator placed inside the rudder, eliminating the thrust generating idea. Furthermore, the generator can control the turbine rotation, which increases the device flexibility. Input parameters for the generator power are equal to usual electricity demands on board a vessel. The CFD analysis showed that due to the existence of the turbine, the pressure distribution is moved in-board the blade tip, which induces additional torque motion sourced from the turbine blade blockage effect. Unfortunately, the change in the axial velocities requires a modification of the propeller geometry. To sum up, the rotational motion component without the turbine in the slipstream takes up to 6.6%, while with the turbine it rises to 8.0%. Finally, the turbine manages to extract 72.5% of the rotational losses.

Overall, regardless of the ESD type or position, in every ESD hydrodynamic design, usually lower order fluid models are employed for the basic design and further optimization and fine tuning is enabled by the CFD simulations. The third step of the experimental analysis is beneficial, but as previously stated, due to wake inequality in model and full-scale, such studies are considered unreliable. Finally, it is important to note that the ESDs can only exploit the energy losses already present in the flow, so for a highly efficient propeller with uniform wake velocities, it is dubious to expect the ESD design to overcome its own drag for the overall propeller and ship efficiency benefits. Furthermore, lumping together multiple ESDs, which recover the same type of energy is not going to achieve the expected combined benefits. For example, the PSS with the VW would make the post-swirl energy for the VW significantly decreased, hence the choice for the suitable ESD depending on the ship, machinery and operational diagram should be carefully considered by the designer.

The current importance of the ESDs in the shipbuilding industry is evident from the above relatively new references, as well as from the special issue edited by Kim [30], which includes eight valuable papers on energy-saving technology with regard to the propulsor, rudder, hull form, and cavity.

An overview of the most important energy saving devices and their reported highest savings are given in Table 1. Overall, the ESDs can provide the complementary amount of thrust and propulsive efficiency to the propulsion system, as proven in numerous studies previously highlighted. Main outlines regarding the ESD can be summarized as follows:

- Benefits the ESD can produce is equal to the amount of losses propeller induces; i.e. if there are no significant energy losses, there is no point to install the device.

- Each type of the ESD is best suited for a specific kind of flow regime.
- The ESD is a part of the propulsive system; hence, the design should be treated from a system point-of-view, and not from an individual characteristic of a device.
- Gains in model test are not equal to full-scale benefits. Furthermore, there is no general extrapolation method for an arbitrary shaped ESD of a specific type. Full-scale results in the CFD are distinguished as the most accurate qualitatively. Experiment and the CFD comparison can serve as a good measure of validating the CFD solution.

Table 1. Overview of energy saving devices and their maximum reported savings
Tablica 1. Pregled uređaja za uštedu energije s maksimalnim postignutim uštedama

	Energy Saving Device	Fuel savings
Zone I	Mewis duct	~8%
	Schneekluth duct	~12%
	Vortex generators	~3%
	Pre-swirl stator	~8%
Zone II	Contra-rotating propellers	~10%
	CLT propeller	~8%
	Propeller boss cap fin	~2%
	Kappel propeller	~4%
Zone III	Twisted rudder	~2%
	Rudder bulb	~3%
	Rudder fins	~7%
	Vane wheel	~10%

3. DESIGN PROCEDURE FOR ENERGY SAVING DEVICES

The hydrodynamic design, the shape of the ESDs and the working principles have been intensively investigated in the research works referenced in the previous section. Although fuel consumption benefits are the primary goal of any ESD and the prerequisite for its instalment, the structural design procedure for such devices is rarely addressed.

This can best be seen in the lack of straightforward classification rules and regulations. One of the main issues is the development of the broader design procedure including waves. Of all the ESDs mentioned in the previous section, the PSS device is, accounting for the long and unsupported length span, the most jeopardized type of structure and liable to ultimate and fatigue stress damage. Calm-water structural responses are relatively easy to assess and require simulations with the propeller rotation at design speed. Snapshot from the simulation with propeller is shown in Figure 4, where complicated pressure distribution due to energetic vortical structure is regularly obtained.

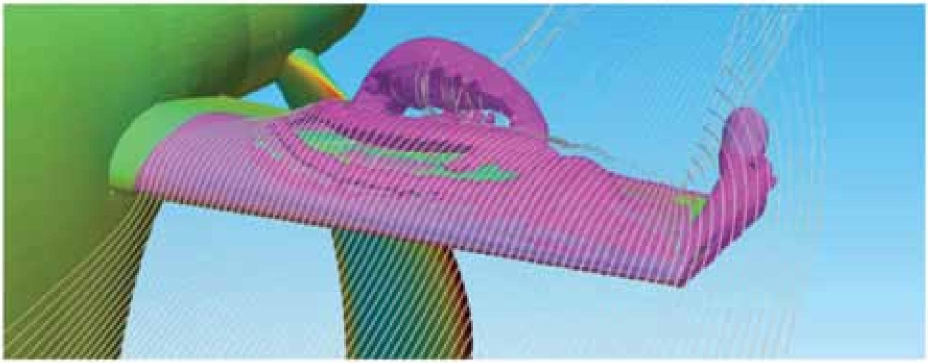

Figure 4. Flow in the vicinity of the PSS
Slika 4. Strujanje fluida u blizini predvrtložnog statora

The main issue with calm-water results is the proper transfer of loads from hydrodynamic to structural mesh, which greatly depends on the mathematical models of each side. As concerns the ESDs, the hydrodynamical model is almost always based on the CFD solvers due to their positioning at the ship stern near the propeller. An example of the CFD mesh with the duct and the PSS is shown in Figure 5. The CFD mesh is volumetric around the hull in order to solve the flow field in the ship vicinity. On the other hand, the structural model most frequently used in the modern engineering computations is based on the Finite Element Method (FEM). This model contains the inner structure of the ESD, as well as the wetted part, as shown for the PSS structure in Figure 6. In order for these two fundamentally different models to be merged, the pressure needs to be consistently interpolated from the hydrodynamic wetted surface to the structural wetted surface. This is not straightforward to perform due to their partially differing geometries. The consistent method for the interpolation of the pressure is presented in [31] for the CFD-FEM fluid structure coupling; interested readers can refer to the publication for details. Stresses computations using the CFD and the FEM in the case of the PSS can be found in [32]. An example of pressure transfer on the PSS is shown in Figure 7 for a specific time instant. However, there are occasions when the load transfer is not satisfactory to the dynamic effects on the structural response. This is a broad subject; the readers can refer [33] for details with the application on the PSS.

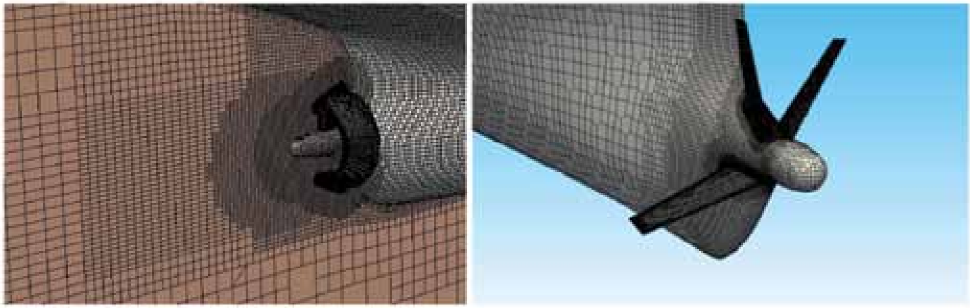

Figure 5. The CFD mesh with duct (left) and the PSS (right)
Slika 5. CFD mreža s vodom (lijevo) i s predvrtložnim statorom (desno)

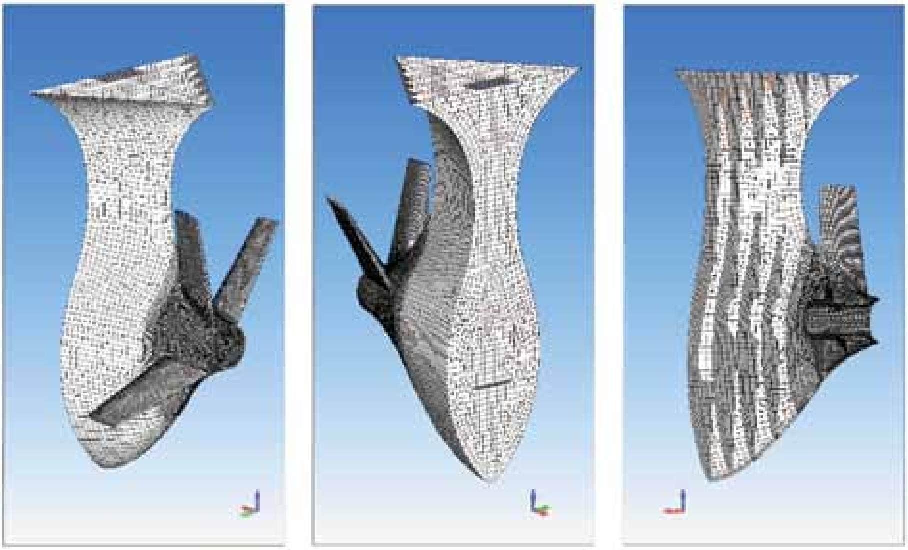

Figure 6. The PSS structural model with adjacent stern aft structure
Slika 6. Model konstrukcije predvrtložnog statora i krmenog dijela broda

For the sea-state analysis, the quantification of wave loads requires some type of simplifications. Considering that the proper hydrodynamic modelling of loads around the ESD assumes the CFD viscous models, all wave spectrums and directions are impractical to consider. With the case of a PSS, Lee et al. [34] first tested a 2-D air foil in both regular and irregular motion. Without going into details, the entire presented procedure assumes one ship speed and one ESD shape, thus significantly losing the mandatory generality a structural safety assessment should have. Further elaboration and generalization are attempted by Ju et al. [35] to consider different PSS shapes and ship speeds. Neural networks are used to lower the amount of the CFD simulations. Importantly, in both works, the hydrodynamic loads are transferred in a simplified manner from the hydrodynamic to the structural model. For the same reason of the PSS design, a GRIP project is initiated [36] for the evaluation of dynamic loads on the appended structure. In the scope of the same project, Paboeuf et al. [37] proposed a Dominant Loading Parameter (DLP) for the evaluation of the ship motion induced loads due to waves, and considered all the possible wave encounters. As it seems, to evaluate the wave loads properly, the most important factors are the definition of the DLP (variable to maximize), the evaluation of the critical cases and their correlated Equivalent Design Waves (EDWs), and their simulation in a more complex, higher order environment.

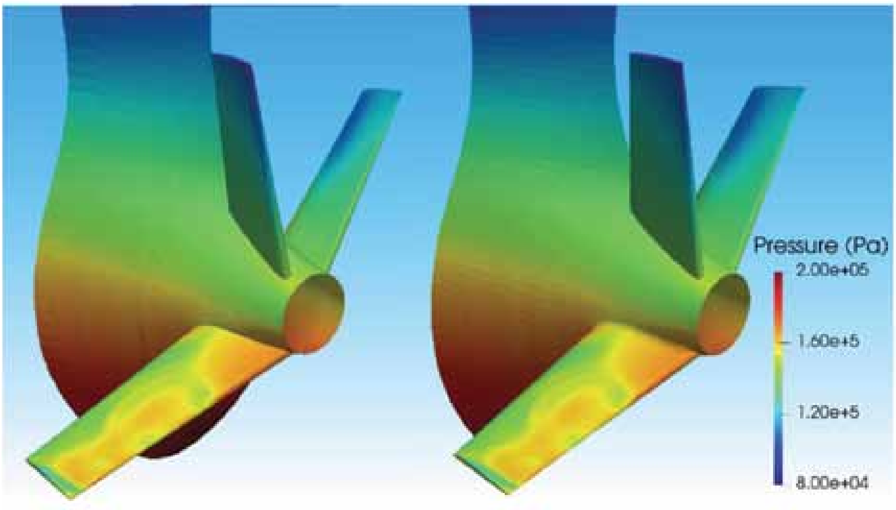

Figure 7. Pressure transfer from the CFD (left) to the FEM (right) [32]
Slika 7. Prijenos tlakova s CFD mreže na mrežu konačnih elemenata [32]

The most complete design proposal with respect to wave loads is presented in [38]. The DLP is defined as the hybrid lift force using potential method for the perturbed component and non-linear method for the steady-state component. Following the proper statistical procedure, the critical cases are defined and their design waves accordingly. The EDWs are run combining high fidelity CFD simulations for hydrodynamics and the FEM for the structural side. The loads are transferred directly to the FEM model from the CFD without simplifications. The overall design procedure is shown in Figure 8. The applicability of the methods can be easily extended to any ESD or appended structures, since the definition of the DLP is different for each, as well as posterior hydrodynamic analysis. Unfortunately, the regression formulas or simpler types of rule-based approaches have so far not been found in the literature.

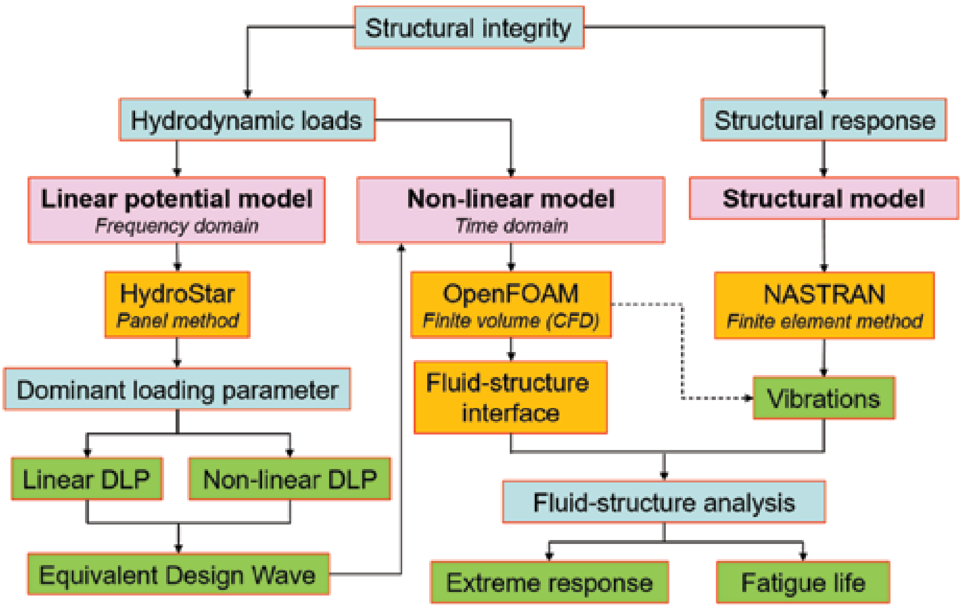

Figure 8. Structural integrity evaluation procedure for ship appendages [38]
Slika 8. Postupak za analizu integriteta konstrukcije brodskih privjesaka [38]

The method shown in Figure 8. is based on the assumption that the potential based DLP model leads to the overall critical loading cases, which require correction by non-linear models; the correction is made by the CFD-FEM coupling here. There are three main steps of the procedure: statistical analysis of the sea states by linear potential model (left column), choice of fluid-structure interaction regime depending on the structural characteristics, and a simulation of a fully CFD-FEM coupled problem at different probabilities for extreme response and fatigue. The outcome of the entire procedure is shown in Figure 9, where the CFD lift force compared to potential obviously has larger differences as the wave steepness is higher (lower probability). This is expected, since the non-linearities are pronounced at higher wave height and wavelength ratios. For design purposes, the peak stresses and stress ranges are of utmost importance; for a particular FEM element with highest liability to fatigue damage, the stress signal is shown in Figure 9. This all leads to the accurate estimation of the wave and ship motion induced structural response of the PSS, to which the long and unsupported beam is subjected to during ship lifetime.

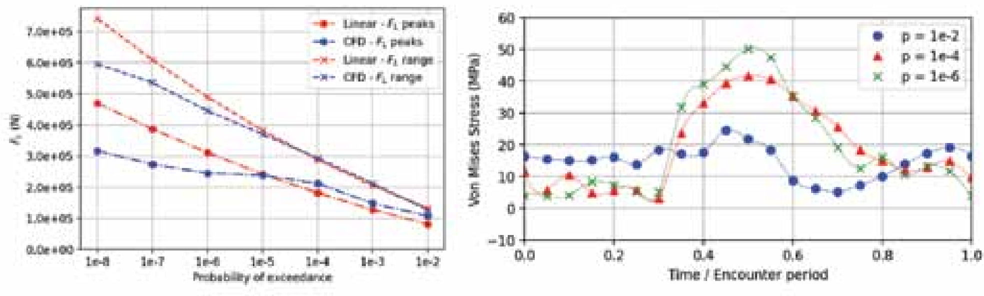

Figure 9. Potential and the CFD lift force for all probabilities (left), stress range in a selected finite element on the PSS (right)

Slika 9. Sila uzgona određena potencijalnom teorijom i računalnom dinamikom fluida (lijevo), raspon naprezanja u odabranom konačnom elementu predvrtložnog statora (desno)

4. CONCLUSION

This paper has presented some of the currently commercialized ESDs and their benefits in the field of ship propulsion. The conclusions can be listed as follows:

- The numerical modelling is most frequently performed with the CFD, since viscous and turbulence effects have great importance in the ship wake. At the design stages of the ESD shape, usually simpler and lower order mathematical models are utilized and subsequently validated using a full-scale CFD.
- Experimental analysis is used only for the verification of the CFD codes at model scale, due to scale effects issues.
- Currently, the most popular and established devices are ducts and pre-swirl ducts from Zone I; they are primarily installed or retrofitted to ships.

- The structural concerns with the ESDs are increasingly investigated and further developed.
- Given the unconventional shape and position, the classification rules have currently no straightforward guidelines and rules for the ESDs, which makes them liable to both short- and long-term damage, i.e. extreme response and fatigue, respectively.

These structural issues are expected to be more and more investigated in the future, since initial forms of structural design procedures are already developed by the scientific community. Given the rapid progress of the computational and technological fields teamed with the rising concern from climate effects, the ESDs are expected to further improve in the future, in both efficiency and structural integrity.

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PROBLEMI MEĐUDJELOVANJA FLUIDA I KONSTRUKCIJE U OSNIVANJU UREĐAJA ZA UŠTEDU ENERGIJE NA BRODOVIMA

Sažetak

Pomorski sektor je pod velikim pritiskom Međunarodne pomorske organizacije (IMO) zbog potrebe smanjenja emisija stakleničkih plinova. Poboljšanje energetske učinkovitosti flote je uvijek bila važna tema za brodovlasnike, ali s novim pravilima, smanjenje potrošnje fosilnih goriva je postala obaveza, a ne više samo poželjna ekonomska mjera. Kako bi brod zadovoljio nove propise, jedan od načina je ugradnja ili naknadno opremanje broda uređajima za uštedu energije (*eng. Energy Saving Devices*, ESDs). ESD-ovi iskorištavaju aksijalne i rotacijske energijske gubitke povezane s radom brodskog vijka. Uređaji se razlikuju po obliku, položaju i vrsti izgubljene energije koju nadoknađuju. U ovom članku dan je pregled sadašnjih trendova i prakse te klasifikacija i opis rada pojedinih ESD-a. Nadalje, iako hidrodinamičko oblikovanje i smanjena potrošnja goriva imaju glavnu ulogu, konstrukcijski zahtjevi su također obuhvaćeni ovim radom s obzirom da se navedena tematika rijetko pronalazi u dostupnoj literaturi. Kada se uzme u obzir složeno polje strujanja u blizini ESD-a pod utjecajem brodskog vijka, gibanja broda, polja sustrujanja i valova, prikladnost pojedinih numeričkih modela je detaljno analizirana s naglaskom na moderne pristupe modeliranja. Sveukupno, od uređaja za uštedu energije se očekuje dodatno poboljšanje u budućnosti uzimajući u obzir stroga pravila zaštite okoliša, njihov potencijal za poboljšanje učinkovitosti broda i nisku cijenu ugradnje.

Ključne riječi: uređaji za uštedu energije; hidrodinamički proračun; proračun čvrstoće; ušteda goriva; utjecaj na okoliš.

Andro Bakica
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
Ivana Lučića 5, 10002 Zagreb, Croatia
e-mail: andro.bakica@fsb.hr

Nikola Vladimir
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
Ivana Lučića 5, 10002 Zagreb, Croatia
e-mail: nikola.vladimir@fsb.hr

Ivo Senjanović
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
Ivana Lučića 5, 10002 Zagreb, Croatia
e-mail: ivo.senjanovic@fsb.hr

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Nakladnik
HRVATSKA AKADEMIJA ZNANOSTI I UMJETNOSTI
Trg Nikole Šubića Zrinskog 11, 10000 Zagreb

Za nakladnika
Akademik Dario Vretenar, glavni tajnik

Grafička urednica
Sonja Batušić

Digitalni identifikator objekta (DOI)
Kristina Polak Bobić

Naklada
100 primjeraka

Tisak
Stega tisak d.o.o.

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