Surf-riding phenomenon occurs when a ship sailing in following waves is accelerated to wave celerity. In this paper, surf-riding occurrence is studied for the parent hull of the Systematic Series D by 3 degrees of freedom (DOF) CFD simulations. Simulation cases are chosen following IMO recommendations for a wavelength to ship length range and following IMO criterion for ship speed cases. Initial conditions for simulations are obtained from 1-DOF surge motion equation solved by bifurcation analysis. The aim is to define surf-riding limits for ship operability with a less conservative approach, taking into account force changes in waves compared to the one used in the 1-DOF model, which considers calm water approximations. After defining surf-riding boundaries in terms of wave heights for different wavelengths and ship speeds, calculated forces are analysed to evaluate the magnitude and trend of non-linear effects due to wave elevation and ship-wave interaction. A detailed analysis is conducted on resistance, thrust, and wave forces in surging and surf-riding conditions, comparing the applied methodologies. The introduction of wave velocity field influence in the thrust force and the calculation of Froude-Krylov wave-force up to actual wave profile have been discussed and identified as possible improvements of 1-DOF approach.

1. Introduction

Since the beginning, around 2002, the development of the Second-Generation Intact Stability Criteria (SGISC) by the International Maritime Organization (IMO) working groups has been concentrated on the evaluation of five stability failure modes: parametric roll, pure loss of stability, surf-riding/broaching to, excessive acceleration and dead ship condition. According to the involved simplifications in the assessment procedures, different levels are defined: Level 1, Level 2 and Direct Stability Assessment (DSA). In the latest years, due to the non-negligible conservatism of the first two levels and the inconsistencies between them in some of the criteria, a greater attention has been given to the DSA, intended to employ the most advanced state-of-the-art technology while being yet sufficiently practical. The DSA procedure is aimed at estimating the likelihood of a stability failure in an irregular wave environment.

The surf-riding phenomenon occurs when a ship, with length and speed of the same order of the wave length and celerity, is sailing in following waves and is caught by a wave and accelerates to wave celerity. In this condition ships are normally directionally unstable and uncontrolable turn to beam position, known as broaching, can occur despite the maximum steering effort being applied.

If the ship speed is slightly higher than the wave celerity and the wave crest is around the bow position then the ship is blocked by the wave and forced to decelerate to wave celerity. This phenomenon, called wave blocking, is less dangerous than surf-riding because it does not lead to capsizing, although once wave blocking phenomenon stops the ship may experience bow diving phenomenon.

IMO defines Level 1 of surf-riding/broaching criterion in an extremely simple way, i.e. the ship is considered vulnerable if she has service speed corresponding to Froude number (Fn) higher than 0.3 and ship length less than 200 m. Since surf-riding always precedes broaching, its occurrence is used as the criterion for broaching failure mode. The surf-riding criterion defines two thresholds: the first - surf riding under certain conditions and the second - surf riding under any condition. The 2nd threshold is used in IMO procedure to define the Level 2 vulnerability criterion.

In the last years, different approaches have been studied in literature to analyse and prevent surf-riding and broaching phenomena: starting from analytical approaches, passing through potential flow numerical methods based on 4 or 6 DOF, all the way to Computational Fluid Dynamics (CFD) applications.
The first surf-riding publications reporting numerical approaches and potential flow codes are the works of Umeda (1999) and Spyrou (1996). In both works, 4 DOF potential flow method together with rudder equation have been analysed through the non-linear dynamics procedure, evaluating the fixed points and their stability in phase plane diagrams. In both works it has been underlined the connection between bifurcation occurrence and stability failure.

Spyrou (2006) has found the solution of the 1-DOF surge motion equation in closed form using Melnikov’s method and his work has been the basis for the IMO’s 2nd level vulnerability assessment.

In Maki et al. (2014) different methods for solving the surge motion equation have been compared. Authors reported results of surf-riding and wave-blocking thresholds obtained from: experimental tests, numerical bifurcation analysis and two analytical formulae: the Melnikov’s method and the continuous piecewise linear (CPL) approximation. For the particular case, both analytical methods have provided accurate results.

Bonacci et al. (2018) evaluated the vulnerability of broaching of high speed craft with time domain simulations based on the potential flow boundary element method theory. For different speed conditions, the direct assessment has been used to evaluate the number of broaches occurring during a time realization of the sea spectrum. This method has been compared with a regular wave stochastic approach, where the probability of broaching to is associated with the probability of encountering a local regular wave that causes a dynamic instability given a certain sea state. The number of instability failures obtained by the two approaches shown opposite trends: with the stochastic approach they decrease when ship speed increases; in irregular waves the trend is opposite. However, Authors highlighted the importance of numerical tools to provide statistical description of the phenomenon in irregular seas.

Studies of the influence that the ship form has on the wave field in following sea conditions when surf-riding phenomenon is likely to occur, have been conducted by Hashimoto et al. (2016) and Yang and Wang (2017). Hashimoto et al. (2016) have analysed the wave induced force variations on different hull forms, derived from the Office of Naval Research Tumblehome (ONRT) hull, throughout 2-DOF CFD simulations. The aim was to improve the prediction accuracy of the wave-induced surge force in IMO surf-riding criterion taking into account the effect of hull form parameters. Furthermore, the consideration of the dynamic vertical position in waves slightly improved the prediction accuracy. Authors concluded that, although the RANS solver showed fairly good agreement with the experiment, it is not realistic to use CFD for practical design and safety assessment, except for the direct stability assessment, due to time and costs of computations, so further investigation, based on the their outcomes, to propose a more reliable correction formula, has been encouraged.

Yang and Wang (2017) studied the stability properties of a ship in surfing and surf-riding conditions, highlighting a great difference in the stability curve values which do not consider the effect of ship motion on the wave field and CFD results performed considering the actual wave profile influenced by ship’s motions.

The technological progress and computing power give the possibility to perform surf-riding and broaching direct assessment by CFD software. Among few numerical CFD studies, one of the first application of an unsteady Reynolds-Averaged Navier Stokes method (RANS) has been demonstrated for an auto piloted ONR Tumblehome by Carrica et al. (2008) using CFDShip-Iowa software. CFDShip Iowa is a single phase level-set approach, using multiblock/overset structured Grids, and discretization based on a second order backwards Euler scheme. The equations of motions have been solved only on the water side and the waves have been implemented through initial and boundary conditions. The propellers have been modelled by an actuator disc/body force approach. Authors concluded that the use of complex codes to study dynamic stability problems could help the design of hull and appendages for safer ships although at a larger cost than other simpler methods.

The effect of different wave induced force assessments (linear Froude-Krylov, captive model test by experimental fluid dynamics (EFD) and CFD) on the surfing-surf riding boundaries has been analysed in Sadat-Hosseini et al. (2011). Although the linear Froude-Krylov formulation overestimated the wave induced forces, Authors concluded that this estimation resulted in non-significant loss in overall assessment of the boundaries. The CFD simulations in waves (for surfing, surf-riding, and broaching conditions) were performed on the ONRT model scale hull and used an actuator disc model with a fixed number of revolutions set to gain the desired Fn in calm water condition. Authors underlined that in the simulations the thrust and torque did not depend on the local flow field near the propeller but on the velocity of the ship; and that the body force was axisymmetric. Simulations for different target headings led to surge, surf-riding or broaching conditions, and in each case motions, forces and moments have been analysed predicting the instability boundaries that were found in good agreement with the ones obtained by EFD.

In this work a further application of a CFD tool for the direct assessment has been explored for surf-riding occurrence of semi-displacement naval ship. 3-DOF simulations performed by OpenFOAM are compared against numerical results obtained by bifurcation analysis. The Naval Hydro Pump software has developed particular set-ups and physical modelling such as: multiphase level-set approach (Sun and Beckermann, 2007), Ghost Fluid method for inter-face treatment (Vukčević et al., 2017; Bo and Grove, 2014), and propeller modelling with velocity correction for propeller in flow (Seb, 2017; Krasilnikov, 2013).

Surf-riding simulations have been performed for the semi-displacement, transom stern, round bilge, parent model of the Systematic Series D by Kracht and Jacobsen (1992). The simulation cases have been chosen following IMO recommendations (SDC5/WP6, 2019) for a wave length to ship length range between 0.75–1.25 and from results obtained by the IMO criterion (SDC7/5, 2019), as applied in Begovic et al. (2018), for the ship speed cases. The initial conditions for the simulations have been obtained from the results of 1-DOF surge motion equation solved by bifurcation analysis. Having defined surf-riding boundaries in terms of wave heights for different wave lengths and ship speeds, the calculated forces have been analysed in order to evaluate the magnitude and trend of non linear effects due to the wave elevation and ship wave interaction. The detailed step by step numerical modelling and the punctual analysis of resistance, thrust and wave force changes in surge and surf-riding conditions, obtained from two methodologies, represent a further contribution to the DSA and a novelty of the presented work.

The introduction of the wave velocity field influence in thrust force, and the calculation of Froude-Krylov wave force up to the actual wave profile have been discussed and identified as possible improvements for 1-DOF approach.

The paper is structured in the following parts: after a description of the 1-DOF mathematical model in Section 2, CFD modelling is introduced in Section 3. Important characteristics of the software are described and compared with other existing software, cited above, to highlight the differences and limitations. In Section 4 the analysis of forces acting on the ship is explained. The test case is presented in Section 5. The validation of the CFD set up against available published experimental data is reported in Section 6.1. Results from the two numerical methods are compared in terms of allowable wave heights in Section 6.2. In Section 7 the effect of linear and non-linear wave celerity is commented. Finally discussions and conclusions are reported in Section 8.

2. 1-DOF surge motion: Mathematical model

The mathematical model for 1-DOF surge motion equation has been described and validated in Acanfora et al. (2019). Two coordinate systems are taken into consideration, as shown in Fig. 1:
the (O; X,Y,Z) Earth fixed reference system, where the X-Y plane coincides with the still water level, Z coordinate points upwards and at time zero the origin O is located at the aft perpendicular of the ship;
- the (G; x, y, z) ship fixed reference system, where the x-y plane coincides with the still water level, the x coordinate points to bow, the z coordinate points upwards and G is aligned with the ship’s centre of gravity. At zero time the wave trough is aligned with the ship centre of gravity, G.

In the fixed to Earth system, the surge motion equation is described by a second order non-linear differential equation:

\[(m + m_X \ddot{a} + R(u)) - T(u) = F_X(X),\]  

where: \(m\) [kg] is the ship displacement; \(m_X\) [kg] is the added mass in surge direction take equal to 10% of the total mass (\(m_X = 0.1m\)), as suggested by IMO (SDC3/WPS, 2016); \(a\) [m/s²] is the ship speed and \(u\) [m/s²] is the acceleration. The \(R[N]\) represents the calm water resistance, approximated with a 5th order polynomial equation function of ship speed and resistance coefficients, \(r_1 \div r_5\), and defined as:

\[R = r_1 u + r_2 u^2 + r_3 u^3 + r_4 u^4 + r_5 u^5.\]  

The \(T[N]\) is the thrust delivered by the propeller in calm water condition defined as:

\[T = N_P r_0 n^2 + r_1 u n + r_2 u^2.\]  

where: \(n\) [rpm] is the number of revolutions fixed to obtain the desired Froude number, \(F_n\), in calm water; \(N_P\) is the number of propellers; \(r_0 \div r_2\) are the propeller’s coefficients calculated as:

\[r_0 = k_0 (1 - t_p) D_p^4,\]  
\[r_1 = k_1 (1 - t_p) (1 - w_p) D_p^4,\]  
\[r_2 = k_2 (1 - t_p) (1 - w_p)^2 D_p^4,\]  

where: \(\rho\) [kg/m³] is the water density; \(D_p\) [m] is the propeller diameter; \(k_0 \div k_2\) are derived from the thrust coefficient, \(K_T\), expressed with the 2nd order polynomial of the advanced ratio \(J = \frac{u}{\omega D_p}\):

\[K_T(J) = k_0 + k_1 J + k_2 J^2;\]  

\(w_p\) is the wake fraction considered equal to 0.1, as recommended by IMO (SDC3/WPS, 2016); \(t_p\) is the deduction thrust defined as recommended by IMO, function of the block coefficient \(C_B\), the propeller diameter, the ship breath, B, and draft, d. SDC3/WPS (2016):

\[t_p = 0.325 C_B - 0.1185 \frac{D_p}{\sqrt{Bd}}.\]  

The \(F_X[N]\) is the wave excitation force defined as:

\[F_X = f_X \sin(\omega t - kX),\]  

where: \(X\) is the distance of the wave trough from the fixed to Earth (O;X,Y,Z) coordinate system; \(k\) [rad/m] is the wave number; \(\omega\) [rad/s] is the wave frequency; \(f_X\) is the wave amplitude calculated considering only the linear Froude-Krylov component, determined with the strip theory method (Belenky and Sevastianov, 2007), IMO (SDC3/WPS, 2016), which considers the wetted surface under the calm water profile.

In this case all forces have been evaluated under calm water condition.

Considering the body fixed reference system, Eq. (1) has been rewritten as function of the surge displacement, \(x\), defined as the relative distance between the ship centre of gravity and the wave trough, and surge velocity, \(\dot{x}\) defined as the difference between ship speed and wave celerity, \(c\):

\[\dot{x} = \frac{1}{(m + m_X)} \left[ T_C - R_C - (A_1 \dot{x} + A_2 \dot{x}^2 + A_3 \dot{x}^3 + A_4 \dot{x}^4 + A_5 \dot{x}^5) \right.\]

\[+ f_X \sin(\alpha t - kX)],\]  

where the coefficients are defined as:

\[T_C = N_P (r_0 n^2 + r_1 u n + r_2 u^2),\]  
\[R_C = r_0 + r_1 c + r_2 c^2 + r_3 c^3 + r_4 c^4 + r_5 c^5,\]  
\[A_1 = r_1 + 2(r_2 - N_P) c + 3r_3 c^2 + 4r_4 c^3 + 5r_5 c^4 - N_P r_1,\]  
\[A_2 = r_2 + 3r_3 c + 6r_4 c^2 + 10r_5 c^3 - N_P r_2,\]  
\[A_3 = r_3 c + 4r_4 c^2 + 10r_5 c^3,\]  
\[A_4 = r_4 c^2,\]  
\[A_5 = r_5.\]  

Around surf-riding conditions the encounter frequency is close to zero, \(\omega_1 = 0\), therefore, the time dependence has been neglected.

Eqs. (11)–(17) are comparable to those used in IMO (SDC3/WPS, 2016) in Melnikov’s method to determine the critical number or revolutions. The difference between the two formulations is found in the number of propellers, \(N_P\), that is explicitly defined and included in the reported formulas.

Following a procedure for nonlinear dynamic systems, the second order differential equation (10) has been transformed into a system of first order equations. The system has been then analyzed in its fixed point following Belenky and Sevastianov (2007) and Strogatz (1994).

When the combination of ship speed and wave characteristics brings to the equilibrium of resistance, thrust and wave forces, two possible types of equilibrium points exist: stable focus and unstable (saddle) according to the values of trace and determinant of the Jacobian Matrix. The unstable fixed point has been chosen as initial condition and the equation has been integrated, with the Runge-Kutta method, forward in time to determine the unstable manifolds and backwards in time to determine the stable manifolds.

The phase plane, obtained by plotting the surge displacement and velocity solutions in time, can be of two types:

- Surf-riding occurrence between the 1st and the 2nd thresholds, as in Fig. 2, where the stable manifolds (blue lines) define the surf-riding domain, while the rest of the plane defines surge motion. The unstable manifolds (red lines) define the ship’s convergence in time to the stable equilibrium point or to the surging dynamic equilibrium.
- Surf-riding occurrence over 2nd threshold, as in Fig. 3, where only surf-riding phenomenon is possible and the stable manifolds divide the different domains of attractions (fixed points). The unstable manifolds (red lines) define the ship’s convergence in time to the stable equilibrium points, on successive or preceding waves.

The change of the phase planes from the condition between the 1st and the 2nd thresholds, to the one over the 2nd threshold, shown in Figs. 2 and 3, has been obtained for the same ship, for a fixed ship speed and wave length and for increasing wave height. It can be noted the same transition can be obtained for a fixed length and wave height by increasing the ship speed.
The numerical discretization of the governing equations is obtained with Finite Volume (FV) method, in which the partial nonlinear differential equations governing the fluid flow are discretized into a corresponding system of algebraic equations using second-order accuracy. For full description and details refer to Jasak (1996).

Following Vukčević (2016) and applying the Ghost Fluid Method (GFM) (described below), the continuity equation, Eq. (18), and momentum equation, Eq. (19), for water, air and free surface, are:

\[ \nabla \cdot \mathbf{u} = 0 \]  \hspace{1cm} (18)

\[ \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \mathbf{u}) - \nabla \cdot (\nu \nabla \mathbf{u}) = - \beta \nabla p_d \]  \hspace{1cm} (19)

where \( \mathbf{u} \) is the velocity field, \( \nu \) is the effective kinematic viscosity, \( \beta = 1/\rho \) is the inverse of density and \( p_d \) is the dynamic pressure field, obtained by decomposing the pressure into its hydrostatic and dynamic parts.

For the free surface flows, the interface is captured with the implicitly re-distanced Level Set (LS) method derived from the Field Phase (PF) equation (Vukčević et al., 2016a), which unites the unboundedness of the signed distance function of the LS method and preserves the hyperbolic tangent profile of the PF method (Sun and Beckermann, 2007).

Following Vukčević et al. (2017), both fluids may be considered incompressible and the approximated jump conditions on the interface are treated with the GFM (Bo and Grove, 2014; Huang et al., 2007; Desjardins et al., 2008) which overcomes numerical errors found in the conventional method by imposing interface kinematic and dynamic boundary conditions, and accounts for the discontinuous density field.

Wave modelling is introduced with a double decomposition method: a solution decomposition, to introduce the wave field, achieved with the Spectral Wave Explicit Navier–Stokes Equations (SWENSE) method (Vukčević et al., 2016a) and a domain decomposition, to reduce the wave reflection, based on the implicit relaxation zone approach (Jasak et al., 2015). The SWENSE method (Ferrant et al. (2002) and Ducrozet et al. (2014)) decomposes the fields into incident and perturbed components, with the idea to capture features of the free surface, with a potential flow incident arbitrary field, and superimpose non-linear, two phase, turbulent effects by extending the incident component to a full Navier–Stokes model via the perturbed component.

To prevent wave reflection, which can cause errors in CFD results, an implicit relaxation zones approach (Jasak et al., 2015) is used to force the perturbed field to vanish in the far-field boundaries. The approach consists in introducing, into the momentum and free surface equations, a relaxation zone operator which imposes the perturbed field to be zero at the boundary. A weight field, described by an exponential function, blends the interior domain solution described by CFD computations and the outer one described by pure wave theory.

The free surface elevation of the regular wave field is described using a flow model with linear wave theory on an infinite domain. The linear solution is extended to incorporate the weakly non-linear effects, yielding higher order Stokes theories (Dean and Dalrymple, 2002).

The rigid body motion equations are introduced along with the governing flow equations to describe ship motions. As described in Gatin et al. (2019), the coupling of the rigid body motion equations and the fluid flow is performed using an enhanced approach: i.e. the rigid body motion equations are solved once per pressure corrector step, and a geometric method is used for integration of rigid body motion equations (Muller and Terze, 2016).

In order to perform self-propulsion simulations, an actuator disc is used. The model is based on the assumption of a thin infinite blade propeller model and the disc is a cylindrical interface with the same diameter as the model propeller (Krasilnikov (2013) and Seb (2017)). To reproduce instant thrust and torque values, the pressure boundary condition is defined to produce the desired pressure jump, following Goldstein distribution (Goldstein, 1929) and the velocity condition...
is set to add a swirl. The pressure and velocity jumps derive from thrust and torque values, obtained from the open water test curves given in dimensionless form with respect to the advance coefficient, function of the number of revolutions, the propeller diameter and the advancement speed. The advancement speed is calculated with axial velocity correction in order to compute the inflow velocity on the propeller plane, taking into account the flow accelerations due to the actuator disc itself, as described in Jasak et al. (2018) and Bakica et al. (2019). This velocity correction is a step forward to the propeller model limitations reported in Sadat-Hosseini et al. (2011).

The governing flow equations and the 6-DOF rigid body equations are solved following a segregated solution algorithm using PIMPLE solver. PIMPLE is composed of an outer loop called Semi-Implicit Method for Pressure Linked Equations (SIMPLE) (Patankar and Spalding, 1972), which starts solving 6-DOF motion equations, moves the rigid mesh and evaluates the incident fields with the potential wave theory, and an inner loop called Pressure-Implicit with Splitting of Operators (PISO) (Issa, 1986), which predicts the perturbed velocity field and solves the dynamic pressure, through pressure-velocity coupling. For each time instance of boundary condition updates, the pressure jump of the actuator disc is added to the current value of the pressure field on the chosen actuator disc faces. Coupling between the body motion and the actuator disc is fully resolved by recalculating the thrust direction axis and actuator disc faces position after each mesh motion update.

The Linear equation solvers, here used, are the preconditioned Krylov subspace linear system (Saad, 2003), in particular, the Conjugate Gradient for symmetric pressure equations and Bi-Conjugate stabilized BICGSTab for the other equations (van der Vorst, 2003).

The turbulence closure is achieved via two equations eddy viscosity models described by $k-\omega$ Shear StressTransport (SST), model (Menter et al., 2003; Pereira et al., 2015).

### 4. Forces description in surging and surf-riding conditions

In the 1-DOF model the forces acting on the hull are distinguished as resistance and thrust, calculated in calm water condition, and linear Froude-Krylov wave force, calculated considering wetted surface in calm water.

Following the forces decomposition as in Eq. (1), the dynamic equilibrium in CFD simulations is given by:

$$m\ddot{x} + F_X - T = 0.$$  \hspace{1cm} (20)

This is because the total force in the x direction, $F_X(N)$, acting on the hull is determined by integrating pressure and viscous contributions, consequently no separation is done between resistance and wave forces, and the thrust force is given by the actuator disc model.

The total force $F_x$ can be therefore decomposed in its components following equation (21):

$$F_X = m\ddot{x} + R_{CW} + F_{FK} + R_{add}.$$  \hspace{1cm} (21)

where $m\ddot{x}$ is the added mass, $R_{CW}$ is the resistance calculated in calm water condition, $F_{FK}$ is the Froude-Krylov component of the wave force, $R_{add}$ is an additional contribution of resistance which includes the added resistance due to waves and the diffraction and radiation component not included in the Froude-Krylov calculations.

In a post processing analysis, from the calculated CFD total force in x direction, the total resistance in waves, $R_{TW}$, considered as the sum of calm water resistance and all nonlinear effects due to waves, has been evaluated following equation (22) after the calculation of the Froude-Krylov component.

$$R_{TW} = R_{CW} + R_{add} = F_X - m\ddot{x} - F_{FK}.$$  \hspace{1cm} (22)

The Froude-Krylov forces have been determined adapting IMO (SDC3/WP5, 2016) formulation for the linear Froude-Krylov forces and considering the non lineairities due to the wetted surface under
Assessment and Operational Measures, simulations have been performed by CFD and 1-DOF results against IMO guidelines on SGISC for Direct Phenomena. Simulations have been conducted to evaluate the occurrence of surging and surf-riding for a ship sailing in following waves free to heave, pitch and surge, having validated preliminary calculations set up.

The chosen test case has been the parent hull form (D1 model) of the Systematic Series D, by Kracht and Jacobsen (1992), originated from a semi-displacement, twin-screw, round-bilge hull form, initially made by the German yard Howaldtswerke-Deutsche Werft. More details on the series are given in Begovic et al. (2018). The ship’s main particulars are reported in Table 1.

<table>
<thead>
<tr>
<th>D1 Main particulars</th>
<th>D1 Hull Full Scale Main particulars.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars</td>
<td>( L_{pp} )</td>
</tr>
<tr>
<td>Draft</td>
<td>( T )</td>
</tr>
<tr>
<td>Breadth</td>
<td>( B )</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>( C_{b} )</td>
</tr>
<tr>
<td>Wetted surface</td>
<td>( S )</td>
</tr>
<tr>
<td>Displacement</td>
<td>( V )</td>
</tr>
<tr>
<td>90 m</td>
<td>3.6 m</td>
</tr>
<tr>
<td>13.5 m</td>
<td>0.5</td>
</tr>
<tr>
<td>1215.11 m²</td>
<td>2243578 kg</td>
</tr>
</tbody>
</table>

(22)

Table 1

The nonlinear Froude-Krylov forces have been evaluated considering the local draft \( d \) and submerged area \( S \) under the linear wave profile, determined by the instant wave crest position obtained from the CFD surge motion variations.

5. Test case: Systematic Series D

The chosen test case has been the parent hull form (D1 model) of the Systematic Series D, by Kracht and Jacobsen (1992), originated from a semi-displacement, twin-screw, round-bilge hull form, initially made by the German yard Howaldtswerke-Deutsche Werft. More details on the series are given in Begovic et al. (2018). The ship’s main particulars are reported in Table 1.

The EFD data of open water tests, calm water resistance tests for the side boundaries, as shown in Fig. 6. Five additional refinement boxes, as shown in Fig. 7, have been added to provide sufficient resolution around the hull surface and in the relaxation zones imposing an adequate thickness with respect to the wave length.

Two hull geometries have been meshed, the first one corresponding to a bare hull and the hub geometries of the full scaled D1 ship. Calculations have been performed with the bare hull geometry because detailed geometries of the rudder, propeller and shaft brackets were not available, therefore for a fair comparison only EFD bare hull results were used. The only appendage geometry considered is an approximated hub to avoid numerical errors for back flow in the propeller disc.

The coordinate system used has the origin at the intersection of aft perpendicular, free surface and ship symmetry plane at time zero as shown in Fig. 5. The x axis is positive towards the bow, the z positive upwards and the y positive to port side, and the system translates with a constant forward speed.

The CFD domain has been meshed with dimensions of about 1.5 \( L_{pp} \) for the inlet, 4.5 \( L_{pp} \) for the outlet, 2.5 \( L_{pp} \) for the side boundaries, as shown in Fig. 6.

5.1. Grid generation and case set-up

An unstructured polyhedral FV grid has been used to mesh the bare hull and the hub geometries of the full scaled D1 ship. Calculations have been performed with the bare hull geometry because detailed geometries of the rudder, propeller and shaft brackets were not available, therefore for a fair comparison only EFD bare hull results were used. The only appendage geometry considered is an approximated hub to avoid numerical errors for back flow in the propeller disc.

The CFD domain has been meshed with dimensions of about 1.5 \( L_{pp} \) for the inlet, 4.5 \( L_{pp} \) for the outlet, 2.5 \( L_{pp} \) for the side boundaries, as shown in Fig. 6.

Table 2

<table>
<thead>
<tr>
<th>Turbulence properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freestream velocity</td>
</tr>
<tr>
<td>Turbulence kinetic energy</td>
</tr>
<tr>
<td>Specific turbulence dissipation</td>
</tr>
<tr>
<td>Turbulence intensity</td>
</tr>
<tr>
<td>Kinematic viscosity</td>
</tr>
<tr>
<td>11.883 m/s</td>
</tr>
<tr>
<td>8475.1935 1/s</td>
</tr>
<tr>
<td>11.883 m/s</td>
</tr>
</tbody>
</table>

Only half of the domain has been meshed in the simulations using the flow symmetry for the considered degrees of freedom, but the resulting forces are reported for the full ship.
Fig. 7. Mesh refinement boxes.

Fig. 8. D1 mesh for calm water resistance simulations.

Fig. 9. D1 mesh with the extended freeboard for the following waves simulations.

Table 3
Calm water Resistance comparison between CFD and EFD results for different Froude numbers, \( F_n \).

<table>
<thead>
<tr>
<th>( F_n )</th>
<th>CFD</th>
<th>EFD</th>
<th>Rel Err</th>
<th>CFD</th>
<th>EFD</th>
<th>diff</th>
<th>CFD</th>
<th>EFD</th>
<th>diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>173480</td>
<td>179276</td>
<td>3.2%</td>
<td>-0.08</td>
<td>-0.07</td>
<td>-0.01</td>
<td>-0.218</td>
<td>-0.219</td>
<td>-0.002</td>
</tr>
<tr>
<td>0.35</td>
<td>26638</td>
<td>257118</td>
<td>-3.6%</td>
<td>-0.07</td>
<td>-0.13</td>
<td>0.06</td>
<td>-0.297</td>
<td>-0.252</td>
<td>0.045</td>
</tr>
<tr>
<td>0.4</td>
<td>461385</td>
<td>465826</td>
<td>1.0%</td>
<td>0.28</td>
<td>0.24</td>
<td>0.04</td>
<td>-0.402</td>
<td>-0.432</td>
<td>-0.03</td>
</tr>
<tr>
<td>0.45</td>
<td>723005</td>
<td>754591</td>
<td>4.2%</td>
<td>0.86</td>
<td>0.88</td>
<td>-0.02</td>
<td>-0.486</td>
<td>-0.501</td>
<td>-0.015</td>
</tr>
</tbody>
</table>

With the unstructured grid and for small motion simulation cases, (considering only the surf-riding phenomenon and excluding the capsize event) in this work a body fitted grid with rigid displacement deformation has been used instead of the overset mesh, which has been used in CFDShip Iowa (Carrica et al., 2008).

The turbulent model used is the \( k-\omega \) SST with the values listed in Table 2.

In a first attempt for fast and steady simulations, as for calm water resistance and self-propulsion, adjustable time step was considered based on fixed Courant number equal to 20. For transient simulations in surf-riding conditions, Courant number has been set to 10. For the PIMPLE algorithms, each number of the inner and outer loops is set to 4.

Although a time step sensitivity study has not been conducted, the large time steps have been proved to achieve acceptable results as reported in the works of Jasak et al. (2018), for full scale self-propulsion simulations, and in Vukčević and Jasak (2015) for seakeeping simulations.

The code validation and verification has been extensively reported in Gatin et al. (2015b) for calm water resistance calculations, in Vukčević et al. (2016b) for wave propagation, in Jasak et al. (2018) for self-propulsion cases and in Gatin et al. (2017) for grid sensitivity in seakeeping simulations.

6. CFD calculation results

6.1. Preliminary resistance and thrust calculations

The validation of the CFD case set up has been conducted for full scale calm water resistance comparing the results with EFD data, available from the publication of Kracht and Jacobsen (1992).
The calculations for bare hull steady state resistance have been performed with free heave (sinkage) and pitch (trim) motions and fixed surge motion, with no wave generation, and have been conducted for 4 different speeds, in a range of Froude number from 0.3 to 0.45. Table 3 and Figs. 11–13 report the comparison between CFD results and EFD results for bare hull full scale resistance, trim and sinkage calculations. The comparison shows the following results: the relative errors for resistance are about 1%–4%; trim values differences are ranging from −0.02 to 0.06 degrees; sinkage differences are ranging from −0.045 to −0.002 m. This is in line with the validation studies for the Naval Hydro Pack (Gatin et al., 2015a).

In order to predict the number of revolutions needed to reach each ship speed, the propeller controller of the actuator disc is set up to achieve zero residual forces (that is zero difference between resistance and thrust).

To compare the trend and order of magnitude, CFD bare hull resulting number of revolutions are represented together with the EFD ones referring to the appended hull, which is the only self-propulsion data available, as shown in Fig. 14. The trend of the two curves is qualitatively similar but not quantitatively. The observed difference is
due to the major resistance of the EFD appended hull case and it has been considered acceptable to validate the numerical set up.

The obtained values of number of revolutions have been used to perform simulations in waves to predict surging or surf-riding tendency, imposing the fixed number of revolutions corresponding to the desired value of Fn in calm water.

6.2. Surf-riding limits: Methodology comparison

After testing and validating the set up in calm water, D1 hull behaviour in regular waves has been tested in different operational conditions and for various wave characteristics, to investigate whether the ship would be caught by the wave, leading to surf-riding phenomenon, or remain in safe surging motion.

Although an extensive grid study is not performed due to the limited availability of time and computational resources, the set ups follow the basic grid study, reported by Gatin et al. (2017) and, in a first attempt, are considered sufficient to validate the present simulations in waves.

Fig. 15 shows the CFD simulation of the ship surf-riding at Froude number equal to \(Fn = 0.35\) in sea conditions with wave to ship length equal to \(\lambda/L = 1\) and steepness equal to \(H/\lambda = 1/22.5\), which corresponds to wave height equal to \(H = 4\ m\).

The aim of performing CFD simulations is to define surf-riding limits for ship operability with a less conservative approach, taking into account force changes in wave conditions, neglected in 1-DOF.

Since CFD simulations are time consuming, the initial conditions for the test cases have been carefully chosen following IMO recommendations, (SDC6/WP6, 2019), and surf-riding limits obtained by 1-DOF model approach.

The 1-DOF approach has been performed on the D1 bare hull for three Froude numbers, \(Fn\) equal to 0.3, 0.35 and 0.4 (corresponding to ship speed of 8.913, 10.398 and 11.883 m/s) and for three wavelength to ship length values, \(\lambda/L\) equal to 0.75, 1 and 1.25 (corresponding to wave celerity of 10.264, 11.852 and 13.251 m/s). Through the phase plane analysis surf-riding limits have been found in terms of wave heights. Table 4 reports the first (lower) wave height value at which the ship experienced surf-riding phenomenon over the 2nd threshold. The reported limit values refer to cases in which the ship is faster than the wave and the only possible occurring phenomenon could be wave blocking. Although the wave blocking limits could be easily found with the same 1-DOF procedure used for the surf-riding ones, Authors decided to focus only on the most dangerous phenomenon of surf-riding and set aside wave blocking limits.

The CFD simulations have been conducted following the 1-DOF grid points of wave to ship length and Froude number cases. For each case, the simulations have been performed starting with the wave height value equal to the limit value for which the ship experienced surf-riding by 1-DOF approach and reported in Table 4. Analysing the ship speed variations and the wave celerity of the CFD simulations, oscillating surging or converging surf-riding motions were defined. If surging motion was observed then a new simulation with increased wave height was performed until surf-riding phenomenon occurred. The simulations have been performed for about 200 or 300 s for surging conditions and 60–150 s for surf-riding conditions in full scale.

Table 5 reports the values of wave heights set in CFD simulations for each wave length and ship speed case, and the corresponding observed motion: surging or surf-riding.

The surf-riding limits, that were identified when the ship experienced surf-riding phenomenon for wave steepness equal to or exceeding the limit value, are shown in Table 6 and Fig. 16 for both 1-DOF and CFD approach.

The averaged values of \(\gamma^*\) of the first layer from the solid walls are about 5870 around the hull patch and 1328 around the hub, for case \(\lambda/L = 1, Fn = 0.35\) and \(H = 3.5\ m\), and about 8481 around the hull patch and 1279 around the hub patch, for case \(\lambda/L = 1.25, Fn = 0.4\) and \(H = 3.5\ m\).

The 1-DOF calculations are performed on a standard notebook with 4 cores and processor Intel Core i7-7700HQ CPU @ 2.80 GHz, and the CPU time is around few seconds. All CFD simulations are run in parallel using 4 cores computer with Intel Core i7-4820 K CPU @ 3.70 GHz, and the CPU time reaches up to 5 or 6 days for each wave case. It should be commented that no surf-riding limit was actually found for wave case \(\lambda/L = 0.75\), but the approximated limit value has been considered in Fig. 16 to give an idea of the tendencies and differences.

It can be noticed that longer the wave and higher the Froude number closer are the results for the two different methods. This result can be expected and explained since a ship is more vulnerable at higher speed even at lower wave heights and because the non-linearities related to the wave force, not included in the 1-DOF approach, decrease with decreasing of wave heights. Moreover, it can be commented that higher the ship speed longer the wave must be to have wave celerity greater or equal to ship speed.
Fig. 16. Surf-riding limits in terms of wave steepness for 1-DOF and CFD approach for Froude range of \(Fn = 0.3-0.4\) and for wave to ship length range of \(\lambda/L=0.75-1.25\).

6.3. Kinematic results from CFD simulations

Having found the surf-riding limits, a detailed analysis of CFD results is done in terms of motions and forces. The differences in forces values obtained by the two approaches are investigated with the aim to discuss possible improvements for the 1-DOF approach.

From CFD simulations, surf-riding occurrence is identified by analysing the ship speed variations and the phase plane transitions for a fixed number of revolutions, a fixed wave length and for increasing wave heights, as shown in Figs. 17 and 18.

The case with fixed \(\lambda/L = 1\) and number of revolutions set to obtain \(Fn = 0.35\) in calm water is shown in Fig. 17. Fig. 17(a) reports the ship speed variations compared with the wave celerity value in time domain simulations. When ship speeds are lower than wave celerity the surging condition was identified, as in the first 2 diagrams (where \(H/\lambda = 1/50\) and \(H/\lambda = 1/30\)) and for increasing wave height when the ship speed reaches the wave celerity the surf-riding phenomenon was observed, as in the last two figures (for \(H/\lambda = 1/25.7\) and \(H/\lambda = 1/22.5\)).

In Fig. 17(b) surge motion and surge velocity are analysed in the phase plane diagram. It can be seen that in surging conditions, displacement and velocity oscillate, while in surf-riding conditions, they tend to the equilibrium point (fixed point).

6.4. Forces results from CFD

Following the CFD force decomposition as in Eq. (20), the resulting total force in \(x\) direction calculated in waves, \(F_x\), and the thrust force, \(T\), for cases \(\lambda/L = 1\) and \(Fn = 0.35\), and \(\lambda/L = 1.25\) and \(Fn = 0.4\), are reported in Figs. 22 and 23 respectively. For lower wave heights the forces oscillate in time, indicating surging conditions, and for higher waves the forces remain constant, defining surf-riding phenomenon.

6.5. Comparison of dynamic results in 1-DOF and CFD approach

Following the forces decomposition as in Section 4, a detailed analysis has been conducted on the trend and magnitude of the forces.

The total resistance in waves, as defined in Eq. (22), where the Froude-Krylov force is calculated up to the linear wave profile, and the thrust, evaluated with CFD simulations, are compared with the respective forces determined by the 1-DOF approach. Both resistance and thrust in calm water have been calculated considering the ship speed variation, defined by \(u = x - c\), where the surge displacement has been obtained directly from CFD.

All the forces have been plotted together with relative wave crest position referred to ship stern. From the analysis of Fig. 24, in
Fig. 18. Surging to surf-riding transition for case $\lambda/L = 1.25$, $Fn = 0.4$ with increasing wave heights.

Fig. 19. Dynamic pressure distribution for case $\lambda/L = 0.75$, $Fn = 0.3$ and $H = 4$ m.

Fig. 20. Dynamic pressure distribution for case $\lambda/L = 1$, $Fn = 0.35$ and $H = 4$ m.

Fig. 21. Dynamic pressure distribution for case $\lambda/L = 1.25$, $Fn = 0.4$ and $H = 4$ m.
surging condition, and Fig. 25, in surf-riding condition, it can be seen how calm water approximations differs from actual forces calculations by CFD simulations.

The difference in thrust may be attributed to the different propeller inflow velocity, since the wave field velocity is taken into consideration only in CFD calculations. From Fig. 24 it can be seen that when the
Fig. 24. Resistance and Thrust trends and differences with CFD and 1-DOF approach for $\lambda/L = 1$ $H = 3$ m and $Fn = 0.35$ in surging condition.

wave crest is around the stern position, the thrust evaluated by CFD is greater because the actual inflow velocity at the propeller is less than the ship speed, since on wave crest the wave field velocity is opposite to the ship speed. When the crest is around amidships and the trough is around the propeller, the inflow velocity is increased, since wave field and ship speed have same directions, and therefore the thrust is lower compared to the calm water one.

The resistance trends and differences are more complex to analyse, because the CFD calculated resistance includes the variations due to wetted surface changes under actual wave profile and the wave diffraction components, non considered in Froude-Krylov determination. From Figs. 24 and 25 it can be seen that when the crest is around stern position CFD values are greater than 1-DOF, which underestimates resistance values especially in this position, particularly favourable for surf riding.

As shown in Fig. 25 in case of surf-riding conditions, calm water values tend to overestimate thrust and underestimate resistance making surf riding more likely to happen.

7. Effect of wave celerity

During the development of the SDC regulations and problem resolution for the 2nd level of the surf-riding criterion, the wave celerity formulation has been long discussed and changed in time. Until 2015 (SDC3/INF10, 2015), IMO documents included two formulas to assess the wave celerity: a linear celerity, as define in Eq. (26), depending only on the wave number, and a non-linear wave celerity, as defined in Eq. (27), depending on the wave number and amplitude.

$$c = \sqrt{\frac{g}{k}}$$  \hspace{1cm} (26)

$$c = \sqrt{\frac{g}{k}} \sqrt{1 + \left( \frac{H}{2} \right)^2}$$  \hspace{1cm} (27)

The comparison of surf-riding limits using linear and non-linear wave celerity, as proposed by IMO, has been reported and discussed in Begovic et al. (2018), where the results showed that adopting the non-linear formulation, Level 2 vulnerability assessment was verified for a higher ship speed limit, around 0.5 knots.

It has to be underlined that in CFD simulations a linear wave theory has been set to initialize wave calculations while in the computational domain the flow calculations are non-linear and this non-linearity consequently influences the evaluation of the wave celerity.

Therefore, a study on the influence of non-linear wave celerity in 1-DOF approach has been conducted for one Froude number for each considered wave length.

Fig. 26 shows the value of wave height at which the 2nd threshold of surf-riding occurs, comparing 1-DOF results with linear and non-linear wave celerity, and CFD ones.

After 2016 (SDC3/WP5, 2016) the IMO group agreed to use the linear wave celerity for the 2nd level assessment.

$$c = \sqrt{\frac{g}{k}}$$  \hspace{1cm} (26)
Fig. 25. Resistance and Thrust trends and differences with CFD and 1-DOF approach for $\lambda/L = 1$ $H = 3.5$ m and $Fn = 0.35$ in Surf-riding condition.

8. Discussions and conclusions

Surf-riding limits found by 3-DOF CFD simulations have been compared against the ones obtained by 1-DOF surge mathematical model. It was not possible to compare numerical results reported in this paper with experimental ones because, to our knowledge, no experimental data for D series in waves is available.

Throughout a force decomposition, calm water resistance and thrust forces trends obtained by 1-DOF approach have been compared to CFD corresponding forces.

The differences found in resistance between the two approaches are due to the wetted surface changes under actual wave profile, the nonlinear effects due to the interaction of ship and wave and the diffraction effect of the incident waves. The thrust differences may be attributed to the wave field influence in the inflow velocity neglected in the 1-DOF methodology.

The physical analysis of the decomposed forces and their quantitative contribution suggests as possible improvements of the 1-DOF mathematical model the following: considering the actual wetted surface in the calculation of Froude-Krylov and in the viscous part of resistance and the introduction of wave field influence including wave particle velocities to calculate the thrust force.

A first implementation, in the surge mathematical model, that takes into account the effect of wave particle velocity in thrust calculations, has been done by Hashimoto et al. (2004), who reported a detailed description and analysis of the wave effect on the ship’s thrust when predicting capsizing in heavy seas, comparing experimental and numerical results. In this work, the wave effect on thrust was taken into account by adding the horizontal wave particle velocity component to the inflow velocity in the propeller which lead to thrust variations. Authors concluded that the importance of the wave effect on propeller thrust was not small enough to be ignored in broaching prediction.

Investigations on resistance variation in surf riding studies have been conducted by Ummeda (1984), theoretically and experimentally. In Spyrou (2006) the ship speed for resistance calculations has been corrected semi-empirically by adding a position-dependent term to the still-water value that represents the averaged wave particle velocity. The effect of wave field on the thrust force has been taken into account by evaluating the velocity of the incoming flow to the propeller by adding to the advanced velocity the local velocity of wave particles. Nevertheless, it was concluded that there was no significant difference in final results.

Moreover, in literature surf-riding studies and force variations in following waves are rare and not directly comparable. Sadat-Hosseini...
Fig. 26. Surf-riding limits in terms of wave steepness for 1-DOF with linear and non-linear wave celerity and CFD one for Froude range of $Fn = 0.3$–0.4 and wave to ship length range of $H/\lambda = 0.75$–1.25.

(2009) and Sadat-Hosseini et al. (2011) reported a detailed study on surf-riding and broaching phenomena, comparing CFD and EFD resulting data for the ONRT hull. Due to the differences in hull form and in the scales used between Sadat-Hosseini’s work and the one reported in this paper no quantitative comparison could be done. Even though a qualitative comparison could be made, the differences in speed range and wave characteristics would bring to a misleading comparison.

Steps for a future research, regarding CFD simulations, will be to include appendages and rudder geometries and to increase the number of degrees of freedom.

Although CFD methodology is clearly better predicting surf-riding phenomenon, the required computing time is still prohibitive to consider it within the probabilistic frame of the Second Generation Intact Stability Criteria and operational guidelines, where simulation in irregular wave at full scale is required for many different environmental and ship conditions.

Nevertheless, it is reasonable to foresee the applicability of CFD in a direct assessment for limited number of critical cases previously identified, as shown in this paper.

**CRediT authorship contribution statement**

**E. Begovic**: Planned and carried out the simulations, Interpretation of the results, Critical feedback and helped shape the research, Analysis and manuscript writing and revising.  
**I. Gatin**: Planned and carried out the simulations, Interpretation of the results, Critical feedback and helped shape the research, Analysis and manuscript writing and revising.  
**H. Jasak**: Planned and carried out the simulations, Interpretation of the results, Critical feedback and helped shape the research, Analysis and manuscript writing and revising.  
**B. Rinauro**: Planned and carried out the simulations, Interpretation of the results, Critical feedback and helped shape the research, Analysis and manuscript writing and revising.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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