Ship capsize dynamics: a numerical sensitivity study

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ABSTRACT

Ship capsize has a very dynamic nature, and it can be caused by more complex mechanics than the lack of static stability. Surf-riding, broaching-to, pure loss of stability and resonant roll are among the typical dynamic phenomena that might lead to large heel and severe consequences. This paper investigates the dynamic of the capsize of a frigate sailing in stern quartering waves using non-linear time domain simulations. Particular interest is directed to the numerical modelling of the dynamic linear and non-linear maneuvering forces acting on the ship hull, and to the effects that these components can cause on the capsize behavior. The results show that the modelling of the maneuvering forces have a significant impact on capsize. This happens not only for capsizes caused by broaching, but also to loss of stability on the wave crest. The study confirms the complexity of this physical phenomena and the still actual necessity of reliable ship dynamics numerical models.

Keywords: *Capsize, dynamic stability, broaching-to, pure loss of stability, manoeuvring model.*

1. INTRODUCTION

Capsize of ships in intact conditions can have several causes, but its study and prevention is usually bound to static stability assessment. The GMT in high waves and the GZ at large heel angles are such that the ship cannot restore the roll caused by the waves, causing the capsize. Past research, both numerical and experimental, showed that the ship capsize has a very dynamic nature, and it can be caused by more complex mechanics than the simple wave and restoring forces counteraction. De Kat et al. discussed already in early 90s about the dynamic stability and capsize of ships by observing the outcomes of free sailing model tests. Umeda et al. described in great detail the dynamics of a capsize occurring on various ship types. Even if stability rules such as the weather criterion (see De Kat) are still widely used to design ships, stability regulations are developing towards the dynamic stability assessment. A stability assessment in waves requires sophisticated and reliable computational tools, seen the highly non-linear behavior of the phenomena involved. The objective of this paper is to point out some of the most important aspects concerning the numerical prediction of capsize. Particular interest is directed to the numerical modelling of the linear and non-linear maneuvering forces acting on the ship hull. These forces were systematically varied in this paper to estimate their influence on the capsize behavior. The maneuvering of ship is not usually directly connected to the capsize dynamics: however, the maneuvering characteristics can play an important role in the motions of the ship in stern-quartering waves. Surf-riding, broaching-to and pure loss of stability on the wave crest are typical phenomena preceding a capsize that are strongly driven by ship dynamics. The numerical tool used in this study is FREDYN, a non-linear time domain method developed by MARIN for the Cooperative Research Navy (CRN). The aim of this tool is not only to predict the capsize risk, but also to model the dynamic phenomena causing the capsize. A correct estimation of the forces acting on the ship is then of high importance. A US Coast Guard Hamilton Class Cutter is considered in this investigation. Model tests were carried out for this ship with the intention of validating FREDYN. As first check prior to the main investigation, FREDYN simulations are compared with the outcomes of the model tests.

2. CAPSIZE MODEL EXPERIMENTS

In 1996 capsize model experiments were carried out (see Thomas and Hoyt) within the CRN framework, with the aim of creating validation material for FREDYN numerical simulations. The tests were carried out for a 1/36 scale fiberglass model of a twin shaft and spade rudders United States Coast Guard Hamilton Class High Endurance Cutter (WHEC). The tests were carried out in stern-quartering regular waves for many combinations of ship speed, wave steepness, period and direction. The model tests were carried out in three different loading conditions (full load, marginal, failed) at decreasing GM_T. Capsize were observed only at the "failed" condition. The outcomes of the experiments highlighted both the capsize and the dynamic mechanisms such as surf-riding, broaching-to and pure loss of stability.

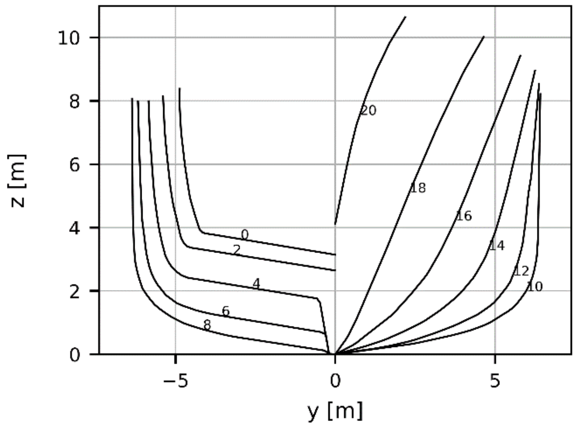

Figure 1: WHEC hull lines

Table 1: Main characteristics of WHEC

Parameter	Value		
LPP [m]	106.68		
B [m]	12.776		
T [m]	4.73		
CB [-]	0.522		
δMAX [deg]	35		
$\dot{\delta}$ [deg/s]	7		
C_ψ [deg/deg]	3.25		
$C_{\dot{\psi}}$ [deg/deg/s]	12		
$C_{\ddot{\psi}}$ [deg/deg/s2]	-189		
Loading conditions	**Full load**	**Marginal**	**Failed**
k4/B [-]	0.4	0.418	0.455
k5/LPP [-]	0.272	0.276	0.276
GMT [m]	0.777	0.683	0.427

3. MATHEMATICAL MODEL

Numerical simulations of WHEC sailing in stern-quartering regular waves were carried out using the non-linear time domain tool FREDYN. FREDYN computes different components of force acting on the hull, as described below.

The hydrostatic and first-order wave forces are computed non-linearly on the actual submerged geometry in waves. The hull geometry is discretized by quadrilateral panels. This allows a more accurate estimation of the force with respect to transversal sections, especially the wave surge force that is important for the surf-riding prediction.

The radiation and diffraction forces are calculated using linear strip-theory. These components are calculated linearly at the draft of the vessel in calm water.

Hull and bilge keels roll damping (lift and bilge keel eddy damping) is calculated using the semi-empirical equations of the Fast Displacement Ship database (FDS, Kapsenberg et al.). Roll damping was validated against model scale roll decay tests, as shown in Figure 2.

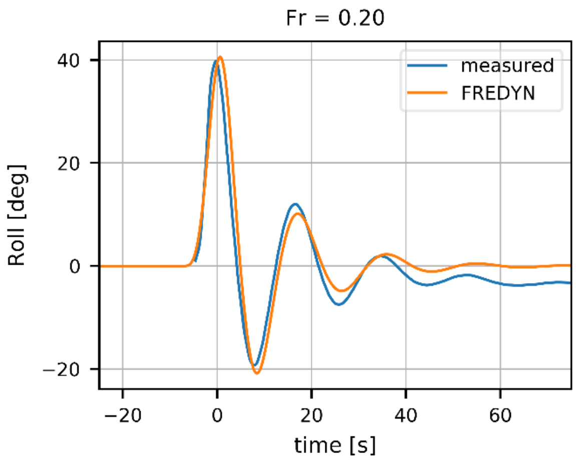

Figure 2: Comparison between measured and predicted WHEC roll decays at speed.

The propeller thrust and the lift on active and passive fins such as rudders, skeg and shaft line struts are calculated by means of semi-empirical equations.

The maneuvering loads are calculated using slender body theory. These components are described in more detail in the next paragraphs.

Maneuvering forces

The total maneuvering forces are calculated as the sum of linear and non-linear (cross-flow drag) components. The linear component is modeled through 1st order polynomials for sway force and yaw moment:

$$F_Y = Y_{uv}|u|v + Y_{ur}ur; \quad (1)$$

$$M_Z = N_{uv}uv + N_{ur}ur. \quad (2)$$

The coefficients of the polynomials are estimated by semi-empirical equations function of the main characteristics of the vessel, namely Fr, T, L_{PP}, the pitch angle τ, C_B, B/T, L_{PP}/B. These equations derive from slender body theory. The non-linear component or cross-flow drag is computed at each ordinate of the vessel as:

$$CD(x) = CD_f CD_0 (1 - x/L_{PP})^n, \quad (3)$$

where CD_f is a correction depending on the Froude number, and CD_0 is a function of the midship sectional area A_{10} and B/T. The value of the exponent n depends on L_{PP}/B and C_B; n=1 if L_{PP}/B is less than 6.5. The cross-flow drag force is calculated at each section of the hull considering the sectional draft in waves. The wave elevation is constant for each section and it is computed as the mean wave height along the hull.

4. NUMERICAL SIMULATIONS

FREDYN is more conservative in predicting the capsize events of the vessel. Although this is a good feature for a capsize risk evaluation, it might affect the modeling of the overall dynamic behavior. Simulations were carried out for the loading conditions of marginal GMT, at a wave direction of 30 deg stern-quartering and wave steepness H/λ of 0.067. Different nominal speeds and wave lengths were considered: between Froude number 0.275 and 0.375 and non-dimensional wave length λ/L_{PP} between 1.0 and 2.5. The RPM of the propellers was kept constant to match the resistance in calm water. For these conditions, no capsizes were observed in the experiments. Instead FREDYN predicts many more capsizes than in the model tests. The capsize region predicted by FREDYN is shown in Figure 3.

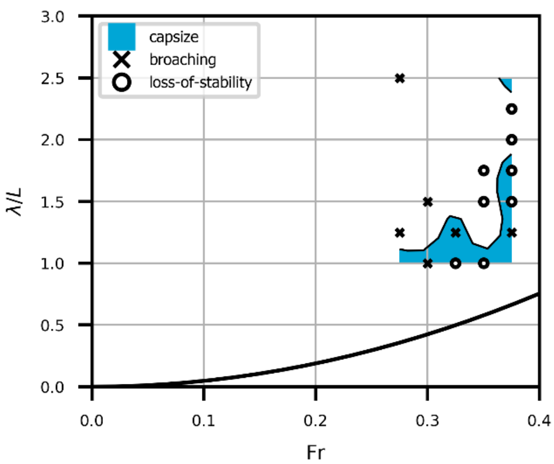

Figure 3: Capsize region (in blue) of the WHEC at 30 deg wave heading and H/λ=0.067. Detected broaching and loss-of-stability events are highlighted. The black continuous line represents zero-encounter frequency.

The wave steepness and heading conditions were chosen for the maneuvering force analysis because the numerical simulations showed a good variety of dynamic stability events. In this way, the differences caused by a variation of the maneuvering force could be more visible on every dynamic aspects of the problem. The WHEC was modeled as described in section 3, including bilge keels, fins, skeg, rudders, shaft lines and propellers. An example of the 3D view of the vessel sailing in waves can be seen in Figure 4.

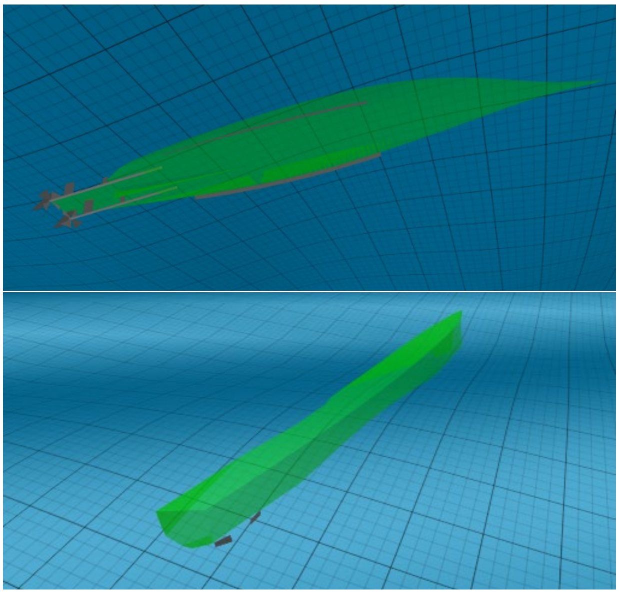

Figure 4: Rendering of a numerical simulation at λ/L=1.0, Fr=0.3, H/ λ=0.067, 30 deg wave heading.

Maneuvering model modification

The linear maneuvering coefficients were modified to obtain three different values of the bare hull directional stability coefficient

$$C = Y_{uv} N_{ur} - (Y_{ur} - m) N_{uv}, \quad (4)$$

corresponding to the default hull setting, a more unstable hull and a more stable hull. The obtained values are shown in Figure 5. The cross-flow drag was modified changing the default value of CD0, therefore obtaining three cross-flow drag longitudinal distributions, as shown in Figure 6.

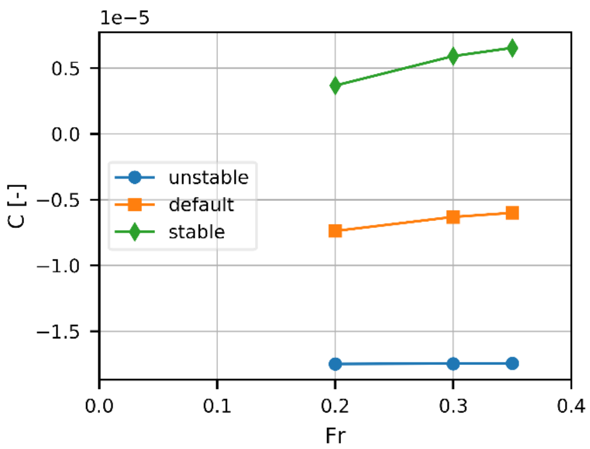

Figure 5: Values of bare hull directional stability coefficient as function of Froude number.

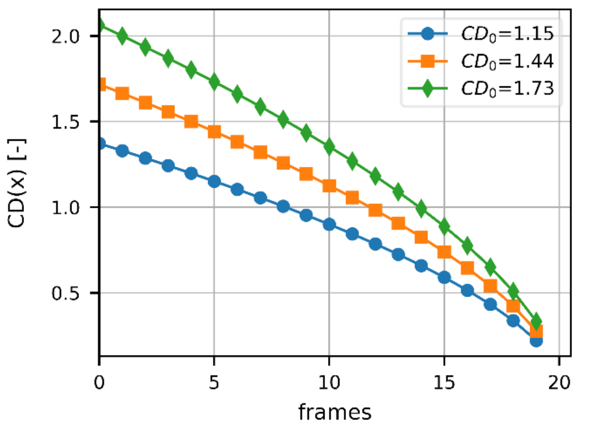

Figure 6: Different cross-flow drag as function of ship frames at varying CD0 values (CD0=1.44 is the default value for the WHEC).

5. DYNAMIC INSTABILITY DETECTION

An algorithm was developed, through the analysis of the simulated and experimental time histories, to detect three main dynamic phenomena: surf-riding, broaching-to and loss-of-stability on the wave crest (see Lena and Bonci).

A surf riding occurs when the vessel is captured by the incoming wave, that pushes the ship forward accelerating up to the celerity of the waves and beyond. It is necessary for a surf-riding that the speed of the vessel is relatively close to the wave crest celerity. A surf-riding is detected when the total ship speed is greater or equal the wave crest celerity. The ship total speed is estimated along the direction of propagation of the waves.

During a surf, the vessel can spend a long period of time in the same position of the wave. When this happens on the wave crest, in this time interval the GMT can decrease causing significant roll angles. This phenomenon is regarded as a loss-of-stability event. This event is detected when:

- the ship experiences a large roll on a wave crest or after but in the same wave cycle;
- the ship experiences surf-riding in the same wave cycle of the roll peak;
- the roll peak value exceeds a prescribed threshold, estimated as the angle of deck submergence.

The position of the vessel in the waves, and thus on the wave crest, is determined by monitoring the wave height at the COG.

A broaching-to is a sudden turn of the vessel sailing in following seas towards beam-to-sea, despite the maximum counteraction of the steering devices. Usually a broach is preceded by surf-riding. A broaching-to is detected when:

- the yaw angle and yaw velocity must be increasing towards beam-to sea;
- the steering devices must be delivering the maximum possible counter action. This can happen at the maximum steering angle, but also at the maximum steering speed when the steering device is moving towards the maximum counteracting angle;
- the previous conditions must lead to a significant yaw deviation of at least 20 degrees.

The yaw deviation is the most visible result of a broaching-to, even if the threshold is arbitrary and depends on many factors. The results of the detection algorithm are shown in Figure 7 and 8 for two experimental runs of the WHEC. The plots show, from top to bottom, the ship CoG position in the waves, the speed and wave celerity in the wave direction of propagation, the yaw and rudder angles, the yaw speed and acceleration, the roll angle and the wave elevation at CoG. Figure 7 shows the detection of a broaching (highlighted in yellow) quickly followed by a capsize. The broaching-to occurs on the wave through during a surf-riding (highlighted in blue). Figure 8 shows instead a capsize due to loss-of-stability on the wave crest. The loss-of-stability event (square marker) is detected after 35 seconds with a roll angle greater than 30 degrees.

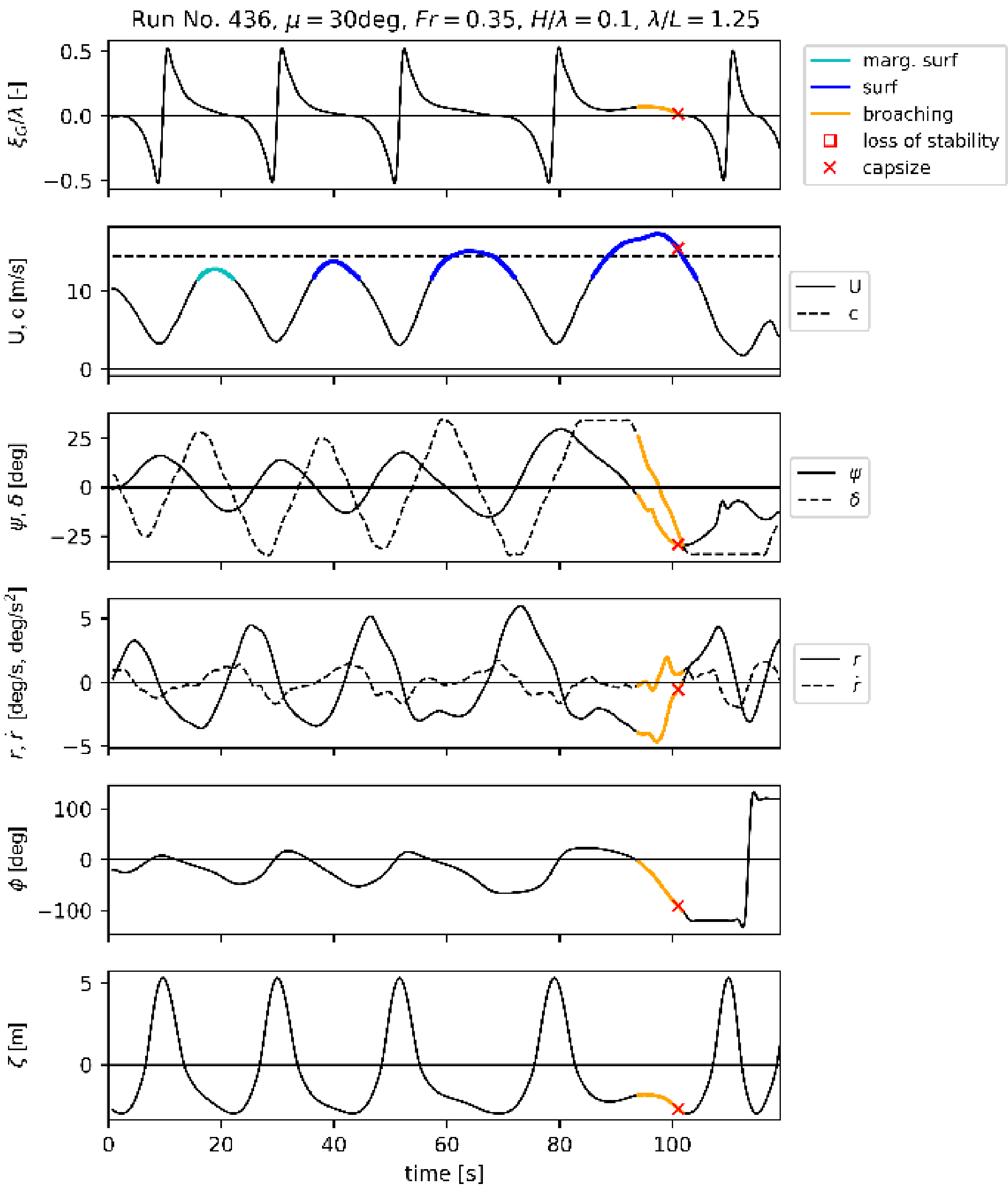

Figure 7: Capsize due to broaching of a WHEC model test run. The run conditions are above the plots.

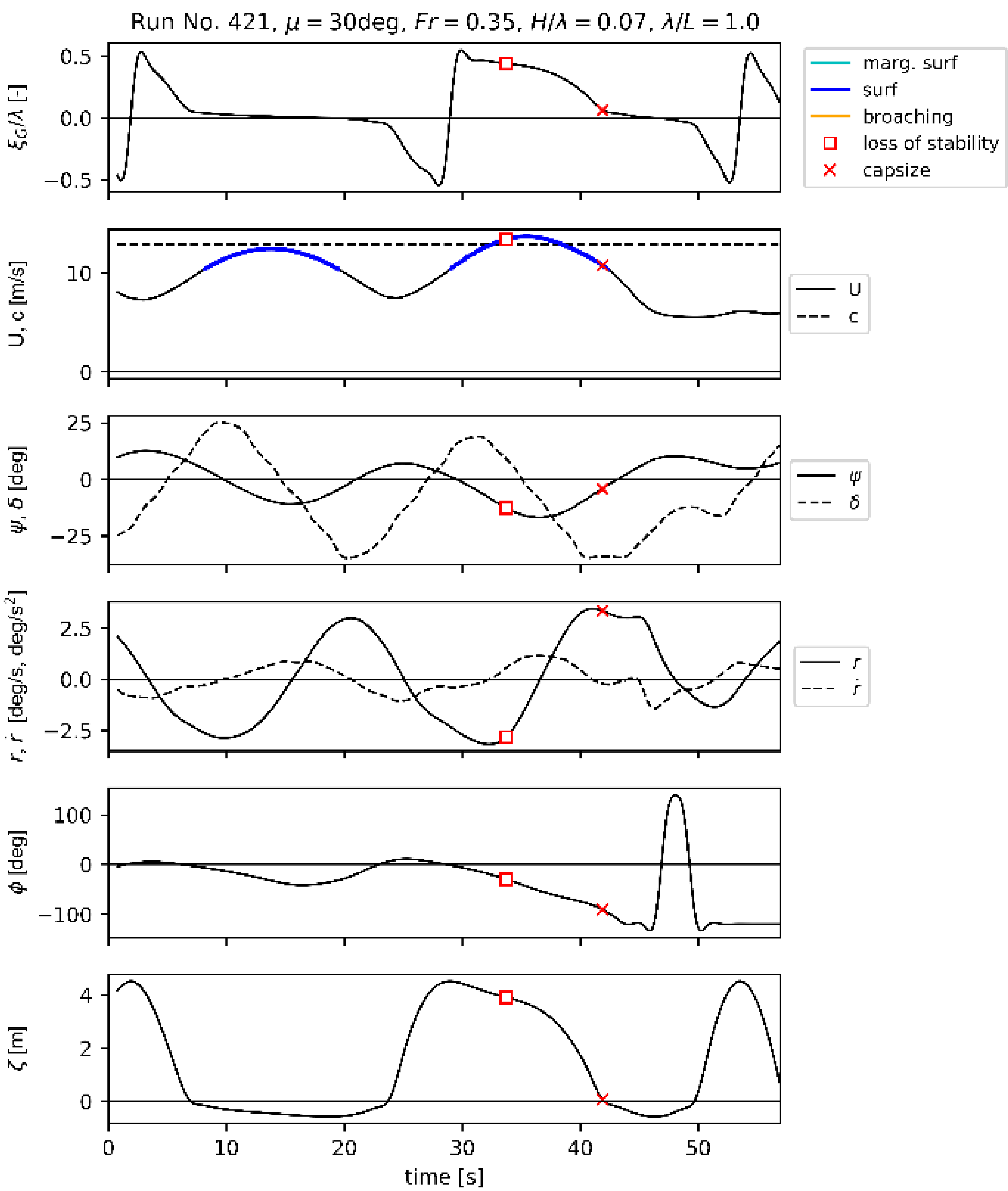

Figure 8: Capsize due to loss-of-stability of a WHEC model test run. The run conditions are above the plots.

6. RESULTS

The surf-riding region modeled by FREDYN is shown in Figure 9 for the simulations with default settings. The simulated surf-riding behavior of the WHEC does not change significantly with a variation of the maneuvering force. As expected, the surf-riding region extends above Froude number 0.3 and for the cases at lower encounter frequencies.

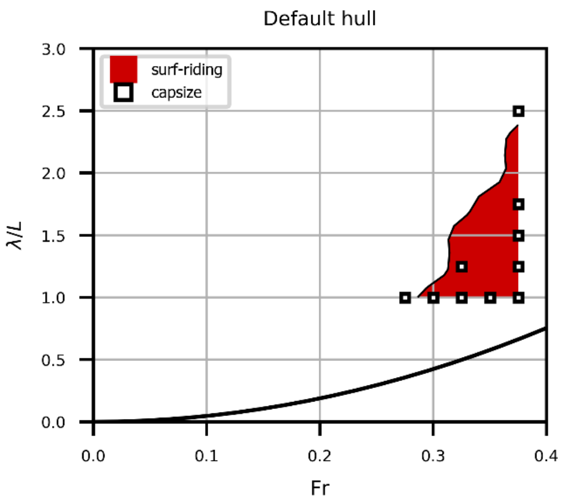

Figure 9: Simulated surf-riding region of the WHEC with default settings. Wave heading: 30 deg; wave steepness 0.067.

As shown in Figure 10, the simulated broaching-to tendency of the WHEC decreases at better directional stability. This is an expected result because a more stable hull results in a large stabilizing yaw moment that counteracts the broaching-to motion. A different directional stability affects also the pure loss of stability. This is less expected, because a loss of stability should be driven by the transverse stability in relation with the relative position in the wave. The motions on the horizontal plane have a significant influence on the location in the wave where the ship is most likely to experience a surf-riding, and thus also stability loss.

Figure 11 shows the results of the simulations for different values of the cross-flow drag coefficient CD0. As expected, a larger cross-flow drag (CD0=1.73) significantly reduces the likelihood of a broaching event. This is due to an increase in non-linear force at aft (see Figure 6) that stabilizes the vessel in yaw. The region of pure-loss of stability does not change significantly at different cross-flow drag. This is different than what observed for the variation of the linear maneuvering forces.

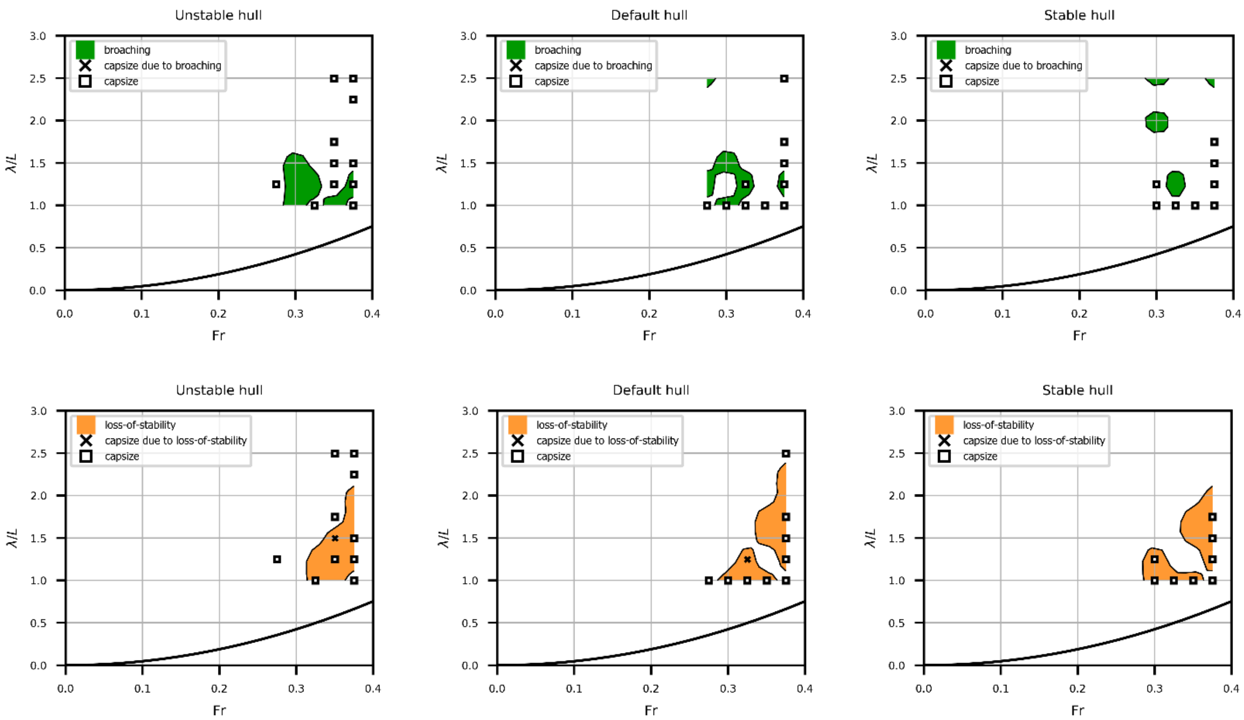

Figure 10: Broaching-to (top) and pure loss of stability (bottom) regions at varying bare hull directional stability. Wave heading: 30 deg; wave steepness 0.067.

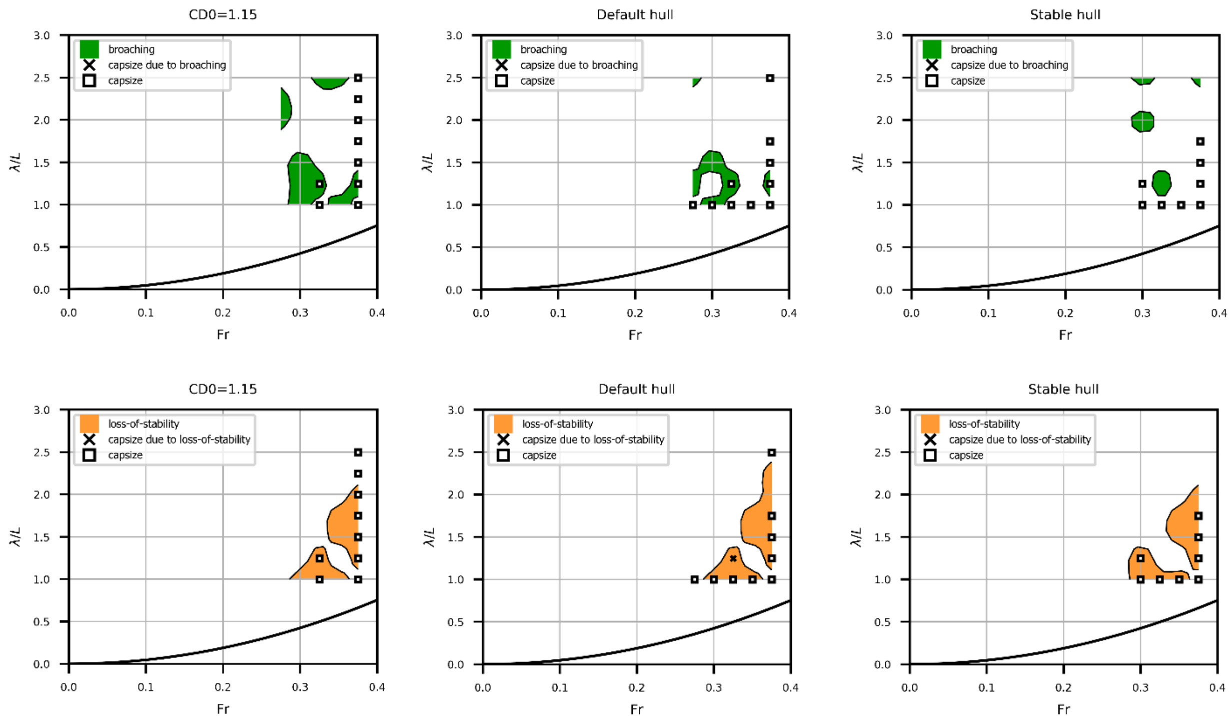

Figure 11: Broaching-to (top) and pure loss of stability (bottom) regions at varying non-linear cross-flow drag. Wave heading: 30 deg; wave steepness 0.067.

The number of capsize events simulated by FREDYN is affected only slightly by the different modeling of the maneuvering forces. In most cases, capsize in FREDYN is not connected to the maneuvering dynamics of the vessel. No capsize was a direct consequence of a broaching or loss of stability, except for the default hull settings at λ/L=1.25 and Fr=0.325. In this case, the capsize was caused by a loss of stability. An example of time histories simulated by FREDYN is shown in Figure 12: a broaching and a loss-of-stability are both detected but none of them is a direct cause of the capsize occurring after about 230 seconds.

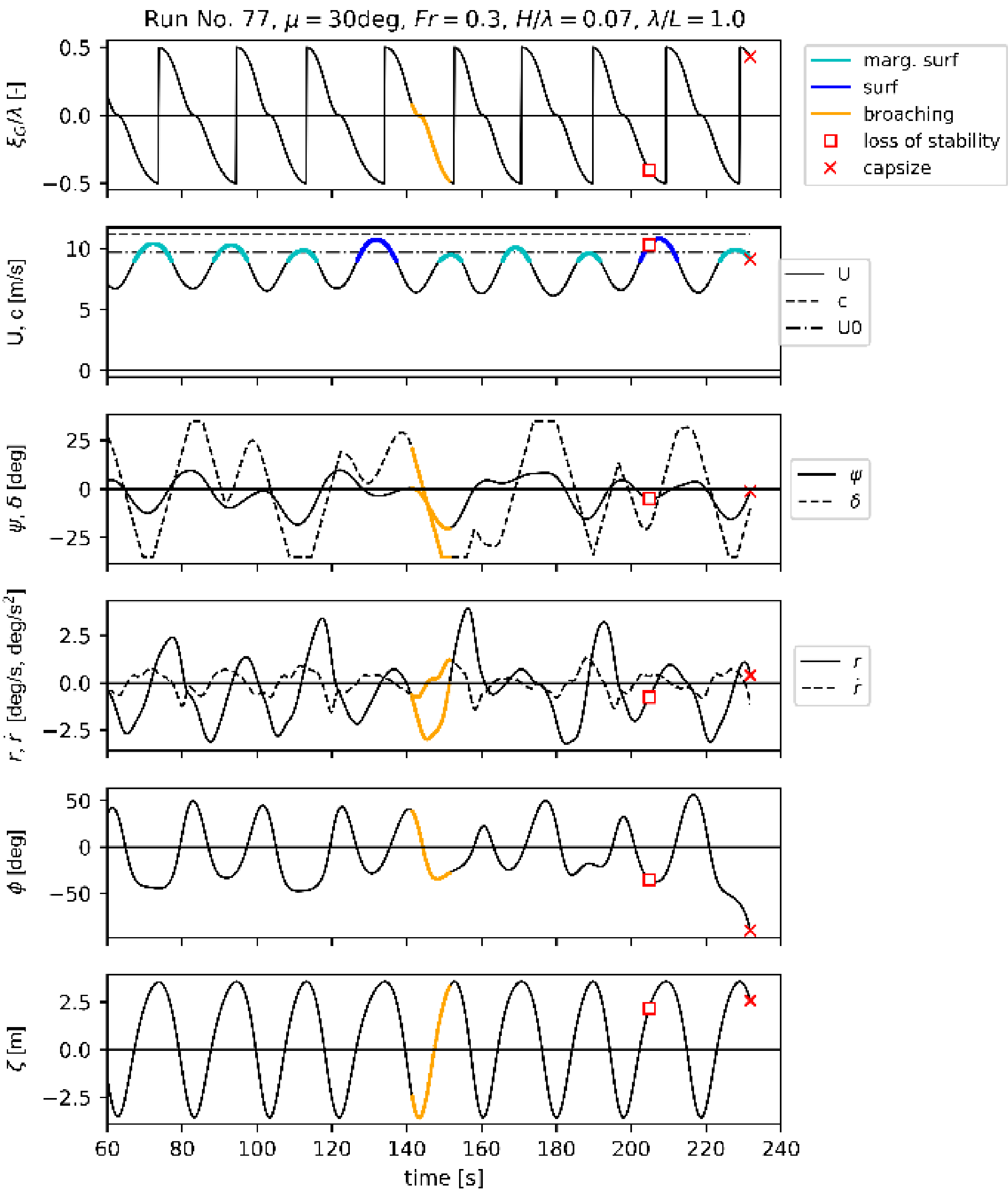

Figure 1210: FREDYN simulation; although both broaching and loss of stability events were detected, none of them causes the capsize.

7. CONCLUDING REMARKS

The capsize behavior of a frigate was investigated through time domain numerical simulations. The results of the investigation showed that the numerical prediction of the capsize behavior and the motion dynamics of the WHEC sailing in stern-quartering waves is highly affected by the modeling of the maneuvering forces. This is an expected results when considering the broaching behavior of a vessel; less expected are instead the consequences on the pure loss of stability on the wave crest. In the numerical simulations, the maneuvering forces govern significantly the ship motions in stern-quartering waves. Therefore they are a decisive factor in the instability and capsize events dynamics, and in determining the position and the speed of the vessel in the waves.

FREDYN is more conservative in predicting capsize with respect to what was observed in the model tests. Although this is a good feature when evaluating the capsize risk of a vessel in extreme sea states, FREDYN lacks in predicting with good accuracy the dynamics that leads to a capsize. An improvement in the maneuvering force modeling might also improve the prediction of the capsize dynamics. However, this behavior is observed regardless of the variation of the maneuvering forces, therefore other factors are contributing to this behavior. A deeper and thorough analysis of the simulation tool seems necessary in future research.

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