UNSTABLE SHIP MOTIONS APPLIED ON SHIP-WEATHER ROUTING ALGORITHM SIMROUTEv2

Bachelor’s Thesis

by

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B.Sc

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Abstract

Some combinations of wave length and wave height under certain operational conditions may lead to dangerous unstable motions for ships in accordance with the IS Code. The susceptibility of a ship to dangerous phenomenon will depend on the stability parameters, ship speed, hull shape and ship size. This signifies that the vulnerability to dangerous responses, including capsizing, and its probability of occurrence in a singular sea state may differ for each ship. During navigation periods these unstable motions are able to be encountered, which may lead to a cargo or equipment damage and the unsafety of the persons on board. The main reason for these causes is rarely known and currently there are just few work such as the International Maritime Organization guidelines which tries to ensure adequate dynamic stability (IMO, MSC.1/Circ.1228, 2007).

Ship routing systems are gaining importance in the maritime sector as the use of these systems can lead to the reduction of fuel usage and reduce costs. Therefore, a mitigation of carbon emissions and improvement of maritime safety happens due to the avoidance of bad weather conditions. The implementation of pathfinding algorithms to determine the optimal ship routing has been widely used for transoceanic distances. However, the evaluation of short distance routes with ship-weather routing algorithms is still scarce, due to the low spatial resolution of wave fields.

Mixing both concepts, that is to say, implementing the ship routing system with common unstable motions makes the algorithm more complete and useful than it was. Thus, equipping ships with these systems will be profitable for the officers because they will be able to modify the established route or, at least, alter the course depending on the danger faced. Results derived from such calculations should only be regarded as a supporting tool during the decision-making process.

SIMROUTEv2 was developed to obtain the optimal route and the minimum distance route recovered from the pathfinding algorithm A* (Grifoll et al., 2016). This system was based on the inclusion of the added resistance by waves on the vessel, the impact of which is significant in terms of time. Ship routing analysis was studied on four relative routes related to five ports in the Western Mediterranean Sea, paying attention to the Short Sea
Shipping activities and the Ro-Pax and Ro-Ro services, being both of them the most frequently performed in the aforementioned area (Basiana et al., 2017).

This project implements safety restrictions for avoiding broaching/surf-riding and parametric rolling according to the guidelines of the International Maritime Organization (IMO circular no. 1228) in the SIMROUTEv2 algorithm. The expected output will be the shortest route in terms of time and safety according to IMO guidelines for preventing these aforementioned unstable motions. The methodology of the unstable motions implementation of this project is based on wave direction, peak wave period, encountered wave period and the type of the vessel in terms of speed, length and the natural rolling period. The work establishes the basis of further development in routes optimization utilized in comparatively short-distances and its systematic use in the Short Sea Shipping maritime industry and also in some other investigations of the unstable motions.

**Keywords.** Unstable motions, broaching, surf-riding, parametric rolling, ship routing, Short Sea Shipping, wave models, safety navigation.
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**Introduction**

One of the main problems in Europe is the abuse of inland modes of transportation. Therefore, the number of emissions of polluting gases is increasing and some roads are still collapsed. European Community, living in this unsustainable model should change the system and should start taking care of the mitigation of high polluting gases emissions.

This problem must be addressed as the vast majority of countries in the European Union are facing this issue (European Commission White Paper, 2011). The solution for this problem is based on an intermodal system, which emphasizes maritime routes in general and particularly Short Sea Shipping. Integration of Short Sea Shipping into an effective transport chain is a potential choice to avoid road congestion, enhance accessibility and to provide ideal maritime routes.

Pathfinding algorithms to determine the optimal ship routing has been applied in a wide way for transoceanic distances. However, the evaluation of using ship routing at short distances has been little studied. SIMROUTEv2 is the ship-weather routing algorithm that it has been chosen to test this short sea distances. Some cases of study have proved its feasibility in the Western Mediterranean, mostly in bad weather conditions (Basiana et al., 2017).

In bad weather conditions it is frequent to find different unstable motions for the ship. These undesirable movements can cause discomfort to the passage, crew members, generation of dynamic loads to the structure and cargo of the ship and it can even cause the capsize of the ship. Despite its importance, it is an aspect that is still scarcely studied. Thus, this project aims, regarding the circulars of the IMO, to implement in the SIMROUTEv2 algorithm some unstable motions.
Background and Literature

Research of unstable motions are still scarce and even more related on ship-weather algorithms. The first study of surf-riding/broaching was done in the 1960’s by (Due Cane and Goodrich, 1962), the unstable motion was justified as a loss of stability of the surging motion (Ananiev, 1966). These works are a little bit antiquated, nowadays it is based on a solid foundation of nonlinear dynamics (Belenky and Sevastianov, 2007).

In the late 1930s the first study of parametric rolling of ships was done in Germany (Kempf, 1938). The aim of this study was to explain the phenomenon of capsizing in small ships such as fishing vessels and coasters in severe following seas. Some experts thought that parametric rolling happens in following seas with small vessels (Wendel, 1960), but some years later there were different cases among different variety of vessels such as cruise ships, ferries and containerships. These ships experienced heavy rolling in head seas, totally different than the aforementioned thoughts. The APL CHINA disaster in October 1998 is a clear example that parametric rolling can happen to different vessels and different wave direction, in this case head seas. Researchers started paying more attention to this phenomenon (Belenky, 2003).

![Figure 2: APL CHINA accident. Source: The Law Offices of Countryman & McDaniel (1998)](image)

Oscillatory rolling motion that increases to a large amplitude after only a few cycles is caused by a little initial perturbation in roll (Clark, 2005). The occurrence of parametric roll is connected to the periodic variation of stability as the vessel moves longitudinally through the waves at a certain speed when the vessel’s wave encounter frequency is almost twice the natural roll frequency and it is impossible to dissipate this parametric roll energy due to the damping of the ship is insufficient (ABS Guide, 2004).
The International Maritime Organization pays attention on both phenomenon surf-riding/broaching and parametric rolling and identified the conditions that trigger the instability so that the seafarers can take action to avoid the occurrence of this phenomenon, e.g. by changing speed or course (IMO, MSC.1/Circ.1228, 2007).

As mentioned in (Basiana et al., 2017), in regards of ship routing optimization through pathfinding algorithms, academic research has been carried out (i.e. Padhy (2008), Szłapczyńska and Śmierzchalsk (2009), Takashima et al. (2009), Wei & Zhou (2012), Mannarini et al., (2013) as well as Larsson and Simonsen (2014)). These contributions take into account the meteorology forecasts of the oceans, such as the waves, the winds or current predictions. Although the vast majority of these ship routing algorithms have been examined using very large distances (oceanic routes), shipping optimization remains unknown in regards to short-distance routes. For instance, within the Short Sea Shipping framework. The dimensional resolution of the meteo-oceanographic predictions (weather scripts) is a serious restriction in this case.

Mannarini used the same wave added resistance formula as the SIMROUTEv2 algorithm for his model. The control variable was ship course. The graph was constructed using 24 edges per node, allowing for a directional resolution of about 27 degrees. This contribution tested the ship routing algorithm in ocean distances (Mannarini et al., 2013). The result of using a network graph for the Indian Ocean was an Optimum Track Ship Routing model. This model enabled ship routers to make better and faster decisions. Instead of hours of manual calculations and chart plotting the model produces generated solutions rapidly (Padhy, 2008). Takashima applies a method for optimizing fuel consumption to two routes along Japan’s coast so the distances were shorter in comparison to the aforementioned papers. A propeller revolution constant number was established during the voyages. By using this constant as well as environmental, speed and engine performance data, the voyage time was calculated. However, when the calculation was distant to the desired voyage time, the authors changed the number of revolutions of the propeller and recalculated the trip (Takashima et.al., 2009).
The three contributions, explained in the above paragraph, were retrieved by the Dijkstra Algorithm (Dijkstra, 1959), although A* Algorithm significantly reduces the computational time (Dechter & Pearl, 1985).

Another pathfinding algorithm that could be used is the Bellman-Ford Algorithm, referring to Ford (1956) and Bellman (1958). This algorithm is slower than Dijkstra’s Algorithm but can detect when the graph does not contain any cycles of negative length (Walden, 2003).

Grifoll (2016) develops a ship weather routing algorithm called SIMROUTEv2 which the methodology was based on the inclusion of the added resistance by waves on the vessel, the impact of which is significant in terms of time testing the pathfinding algorithms Dijkstra and A*. The work established the basis of further development in routes optimization utilized in comparatively short-distances and its systematic use in the Short Sea Shipping maritime industry.

A research was carried out, investigating in which weather conditions the algorithm SIMROUTEv2 is feasible or not. This system was developed to obtain the optimal route and the minimum distance route recovered from the pathfinding algorithm A*. Ship routing analysis was studied on four relative routes related to five ports in the Western Mediterranean Sea, paying attention to the Short Sea Shipping activities and the Ro-Pax and Ro-Ro services (Basiana et al., 2017).

Szłapczynska’s and Smierzchalski’s method is based on an evolutionary algorithm that takes into account multiple criteria such as voyage risk and time as well as fuel consumption time resulting in an optimized route (Szłapczynska & Smierzchalski, 2009).

Wei and Zhou (2012) demonstrated a new method to minimize fuel consumption in weather routing through optimization of ship power and ship course, as opposed to the common approach which optimizes only ship course. This contribution studies a route close to the Equator with a voyage length of 10 days.

Relating both terms weather-routing algorithms and unstable motions, the enhancement of the safety on board is noticeable. A study of different routes taking into account the areas that surf-riding and parametric rolling exist was done. The speed and the parameters
of the vessel were constant; the only alteration was the course of the vessel which was avoiding the areas of these unstable motions. Indeed, real vessels have a limited maneuverability, and a tight zig-zag motion might be not always possible. Thus, they do not believe in an increased grid resolution (Mannarini et al., 2013).
Aims and Objectives

Main objective

This project will introduce a new module based on ship unstable motions to the ship-weather routing algorithm SIMROUTEv2. Unstable motions are evaluated through the parameters such as peak wave period, emitted by the weather forecast, encountered period, calculated by formula, and natural rolling period, established in the information of each ship. With this new module, the algorithm will improve navigation in terms of safety, consumption and contamination.

Specific objectives

- Research the existent different types of motions of a ship (stable and unstable) and identify the most frequent unstable motions to be considered for the case of study
- Research and select the parameters of the ships which will be considered in this study. The selection will be based on three different routes in the West Mediterranean Sea
- Research particular parameters of the waves related on the case of study
- Implement the algorithm code in terms of unstable motions of the chosen ships
- Run the simulations applied on the different cases and interpret the results
Methodology

In order to conduct the implementation of the ship-routing algorithm to avoid the frequent unstable motions the following steps have been done:

On the one hand, an in-depth research of the different motions of the ship has been done as the unstable motions are a consequence of the following 6 degrees of freedom of a ship’s motions:

- Translational motions: Heave, Sway and Surge
- Rotational motions: Yaw, Pitch and Roll

On the other hand, a deep literature review was undertaken in order to know the common variety of unstable motions to concern that is an important topic to take into account due to the risk of suffering different damages (crew/passengers, cargo and ship). The unstable motions found were:

- Surf-riding/Broaching
- Parametric rolling
- Synchronous rolling
- Slamming
- Green water

Once the unstable motions research was done, it was considered to look into different articles such as Mannarini et al., (2013) and Hansen & Pedersen (2008), among others, and also focusing on the IMO Circulars (MSC.1/Circ.1228) in order to choose the most frequent unstable motions to implement into SIMROUTEv2 algorithm. Finally, the work was based on the two unstable motions that were possible to obtain the parameters related on the formulas, surf-riding/broaching and parametric rolling. Other unstable motions such as slamming, pressures upon the hull of the ship, among other parameters, were required being the objective for possible future research.

A study of the formulation and the identification of the parameters required of make the unstable motions (surf-riding/broaching and parametric rolling) was carried out.
Three hypothetical vessels were selected in this case of study. According to (Basiana et al., 2017) vessels that carry vehicles and passengers with different speeds were selected, due to the importance of these vessels in the Western Mediterranean Sea doing Short Sea Shipping. These vessels and their particulars were the following:

- Conventional ship (developing up to 23 knots)
  - Speed of the ship: 21.5 knots
  - Length of the ship: 166.41 meters
  - Beam of the ship: 25.5 meters
  - Draft of the ship: 14.29 meters
  - Transversal metacentric height: 2.63 meters

- Fast ship (23 to 30 knots)
  - Speed of the ship: 28 knots
  - Length of the ship: 175.4 meters
  - Beam of the ship: 30.41 meters
  - Draft of the ship: 15.95 meters
  - Transversal metacentric height: 1.5 meters

- High speed craft (more than 30 knots)
  - Speed of the ship: 40 knots
  - Length of the ship: 86.9 meters
  - Beam of the ship: 16.7 meters
  - Draft of the ship: 3.53 meters
  - Transversal metacentric height: 1.54 meters

The selected area for this study was Western Mediterranean Sea. The data was provided from the contribution of (Basiana et al., 2017), who studied different ports considering for their importance of Short Sea Shipping handling of goods. This work was conducted on the following ports:

- Port of Barcelona
- Port of Oran
- Port of Civitavecchia
Port of Sousse

Wave scripts were searched and obtained from the website *Puertos del Estado* (2016) giving insight into daily weather patterns. Two different wave height scenarios were chosen for each route:

- Smooth-Moderate sea; Hs = 0.1-2.50 meters
- Rough-High sea; Hs = 2.5-9.00 meters

In the aforementioned wave scripts, two weather parameters were taken into account in order to see if surf-riding/broaching and parametric rolling occurred:

- Wave direction
- Wave period

Different cases of study were run in order to find cases of surf-riding/broaching and parametric rolling in the different routes.

SIMROUTEv2 was the ship-weather routing algorithm used for this project. A summary of the algorithm and its structural basis (route function and wave function) was provided. Additionally, a description of how the algorithm works (the use of important commands that are taken into account) was given.

The results of the specific cases were provided by the algorithm. In each case, the route can be seen in blue color and the length of the nodes that had unstable motions in red. All the cases were calculated by SIMROUTEv2.

Finally, some conclusions from the results were done. Specific cases where these two unstable motions occurred were highlighted.
1. General motions of a ship

1.1. Stable motions

The denominated stable motions are the ones that traditionally and technically are called as the six freedoms of a ship’s motion\(^1\) in a seaway. Waves, wind, currents, cargo (including crew and passengers) and every element that is able to interact considerably with the ship is able to produce different complex motions. These motions are a mixture of the translational and rotational forces in response of the action of the aforementioned elements.

On the one hand, the motions in the horizontal plane are the following: yaw, sway and surge. When these motions happen the ship doesn’t return to the start position unless someone alters the position of the ship through the bridge deliberately. Hence, these motions are called non-restorative.

On the other hand, the motions in the vertical plane are the following: heave, pitch and roll. These three motions affect the balance between the forces of weight and buoyancy and so moving the ship from the equilibrium, or mean, position creates a restoring force or moment that is proportional to the displacement of the ship from its mean position. They are called restorative motions. (Clark, 2005).

\(^1\) Six degrees of freedom refers to the freedom of movement in a three-dimensional space, translation combined with rotation in three perpendicular axes.
### Table 1: Classification of the six degrees of freedom. Source: Own elaboration

<table>
<thead>
<tr>
<th>Axis</th>
<th>Translation</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical (z)</td>
<td>Heave</td>
<td>Yaw</td>
</tr>
<tr>
<td>Transverse (y)</td>
<td>Sway</td>
<td>Pitch</td>
</tr>
<tr>
<td>Longitudinal (x)</td>
<td>Surge</td>
<td>Roll</td>
</tr>
</tbody>
</table>

#### 1.1.1. Yaw

Yawing is the rotational motion that most concerns ship’s officers, who are not even particularly aware of surge and sway most of the time, though these are significant if a ship’s position is controlled by a DP\(^2\) system (Clark, 2005).

![Figure 4: Yaw motion. Source: Clark (2005)](image)

The ship diverts from the straight direction of her path and requires to use the rudder, and thus the increasing of the resistance as well as appearing yaw list\(^3\) which it is impossible to control, not even by stabilizers (Garcia-Doncel, 1972).

Oscillating yawing moments are created by the rhythmic variation in the longitudinal alignment of the pressure centers on the port and starboard sides of the immersed hull when a ship encounters waves off the bow or quarter. The yawing moments are reinforced by the dynamic force of the water’s orbital motion in the wave, as a torque is created by

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\(^2\) Dynamic Positioning is a computer-controlled system to automatically maintain a ship's position and heading by using its own propellers and thrusters.

\(^3\) When a ship is yawing for the effect of a wave it behaves like when she does the initial turn (spin) by the effect of the rudder. In the beginning the ship follows his original movement direction, that now is oblique to his symmetric plane. This situation produces an increasing of the water pressure upon a side of the ship and it takes place to an initial list that finally is able to increase for the effect of the centrifugal force which corresponds to the spin.
the water at a wave crest pushing the hull direction of the wave whilst the water in a
trough is pushing in the opposite direction⁴ (Clark, 2005).

1.1.2. Sway

Waves, winds and currents are the three most relevant factors that produce the transla-
tional motion called sway. In general, the higher the relation between the emerged hull
and the immersed hull of the ship the most sway is able to suffer.

![Figure 5: Sway motion. Source: Clark (2005)](image)

Looking into a wave cycle and taking into account that a ship is stationary and there is a
beam sea wave celerity coming from starboard to port side the following process happens:

1. Ship situated on the crest of the wave: sway velocity is maximum to port through
   mean position
2. The ship is descending: Sway velocity is zero, port displacement is maximum
3. Ship situated on the trough of the wave: Sway velocity is maximum to starboard
   through mean position
4. Sway velocity is zero, starboard displacement is maximum
5. End of the process: Sway velocity is maximum to port through mean position

![Figure 6: Wave cycle and ship positions. Source: Own elaboration](image)

⁴ The orbital motion in deep waters follows a circumference shape in rotational movement where the crest
moves on the same sense of the wave, while the under part of the surface moves on the other sense. In
contrast, when the coast is nearer, in shallow waters, the shape evolves into an ellipse.
1.1.3. Surge

When the water flow is passing a ship creates a resistance that acts on the immersed hull surface to accelerate the vessel in the same direction of the flow at a rate that is proportional to the ship’s virtual mass\(^5\). The added mass for the translational motion called surge is only about 6-10% of normally shaped ship, which to be expected as the ship-shaped hull is built to move fore and aft having the least resistance from the water (Clark, 2005).

![Figure 7: Surge motion. Source: Clark (2005)](image)

Although this translational movement in the longitudinal axis is governed by the main propeller going back or forward, it is known that the external forces (waves, winds and currents) acts indirectly to the ship influencing surge motion in a positive or negative way.

1.1.4. Heave

This is the vertical translation upward or downward movement in the water of the ship’s center of gravity. This restorative motion is compared as a mass-damper-spring system, such as a suspension of a car.

![Figure 8: Heave motion. Source: Clark (2005)](image)

When a ship is submerging more than the equilibrium waterline, there is an excess of buoyancy\(^6\). An excessive downward heave can swamp the ship (Clark, 2005).

---

\(^5\) Ship’s mass plus added water mass.

\(^6\) Where ‘Z’ is the downward or upward displacement from the equilibrium waterline; ‘\(\rho\)’ is the water density (kg/m\(^3\)); ‘\(g\)’ is the gravity (m/s\(^2\)) and WPA is the waterplane area of the hull (m\(^2\)).
\[ Excess_{buoyancy} = -Z \rho g(WPA) \]  \hspace{1cm} (1)

Looking to the other way round, if the ship is emerging above the equilibrium waterline there is an excess of weight (Clark, 2005).

\[ Excess_{weight} = +Z \rho g(WPA) \]  \hspace{1cm} (2)

So the natural heave period\(^7\) is:

\[ T_0 = 2\pi \sqrt{\frac{M_v}{\rho g(WPA)}} \]  \hspace{1cm} (3)

1.1.5. Pitch

Due to the magnitude of the longitudinal mass’ inertia moment of the majority of the vessels, rotational motion called pitch is partially impossible and is only considered between the waves in calm seas.

In the vast majority of the seas and oceans, excluding Mediterranean Sea and few others, the wave longitude is great in comparison with the beam of the ships. In regards to the pitch motion the waterline cannot be seen as a plane, due to the profile of the wave is completely projected upon the hull and this profile is not flat. In this case the buoyancy center has to be determined in accordance to the considered profile (Garcia-Doncel, 1972).

![Figure 9: Pitch motion. Source: Clark (2005)](image)

\(^7\) In the natural heave period, \( M_v \) is the virtual mass, in other words, the mass of the ship plus the added mass to account for the water put in motion.
Encountered wavelengths much longer than the ship generally also have long periods of encounter so the ship follows the fore and aft wave profile without any significant phase lag. The vessel rides the waves easily and though the trim angle varies with the horizontal, it remains nearly parallel to the waterline so the pitching moments are minimum. In other words, if the wave period is significantly longer than the ship’s pitching period its trim will tend to follow quite close behind the wave profile and the ship should climb and descend each wave in a normal way. The ship’s natural pitching period\(^8\) is the following one:

\[
T_p = 2\sqrt{k \times d}
\]

(4)

1.1.6. Roll

This rotational motion in which the ‘springiness’\(^9\) is due to wave action moving the forces of weight and buoyancy out of vertical alignment as buoyancy distribution changes with the alternating waterline slope across the ship’s beam. This situation creates a righting moment to reestablish the ship to the stable or optimal position that is approximately proportional to the ship’s inclined angle to the waterline when the angle is small. If the vessel suffers an external force repeatedly, it will balance with inclination angle that will be different according to the value and the rhythm of the applied force.

From the moment when the external force is not zero, the moment of righting acts and produces the turn of the ship to the upright position, so that the total energy stored in the

---

\(^8\) ‘k’ is the correction factor for the moment of inertia of the added mass; ‘d’ means the draft of the vessel.

\(^9\) Understanding springiness as the capacity of straighten the vessel with respect to its vertical axes.
inclined position acts as kinetic energy that takes the ship to a symmetrical position with the previous one in relation to the longitudinal resting plane, repeating this movement indefinitely. (Garcia-Doncel, 1972).

The natural roll period, in terms of ‘GM’ and radius of gyration\(^{10}\) is the following one:

\[
T = 2\pi \sqrt{\frac{R_v^2}{GM \times g}}
\]  
\(5\)

### 1.2. Unstable motions

Operational conditions depend, in large part, on the stations of the year and the navigation area, as well as other conditions. Despite its importance, it is an aspect that has been little studied when it comes to making the project of the ship. The idea of ship’s comfortability has just begun to develop recently, thanks in part to the new applications.

When a ship navigates with sufficiently large waves in relation to its size, it experiences undesirable movements that can cause discomfort to the passage, crew members, generation of dynamic loads to the structure and cargo of the ship. These undesirable movements are the so-called unstable motions produced by these external meteorological phenomena and are combinations of the six degrees of freedom of the ship. There are several types of unstable motions and they depend at least on the speed, displacement, weight distribution, hull design and location of the appendages.

#### 1.2.1. Surf riding/Broaching

One of these unstable motions is surf-riding and consequent broaching which are associated with following and quartering seas. Large following waves acting on the ship can force her to move with the same speed, so a ride upon the wave happens and is able to provoke a rough twist and a considerable heel to the vessel and can finish with a capsize.

\(\text{\( R_v \) could be expressed as } 0.4 \times \text{Beam.}\)
The phenomenon which the vessel starts to move with the wave simultaneously is known as surf-riding. The vast majority of the vessels are directionally unstable during waves. As can be seen in Figure 11, the vessel is in following seas and presents a clear unstable motion of surf-riding. It is starting to ride on the crest and once the wave has passed the length of the vessel, it starts to do a considerable heel that could conclude to a broaching motion.

![Simulation of surf-riding](image)

*Figure 11: Simulation of surf-riding. Source: Umeda (2015)*

The moment that the vessel is turning in an uncontrolled way is called broaching. Broaching endangers the ship to capsize as a result of the circumstance of an unexpected change of the ship’s heading and an important heel angle produced by circulation and wave heeling moment usually acting in the same direction.
When a ship is riding on the wave crest, the intact stability can be reduced considerably according to the alteration of the submerged hull form. This stability reduction may become critical for wave lengths between the range of 0.6 L\(^1\) up to 2.3 L. When the wave length is found within these values the amount of stability reduction is nearly proportional to the wave height. This situation is extremely dangerous in following and quartering seas, due to the increase of the duration of riding on the wave crest, which coincides to the time interval of reduced stability (IMO, MSC.1/Circ.1228, 2007).

Officers of a ship are recommended to take care of the following instructions in order to avoid the dangerous situations when navigating in severe weather conditions:

- It has to be taken into account that surf-riding and broaching-to may occur when both of these conditions\(^2\) are fulfilled (Mannarini et al., 2013):

\[
135^\circ < \alpha < 225^\circ \tag{6}
\]

And also:

\(^{11}\) ‘L’ is the ship’s length in meters.
\(^{12}\) Being ‘\(\alpha\)’ the ship-to-wave relative direction in degrees, ‘\(L_{ship}\)’ the length of the ship in meters and \(v_{ship}\) the speed of the ship in knots.
\[
\nonumber v_{\text{ship}} > \frac{1.8/L_{\text{ship}}}{\cos(180°-\alpha)}
\]

(7)

In order to avoid surf-riding and possible broaching the ship speed, the course or both of them should be taken outside from the dangerous region as it is possible to be seen in Figure 13 (IMO, MSC.1/Circ.1228, 2007).

This guidance is applicable to all types of conventional ships navigating in rough seas, provided the stability criteria specified in resolution A.749(18), as amended by resolution MSC.75(69), are satisfied (IMO, MSC.1/Circ.1228, 2007).

1.2.2. Parametric rolling

Parametric rolling is caused by pitching motions on vessels defined with very fine bow-lines together with very wide and full stern contours. One such ship type is the containership. In Figure 14 a containership with parametric rolling problems is shown.
The cause of this phenomenon depends very much on the parameters of the vessel, hence the name parametric rolling.

On the one hand, when $T_E = T_R$ (encounter ratio 1:1) the stability attains a minimum once during each roll period. This situation is characterized by asymmetric rolling, for instance the amplitude with the wave crest amidships is bigger than the amplitude to the other side. Due to the large amplitude a retarded up-right is produced and the roll period $T_R$ may adapt to the encounter period to a certain extent, so that this kind of parametric rolling may occur with a wide bandwidth of encounter periods. In quartering seas, a transition to harmonic resonance may become appreciable (IMO, MSC.1/Circ.1228, 2007).

On the other hand, when $T_E = 1/T_R$ (encounter ratio 1:0.5). The stability attains a minimum twice during each roll period. In the situations of following or quartering seas, where the encounter period is larger than the wave period, this may only occur with very large roll periods $T_R$, indicating a marginal intact stability. As a consequence, symmetric rolling happens with large amplitudes, again with the tendency of adapting the ship response to the period of encounter because of the loss of stability when the ship is on the wave crest. Parametric rolling with encounter ratio 1:0.5 may also occur in head and bow seas (IMO, MSC.1/Circ.1228, 2007).
Apart from following and quartering seas, where the change of stability is only affected by the waves that pass along the ship, heavy heave and pitch motions that are frequent in head or bow seas may contribute to enlarge the variation of the stability, specifically due to the periodical immersion and emersion of the flared stern frames and flared bows of modern ships. This may conduct to dangerous parametric roll motions even with stability variations induced by small waves (IMO, MSC.1/Circ.1228, 2007).

As the stern dips into the waves it produces a rolling action. This remains unchecked as the bow next dips into the waves due to pitching forces. It is worst when $T_E = T_R$ or when $T_E = 1/T_R$.

In effect, the rolling characteristics are quite different at the bow to the ones at the stern. This situation produces a twisting or torsioning along the ship as can be seen in Figure 15, leading to extra rolling motions.

![Figure 15: Parametric rolling on a container vessel. Source: Barrass & Derrett (2012)](image)

Parametric rolling will only happen if a steady angle of heel or list exists, such as may be created by the cargo inequalities in different parts of the vessel, the wind acting on one of the emerged sides or the fuel between the starboard and port sides. Normally, the officers of the ship try to ensure that cargo is properly loaded and fuel is drawn equally from tanks that are usually daily alternated between the starboard and port sides of the ship but, even though, a little list can appear, and obviously, wind heel is hardly ever avoidable.
It has to be taken into account that parametric rolling may occur when one of these following conditions\(^\text{13}\) are fulfilled (Mannarini et al., 2013):

\[ |T_E - T_R| = \varepsilon \times T_R \]  \hspace{1cm} (8)

Or:

\[ |2T_E - T_R| = \varepsilon \times T_R \]  \hspace{1cm} (9)

When a ship is operating at reduced speed in heavy sea conditions the phenomenon of parametric rolling is even worse. In this condition containers are able to be lost overboard because of the broken deck lashings. Parametric rolling problems are least on box-shaped vessels or full-form barges where the forward and aft shapes are not too different (Barrass & Derrett, 2012).

In order to avoid parametric rolling in quartering, following, head, bow or beam seas it is necessary to select the course and the speed of the vessel in a way to stay away from the aforementioned conditions: the encounter period is close to one half of the ship roll period \((T_E = \text{approximately equal } 0.5 \times T_R)\) or the encounter period is close to the ship roll period \((T_E = \text{approximately equal } T_R)\).

---

\(^{13}\) Being ‘\(\varepsilon\)’ the tolerance, ‘\(T_E\)’ the encountered period and ‘\(T_R\)’ the natural roll period.
1.2.3. Synchronous rolling

Large rolling motions happen when encounter wave period coincides with the natural rolling period of a vessel. During the navigation periods, in situations of following and quartering seas this may occur when the transverse stability of the vessel is insignificant and consequently the natural roll period becomes longer.

Synchronous rolling to the encountered wave period coordinated with a ship’s natural roll period is not cushioned by a normal smooth hull form, therefore roll amplitudes can reach quite alarming levels before the energy of the roll is dissipated. As with synchronous heave\textsuperscript{14}, the synchronous rolling of a vessel lags 90° in comparison the rolling force, which is now the wave slope rather than its height, thus the ends of the roll goes in tune with both a wave crest or trough. This can be confusing as motion analysis must refer phase differences for all the ship’s motions to a common reference, which is usually the wave surface elevation, so the phase lag for synchronous rolling is often given as zero because the roll is in phase with the annoying wave elevation. However, if the wave slope is stucked for the moment, which is the authentic annoying factor, then it is possible to see the same pattern of rolling endeavor as shown by the heave motion. The wave slopes with greater periods in comparison the natural roll period varies in a calm way that the roll of

\textsuperscript{14} A ship subjected to regular waves of the same frequency as the ship’s natural heave response.
the vessel can balance with the profile of the wave and keep in phase with the wave slope. In the situation of shorter period, wave slopes vary so quickly that the lags of the roll are approximately 180° behind as the roll response of the ship to each wave is stopped by the arrival of the following wave (Clark, 2005).

When the transverse wave period is lower than the natural roll period, the following wave reverses its roll in advance due to the fact that natural roll period is slower than the wave speed. The vessel is always heeling into the wave slope (Clark, 2005).

When the transverse wave period is equal to the natural roll period, the maximums of the natural roll period coincide with the wave crest or trough such that the return roll is strengthened by the changing waterline of the successive wave. Thus, roll amplitude grows by each following wave appearing synchronous rolling, large roll dangerous angles can occur (Clark, 2005).

When the transverse wave period is higher than the natural roll period, the vessel response to the wave motion acting upon the hull is quick enough to allow the vessel to follow the wave slope so it heels away from the successive wave (Clark, 2005).
Ship’s master should avoid a synchronous rolling motion which will occur when the natural roll period \( T_R \) is almost equal to the encounter wave period \( T_E \).

### 1.2.4. Slamming

Slamming is a singular undesirable phenomenon that is most likely to occur when a vessel is pitching to head waves, and these ones are a little bit longer than the vessel’s lengths. In the case of pitch and heave combination, the bottom’s front part of a vessel can be considerably elevated from the sea surface and a slam take place when the vessel restores its position. When the vessel is coming back to its position take a great inertia due to its weight, so an upward force momentarily acts upon every flat surface and the vessel impacts on the water faster than the water can be displaced, therefore this impact is heavy. A parallelism of this case could be the moment when someone do a ‘belly flop’ dive into a swimming pool. When this situation is transferred to a vessel will be the same, a great ‘belly flopping’ on a grand scale and then the surface of the sea is completely smashed into large amounts of drops that are thrown high up in the air and the whole vessel shudders and shakes as it slows down (Clark, 2005).

When the relative motion between the vessel and the sea is great, the bulb can emerge. If the entire bow returns in a calm way nothing on board will be appreciated apart from the movement, but if it falls in a violent way, it will affect to the structure of the ship due to a heavy dynamic impact that will be produced in the bottom of the ship. A part of the kinetic energy of the ship is transmitted to the water and the other part to the hull where elevated pressures are generated. These pressures produce great oscillatory tensions which make the ship vibrate in her natural frequency. Slamming can produce personal damages, breaks, failures of important operational equipment, etc.
1.2.5. Green Water

The pitching motion in rough and heading seas can produce the submersion of the bow main deck area. When the vessel emerge from the water can embark some part of water mass, called green water. In most green water incidents, the shipped water will not have any destabilizing effect. However, in some cases until this water mass doesn’t return to the sea through the sides or the scuppers of the ship, it moves on the main deck uncontrolled producing the following undesirable effects: loss of operability, loss of stability, critic situation if this mass moves together with the roll motion, damage on the main deck equipment, structural problems, among others (Hansen & Pedersen, 2008).

The probability of green water on deck to occur can be written as (Faltinsen, 1990):
\[ P(\text{GreenWater}) = \exp \left[ -\frac{d_f^2}{2\sigma_r^2} \right] \] (10)

Where \( d_f \) is the freeboard distance and \( \sigma_r^2 \) is the variance of the relative motion.
2. Unstable motions parameters

The IMO MSC.1/Circ.1228 concerns the officers with the different formulas of the two unstable motions worked in the case of study. The parameters and the constants which compose these formulas are the key to safe the vessel, its cargo, passengers and crew members. Managing these parameters will be a good method for avoiding vessels getting into the dangerous areas aforementioned in the section 1.2.1 and 1.2.2.

Fixed parameters are obtained from three hypothetical different vessels. The first vessel is a Conventional Ship, developing a speed of 21.5 knots. The second vessel is a Fast Ship which has a speed of 28 knots. The third vessel is a High Speed Craft (HSC) with a speed of 40 knots. These vessels were chosen in order to see if unstable motions can occur to vessels with different speeds. It has to be taken into account that a HSC would not do these large routes.

Considering the distribution by sea regions, Mediterranean ports handled the most tonnage at 29% of the total EU Short Sea Shipping tonnages in 2015. In addition, two of the vessels chosen are inspired in Ro-Pax vessels which represents the 13% of the vessels handling goods in the Mediterranean Sea in 2015. Although this is not a very large representative amount in contrast with the other type of cargo, it has been chosen for the study of this paper due to the benefits that these vessels contribute. This contribution can be seen in terms of environmental protection, transport safety and decongestion of roads, that is, the less trucks in the roads, the fewer pollutants in the atmosphere, the fewer traffic accidents and the traffic would be more fluid. For these reasons this area and these three vessels have been selected in this case of study (Basiana et al., 2017).

Moreover, the selection of the unstable motions was based on the different parameters that were available. Hence, surf-riding/broaching and parametric rolling were the two unstable motions selected for being implemented into the algorithm due to the fact that parameters of their formulas were obtained through the three aforementioned vessels and because the IMO MSC.1/Circ.1228 give relevance to both of them.
2.1. Surf-riding/Broaching parameters

As it is seen in the formulas of surf-riding/broaching phenomenon

\[ 135^\circ < \alpha < 225^\circ \] \hspace{1cm} (6)

And also:

\[ v_{ship} > \frac{1.8 \sqrt{L_{ship}}}{\cos(180^\circ - \alpha)} \] \hspace{1cm} (7)

In regards of this formula, the parameters are the following ones:

- **Angle of encounter (\(\alpha\))**
  Angle \(\alpha\) being the ship-to-wave relative direction \((\alpha = 180^\circ\) for following seas). In other words, the wave direction angle minus the vessel course.

- **Length of the ship (\(L_{ship}\))**
  In this case of study, the distance between the distance between the perpendicu-lars.

- **Speed of the ship (\(v_{ship}\))**
  The speed selected for this study is the one which corresponds to the full sea ahead engine order.
2.2. Parametric rolling parameters

As said before, so that parametric rolling phenomenon occurs one of these following formulas have to be true:

\[ |T_E - T_R| = \varepsilon \times T_R \]  

(8)

Or:

\[ |2T_E - T_R| = \varepsilon \times T_R \]  

(9)

In regards of this formula, the parameters are the following ones:

- **Tolerance in period matching** (\(\varepsilon\))
  
  The value that has been chosen for this parameter is a 10% and it is obtained from the article of Mannarini et al. (2013).

- **Encountered period** (\(T_E\))
  
  The period of encounter \(T_E\) could be either measured as the period of pitching by using stop watch or calculated by the *Formula (11)*, where ‘\(v\)’ is ship’s speed in
knots and ‘α’ the angle between keel direction and wave direction (α = 0° means head sea).

\[ T_E = \frac{3T_w^2}{3T_w + v_{ship}\cos(\alpha)} \]  \hspace{1cm} (11)

The diagram in Figure 22 may as well be used for the determination of encounter period.

- **Natural roll period (TR)**

  It measures the period of rolling motions preferably when the ship is in calm sea. This period is obtained through the following formulas, and the parameters are taken from the vessel chosen (model from a simulator).

\[ T_R = \frac{2 \cdot C \cdot B}{\sqrt{GM_t}} \]  \hspace{1cm} (12)
- **Coefficient (C)**

\[ C = 0.373 + 0.023 \cdot \left( \frac{B}{d} \right) - 0.043 \cdot \left( \frac{L_{ship}}{100} \right) \]  

(13)

- **Beam of the ship (B)**

The overall width of the ship measured at the widest point of the nominal waterline.

- **Draft of the ship (d)**

The vertical distance from the bottom of the keel to the waterline.

- **Metacentric height of the ship (GM)**

The measurement of the initial static stability of a floating body.

- **Peak wave period (T_w)**

Waves should be observed regularly. In particular, the wave period T_w should be measured by means of a stop watch as the time span between the generation of a foam patch by a breaking wave and its reappearance after passing the wave trough. In other words, the time elapsed by a crest or a trough to travel a distance equal as a wave length. It is obtained from the scripts of the website *Puertos del Estado*.

\[ T_w = \frac{L_w}{v_w} \]  

(14)

*Figure 23: Representation of a peak wave period. Source: Olivella (1998)*
- **Wave length** ($L_w$)
  The wave length is determined either by visual observation in comparison with the ship length or by reading the mean distance between successive wave crests on the radar images of waves.

- **Wave speed** ($v_w$)
  This parameter depends of the wave length and the period of the wave. Waves of different periods and lengths will be propagated with different speeds, being so dispersive. A fact that is based on observation is that the large waves travel faster than the short waves.

If the definitions of frequency $\{w = \frac{2\pi}{L_w}\}$ and number of wave $\{k = \frac{2\pi}{T_w}\}$ are taken into account, the wave speed will depend on these parameters:

$$v_w = \frac{2\pi \cdot L_w}{T_w \cdot 2\pi} = \frac{w}{k} \tag{15}$$
3. SIMROUTEv2

3.1. Basis and Algorithm

The two well-known pathfinding algorithms normally used are the Dijkstra Algorithm (Dijkstra, 1959) and the A* Algorithm (Dechter and Pearl, 1985). Dijkstra Algorithm was tested in some investigations and it is configured in the SIMROUTEv2. However, it was proved, in terms of calculation time, that A* Algorithm was much faster. For this reason, A* Algorithm was selected to do this case of study.

Gridded meshes is the way how these pathfinding algorithms are represented. The meshes are made by different points (nodes). Every single node is separated by the same distance, both horizontal and vertical axes, from another neighbor node. Therefore, a gridded mesh is built like the following (Grifoll et al., 2016):

![Sample of a node gridded mesh](source: Own elaboration)

To each connection (edge) a weight related with the distance is established. The great circle (orthodromic) distance is used for the spherical coordinates of the grid nodes as the transoceanic pathfinding algorithms use.

On the one hand, Dijkstra Algorithm in gridded meshes picks the unvisited vertex with the lowest distance, calculates the distance through it to each unvisited neighbor and updates the neighbor’s distance if smaller. Dijkstra algorithm has been used previously in ship routing applications (Mannarini et al., 2013; Montes, 2005).
On the other hand, A* algorithm finds solutions by looking at all the possible path combinations to the result (goal) for the one that obtains the minimum cost (shortest time, shortest distance travelled, etc.) and among these paths it selects the ones that appear to be the fastest to the solution. It is depicted in terms of weighted graphs: beginning from a particular node of a graph, it creates a tree of paths, expanding all these paths one node at a time, until one of the paths reach a predestined goal node. At each repetition of its main loop, A* algorithm needs to establish which of its unfinished paths to expand into one or more longer paths (Grifoll et al., 2016).

\[ f(n) = g(n) + h(n) \]  \hspace{1cm} (16)

Where “n” is the last node on the path, \( g(n) \) is the cost of the path from the start node to “n”, and \( h(n) \) is a heuristic that estimates the cost of the cheapest path from n to the goal. The heuristic is problem-specific. For the algorithm to find the actual shortest path, the heuristic function must be admissible, meaning that it never overestimates the actual cost to get the nearest goal node. In the case of the study, the heuristic function is the minimum distance between origin and destination (Grifoll et al., 2016).

In function of the grid resolution, path connection options between nodes may vary. In consequence, the sequence of edges followed by the shortest path will be limited by the grid resolution and the connected nodes. As it is seen in Figure 25, edges are connecting nodes displayed by arrows. Every single arrow represents different potential ship courses or directions. Grid resolution can vary according to the investigator’s preferences. In this work, different grid resolution has been tested obtaining similar conclusions than (Mannarini et al., 2013), which contemplated that at least 16 edges are required in order to be precise (Grifoll et al., 2016).
3.2. Waves

Ships can experience challenging operating conditions due to a constant action of waves. Complete knowledge of the expected sea states is important when considering vessel safety.

Wave action is the major factor that affects the ship performance and safety navigation (Hu et al., 2014). Wave field affects the ship motions decreasing the propeller thrust and adding a resistance in comparison to absence of waves. A simple formula to include ship speed reduction to waves is suggested by (Bowditch, 2002). The final speed is computed in function of the non-wave affected speed ($v_0$) plus a reduction in function of the wave parameters (Grifoll et al., 2016):

\[ v(H, \Theta) = v_0 - f(\Theta) \cdot H^2 \]  \hspace{1cm} (17)

Where $H$ is the significant wave height and $f$ is a parameter in function of the relative ship wave direction. The values of $f$ coefficient are shown in Table 3 (Grifoll et al., 2016).
Table 3: Values of the \( f \) coefficient. Source: Own elaboration

<table>
<thead>
<tr>
<th>Ship-wave relative direction</th>
<th>Wave direction</th>
<th>( f ) (in kn/ft(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0^\circ \leq \Theta \leq 45^\circ )</td>
<td>Following seas</td>
<td>0.0083</td>
</tr>
<tr>
<td>( 45^\circ &lt; \Theta &lt; 135^\circ )</td>
<td>Beam seas</td>
<td>0.0165</td>
</tr>
<tr>
<td>( 135^\circ \leq \Theta \leq 225^\circ )</td>
<td>Head seas</td>
<td>0.0248</td>
</tr>
<tr>
<td>( 225^\circ &lt; \Theta &lt; 270 )</td>
<td>Beam seas</td>
<td>0.0165</td>
</tr>
<tr>
<td>( 270^\circ \leq \Theta \leq 360^\circ )</td>
<td>Following seas</td>
<td>0.0083</td>
</tr>
</tbody>
</table>

The relation of the wave direction related on ship navigation can be described as follows:

- **Following seas**
  “There are many factors that can have a negative impact on stability and ship handling when sailing in the same direction as the waves if the waves are high compared to a vessel. The most notorious is broaching, whereby the vessel is turned violently to one side, leaving it broadside to the oncoming waves. The risk of broaching can be reduced by reducing ship speed to a fraction of the wave speed; but this again increases the risk that overtaking waves wash along upper decks from astern without this being noticed by the operators on the bridge” (Niclasen, 2010).

- **Beam seas**
  “Sailing in beam seas can results in large roll angles and, in extreme conditions, the vessel can capsize” (Niclasen, 2010).

- **Head seas**
  “Sailing against the waves is in most cases the best way to negotiate a series of large waves, but this also inflicts the most violent forces on the vessel, increasing the danger of slamming and shifting of cargo. The impact forces can be limited, to some extent, by reducing the vessel speed, or altering course” (Niclasen, 2010).
- **Quartering sea**
  “Large quartering waves are unfortunate because the vessel stability is affected by the negative effects of both beam and following seas” (Niclasen, 2010).

- **Crossing sea**
  “It is always difficult to handle small vessels in severe sea, but severe crossing sea is particularly dangerous as the waves will approach a vessel from different directions. In such circumstances, the captain loses the ability to use the vessel heading to protect against beam seas” (Niclasen, 2010).

![Figure 26: Typical speed reduction curves. Source: Padhy (2008)](image1)

![Figure 27: Encounter angle. Source: Lu et al., (2015)](image2)
Looking at Equation (17), we can see that the $f$ coefficient has a significant impact on the speed of the vessel. The speed varies depending upon the wave height as well as the wave direction.

Bowditch formula fits in the algorithm and it subtracts the speed of the vessel with the resistance of the wave in terms of height and direction. However, this formula is a little bit simple that is why in a further study will be an implementation of a more sophisticated resistance wave formula.

3.3. Commandos

The algorithm in Matlab possesses folders that have previously been created. In the folders are different files that have been made with the “.m” format in order to introduce the needed data and make them run in a concrete order. Following this paragraph, the procedure is explained:

Firstly, through the “make_mesh.m” file the corresponding latitudes and longitudes are introduced. After running script within this file, the Western Mediterranean mesh is created.

When looking at the “make_waves.m” file, the use of the correct wave scripts has to be ensured. The wave scripts, taken from Puertos del Estado website, have to be introduced in the file. Each script poses the waves conditions (wave height and direction) of one entire day. For instance, if the path of the route takes 80 hours and only 3 wave scripts (accounting for 72 hours) have been introduced, the algorithm will have an error. Once the correct wave scripts are introduced and the estimated time of departure (ETD) is established, an output wave script is obtained and it is used for running, “simroute.m” file.

When, “simroute.m” is opened the output script obtained previously is inserted into the file and then the initial speed of the vessel ($v_0$) is modified. It has to be taken into account that through the, “coord_ports.m” file the initial and end nodes (ports) for each route are created. These nodes are also introduced in the, “simroute.m” file. The, “simroute.m” is run and the results of the optimum route, in hours, is obtained.
Through the output scripts that, “simroute.m” creates, “simroute_fix.m” can be run and the results of the shortest path route with and without waves, in hours, will be obtained.

Once the optimum route is obtained, “Surfriding_Parametricrolling_modificat.m” will be the following step. This program is the implemented code aforementioned in last section. It calculates the encountered angle that is needed for each node, so it makes a loop in order to travel through all the nodes doing a mathematical subtraction of the wave direction and the vessel course. Vessel course is obtained by another small program called “ang_edge.m” that calculates the arc tangent between the nodes of the route. As a result of the mathematical subtraction, the vector ship-to-wave relative direction is created.

Afterwards, the formulas are ready to be run because all the parameters are defined. Both parametric rolling and surf-riding have two different iterations in order to see if the different nodes of the trip comply with the formulas. Hence, if these unstable motions occur, they will appear represented within the route in two different plots. It has to be taken into account that in the beginning of this implemented code is necessary to load the route calculated in the other steps.
4. Results

The two aforementioned unstable motions, surf-riding/broaching and parametric rolling, were implemented in the algorithms using the presented methodologies. All together was applied in the Western Mediterranean Sea.

Due to the majority of studied routes taking place over 1 or 2 days, differences in the wave heights, wave periods and directions can occur. The wave ranges used (Smooth-Moderate sea: 0.1-2.50m and Rough-High sea: 2.5-9.00m) mean that at a certain point during the route, over a considerable period of time, wave heights within this interval were noticed.

Three vessels were chosen in order to see the differences among these ones as a result of the different parameters. These vessels were doing three different routes; Barcelona-Oran, Barcelona-Sousse and Barcelona-Civitavecchia. Moreover, as said in the paragraph above, in each route two different cases of weather conditions were run. Hence, a total of 18 different cases were studied as seen in Table 5.

Table 4: Particulars of the three selected vessels. Source: Own elaboration

<table>
<thead>
<tr>
<th></th>
<th>Conventional Ship</th>
<th>Fast Ship</th>
<th>High Speed Craft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (knots)</td>
<td>21.5</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>Lship (meters)</td>
<td>166.41</td>
<td>175.4</td>
<td>86.9</td>
</tr>
<tr>
<td>Bship (meters)</td>
<td>25.5</td>
<td>30.41</td>
<td>16.7</td>
</tr>
<tr>
<td>dship (meters)</td>
<td>14.29</td>
<td>15.95</td>
<td>3.53</td>
</tr>
<tr>
<td>GMT (meters)</td>
<td>2.63</td>
<td>1.5</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Table 5: Eighteen cases selected in regards to the vessel, routes and weather conditions. Source: Own elaboration

<table>
<thead>
<tr>
<th></th>
<th>Conventional Ship</th>
<th>Fast Ship</th>
<th>High Speed Craft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bcn-Oran</td>
<td>Smooth-Moderate sea</td>
<td>Rough-High sea</td>
<td>Smooth-Moderate sea</td>
</tr>
<tr>
<td>Bcn-Sousse</td>
<td>Smooth-Moderate sea</td>
<td>Rough-High sea</td>
<td>Smooth-Moderate sea</td>
</tr>
<tr>
<td>Bcn-Civitavecchia</td>
<td>Smooth-Moderate sea</td>
<td>Rough-High sea</td>
<td>Smooth-Moderate sea</td>
</tr>
</tbody>
</table>
The results have been obtained using A* algorithm due to the significant reduction of computational time that this one has. This reduction in time occurs because less nodes are considered in comparison to the Dijkstra algorithm.

The cases are shown in different plots as shown in Figure 28. In the upper left part of the figure there is the surf-riding plot. This plot draws the line of the optimum path of the trip, and upon this line different cases of surf-riding are represented with a green star in each node that this unstable motion occurred as shown in Figure 37. In the lowest part of this plot wave period is represented in different colors and the measure, in seconds, is shown on the color board. In addition, it is possible to observe the different black arrows in the plot representing the wave direction.

Looking at the upper part but in the right side there is the parametric rolling plot. This plot draws the line of the optimum path of the trip, and upon this line different cases of parametric rolling are represented with a red star in each node that this unstable motion occurred as shown in Figure 28. In the lowest part of this plot the height of the wave is represented in different colors and the measure, in meters, is shown on the color board. Besides, it is also possible to observe the different black arrows in the plot representing the wave direction.

On the two lower plots it is possible to see two different paths. The black track is the shortest path. It represents the orthodromic distance between the initial node to the ending node. This path gives two results; one result doesn’t consider the added resistance due to the waves while the other path takes this resistance into account. The pink track is the optimum path, avoiding large significant wave height. It goes from the initial node to the ending node. This path considers the added wave resistance that alters the speed of the vessel.

All the 4 aforementioned plots are laid out in the following manner:

- Upper horizontal axis represents hours since time of departure
- The lower horizontal axis and the left vertical axis the longitude and latitude are displayed respectively.
4.1. Conventional Ship (21.5 knots)

1st Case: Barcelona-Oran / Smooth-Moderate seas

As can be seen in Figure 28, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there are just two nodes affected by this unstable motion. Wave periods and wave heights around these nodes were about 4 seconds and 0.5-1 meters, respectively. Wave direction average from 090 degrees with respect to the North.

![Surf-Riding and Parametric Rolling plots](image)

**Figure 28**: Bcn-Oran/Smooth-Moderate sea/Conventional Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (10th hour of the trip); Wave period plot (10th hour of the trip). Source: Own elaboration
2nd Case: Barcelona-Oran / Rough-High seas

As seen in Figure 29, the surf-riding and parametric rolling plots do not show any nodes affected by these unstable motions. Wave periods and wave heights average were around 5 to 7 seconds and 6 to 10 meters, respectively. Wave direction average from the North.

Figure 29: Ben-Oran/Rough-High sea/Conventional Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (19th hour of the trip); Wave period plot (19th hour of the trip). Source: Own elaboration
3\textsuperscript{rd} Case: Barcelona-Sousse / Smooth-Moderate seas

As can be seen in Figure 30, surf-riding and parametric rolling plots do not show any nodes affected by these unstable motions. Wave periods and wave heights average were around 3 to 5 seconds and 1.5 to 2.5 meters, respectively. Wave direction average from 090 to 135 degrees with respect to the North.

![Figure 30: Bcn-Sousse/Smooth-Moderate sea/Conventional Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (28th hour of the trip); Wave period plot (28th hour of the trip). Source: Own elaboration](image)
4th Case: Barcelona-Sousse / Rough-High seas

As can be seen in Figure 31, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there are five critical areas of this unstable motion. The master should alter the course or reduce the speed. Wave periods and wave heights around these nodes were about 6 to 9 seconds and 2 to 5 meters, respectively. Wave direction average from 045 to 315 degrees with respect to the North.

![Figure 31: Bcn-Sousse/Rough-High sea/Conventional Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (12th hour of the trip); Wave period plot (12th hour of the trip). Source: Own elaboration](image)

Source: Own elaboration
5th Case: Barcelona-Civitavecchia / Smooth-Moderate seas

As can be seen in Figure 32, surf-riding and parametric rolling plots do not show any nodes affected by these unstable motions. Wave periods and wave heights were around 4 to 5 seconds and 1.5 to 2 meters, respectively. Wave direction average from 045 to 090 degrees (Barcelona-Bonifacio) and from 135 degrees (Bonifacio-Civitavecchia) with respect to the North.

Figure 32: Bcn-Civitavecchia/Smooth-Moderate sea/Conventional Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (18th hour of the trip); Wave period plot (18th hour of the trip). Source: Own elaboration
6th Case: Barcelona-Civitavecchia / Rough-High seas

As can be seen in Figure 33, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there are two critical areas where this unstable motion occurs. These areas should be avoided altering the course or reducing the speed. Wave periods and wave heights around these nodes were about 5.5 to 6 seconds and 3 to 4 meters, respectively. Wave direction average from 315 to 045 degrees with respect to the North.

Figure 33: Bcn-Civitavecchia/Rough-High sea/Conventional Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (10th hour of the trip); Wave period plot (10th hour of the trip). Source: Own elaboration
4.2. Fast Ship (28 knots)

7th Case: Barcelona-Oran / Smooth-Moderate seas

As can be seen in Figure 34, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there is one node affected by this unstable motion, this is practically insignificant due to the corresponding short period of time. Wave periods and wave heights around the nodes were about 3 to 3.5 seconds and 0.5 meters, respectively. Waves from 090 degrees with respect to the North.

![Figure 34](image-url)
8th Case: Barcelona-Oran / Rough-High seas

As can be seen in Figure 35, surf-riding and parametric rolling plots do not show any nodes affected by these unstable motions. Wave periods and wave heights were around 6 to 8 seconds and 3 to 7 meters, respectively. Wave direction average from 015 degrees with respect to the North.

**Figure 35:** Bcn-Oran/Rough-High sea/Fast Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (10th hour of the trip); Wave period plot (10th hour of the trip). Source: Own elaboration
9th Case: Barcelona-Sousse / Smooth-Moderate seas

As can be seen in Figure 36, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there is one node affected by this unstable motion, this is practically insignificant due to the corresponding short period of time. Wave periods and wave heights around the nodes were about 5 to 6 seconds and 2.5 meters, respectively. Wave direction average from 090 degrees with respect to the North.

![Graphs showing surf-riding and parametric rolling plots with wave height and period plots](image)

**Figure 36:** Ben-Sousse/Smooth-Moderate sea/Fast Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (19th hour of the trip); Wave period plot (19th hour of the trip). 
*Source: Own elaboration*
10th Case: Barcelona-Sousse / Rough-High seas

As can be seen in Figure 37, surf-riding plot shows a considerable area next to Cagliari where this unstable motion occurs. In parametric rolling plot, half of the route is plotted in red. All these dangerous areas should be avoided altering the course or the speed. Wave period in the parametric rolling area was between 6 and 9 seconds and wave height was between 2.5 and 5 meters. Wave direction from 345 degrees in respect to the North around the surf-riding area.

Figure 37: Bcn-Sousse/Rough-High sea/Fast Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (12th hour of the trip); Wave period plot (6th hour of the trip). Source: Own elaboration
11th Case: Barcelona-Civitavecchia / Smooth-Moderate seas

As can be seen in Figure 38, parametric rolling plot does not show signs of this unstable motion. In surf-riding plot there is one node affected by this unstable motion, this is practically insignificant due to the corresponding short period of time. Wave periods and wave heights around the nodes were about 3 to 4 seconds and 1.5 meters, respectively. Wave direction from 270 degrees with respect to the North.

![Figure 38: Bcn-Civitavecchia/Smooth-Moderate sea/Fast Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (12th hour of the trip); Wave period plot (12th hour of the trip). Source: Own elaboration](image-url)
12th Case: Barcelona-Civitavecchia / Rough-High seas

As can be seen in Figure 39, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there is a large area affected that should be avoided. Wave periods and wave heights around these nodes were about 6 to 8 seconds and 4 to 5.5 meters, respectively. Wave direction from 315 degrees with respect to the North.

Figure 39: Bcn-Civitavecchia/Rough-High sea/Fast Ship. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (5th hour of the trip); Wave period plot (5th hour of the trip). Source: Own elaboration
4.3. High Speed Craft (40 knots)

13th Case: Barcelona-Oran / Smooth-Moderate seas

As can be seen in Figure 40, surf-riding and parametric rolling plots do not show any nodes affected by these unstable motions. Wave periods and wave heights were around 2.5 to 4 seconds and 0.1 to 1 meters, respectively. Wave direction average from 090 degrees with respect to the North.

**Figure 40**: Bcn-Oran/Smooth-Moderate sea/High Speed Craft. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (9th hour of the trip); Wave period plot (9th hour of the trip). Source: Own elaboration
14th Case: Barcelona-Oran / Rough-High seas

As can be seen in Figure 41, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there is a small area affected by this unstable motion which should be avoided. Wave periods and wave heights around these nodes were about 6 to 9 seconds and 3 to 4 meters, respectively. Wave direction average from the North in this small area.

Figure 41: Bcn-Oran/Rough-High sea/High Speed Craft. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (9th hour of the trip); Wave period plot (9th hour of the trip). Source: Own elaboration
15th Case: Barcelona-Sousse / Smooth-Moderate seas

As can be seen in Figure 42, surf-riding plot does not show signs of this unstable motion. In parametric rolling plot there is a small area (2 neighbor nodes) affected by this unstable motion that should be avoided. Wave periods and wave heights around these nodes were about 5 seconds and 2 meters, respectively. Wave direction average from 090 degrees with respect to the North in this small area.

![Figure 42: Bcn-Sousse/Smooth-Moderate sea/High Speed Craft. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (13th hour of the trip); Wave period plot (13th hour of the trip). Source: Own elaboration](image)

67
16th Case: Barcelona-Sousse / Rough-High seas

This case is similar to 10th case. As can be seen in Figure 43, surf-riding plot shows a considerable area next to Cagliari where this unstable motion occurs. In parametric rolling plot, half of the route is plotted in red. All these dangerous areas should be avoided altering the course or the speed. Wave periods in the parametric rolling area were around 6 to 9 seconds and wave heights were around 2.5 to 5 meters. Wave direction from 345 degrees around the surf-riding area.

Figure 43: Bcn-Sousse/Rough-High sea/High Speed Craft. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (6th hour of the trip); Wave period plot (6th hour of the trip).
Source: Own elaboration
17th Case: Barcelona-Civitavecchia / Smooth-Moderate seas

It is the same as 5th case. As can be seen in Figure 44, surf-riding and parametric rolling plots do not show any nodes affected by these unstable motions. Wave periods and wave heights were around 4 to 5 seconds and 1.5 to 2 meters, respectively. Wave direction from 045 to 090 degrees (Barcelona-Bonifacio) and from 135 degrees (Bonifacio-Civitavecchia) with respect to the North.

![Figure 44: Bcn-Civitavecchia/Smooth-Moderate sea/High Speed Craft](Image)

Source: Own elaboration
18th Case: Barcelona-Civitavecchia / Rough-High seas

As can be seen in Figure 45, surf-riding plot shows a large area where this unstable motion occurs (approximately 3 consecutive hours). In parametric rolling plot there are two affected areas. All these dangerous areas should be avoided. Wave periods were around 5 to 7 seconds and wave heights were around 2 to 6 meters. Wave direction from 315 to 045 degrees with respect to the North in the surf-riding area.

**Figure 45**: Bcn-Civitavecchia/Rough-High sea/High Speed Craft. From left to right and from top to bottom: parametric rolling plot; surf-riding plot; Wave height plot (8th hour of the trip); Wave period plot (2nd hour of the trip). Source: Own elaboration
5. Conclusions

The presented work in this project is the study of the surf-riding/broaching and parametric rolling and the implementation of these unstable motions in the ship-weather routing algorithm SIMROUTEv2. A considerable quantity of cases was run in order to assure that these dangerous phenomena can occur in Short Sea Shipping routes in the Western Mediterranean Sea.

Mediterranean Sea is thought to be an area with small wave periods, and this is what might someone think that the occurrence of these unstable motions might almost be impossible. Considering the obtained results in section 4, it can be seen that 12 cases out of 18 at least one of the two phenomena happened.

During the results section, it was observed that the surf-riding unstable motion was impossible to occur with Conventional Ship. The phenomenon speed formula could not comply with the vessel speed and length parameters. Parametric rolling was the only unstable motion that happened in different cases, highlighting the 4th case which has different dangerous areas. In contrast, Fast Ship and High Speed Craft show different highlighted cases of surf-riding due to their speed is greater.

The different plots confirm the formulation of the phenomena; the two implemented unstable motions do not depend on the wave height. There is clear evidence in Smooth-Moderate sea which is more difficult that these unstable motions occur, above all in parametric rolling cases.

The greater the wave height the larger the wave period. Thus, implicitly, parametric rolling is linked to the wave height. However, this does not mean that whenever there is a large wave period parametric rolling occurs.

In regards to surf-riding, it occurs when the waves come from the aft or the quarters and with a significant wave period. A clear example is case 18 which shows a large dangerous of surf-riding due to wave height was 2 to 5 meters and wave period was 4 to 7 seconds.
Implementing the unstable motion formulas into the algorithm is an interesting tool in order to know and avoid all the dangerous nodes from the route. Consequently, complying with IMO MSC.1/Circ.1228 will produce an enhancement of the safety on board, such as crew members, passengers, cargo and ship integrity.

To sum up, in the Western Mediterranean Sea it is possible to find different cases which surf-riding/broaching and parametric rolling occur. Hence, having this algorithm on board would be ideal for the safety. Besides, the higher speed the bigger possibilities to have surf-riding as long as wave direction come from the aft or the quarters of the vessel. In regards to parametric rolling, there are more possibilities to occur with large wave periods.

Future work includes more implementation of the algorithm, taking into account external factors such as wind and currents and avoiding the unstable motions recalculating the optimum route. In addition, it proves beneficial to include one function for the fuel savings, as well as another function for the savings of the atmospheric pollutants. It will also be useful to take into account the seasickness of the crew members and the passengers.
6. References


7. Figure References


**Figure 3:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.

**Figure 4:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.

**Figure 5:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.

**Figure 6:** Own elaboration.

**Figure 7:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.

**Figure 8:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.

**Figure 9:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.

**Figure 10:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.


**Figure 12:** Clark, I. C., (2005) *Ship Dynamic for Mariners*. London, The Nautical Institute.


Figure 24: Own elaboration.

Figure 25: Own elaboration.


Figure 28: Own elaboration.

Figure 29: Own elaboration.

Figure 30: Own elaboration.

Figure 31: Own elaboration.

Figure 32: Own elaboration.

Figure 33: Own elaboration.

Figure 34: Own elaboration.
Figure 35: Own elaboration.

Figure 36: Own elaboration.

Figure 37: Own elaboration.

Figure 38: Own elaboration.

Figure 39: Own elaboration.

Figure 40: Own elaboration.

Figure 41: Own elaboration.

Figure 42: Own elaboration.

Figure 43: Own elaboration.

Figure 44: Own elaboration.

Figure 45: Own elaboration.
8. Table References

**Table 1:** Own elaboration.

**Table 2:** TRANSAS, (2014) MANOEUVRING BOOKLET V2.01 Mathematical model of Ro-Ro Passenger Ferry 8 (Dis.21104t).

**Table 3:** Own elaboration.

**Table 4:** Own elaboration.

**Table 5:** Own elaboration.
Appendixes 1. Code Implementation

close all, clc, clear all

%%%TENACIA (21.5kt)
load('C:\Users\lluis\Desktop\CasosSimroutev2_Matlab\SIM-ROUTE2_BCN_ORAN\out\BCN_ORAN112017012108.mat')

%%%TENACIA
Lship=166.41; %m
Bship=25.5; %m
dship=14.29; %m
tolerance=0.1;
GMt=2.63; %m

coef=0.373+(0.023*(Bship/dship))-0.043*(Lship/100);
T_roll=(2*coef*Bship)/(sqrt(GMt)); %s

%Dirt relativa
k=0;
ntrip=length(nods_trip);
alfa=zeros(size(nods_trip));
angle_encounter=zeros(size(nods_trip));
for k=1:ntrip-1
    nod_ini=nods_trip(k);
    nod_end=nods_trip(k+1);
    alfa(k+1)=ang_edge(nod_end,nod_ini);
    angle_encounter(k+1)=dirt(k+1)-alfa(k+1);
end

%%%Surf-riding
k=0;
nodes_surf(1)=nods_trip(1);
for i=1:ntrip
    velo=(1.8*sqrt(Lship))/cosd(180-dirt_relativa(i));
    if (135 < dirt_relativa(i)) && (dirt_relativa(i) < 225) && (velo < v0)
        k=k+1;
        nodes_surf(k)=nods_trip(i);
    else
        end
    end
end
%%parametric rolling
p=0;
nodes_para(1)=nods_trip(1);
for i=1:ntrip
T_encount=(3*(fpt(i))^2)/((3*fpt(i))+(v0*cosd(dirt_relativa(i))));
tol1=(abs(T_encount-T_roll))/T_roll;
tol2=(abs(2*T_encount-T_roll))/T_roll;
    if (tol1<0.1) || (tol2<0.1)
        p=p+1;
        nodes_para(p) = nodes_trip(i);
    end
end
load./in/ldr_euro_i_mask.mat
figure('position',[488.2000 337.8000 976.8000 424.0000])
subplot(1,2,2)
hold on
axis([-3 21 32 45])
p1=plot(nodes(nods_trip(:,1),nodes(nods_trip(:,2),'-b','linewidth',1)
hold on
p2=plot(nodes(nodes_para(:,1),nodes(nodes_para(:,2),'*r','linewidth',1)
p3=plot(nodes(nods_trip(1),1),nodes(nods_trip(1),2),'*k','linewidth',1)

title('Parametric Rolling')
xlabel('Lon (º)');ylabel('Lat (º)');
plot(lon,lat,'k')
legend([p1 p2 p3],[{'Ship route','Para.Rolling','Origin'}])
box on

subplot(1,2,1)
hold on
axis([-3 21 32 45])
t1=plot(nodes(nods_trip(:,1),nodes(nods_trip(:,2),'-b','linewidth',1)
hold on
t2=plot(nodes(nodes_surf(:,1),nodes(nodes_surf(:,2),'g','linewidth',1)
t3=plot(nodes(nods_trip(1),1),nodes(nods_trip(1),2),'*k','linewidth',1)

title('Surf-Riding')
xlabel('Lon (º)');ylabel('Lat (º)');
plot(lon,lat,'k')
legend([t1 t2 t3],[{'Ship Route','Surf-Riding','Origin'}])
box on