A SHIP MOTION SHORT TERM TIME DOMAIN SIMULATOR AND ITS APPLICATION TO COSTA CONCORDIA EMERGENCY MANOEUVRES JUST BEFORE THE JANUARY 2012 ACCIDENT

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ABSTRACT

In this paper we will present a simple but reliable methodology for short term prediction of a cruise ship behaviour during manoeuvres. The methodology is quite general and could be applied to any kind of ship, because it does not require the prior knowledge of any structural or mechanical parameter of the ship. It is based only on the results of manoeuvrability data contained in the Manoeuvring Booklet, which in turn is filled out after sea trials of the ship performed before his delivery to the owner.

We developed this method to support the investigations around the Costa Concordia shipwreck, which happened near the shores of Italy in January 2012. It was then validated against the data recorded in the "black box" of the ship, from which we have been able to extract an entire week of voyage data before the shipwreck. The aim was investigating the possibility of avoiding the impact by performing an evasive manoeuvre (as ordered by the Captain some seconds before the impact, but allegedly misunderstood by the helmsman). The preliminary validation step showed a good matching between simulated and real values (course and heading of the ship) for a time interval of a few minutes.

The fact that the method requires only the results registered in the VDR (Voyage Data Recorder) during sea trial tests, makes it very useful for several applications. Among them, we can cite forensic investigation, the development of components for autopilots, the prediction of the effects of a given manoeuvre in shallow water, the "a posteriori" verification of the correctness of a given manoeuvre and the use in training simulators for ship pilots and masters.

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1. INTRODUCTION

The problem of simulating the ship motion under the effect of propellers and external forces (wind and drift are the most important) is a central question in the field of naval engineering and training centres for ship pilots and bridge officers. In (ITTC 1999) two different typologies of ship manoeuvring simulation models are described, together with the guidelines for their validation. The distinction is made between models for prediction of ship manoeuvrability (predictive models) and models for ship simulators (simulator models). The targets are quite different.

In the first case, "…*prediction of standard ship manoeuvres is needed at the design stage to ensure that a ship has acceptable manoeuvring behaviour, as defined by the ship owner, IMO (International Maritime Organization) or local authorities*".

In the second one "*Simulator, or time-domain, models are used in real-time, man-in-the-loop simulators, or fast-time simulators for training of deck officers or investigation of specific ships operating in specific harbours or channels*".

The first type of model is generated before the ship is built with the aim to foresee, at design stage, some typical manoeuvring characteristics defined by IMO, such as the radius of turning circles or the parameters of Zig-Zag manoeuvres.

The second type of model can be realized after the ship is built up and some mandatory manoeuvrability tests have been performed. This type of model is capable to operate in time domain and can be utilized in simulators for the training of pilots or for other purposes, like that described in this paper.

For simulator models a sort of "black-box" approach can be used in which the set of parameters needed in the equations of motion is directly extracted from the experimental data.

So-called black-box models are widely employed in many application areas. They are built by listing the external and internal factors which could influence the behaviour of the simulated system, by writing a more

or less domain-dependent mathematical model and by setting its coefficients to values determined by means of some fitting process which makes use of experimental data collected on the real system.
The procedures used to determine the coefficients are well established, and in their simplest form date back to the interpolation theory. Different choices of basis functions (such as polynomials, exponentials of Gaussian functions) present varying flexibilities with respect to the ability to describe some system behaviours (Maffezzoni et al., 1995). Recently, such approximation theories as neural network approximation and machine learning approaches in general have demonstrated robust properties in modelling complex phenomena and systems (Poggio et al., 1990). All of them, unfortunately, show a tendency to diverge from the real behaviour when used outside the interval in which the coefficients have been fitted. To this end, integration schemes based on stiffly-stable methods can be of help in delaying the onset of such divergence (Gear et al., 1971).
In the present application, the experimental data used are the results of the manoeuvrability tests performed before the boatyard delivery of the ship to the owner. Several international organizations are qualified for granting the manoeuvrability certificate (the so-called Manoeuvring Booklet); among them, the CETENA S.p.a. is the Italian Company of Fincantieri Group in charge of certifying the compliance of ship sea trials with IMO regulation.
There are a lot of papers, reports, researches available in literature concerning predictive models which are very important for ship designers and naval architects, as well as for boatyards (Revestido et al. 2001; Sutulo et al. 2002; Oltmann 1996; Ishiguro et al. 1996; ITTC 1996, ITTC 2002a, ITTC 2002b). Conversely, there is very little material concerning time domain simulators of ship motion (Gatis et al. 2007; Shyh-Kuang et al. 2008; Mohd et al. 20012, Damitha et al. 2010). Here we will briefly comment two of them.
In (Mohd et al. 2012), after extracting the equations of motion in which the forces and moments acting on hull appear together with those induced by propellers and rudders, the authors perform some numerical simulations. Anyway, the authors do not present any form of validation of the simulator, by means of comparison between simulated and experimental data.
In (Damitha et al. 2010) the authors describe a true real time simulator, a software tool that simulates the motion of the ship and could be used, for instance, for pilots and masters training. The approach used by the authors is very similar to that of this work. In fact, as the authors say, "*The simulation system consists of a ship motion prediction system using a few model parameters which can be evaluated by means of standard ship manoeuvring test or determined easily from databases such as Lloyd's register*." In the paper, the validation is performed by the sea trials of the oil tanker ESSO Osaka (turning circle), but the simulations result in relevant errors: the simulated turning circle radius is about 550 m while the measured value amounts to about 375 m. These results can be compared with those reported in Figure 2 to give a preliminary idea of the reliability of the simulator presented in this paper.
We can conclude that, as far as the authors know, there is no evidence in literature of a real time simulator with reliable behaviour and an extensive characterization of the errors.
After this introduction, in Section 2 of this paper we will describe the data used to extract the model parameters and to validate the reliability of the simulator. Then, in Section 3 we will describe the motion equations which allowed us to calculate the effect of the forces (internal and external) applied to the hull, whereas in Section 4 we'll present some preliminary results. Finally, Section 5 contains some conclusions together with a description of future improvements of the model and a list of possible applications.

2. MANOUVERING BOOKLET AND VOYAGE DATA RECORDER (VDR) DATA

In this section a brief description of the experimental data used in this work is given. These data were used to extract the model parameters and to validate the simulator by estimating the entity of the errors between simulated and experimental data.

Manoeuvring Booklet

The Manoeuvring Booklet of a ship reports the results of sea trials performed by the ship before its delivery. Some mandatory tests have to be performed, such as the ones listed in the IMO resolution A - 160 (es IV) of 27/11/1968 and following release. The main tests are:

1) "Turning test", used to determine the effectiveness of rudder to produce steady-state turning (Figure 2).
2) "Free stop", carried out by suddenly halting a fast moving ship and measuring the space needed to come to a full stop.
3) "Crash-stop", similar to the previous one but also including some measures to come to a stop in a shorter time (for example by backing power).
4) "Zig-Zag manoeuvre", performed by moving the rudder from central position to an assigned angle (usually 10 or 20 degrees) alternatively to starboard and to port (Figure 3).
5) "Williamson turn", the manoeuvre performed to recover a man overboard (Figure 4).

The sea trials were confined to the area covered by the Differential GPS test range in order to obtain accurate tracking information. This way the position error is reduced to a maximum of 2 m.
During the trials, the position, heading (measured with a gyrocompass), rudder angles, propeller revolution per minute (Costa Concordia had two rudders and two propellers) and shaft power were recorded with a sampling frequency of 1 Hz and stored for further elaborations.

VDR data

Voyage Data Recorders (VDRs) are systems installed on modern vessels to preserve details about the ship's

status, and thus provide information to investigators in case of accident. The ongoing data collection is performed by various devices, and the actual recording of this information is entrusted to an industrial grade computer (Piccinelli and Gubian 2013).
The use of VDRs on ships is subjected to the regulations contained in chapter V on "Safety of Navigation" of the "International Convention for the Safety of Life at Sea" (SOLAS). This chapter has been amended in 1999 to adopt the IMO resolution A.861(20) “Performance Standards for Shipborne Voyage Data Recorders (VDRs)" (IMO 1997). These regulations, entered into force on July 1st, 2002, specify the kinds of ships that are required to carry Voyage Data Recorders; all in all, the list encompasses almost any medium-to-bigger sized ships currently at sea.
The IMO resolution also sets requirements about the operation of the VDR and the kind of information it is required to store. Among the mandatory list, most interesting elements for our analysis are surely the position, speed and heading of the ship, the date/time referenced to UTC, the radar data and the ship automation data, such as the speed of the propellers and the position of the rudder(s).
These informations are collected from a large network of different sensing devices scattered all around the ship. The core of the VDR system is the “concentrator”, usually an industrial grade computer, which collects all the data and stores it in a digital memory. The concentrator is powered by the ship’s electrical system and also sports a dedicated power source which allows it to work at least 2 hours after the loss of main power. At last, a copy of the last 12 hours of recording is also maintained inside the digital memory of the FRM (Final Recording Medium), a rugged capsule designed to survive an accident and thus be recovered by the investigators.

3. MATHEMATICAL MODEL

The aim of the model is to correlate the input given by the pilot (i.e. motors’ power and rudders angles) to the output of the system (i.e. ship’s position and orientation). The really complex physical system of the ship has been simplified and schematized with a three-Degrees-Of-Freedom (DOF) model which is adequate for our purpose and consists of the short term prediction of the trajectory of the ship (Maimun et al 2011). Another simplifying assumption is that the effect of wind and current are negligible for short-term simulations. However, this effects have been studied and modelled in the past and could be taken into account in a future improved version of the simulator. Figure 1 represents the chosen DOFs (est, nord coordinates and heading ϑ) and their meaning. Using the model of Figure 1, z translation and pitch and roll angles are neglected: those DOFs are crucial for ship’s stability studies, but are not relevant for positioning estimation.
Starting from this simple model, we could write the three Newton equations that correlate the accelerations along the three DOFs with the forces acting on the ship:

$$\ddot{\vartheta} = \frac{M_z}{I_\vartheta} = \frac{1}{I_\vartheta}(M_\delta + M_r + M_P) \quad (1)$$

$$\ddot{x} = \frac{F_x}{m} = \frac{1}{m}(F_u + F_P + F_{\vartheta,u}) \quad (2)$$

$$\ddot{y} = \frac{F_y}{m} = \frac{1}{m}(F_v + F_{\vartheta,v}) \quad (3)$$

where M_δ, M_r, M_P represent the torque made by the rudders, the water viscosity and the propellers respectively. F_u, F_v represent the viscous force made by the water in x and y direction respectively. F_P represents the force made by the propellers. $F_{\vartheta,u}$, $F_{\vartheta,v}$ are the apparent forces (e.g. centrifugal force) due to the ship rotational speed ($\dot{\vartheta} = r$). I_ϑ represents the moment of inertia along the z axis and m represents the ship’s mass.

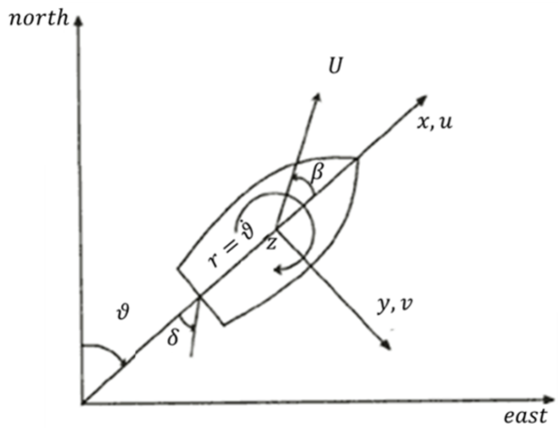

Figure 1: Reference frame.

The exact knowledge of those quantities, and an accurate calculation “a priori”, would need a deep study of the ship geometry and of the water conditions (Maimun et al. 2013). Anyway, this work is not aimed to predict the ship behaviour starting from design parameters. Since a sufficient amount of manoeuvring data is available from the Manoeuvring Booklet (CETENA files in the case of Costa Concordia) and from the ship’s VDR, it is possible to estimate the relation between the main quantities with an interpolation algorithm.
Eqs. (1), (2) and (3) can then be rewritten in these simple expressions:

$$\ddot{\vartheta} = N_1 \sin(\delta)\, u|u| + N_2 r|r| + N_3(p_1|p_1| - p_2|p_2|) \quad (4)$$

$$\dot{u} = X_1\,(p_1|p_1| + p_2|p_2|) + X_2 u|u| + X_3 r^2 + X_4\ddot{\vartheta} \quad (5)$$

$$\dot{v} = Y_1\, v|v| + Y_2\ddot{\vartheta} + Y_3 r^2 \quad (6)$$

In Eqs. (4), (5) and (6), N_i, X_i, Y_i represent constant parameters which are estimated starting from the CETENA data.
These equations give a simplified expression of the more complex relations between the relevant quantities. Indeed, they could not be used in an “a

priori" model, but the simplification introduced by the use of these expressions is compensated by the constant parameters extracted with an interpolation algorithm. Thanks to these parameters, the model is able to learn from known data how the ship would behave answering to certain input.

Parameters extraction

The constant parameters needed to integrate the equation of motion (Eqs. (4), (5) and (6)) were obtained from sea trials results collected in CETENA files. To do that, it is useful to consider as an example Eq. (4), which can be rewritten to highlight the time-varying terms.

Given that in the CETENA data all the time-varying quantities are known, while the constant parameters are unknown, it is possible to rewrite Eq. (4) in a matrix form:

$$\begin{bmatrix} \ddot{\theta}(t_1) \\ \dots \\ \ddot{\theta}(t) \\ \dots \\ \ddot{\theta}(t_e) \end{bmatrix} = \begin{bmatrix} \sin(\delta(t_1))\, u(t_1)^2 & r(t_1)^2 & (p_1(t_1)^2 - p_2(t_1)^2) \\ & \dots & \\ \sin(\delta(t))\, u(t)^2 & r(t)^2 & (p_1(t)^2 - p_2(t)^2) \\ & \dots & \\ \sin(\delta(t_e))\, u(t_e)^2 & r(t_e)^2 & (p_1(t_e)^2 - p_2(t_e)^2) \end{bmatrix} * \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} \quad (7)$$

In this expression, the number of equations is much greater than the number of unknown terms, so that the system can be solved in terms of a least square interpolation performing a pseudo-inverse of the matrix ($pinv$ function). The same procedure can be repeated for the other two equations of motion (Eqs. (5) and (6)) in order to calculate all the constant parameters needed (i.e. N_i, X_i, Y_i). The maneuver described in CETENA records used for this calculation was the turning circle (Figure 2).

Initial conditions

Once the parameters have been estimated, it was possible to integrate Eqs. (4), (5) and (6) to obtain a simulation of the ship behaviour. The integration method used was the Forward Euler method. The simulator needs as an input the pilot's instruction (i.e. rudder angles and propellers speed) and the initial conditions (i.e. starting coordinates and heading and starting linear and rotational speed). The speed information could be obtained by deriving coordinates and heading with respect to the time. Anyway, those data are affected by the error caused by the GPS and the compass sensitivity, so that a correct estimation of the initial speed is not trivial. A simple incremental ratio would give an unstable result, considering two consequent points, because of the measures noise. A more robust way to proceed is using a polynomial interpolation to approximate the position and the heading data, in order to filter out such spurious effects.

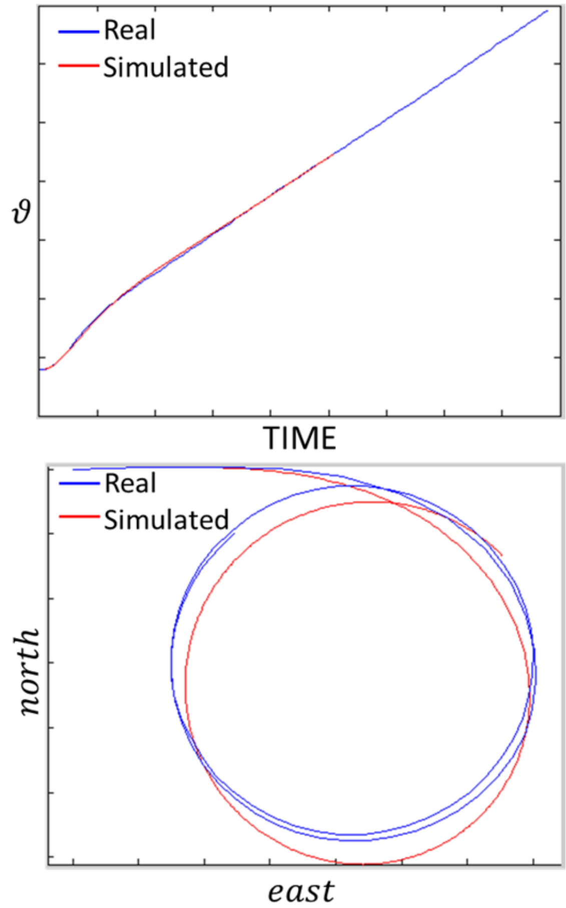

Figure 2: Turning circle: simulation time 500 s.

Validation

The best way to validate the aforementioned algorithm is to perform simulations of known data, in order to compare the simulated results with real ones. This was done with CETENA data contained in the Manoeuvring Booklet. The IMO standard manoeuvres were simulated by giving to the simulator the same values of rudder angles and propeller rpm (round per minute) used in real manoeuvres. The real data (position and heading) recorded by the sensors used during the sea trials were then compared with the simulator output. In Figure 2, Figure 3 and Figure 4 the results of this comparison are shown for turning circle, zig-zag and Williamson turn manoeuvres respectively. The results are surprisingly good if we take into account the simplicity of the mathematical/physical model used and the few information required to build it (i.e. the set of data collected during the sea trials).

To better prove the reliability of the simulator, a further validation was performed by using the data recorded in the VDR of Costa Concordia during the week before the shipwreck. It must be noted that the real time simulator had been realized for short-term simulation, and that the final goal was the simulation of the manoeuvres ordered by the Master of the Costa Concordia just before the impact with the rocks.

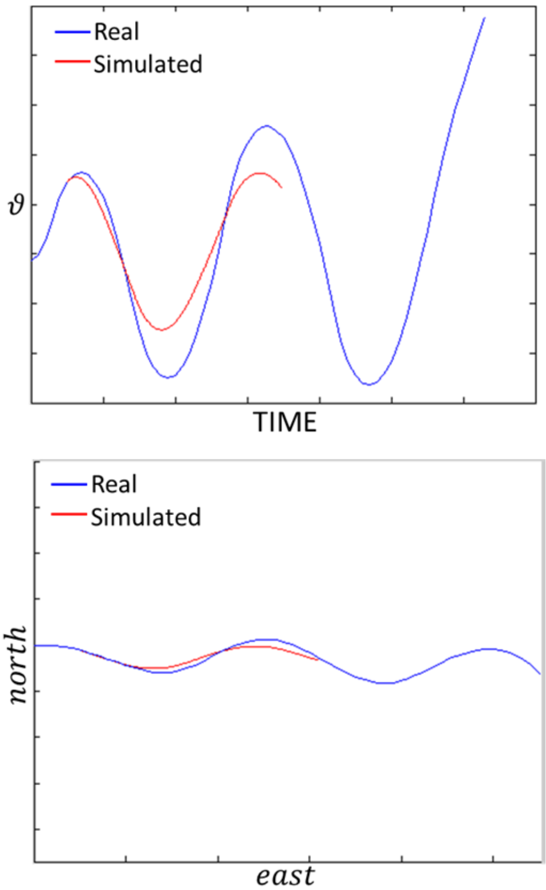

Figure 3: Zig-Zag: simulation time 300 s.

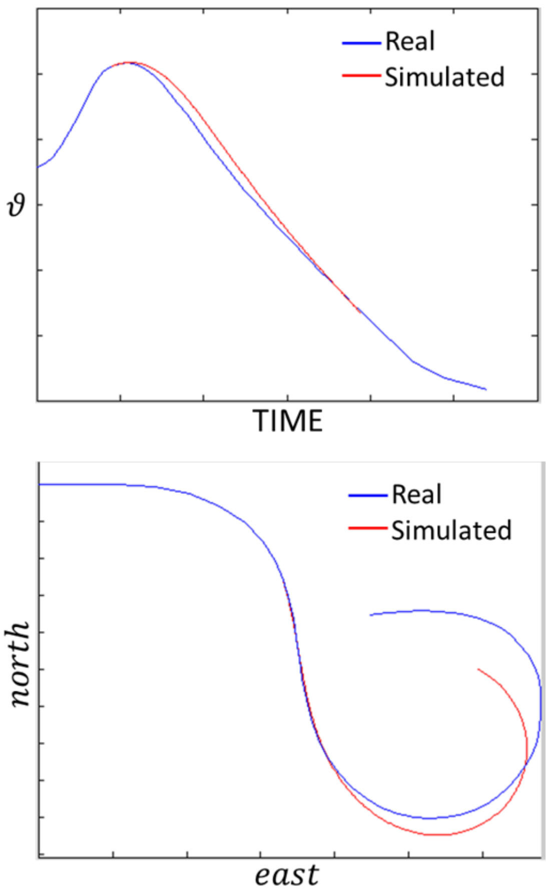

Figure 4: Williamson turn: simulation time 300 s.

Three events of the navigation recorded in the VDR were selected for validation. We will call them Palamos Turn, Palma Zig-Zag, Giglio Zig-Zag, because of the site in which they occurred and the manoeuvre typology. It is worth to underline that Giglio Zig-Zag manoeuvre ends with the impact against the rocks. Comparison results are reported in Table 1, in terms of position and heading errors. The errors were calculated at different simulation times.

Palamos Turn			
Sim. time [s]	***east* error [m]**	***north* error [m]**	**Heading error [°]**
30	1.6	0.3	-0.76
60	15.9	2.9	-3.42
120	82.2	-40.8	-14.60
Palma Zig-Zag			
Sim. time [s]	***east* error [m]**	***north* error [m]**	**Heading error [°]**
30	-0.5	-0.8	-0.07
60	-1.5	-2.1	-0.09
120	-4.1	-7.6	-0.21
Giglio Zig-Zag			
Sim. time [s]	***east* error [m]**	***north* error [m]**	**Heading error [°]**
30	5.3	5.2	-0.26

Table 1: Simulation errors.

As can be seen, the simulation results are reliable for a simulation time of about 60 s, while the error increases as the simulation time reaches 120s. This can be justified by the fact that in a short time simulation, environmental conditions, neglected in the model, play a second order role in ship behaviour, while become much more important as the simulation time increases. Furthermore, the integration method used is really simple in order to reduce simulation time, then the effects of the errors cumulate as simulation time increases.

4. RESULTS

In the case of Giglio Zig-Zag the simulated position of the ship at 21.45.11 (the impact time and the end of the simulation time) is considered. This simulation begins 30 seconds before the impact, that is, more or less the instant at which the Master saws the rocks and made the extreme attempt to avoid the impact by ordering a "Zig-Zag" manoeuvre. Apparently, the helmsman did not understand the orders of the master and made a mistake, by putting the rudder hard to starboard instead of hard to port as he was ordered. At this point, we repeated the simulation by giving to the simulator the correct position of the rudders as ordered. The timing of the order and the order itself were found in the recordings of the bridge audio, which was stored in the VDR, according with IMO Regulation. The result is shown in Figure 5, where the blue line represents the real position of the ship at the impact time and the green one indicates the simulated position of the ship without the error of the helmsman. The black square in the figure represents the rock. The quite surprising conclusion is that the impact point at the left side of the ship in the simulation is more or less 10 m far from the rock. Taking into consideration the sea bottom shape at the accident site, this distance would be enough to allow the ship to pass next to the rock without any damage.

To complete the discussion, we also considered the error worst case. The maximum observed value of the error after 30 s of simulation is about 7 m: in this case, we would still have an impact but the actual impact point would have been about 18 m behind the actual one. It is our opinion that, in this worst case, at least one of two engine rooms (more likely both of them) would have been left unscathed by the accident, and the ship would have been capable to stay afloat. In this case, the final consequences on the ship and the passengers would have been really different.

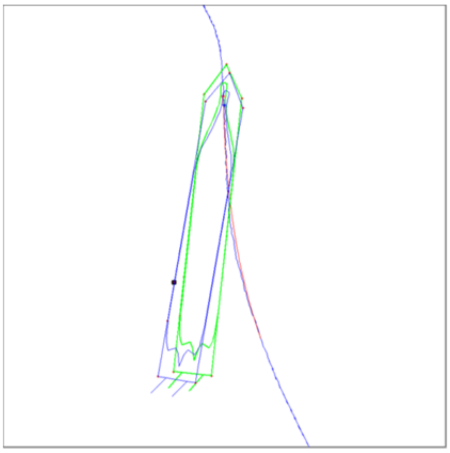

Figure 5: Real (blue) and simulated (green) position of the ship at the instant of the impact.

5. CONCLUSION

A simple time domain short-term simulator of the motion of a ship in free water has been presented. The simulator is based on a quite simple “black-box” model that does not require the knowledge of structural and mechanical characteristics of the ship. The position of the ship and its orientation versus time are calculated by using a mathematical model in which ten free parameters are used. These parameters are bound to the manoeuvrability characteristics of the ship, and can be obtained by using the recorded results of sea trials performed with the ship before its delivery.

Despite the great number of papers in literature dealing with the problem of simulating the manoeuvres of a specific ship, just a few of them deal with the problem of a time domain algorithm able to simulate, at least for a short time, the effect of propellers and rudders during a manoeuvre.

Our simulator could be used for pilots and masters training, in autopilot systems, in emergency manoeuvre foreseeing and so on. Further improvements will be introduced in the model in order to take into account the effects of wind and stream.

In the second part of the paper, the procedure has been used to simulate the Costa Concordia cruise ship behaviour, in order to study the effect of the allegedly wrong manoeuvre performed by the helmsman just before the impact. The result was that if the helmsman would properly execute the Master’s orders, the impact could have been avoided or, at least, by considering the worst case, its effects could have been much less devastating. Finally, to definitely confirm these conclusions, the Concordia’s twin ship, Costa Serena, could be used to perform a sea trial in which the manoeuvres with and without the helmsman’s error should be executed. The different tracks recorded during the test could then be compared to evaluate the actual consequences of the helmsman’s error on the Costa Concordia shipwreck.

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