

LONG - TERM PREDICTION OF NAVIGATIONAL RISK FOR DESIGN OF COASTAL APPROACH CHANNELS AND HARBOR WATERS

N.M. Quy¹, J.K. Vrijling², P.H.A.J.M Gelder³, R. Groenveld⁴ and L. Gućma⁵

ABSTRACT: This paper presents a new approach for long - term prediction of navigational risk regarding the possibility of ships exceeding the channel limits or navigable areas, assumed as grounding or collision with a fixed structure. The method, which is based on real time simulation results, consists of two developed models: (1) an ARMAX (Auto Regressive and Moving Average eXogenous) model is adopted to identify the ship steering dynamic system. With the help of this model, the outputs of the system (course, position, etc.) can be estimated on the basis of the system input conditions (rudder, engine, etc.); (2) the stochastic sequences of the inputs for the first model used are generated using a semi-Markov model. One implementation of the semi-Markov model for rudder actions has been described. The study used input/output measurements from a ship-handling simulator to estimate the model parameters, so the human factor has been included in the models. The method allows us to extend the results obtained from the simulator to predict future conditions of the system outputs. On the basis of the predicted results, the long-term assessment of the navigational risk can be realized, which amounts a straightforward use for optimal design of maritime engineering (e.g. coastal channels, fairways and harbor water areas).

1. Introduction

Maritime simulator is a reliable and indispensable tool in the assessment of navigational safety of a ship in conjunction with maritime engineering. The main application focuses essentially on the waterway or harbor designs to indicate the ship maneuverability and possible accident occurrence in relation to the human behavior and environmental conditions. This approach usually consists of a two-step process: application of a ship-handling simulator for generating the data of ship motions and assessment of navigation risk based on this data.

¹PhD candidate, Section of Hydraulic Engineering & Probabilistic Design, Delft University of Technology (TUDelft), Stevinweg 1, Delft, Netherlands, q.nguyenminh@tudelft.nl

²Professor, Section of Hydraulic Engineering & Probabilistic Design, TUDelft, J.K.Vrijling@tudelft.nl

³Associate Professor, Section of Hydraulic Engineering & Probabilistic Design, TUDelft, Stevinweg 1, Delft, Netherlands, P.H.A.J.M.vanGelder@tudelft.nl

⁴Lecturer in Ports and Waterways, Section of Hydraulic Engineering & Probabilistic Design, TUDelft, Stevinweg 1, Delft, Netherlands, R.Groenveld@tudelft.nl

⁵Doctor, Department of Marine Traffic Engineering, Technical University of Szczecin, Waly Chrobrego 1-2, 70-500, Szczecin, Poland, lucek@am.szczecin.pl

1.1. Ship handling simulators in waterway design

A number of ship simulators exist worldwide for different applications with various levels of capacities. Essentially, a ship-handling simulator is a computer-generated system that simulates the actual operation parameters of the ship in various maneuvering conditions in real time and displays the scenery from the navigation bridge visually audibly on the screen. The simulators comprise wide range facilities and man-machine interfaces as simplified schematically in Figure 1. An advanced ship simulator includes models of a ship, the simulated navigation channel, the environmental impacts, the visual scene, the radar image, tugs and thrusters, the ship bridge control, and typical bridge instruments.

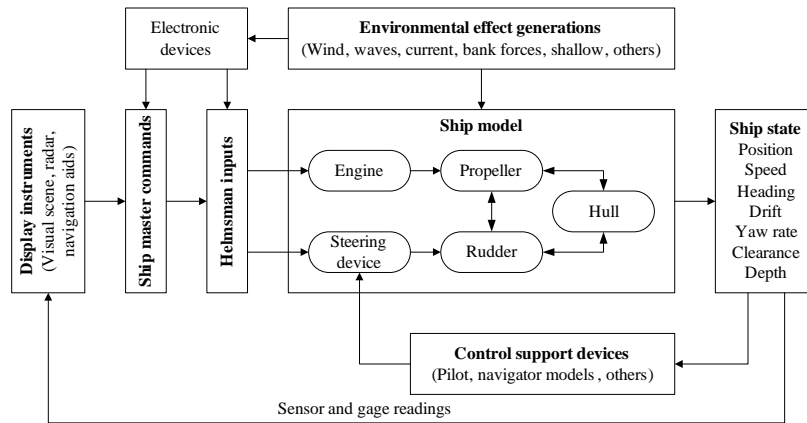


Figure 1: A simplified ship-handling simulator

The core of the ship dynamic model is the set of hydrodynamic equations of ship motion referred to a coordinate system commonly fixed in the ship. The equations should be complete and realistic with ship hull dynamics, engine thrust, bank and shallow water effects, currents, wind and wave impacts, and tug supporting forces.

The simulators with high reliable performance and wide range application are able to serve various needs of the assessment of the safety of ports and waterways, the research and development of safe operation and management of ships, and efficient education and training of the crews.

The most important data and results derived from simulator experiments for the use of waterway design are

- Track distance and ship trajectory, which include the proposed channel borders and the ship position at predetermined time intervals;
- Time series tables of different maneuvering characteristics (rudder angles, ship speed, turning rate, engine revolutions, etc.) throughout the simulation;
- Swept path plot.

Details of the illustration and application of simulators in the waterway design process could be found in some publications (Webster, 1992; PIANC, 1992).

1.2. Literature review of overall risk assessment models

Real time simulations should be executed for a wide range of environmental conditions (grouped into scenarios) and several repetitions for each condition in real time scale. So the time required would be comparable to the lifetime of the maritime engineering. These requirements are really expensive and seem impossible due to time consumption (Webster, 1992). From this arises the question of how to estimate the probability of ship accident during the lifetime of the channel project, the so-called “overall risk”. The real time simulations are based only on a limited number of conditions and trials in each condition. So the risk calculated from the simulated data does not equal to the overall risk. Generalization of the real time simulation results for long-term period research turns out to address the disadvantage of the ship handling simulator method. Finding ways of extending the real time simulation experimental results and applying to lifetime channel risk analysis is still challenging to researchers. Considerable efforts have been devoted and three main groups of research could roughly be categorized.

The first group has focused on developing probabilistic simulation - based models to generate the data of ship passages and tracks applying the Monte Carlo method. The variables were introduced into these models through either probability distribution of navigation error (Vrijling, 1995) or by means of stochastic external disturbances (Huchison, 2003). The parameters of the simulated ship tracks were chosen by comparing with those obtained from the real time simulations. This group approach is rather crude because the determination of distribution parameters of the random variables relies mainly on expert judgment. The second type focused on development of a new fast time simulation model, the so-called “probabilistic fast time simulation model”, which has been under developing by the Dutch Institute MARIN (Lan, 2003). To make fast time simulation results more realistic, four random variables including the time intervals of command setting, rudder error, position threshold and rudder threshold, which all relate to human pilot behavior, were applied to the design of autopilot model. One of the most advanced models of this type was developed by Itoh (2001). A ship navigator cognitive model was constructed for simple course-tracking task based on cognitive task analysis of experimental navigation sessions using a maritime simulator. However, this model was programmed to control a ship only in a so-called simple single-ship situation. As pointed out by the authors, significant efforts should be made to consider more complex navigation tasks (multi-ship situation) in order to extend the model to more realistic ship navigation as met in the real world. The third group comprises a model demonstrated by Gucma (2006), which differs from the above in several ways. The model is based on the assumption that the next ship position can be generated from the past consecutive position using two types of probability distributions. The first type describes the probability distribution of maximum and minimal points of ship track on starboard and port sides respectively. The second is the conditional distributions between the ship course and the generated track distance. The probabilistic model parameters were also obtained from statistic analysis results of the real time simulations. The critical point of this model retails further treatment in aspect of sudden changes in the generated tracks.

2. Methodology

This study is an ongoing effort that deals with the development of two models: the first model uses ARMAX technique to estimate the system outputs (course, position, etc.) from the inputs (rudder, engine, etc.) of the ship steering dynamics. The stochastic sequences of the inputs for the

first model used are generated using a semi-Markov model. One implementation of the semi-Markov model for rudder actions has been studied. The study used input/output measurements from a ship-handling simulator to estimate the model parameters. The human factor has therefore been included in the models. The method allows the results obtained from the simulator to be extended to predict the future conditions of system outputs. On the basis of the predicted results and using probabilistic approach, possible margins of ship maneuvering area will be identified and the long - term assessment of the navigational risk can be implemented involving a straightforward use of the optimal design of maritime engineering. Good results were obtained even where there was only limited ship handling results available. However, the study is constrained to one failure mechanism when it comes to the matter of ships exceeding the channel limits or navigable areas and being viewed as grounding or colliding with surrounding structures. The general procedure for the study is presented in Figure 2.

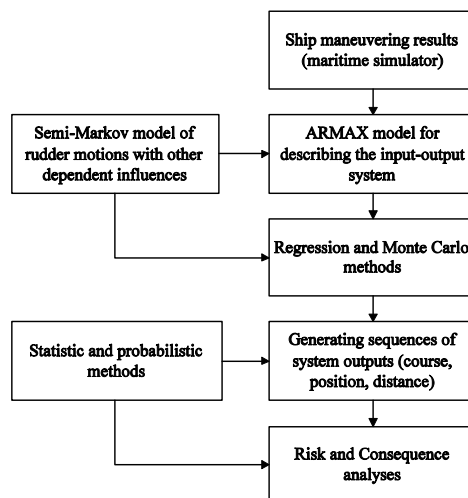


Figure 2: General procedure of the study

2.1. Conventional analysis of real time simulation results

The understanding of the type of information that simulation attempts to provide is fundamental to evaluate how simulation can contribute to the design process. Real time simulations are conducted by human pilots to navigate the simulated ship through the modeled waterway in real time scale. Interpretation of the simulated ship tracks provides insight into the various navigation factors (characteristics and dimensions of the waterway) and safety aspects (grounding or collision risks). Typically used analysis of the real time runs aims at finding the ship response parameters (including human factors) based on:

- Distribution of ship track distances (center of gravity and extreme starboard and port points of ships) in respect to center of the waterway;
- Distribution of ships courses; and
- Distribution of ships speed (horizontal, vertical and angular).

One of the most important measures for the risk assessment associated to the maritime engineering design is the probability of ship accidents in each of the waterway sections. The probability of a ship exceeding from a certain waterway width, P_{ex} , can be determined as follows

$$P_{ex} = P(y > Dr | Env = h) = \int_{Dr}^{\infty} f(y)dy \quad (1)$$

Where Dr is half of the channel width; $f(y)$ is the density function of the ship positions for the environmental scenario i^{th} as shown in Figure 3.

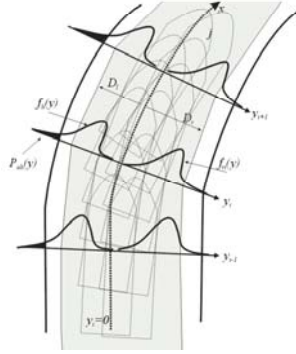


Figure 3: Probability of ship accident denoted by black zone

The simulations are usually conducted in series, performed in different environmental conditions, each consist of several trials. In principle, the environmental conditions of wind, waves, and currents are divided into a number of regions or categories to facilitate the probability assessment of the navigation results. These environmental categories, reflecting the frequency of occurrence and severity, are selected to define the different combinations of the environmental conditions that might be present when the ship is navigating the approach channel. The different combinations of environmental conditions are divided into various classes (normally three or four), known here as "maneuvering scenarios", by ordering degree of affecting the ship maneuverability. The probability of ship accident from the channel section borders during a given time period, P_{life} , can be determined as

$$P_{life} = N_{ship} \sum_{i=1}^{N_e} P_{ex} P_{oc}[Env = i] \quad (2)$$

Where N_{ship} is the number of ships presents in the channel during a given time period; N_e is the number of the maneuvering scenarios; $P_{oc}[Env = i]$ is the occurrence frequency of the maneuvering scenario i . Estimation of occurrence frequencies of the maneuvering scenarios is also an important topic. Two approaches could be found in the literature, which based on a linear programming technique (Brigs, 2003) or classifying external forces on ship hull (Quy, 2007).

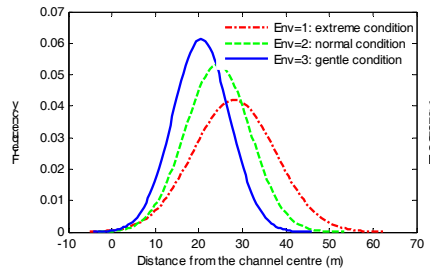


Figure 4: Density function of distance from the center of the channel fitted with normal distribution (in starboard side)

Figure 4 shows the distributions of ship track distance respectively with three maneuvering scenarios that are defined applying the above principle. The ship track samples can be well described by a normal Gaussian distribution. The figure has been created based on the data of the study case at the entrance channel of Ennore Port (Vrijling, 1995). Real time simulations were performed with the use of a 4.500 TEU container vessel. Eighteen scenarios of environmental conditions which are grouped into three scenarios (extreme, normal and gentle conditions) were carried out. For each scenario, several runs were executed.

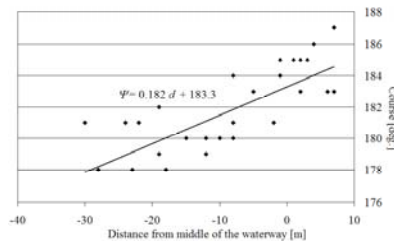


Figure 5: Linear correlation between distance from the waterway center and ships course for one investigated simulation trial (single section)

Distribution of ship courses is strongly correlated with ship positions referred to the middle of the waterway. It can be straightforwardly explained that the more the ship is away from the center of the waterway the more the navigator changes the course to come back to the desired track (Gucma, 2006). This phenomenon can be seen on the Figure 5. To include such observable fact for the later analysis of the navigation risk, it is proposed to use a simple linear regression model. The distance from the middle of the waterway could therefore be calculated by the distribution of courses using this regression formula.

It should be noted that the Eqs. 1 and 2 can only give the probability results of ship excursion for the analysis in each particular section of the channel; they are no indications for the channel as whole. Two approaches of integrated risk for entire channel have been presented in the literature (Burgers, 1989; Quy 2006).

In the following sections, we will deal with the use of ARMAX model and semi-Markov process to extend real time simulation results for long term-prediction of navigation risk.

2.2. ARMAX model of ship steering dynamic

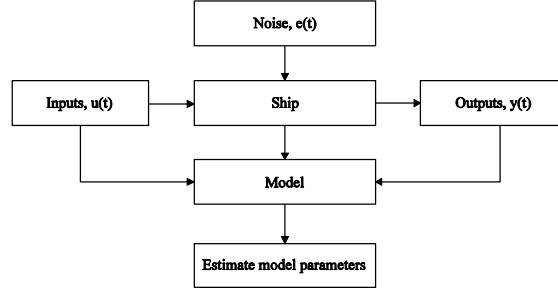


Figure 6: Simplified model of ship dynamic

A ship operating in seawater is assumed a dynamic system with inputs $u(t)$, outputs $y(t)$ and white noises $e(t)$ as shown in Figure 6. The inputs can be rudder angle, propellers, and thrusters and so on. The outputs are ship heading (yaw), sway, surge, roll, yaw rate, sway velocity, surge velocity, roll rate and etc. There are several ways to represent the relationship between the outputs and inputs, for example, by means of a continuous time model (classical way or differential equation), a model in transfer function form, a model in time or frequency domain, and a discrete time model (digital technique or difference equation) (Fossen, 1994). In this paper, discrete-time Auto-Regressive Moving Average eXogenous (ARMAX) model is adopted.

The ARMAX model applied to the above-described dynamic system can be assumed as a discrete-time model, a multiple - input and single-output (MISO) system in a transfer function form as follows (Ninness, 2005)

$$y(t) = G(q)u(t) + H(q)e(t) \quad (3)$$

In above $u(t)$ and $y(t)$ are sequences of the multiple - input ($u(t) \in R^m$) and single-output ($y(t) \in R_1$) system with the same length; $G(q)$ is $1 \times m$ rational transfer function of the system; and $H(q)$ is rational transfer function of the filter which are defined as

$$G_i(q) = q^{-n_{ki}} \frac{B_i(q)}{A_i(q)}; \quad H_i(q) = \frac{C(q)}{A_i(q)} \quad (4)$$

Here n_{ki} is the number of delays from input to output of the i^{th} input, q^{-1} is the backward delay operator, $A(q)$; $B(q)$ and $C(q)$ are polynomials of q^{-1} defined as

$$A_i(q) = 1 + a_1q^{-1} + a_2q^{-2} + \dots + a_{na}q^{-na_i} \quad (5)$$

$$B_i(q) = b_o + b_1q^{-1} + b_2q^{-2} + \dots + b_{nb}q^{-nb_i} \quad (6)$$

$$C(q) = 1 + c_1q^{-1} + c_2q^{-2} + \dots + c_{nc}q^{-nc} \quad (7)$$

Where n_{ai} , n_{bi} and n_c are orders of polynomials A_i , B_i and C , respectively. Having observed the input-output data (u, y) , the most appropriate orders and the parameters of the polynomials can be determined using prediction error, $e(t)$, method (Ninness, 2005), which is available in the Matlab Identification System Toolbox (Matlab, 2005).

The model described in Eq. 4 with known A , B and C can then be applied to generate a random sequence ship course from the inputs $u(t)$. The following section will present how to apply a semi-Markov model to describe rudder motions based on measured rudder angles achieved from the real time simulation.

2.3. A semi-Markov model of rudder motions

Markov chains and semi - Markov models are powerful and commonly used technique for the studying of the reliability and the characteristics of complex systems. In essence, these models use a set of data observed in present to predict system behavior in future by generating a random sequence that contains patterns of data characteristics. Details about this class of processes can be found in (Jacques, 2006).

Consider a finite set of rudder angles $R=[r_1, r_2, \dots, r_k]$ (degree) and respectively numbered and represented by rudder states $S=[1, 2, \dots, k]$ that occur at random times during all the simulation trials, and denote $p(i, j)$ as the transition probability that the helmsman moves the rudder randomly from state i (at rudder angle r_i) at time t_i to state j (at rudder angle r_j) at time t_j . A Markov chain is a discrete-time stochastic process, where the conditional probability of any future event depends on only the present state; the transition probability $p(i, j)$ is expressed by this law as

$$P(S_{t_j} = j | S_{t_i} = i) = p(i, j); \quad t_j > t_i \quad (8)$$

In practice, the transition probabilities $p(i, j)$ can be determined from the measured data as

$$P(i, j) = \frac{n(i, j)}{n(i)}; \quad n(i) = \sum_{j=1}^k n(i, j) \quad (9)$$

Here $n(i, j)$ is the number of times that the rudder is moved from state i to state j . The quantity $p(i, j)$ is an element of square matrix, called the transition probability matrix (or transition matrix) in which the size $(k \times k)$ equals to the number of the states. All the transition probabilities of the Markov process can be estimated based on the data recorded in the simulator trials. Now we can extend the Markov chain to the semi-Markov model by taking into account the times that the helmsman used to move the rudder from state i to state j and retain it in each state.

The rudder motion records during a series of the simulator trials were obtained as shown in Figure 7, where the ship sailed in calm undisturbed water. The real time simulations were carried out at the Piastowski canal, in the Baltic Sea. A total of 45 trials with various environmental conditions were performed at Paprotno Mielin bend part with the use of a 4.500 TEU container vessel. The rudder of the ship can be adjusted from 35 degrees port to 35 degrees starboard with a unit angle $\Delta r=1$ degree.

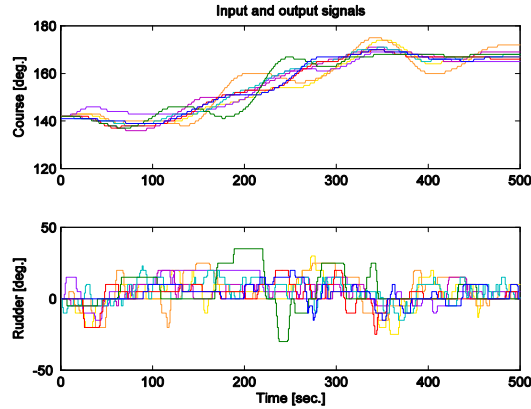


Figure 7: Measured rudder angles in calm environmental condition for total 15 real time simulation trials.

It was observed that in all trials the helmsman tried to move the rudder with the same rudder rate, V_r . The time that the helmsman spent moving the rudder from state i to state j can therefore be determined as

$$t(i, j) = t_j - t_i = \frac{|r_j - r_i|}{V_r} = \frac{|j - i| \Delta r}{V_r} \quad (10)$$

It is clear that in this case the time spent on the transitions (or moving rudder) is a deterministic quantity. The model thus has a transition time matrix analogous to transition probability matrix. Now the only thing left is to estimate the time (called sojourn time) that the helmsman maintains the rudder angle in every rudder state. The sojourn times $t(i, i)$ are, of course, random and depending on many factors where the helmsman's competence, ship characteristics and navigational conditions are the main factors. Usually a certain distribution can be found to fit the sojourn times obtained from simulator trials. Figure 8 shows, for example, distribution of the sojourn times in the state with the 5 degrees rudder angle fitted lognormal distribution. It should be clear that the sequence of rudder angles from the simulation is commonly recorded for every one second, the sojourn time in a state therefore exactly equals to the number of times, $n(i, i)$, that the same rudder angle values have continuously been recorded. It means that the length of the sojourn times increases proportionally to the transition probabilities $p(i, i)$. This makes it easier to generate the sojourn times in each state.

2.4. Results

Figure 9 presents sequences of rudder angles generated randomly from the semi -Markov model developed in the above section. The results seem similar to those measured from the simulator trials in time series. But some differences can be found in the shape of their probability distributions and power spectra as shown in Figure 10 and Figure 11.

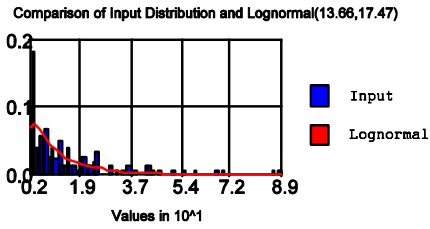


Figure 8: An example of distribution of the sojourn time fitted with lognormal distribution

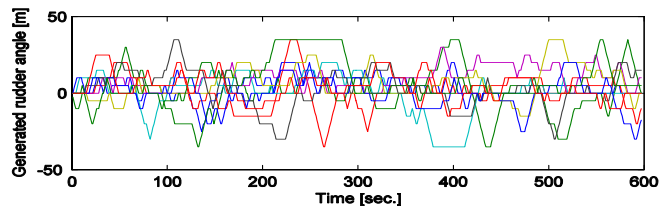


Figure 9: An example of sequences of generated rudder angles from the semi – Markov model

It is more interesting to observe the results in the frequency domain. In both cases, the power spectra of the motions show significant peaks around zero frequency, but the higher peak is obtained in the generated rudders than in the simulator. However, the amount of the rudder motion in the simulator is larger by comparison in the frequency range from 0.2 to 0.7 (rad/s) and then both approximately drop to zero.

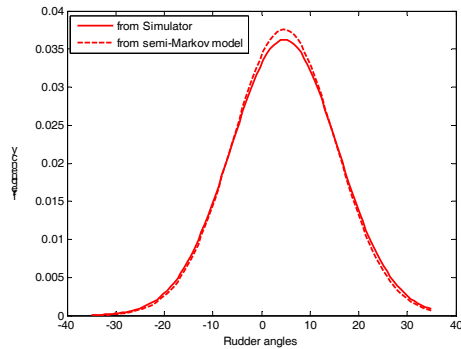


Figure 10: Comparison of rudder distribution between the real time simulation and new model

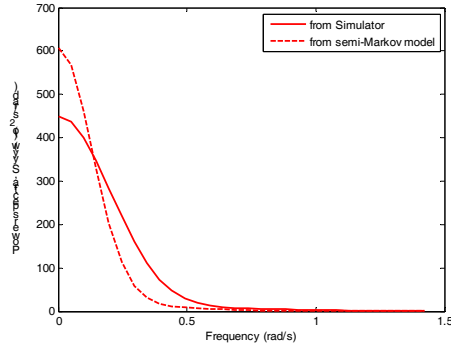


Figure 11: Comparison of rudder power spectra between two models

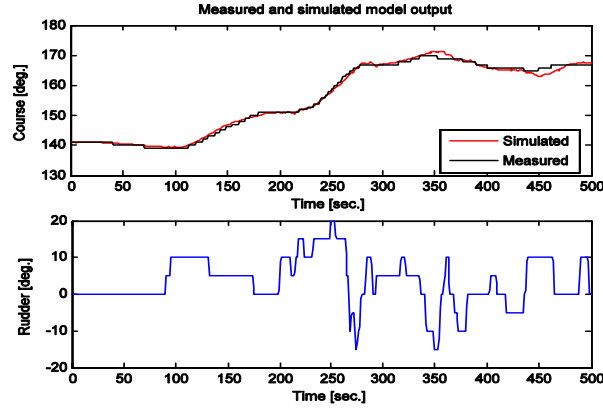


Figure 12: Comparison between simulated and measured courses

Here remained only the problem of estimating parameters of the ARMAX model. For the measured data of rudders and courses as shown in Figure 12, the resulting model has been found as follows

$$\begin{aligned}
 A(q) &= 1 - 1.878q^{-1} - 0.1112q^{-2} + 2.456q^{-3} - 1.423q^{-4} - 0.5896q^{-5} + 0.5371q^{-6} \\
 B(q) &= 0.05611q^{-4} - 0.1714q^{-5} + 0.1408q^{-6} + 0.0858q^{-7} - 0.1982q^{-8} + 0.08981q^{-9} \\
 C(q) &= 1 - 1.108q^{-1} - 0.8104q^{-2} + 1.744q^{-3} - 0.2931q^{-4} - 0.5921q^{-5} + 0.1367q^{-6}
 \end{aligned} \quad (11)$$

It can be seen from Figure 12 that the simulated courses from the above ARMAX model compare well with those from the simulator for the same generated rudder of the semi-Markov model. However, there is still slightly different in aspect of a higher resolution in the simulated course. This requires more effort on finding the parameters of ARMAX model.

Having determined the semi-Markov model of rudder motions and the ARMAX model of the system, sequences of the course fluctuation can be achieved, which may represent “true” behavior of the ship - human performance. The ship positions can then be calculated from the regression formula as investigated in Figure 4. One of the most important aspects provided by the ship positions achieved from regression formula might well be the validation with the use of extreme value distributions. The probability of the ship exceeding any margin of the designed channel section widths or navigable areas during a given period can be estimated using Eqs 1 & 2.

3. Conclusions and Future Study

This paper presented the typically used procedures of the analysis of simulation results and a brief review of the existing approaches to extend the simulation results for long-term risk assessment. Developing a probabilistic model of an autopilot or a cognitive simulation of navigation is a promising approach. However, such procedure requires reliable description of human behavior, which is still beyond today's possibilities. The other approaches focus on generation of ship passages and track distances using the probabilistic-based model and the Monte Carlo method. However, they generally fail to achieve satisfactory model parameters.

The emphasis has been placed on the development of a new method with the application of ARMAX and semi-Markov models that can be used for long - term prediction of navigational risk in the restricted channels. Information that is lacking in the real time simulation due to the limited number of trials can be realized in the proposed models that will thus provide more accurate readings of the system behavior. The parameters of the system outputs achieved from these models can satisfy several aspects of the risk and consequence analysis in long-term studies. However, the method is restricted to the problem when the trajectories of ship passage are “stationary” random process.

Following this approach, definition of whether the ship trajectories are “stationary” or “non-stationary” random processes is an important task, as has been presented in (Quy, 2006). This restriction produces issues that we will improve our model more comprehensive in the future. First, the transition matrix should be time - dependence conditional probabilities. It means that the next state of the rudder is not only depending on the present state but is also subjected to the space (position) given that state. The procedure calculation is the same as that presented in this paper, although of greater complexity because more than one transition matrix is being estimated. Secondly, more efforts should also be made on the analysis of dependence between ship speed and rudder states.

There is a difficulty for engineering designers to define the appropriate orders n_{ai} , n_{bi} and n_c , and the accurate parameters A_i, B_i and C , of the polynomials in the ARMAX model of ship steering dynamic, as described in Eq 4. However, this problem may be easily undertaken by the consultation of automatic control systems designers.

References

- Briggs, M. J. and Borgman, L. E. and Bratteland, E. (2003). Probability assessment for deep-draft navigation channel. *Coastal engineering* **48**, 29-50.
- Burgers, A. and Kok, M. (1989), The statistical analysis of ship maneuvering simulator results for fairway design based on the interdependency of fairway cross-section transits. *Proc. 9th International Harbour Congress*, Antwerp, Belgium.

- Fossen, Thor I., (1994). *Guidance and control of ocean vehicles*, John Wiley & Sons.
- Gucma, L. (2006). The method of navigational risk assessment on waterways based on generalized real time simulation data. *Proc. International Conference on Marine Simulation and Ship Maneuverability (MARSIM'06)*, Terschelling, Maritime Institute Willem Barentsz (MIWB), Netherlands.
- Huchison, B. (2003). Maneuvering simulation: an application to waterway navigability. *Proc. the World Maritime Technology Conference*, San Francisco, USA.
- Itoh, K. and Yamaguchi, T. and Hansen, J. P. and Nielsen, F. R. (2001). Risk analysis of ship navigation by use of cognitive simulation. *Cognition, Technology and Work*, **6**, 4-21.
- Jacques Janssen and Raimondo Manca. (2006). *Applied semi-Markov processes*, Springer Science, Inc.
- Lan, J. (2003). *Development and application of a probabilistic fast time simulation*. Msc. Thesis, International Institute for Infrastructure, Hydraulic and Environmental Engineering, Delft, Netherlands.
- Matlab, (2005). *System Identification Toolbox, Licence 58666*, The MathWork, Inc.
- Ninness, Brett and Wills, 2005. *Identification Toolbox (UNIT) - Technical Report EE05031*, The University of Newcastle.
- PIANC (1992). *Capacity of ship maneuvering simulation models for approach channels and fairways in Harbors*. Supplement to Bulletin No.77, Brussels, Belgium.
- Quy N.M., Vrijling, J. K., Gelder, P.H.A.J.M., and Groenveld, R. (2007). Identification and estimation of ship navigation limits for designs of approach channel widths, to appear in: *Proc. 4th International Conference on Collision and Grounding of Ships*, Hamburg, Germany.
- Quy, N.M., Vrijling, J.K., Gelder, P.H.A.J.M, Groenveld, R., and Guema, L. (2006). On the probabilistic analysis of non-stationary ship maneuvering results for waterway design. *Proc. 31st PIANC Congress*, Estoril, Portugal.
- Vrijling, J. K. (1995). *Probability of obstruction of the entrance channel, Ennore Coal Project*. Haskoning B.V. and Delft University of technology, Netherlands.
- Webster, C. (1992). *Ship-handling simulation application to waterway design*. National Academy of Sciences, United States of America, New York.