A STUDY OF MODELING, SIMULATION AND CONTROL STRATEGIES FOR MARINE CONTROL SYSTEMS

D. P. Dave*

Dr. A. A. Ghatol**

Abstract:

This paper presents a review of various recent papers on development of models for control systems of large and complex processes of a vessel's main and auxiliary systems. The aim of this paper is to bring together the, technological developments, new concepts, and comprehensive studies in the area of ship's process modeling and simulation. The effort is focused towards providing a list of references to recent papers, conferences and proceedings related to modeling and simulation of ship's control systems. The control systems related to ship's main systems like engine, propeller, rudder, thrusters, fins and major auxiliary systems like Boiler, Governor, Steering system, turbo-charger, ODMCS etc. have been included. Additionally, basic information (reference, publication type, modeling/ simulation methodology, broad problem area etc.) about grouped references has been given. The paper also discusses various software tools, which may be used for modeling and simulation purpose.

KEY WORDS: Control; Marine Systems; Modeling; Simulation.

* M.E., Associate Professor, Tolani Maritime Institute, Induri, Taluka - Maval, Dist - Pune, India.

** Ph. D., Former Vice Chancellor, Dr. Babasaheb Ambedkar Technological University, Lonere, Raigad, India.

INTRODUCTION:

The main objective of this paper is to provide a quick start-up reference to a any one who intends to begin research in the area of control system modeling and simulation in general and ship's control systems in particular. The mathematical modeling and simulations of electrical, mechanical, thermal, chemical, hydraulic, hydro-mechanical and hydrodynamic systems is a very useful tool to understand and predict system dynamics and control characteristics. These simulations are used to support the entire life cycle of a ship or system: from concept tradeoffs, through system optimisations and detailed design, to support sea trails, for problem resolution after deployment, and to evaluate the impact of design changes throughout vessel life. Mathematical equations describing the dynamic behavior of the ship and system components are first developed and they are then combined into a unified computer simulation that predicts the transient and steady state response of the complete system. Engineers design and analyse simulation experiments to reduce technical risk by quantifying performance, designing and analysing controls, exposing potential performance problems, and designing corrective changes. The references on modeling and simulation of various marine control systems have been categorized as shown in Fig. 1. There are five categories: i) Ship Motion, Hydrodynamics and Stability, ii) Ship Machineries and subsystems, iii) Condition Monitoring and Safety, iv) Sea Conditions, and v) References on other important systems onboard (not included in other four categories) and other aspects of marine field. The references in each category are listed in Tables 1-5.

Additionally, the other important sources of information related to modeling, simulation and control of marine systems; like books, handbooks, theses, journals, conferences & seminars, lecture notes, reports, case studies, web-links etc. have also been listed in the references. The important tools and techniques used for modeling and simulation are also briefly described. The emphasis is given on the software tools as these tools support modeling and simulation of actual systems.

Each table gives the references in the respective category in chronological order along with author name, year of publication, reference type (book, paper in journals, conference

proceedings, handbooks, report, case study, manual, thesis, online article etc.), problem area/modeled system and methodology used/remarks.

SHIP MOTION HYDRODYNAMICS AND STABILITY:

The references under this category mainly involve the modeling and simulation for ship motion control under various sea conditions (disturbances) and stability analysis of the control systems. The main problem areas under this category are course keeping and manoeuvring, roll-stabilization using control surfaces (like hull, rudder and fins), heave compensation, assisted position mooring and dynamic positioning of the ship.

There are 15 references in this category as listed in Table 1. This includes the models of a diversity of ship motion control problems and modeling methods. The systems and problem areas like mooring lines, steering and manoeuvring, weather optimal position control, roll stabilization, dynamic positioning, station keeping etc. are included. The different methodologies used includes finite element method, adaptive back stepping method, strip theory, acceleration feedback, statistical and empirical methods, estimation methods, state space models, hydrodynamic equations, fuzzy logic etc.

SHIP MACHINARIES AND SUBSYSTEMS:

The references under this category involves the modeling, simulation and control of various main and auxiliary machines onboard the ship like propeller, thrusters, engine, turbine, turbo-charger, boiler, steering & autopilot system, electric drives etc. There are 17 references listed under this category as given in table 2. The references under this includes the modeling, simulation, identification and control aspects of various machineries and their subsystems onboard the ship. The references cover modeling and simulation methodologies like nonlinear hydrodynamic model, model based on body forces, real-time simulation using MATLAB and data acquisition card, development of control algorithms, state space model, numerical model, artificial neural network based model etc

CONDITION MONITORING AND SAFETY:

The category Condition Monitoring and Safety; contains references on monitoring, analysis and control of systems based on condition or state of a few variables. These variables are mainly vibration, temperature, noise (acoustics), optical etc in nature. This category also includes the references on safety assessment of the ship. Although vibration monitoring and control is a very vast subject and deserves an independent treatment, a few references are given here as a starting point for one who wants to pursue rigorous study of this subject. Majority of the papers in this category are on vibration analysis of various ship structures like hull, machine components, propulsion system etc.

There are 15 references in the category as listed in Table 3. The methodologies used include signal processing and interpretation, diagnostic and prognostic algorithms, fault modeling based on artificial intelligence paradigms; like artificial neural networks, genetic algorithms, fuzzy logic and their hybrid versions, aspect oriented programming, empirical and statistical fault modeling, finite element model etc.

SEA CONDITIONS:

Modeling sea conditions is necessary as these acts as a disturbance signals to various control systems onboard the ship. The vibrations may cause serious problems for the electronic instrumentation and mechanical systems onboard the ship. Rotational moments like roll, pitch, and yaw caused due to rough weather adversely affect the efficiency and reliability of the machinery and personnel on board the ship. A lot of research effort has gone into modeling sea conditions so as to control the adverse effects caused due to them. The category Modeling Sea Conditions; involves references on modeling and simulation of ocean waves, wind forces, ocean currents etc.

Table 1 Ship Motion, Hydrodynamics and Stability

Reference	Ref. Type	Problem Area / Modeled System	Methodology/Remarks
Ammo O., et al. (2001)	Journal	Modeling of Mooring Lines	Finite Element Model
Fossen T., et al. (2001)	Journal	Weather Optimal Position Control (WOPC)	Nonlinear and Adaptive back stepping (PID Control), Disturbance Modeling
Clarke D. (2003)	Conf. Paper	Steering and Maneuvering	Basic concepts of control requirements in steering and Manoeuvring
Jouenee J. et al. (2003)	On-line article	Theoretical Manual of Strip Theory Program	Strip Theory
Lindergaard K. (2003)	Ph. D. Thesis	Acceleration Feedback in Dynamic Positioning	Inertia shaping for marine vessels using acceleration feedback
Perez T. (2003)	Ph. D. Thesis	Roll stabilizers for ships	6 DOF state space model
Fossen T. et al. (2004)	Conference Paper	Low speed maneuvering and station-keeping	Nonlinear time-domain strip theory formulation
Ikeda Y. (2004)	Journal	Roll damping and determination of optimum stabilization devices	Statistical and empirical methods.
Nicolau V. (2004)	Conference Paper	Rudder Role Damping	Fuzzy logic based model
Perez T. et al. (2004)	Technical Report	Sea-keeping and Maneuvering model	State space model (with memory effects)
Skjetne R., et al. (2004)	Conf. Paper	Modeling, Identification and Control for ship maneuvering.	3 DOF maneuvering model using rigid body and hydrodynamic equations of motion.
Fossen T. (2005)	Lecture Note	Ship Maneuvering and Control	Non-linear unified state space model
Goodwin G. et al. (2008)	Journal	Predictive control of ship fin stabilizers to prevent dynamic stall	Estimation of the effective angle of attack and setting a conservative constraint on it as part of control objective.
Mizuno N. et al. (2007)	Journal	Minimum Time Ship Maneuvering Method	Artificial Neural Networks
Roberts G. (2008)	Journal	Trends in Marine Control Systems	

There are 11 references in this category as listed in Table 4. The modeling methods used are numerical modeling, statistical modeling, Gerstner model, quasi-linear theory of wind-wave generation, stochastic modeling, probability density functions etc.

OTHER SYSTEMS AND ASPECTS RELATED TO MARINE FIELD:

This category contains references on the important systems onboard the ship, which are not covered in previous categories. These systems include Oil Discharge Monitoring and Control System (ODMCS), RADAR, Power Generation and Distribution System, Supervisory Control and Data Acquisition System (SCADA), Global Positioning System (GPS) etc. This category also includes papers and articles on some of the other important aspects of marine field such as corrosion prevention, pollution control, modeling and simulation for operator training etc. There are 12 references in this category as listed in Table 5.

Table 2: Ship Machineries and Subsystems

Reference	Ref. Type	Problem Area / Modeled System	Methodology
Chesse P. et al, (2000)	Journal	Performance simulation of sequentially turbocharged marine diesel engines	Mathematical modeling
Hountalas D. (2000)	Journal	Prediction of marine diesel engine performance under fault conditions	Mathematical model using energy and mass balance equations
Yoerger D. et al, (2002)	Journal	The influence of thruster dynamics on underwater vehicle behavior and their incorporation into control system design	Nonlinear parametric model of a torque-controlled thruster
Huang Y. (2003)	Ph. D. Thesis	Modeling and simulation of combustion dynamics in lean-premixed swirl-stabilized gas-turbines	Numerical model for unsteady flame dynamics
Krüger S., et al., (2004)	Symposium	Propulsion Control System	Time domain model for manoeuvring purpose based on body forces
Fang M. et al., (2005)	Journal	Simulation of a ship steering in waves with autopilot system.	Nonlinear Hydrodynamic Model
Sorensen A. et al. (2005)	Symposium	Reconfigurable electric propulsion and marine control system.	This paper addresses various aspects related to design and operation of marine control and propulsion systems.
Diao L. et al. (2005)	Conference Paper	Simulation system for marine propeller load characteristics for electric propulsion motor examination.	Real-Time simulation and control using MATLAB and data acquisition card
Galindo J. et al., (2005)	Journal	Combustion simulation of turbocharger HSDI diesel engines during transient operation	Artificial Neural Networks (Empirical Model)
Yu Y. et al, (2005)	Journal	Digital control system of marine three-shaft gas-turbine	Matlab/Simulink based simulation
Liptak B. (2005)	Handbook	Process Control	The paper describes modern trends and challenges in process modeling and control.
Solberg B. et al., (2005)	Proceedings	Model based control of a bottom fired marine boiler	Dynamic modelling, LQG control
Kim S. et al., (2007)	Symposium	Suppression of thrust loss due to cavitation	Development of Algorithm
Boukhezzar B. et al. (2007)	Journal	Multivariable control strategy for variable speed, variable pitch wind turbines	Nonlinear dynamic state feedback torque control strategy with a linear control strategy for blade pitch angle.
Smogeli Ø., et al. (2008)	Journal	Anti-spin Thruster Control	Mathematical modeling of motor and shaft dynamics, in-line velocity fluctuations and in-and-out-of water effects
Świtoński E. (2008)	Conference Paper	Modeling electro-mechanical drive systems	Optimization of dynamic forces using kinematical model.
Rodriguez J. et al., (2008)	Journal	Steam pressure control of a fire-tube boiler	Modeling using System Identification

Table 3 Condition Monitoring

Reference	Ref. Type	Problem Area / Modeled System	Methodology
Kouremenos D. et al., (1997)	Journal	Modeling and simulation of medium speed marine diesel engine for condition monitoring	Thermodynamic model. A diagnostic algorithm based on exhaust gas temperature measurement of diesel engine.
Hadden G., et al., (2000b)	Proceedings	Ship machinery diagnostics and prognostics/ Condition based maintenance	Predictive fault model for condition monitoring of ship machineries, based on signal processing of vibration, temperature, pressure, current, voltage and so on.
Hadden G. et al., (2000a)	Workshop	System health management for complex systems	System health and performance modeling using diagnostic and prognostic algorithms for processing vibration data
Hua J., et al., (2000)	Case Studies	Case I: Analysis of propeller induced underwater pressure signal, Case II: Acceleration due to structural vibration of a planning boat in waves.	Wavelet method in signal analysis of vibration (pressure, noise) signals
Wang G. et al., (2001)	Journal	Fault modeling for Ship hull monitoring	Real-time structure monitoring using fiber optic sensors (bragg grating technology) and signal processing
Thai J. et al., (2001)	Conference Paper	Software based system health indicators	Aspect oriented software based model for system health index
Wu T., (2001)	Periodical	Analysis of vibration characteristics on merchant vessels	Empirical Method, Finite Element Method
Masayoshi K., et al., (2003)	Journal	Safety indexing for ships	Statistical Model
Ozsoysal R., (2004)	Journal	A review of recent ship vibration papers	Presents a very comprehensive review of various aspects of ship vibration
Bengtsson M., et al., (2004)	Case Study	Design of condition based maintenance systems	Data model based on equipment criticality and fault modes, combined neural network diagnosis and prediction, and hybrid reasoning techniques based maintenance decision
Salva M. (2004)	Journal	Condition monitoring based on temperature measurement	Infrared thermography based predictive maintenance algorithms
Bob-Manuel K., (2004)	Journal	Condition monitoring, budgeting and part management of marine power plant.	Expert System
Funk P. et al., (2005)	Conference Paper	Experience based diagnostics and condition based maintenance	Artificial intelligence, knowledge discovery and case-based reasoning
Avudainayagam A., et al., (2005)	Book	Safety indexing for Ships	Empirical Model
Charchalis A., (2006)	Transactions	Determination of permissible in-service imbalance, Estimation of operating time of turbine rotors and vibration control of mis-alignment of propulsion shaft.	Estimation Model based on analysis of vibration and acoustic data.

TOOLS FOR MODELING, SIMULATION, AND CONTROL:

The purpose of discussion about tools here is only to give a new entrant in this vast area, a brief idea about the existing tools and practices in modeling, simulation and control of marine systems. For study of a particular tool in more details, some useful references are listed. Presently, MATLAB with SIMULINK and other toolboxes (Chipperfield, 1993) are among the most popular tools for modeling, simulation and control. One of the very useful custom-made toolbox for marine system simulation and control is Marine System Simulator (MSS), which is available freely and may be updated/augmented by marine control M&S community. The scope, features, capabilities, applications and other important aspects of MSS are given in (Perez, Smogeli, Fossen, and Sorensen, 2004).

Modelica is a object oriented language for modeling and simulation of physical systems (Fritzson, and Engelson, 1998). This is well suited for hybrid systems and presents a hierarchical approach to development of models and their simulation. LabVIEW is another software tool widely used by control community for modeling, simulation and testing of marine control systems. The details of this tool may be obtained easily by online search. A free e-book titled 'LabVIEW Fundamentals' is available online as given in (National Instruments, 2005).

Table 4 Sea Conditions

Reference	Ref. Type	Subject Area / Modeled System	Methodology
Kareem A (1985)	Proceedings	Structure of Wind Field over the Ocean	Numerical Method
Collar P. G. (1986)	Journal	Measurement of Surface Currents	Statistical Modeling
Hogben N. et al. (1986)	Journal	Global Wave Statistics	Statistical Modeling
Fournier A. (1986)	Journal	A Simple Model of Ocean Waves (surface of the ocean).	Based on Gerstner Model (particles of water describe circular or elliptical stationary orbits).
Janssen P. (1988)	Journal	Wave-Induced Stress and Drag of Air Flow over Sea Waves	Quasilinear theory of wind-wave generation
Kat De J. et al. (1991)	Journal	Behavior of Moored Ship in Unsteady Current, Wind and Waves	Numerical Method
Tucker M. (1991)	Book	Waves in Ocean Engineering: Measurement, Analysis, Interpretation	Statistical and Numerical Methods
Ochi M. (1998)	Book	Ocean Waves: The Stochastic Approach	Stochastic Model
Gupta A. (2001)	Ph. D. Thesis	Modeling and assessment of ambient, Air, and Water quality of a harbor.	Statistical Model
Perez T. et al. (2002)	Technical Report	Simulation of Ship Motion in Seaway.	An algorithm for tuning shaping filters to filter white noise. Discrete frequency approximation of motion spectrum.
Myrhaug D. (2004)	Lecture Notes	Probabilistic theory of Sea Loads	Probability Density Functions

Some of the other software packages available for modeling and simulation of control systems are; ACSL (Advanced Continuous Simulation Language), SIMNON (SIMulation of linear and NONlinear systems), CTRL–C, MATRIX/PC, CC etc. The important features and sources for these programs may be obtained by online search or from (Gopal, 2005, pp. 948). Some of the books are dedicated to marine control engineering for e.g. (Perez, 2005), (Egeland, and Gravdhal, 2002), (Fossen, 1995), which provide a deeper insight into modern methodologies and trends pertaining to the subject.

CONCLUSION:

In the references section, 78 references dealing with modeling and simulation of various marine systems and their control aspects, published recently, have been listed. This paper is aimed at helping researchers, teachers, students and professionals working in the area of marine control engineering to provide a birds-eye view of the subject area and to gain rapid access to the listed

Table 5 Other Important References

Reference	Ref. Type	Problem Area / Modeled System	Methodology
Stronach A. et al, (1988)	Journal	Model of a diesel engine prime-mover for power system studies	Quasi-steady-state model (compromise between the simple linear model and one in which full thermodynamic effects are accounted for)
Craig K., et al., (1991)	Proceeding	Modeling effect of multipath and ducting on RADAR systems	The parabolic equation (using split-step algorithm) approach to the modelling of clear-air propagation, performance assessment of radar in presence of multipath and ducting
C. Lin, (1991)	Book	Modeling-Design-Analysis-Simulation of Navigation guidance and control processing	Target Noise and Target Maneuver Modeling, Two-Dimensional Target Tracking State Modeling, Three-Dimensional Intercept State Modeling
Bjornar V., et al., (2001)	Conference Paper	Integration of Global Positioning and Inertial Navigation Systems (INS)	A nonlinear observer suitable for direct integration is presented. Global exponential stability of the origin of the combined attitude and velocity error systems is proven.
Bacso J., et al., (2002)	Proceeding	Object oriented architecture for standardization of RADAR models	A fully object oriented standards based architecture is presented for collaboration amongst modeling and simulation community.
Sebastião P. et al. (2003)	Journal	Oil spill simulation	Algorithm to forecast trajectory of oil spill based on geo-referenced information, such as bathymetry and mean conditions of wind, waves and currents
Ford M., (2003)	Conference Paper	Vessel condition monitoring and control	Using Supervisory Data Acquisition and Control (SCADA)/Distributed Control System (DCS) / Vessel Monitoring System (VMS)
DeGiorgi V. et al, (2005)	Journal	Corrosion damage protection system	- Geometric homogenization approach - Sub-region modeling
Dave D. et al., (2006)	Conference Paper	Oil Discharge Monitoring and Control System	Strategy proposed to test compliance of MARPOL norms with fully automatic system
Tucker J. et al., (2006)	Conference Paper	Modeling and Simulation of Navigating in Ice	Numerical Models, This paper discusses the incorporation of simulation into ice navigation training for mariners.
Tsourapas V. et al., (2008)	Journal	Modeling of autothermal JP5 fuel reformer	Ideal gas law and energy balance principles
Iassinovski S. et al., (2008)	Journal	Online simulation, decision making and discrete process control	Expert System, Hierarchical object-based representation of a complex discrete system and a production rules based representation of discrete processes

references. The methodology used in majority of references includes statistical modeling/estimation method, empirical modeling, dynamic state space model, finite element model, hydrodynamic equation, mass/energy/heat balance equations etc. The new trend is towards using humanistic/intelligent models (cerebral models) like fuzzy logic, artificial neural networks, genetic algorithms and hybrid models.

The authors have come to the conclusion, based on their literature survey and above discussion that a considerable amount of research work has already been done in modeling and simulation of sea conditions. Also, a lot of research work has been already done and ongoing in the areas

like ship motion control, hydrodynamics, stability analysis, modeling and simulation of machineries and subsystems etc. However, there are areas like geographical information based position control, fault estimation and forecasting, safety analysis and indexing, usage of supervisory data acquisition and control systems in marine applications like energy, fault and emergency management etc., where there is a lot of scope for further research work. The author has particularly short-listed the problem of modeling, simulation and complete automation of ODMCS for his further research work.

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