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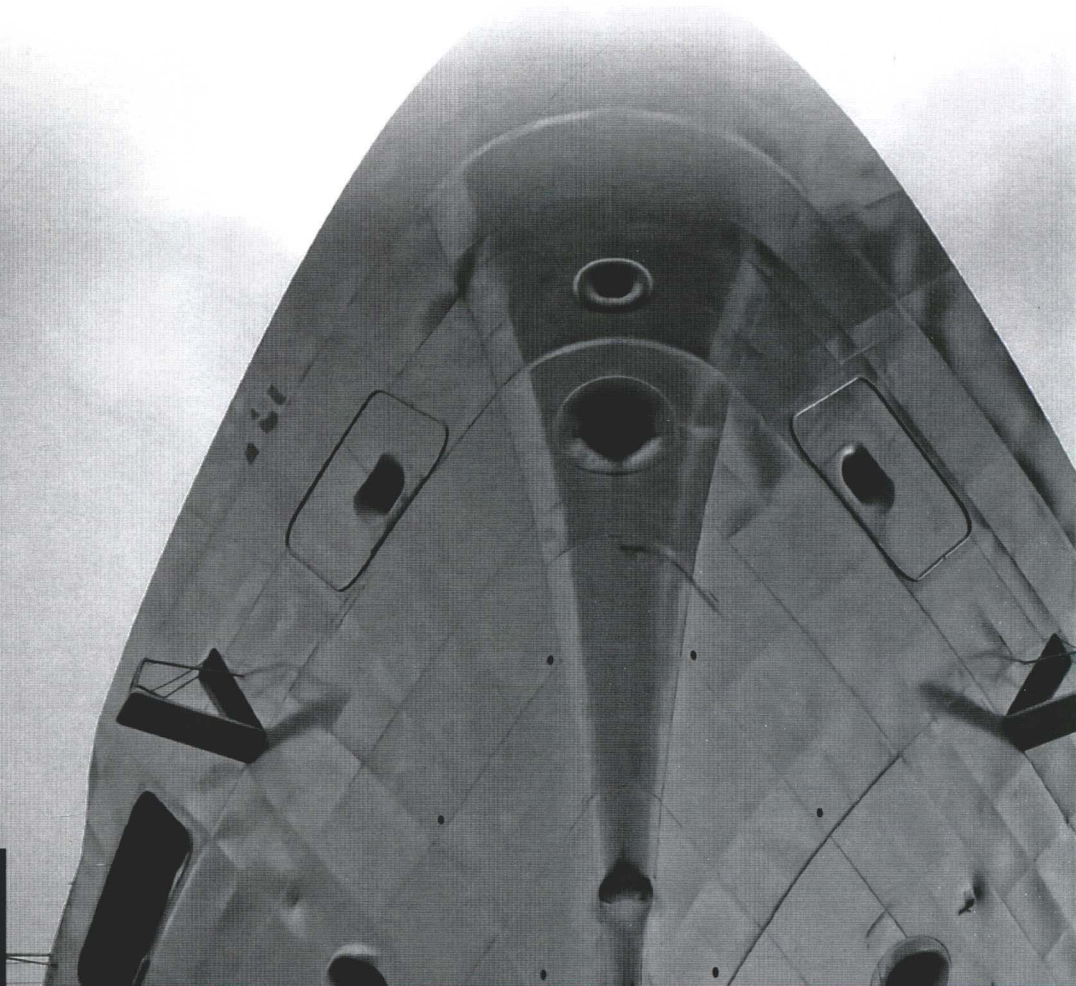
Michele Martelli

MARINE PROPULSION SIMULATION

METHODS AND RESULTS



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Managing Editor: Elisa Capello

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Contents

1 Introduction

This work is the result of three years of research carried out between January 2010 and December 2012 as part of The XXV cycle Ph.D course in Naval Architecture and Marine Engineering. This course is provided by the "Ph.D. School in Science and Technologies for Engineering" of the Università Degli Studi Di Genova (UNIGE).

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The challenge of this work is to develop a multi-physics simulation platform able to represent the dynamic behaviour of a ship in the time domain. With respect to previous work available in literature, where the systems are often modeled one at a time, the aim is to merge into a unique platform three ship macro-systems that contribute to the global ship dynamics: the ship manoeuvrability, the ship propulsion plant, and the control system. In this way, it is possible to catch the mutual interaction between all the involved elements treating the ship as a whole.

Design and optimization of the propulsion plant is a crucial task of the ship design due to the fact that the global behaviour of a ship is greatly influenced by the dynamic performance of the propulsion system. Different operational speeds, acceleration, deceleration, crash stop, and heavy turning are some examples of transient situations that a propulsion system has to sustain without reducing ship safety and reliability. These aspects become crucial issues if the ship is a naval vessel. The dynamic behaviour of the propulsion system is mainly affected by the control system performance, i.e., the capacity of the control system to properly use the power necessary to perform the required task within the boundary conditions imposed by machinery or environmental constraints.

The main focus of this work is to develop and use the platform for the designs of the propulsion plant and the propulsion control system for a naval vessel in the early design stage. Using this platform, it is possible to develop the control system; to try new control logics; to choose the main engines; to test the control system under different operational conditions before the ship is built. In this way, the global design time could be reduced and the final product could be better compared to the standard design technique. It also can reduce the time and cost of the sea trial for final tuning.

To reach this goal, the propulsion control logics have been first developed in a virtual environment and then in a real PLC to increase result reliability. The PLCs, linked to the ship virtual model, has been thoroughly tested and optimized. This involves a set of technical problems. The crucial task is to develop a ship simulator able to run in real time, so particular attention has been dedicated to the choice and the development of system physical models and their computation time.

The ship motion model taking into account all six degrees of freedom has been developed, and the model for rudders and propellers has been developed considering the motion three-dimensionally. The propulsion plant model includes both the main engines and the transmission line dynamics. The propulsion control system, as it is the lead objective of this work, is a subpart of the control system that has also been modeled.

Finally, an experimental campaign has been performed to validate the simulation platform.

2 Ship Dynamics

2.1 Simulation Approach

Hundreds of years ago, buildings, boats, and machineries were first tested as prototypes before being constructed on a large scale. In naval field, the pioneer William Froude established, in 1861, a methodology by which the results of small-scale towing tank tests could be used to predict the behaviour of full-sized hulls.

With the emergence of electronics came the possibility to represent complex dynamic systems by equivalent systems of electronic components using analogies between electronic circuits (capacitors, resistors, and inductors) and mathematical operations (integration, multiplication, and derivation). With advances in computer science, the behaviour of complex systems can now be simulated on a computer without even constructing and testing the real system. The computer can quickly and precisely process any mathematical or logical formulation; these new developments have led to unimaginable possibilities in all engineering domains and scientific fields.

The system dynamic behaviour can be studied by two different approaches [17].

The first approach is to describe the system behaviour from observations of one or several identical systems, observing how they change (output) under different conditions (input). Then, the description is used to create mathematical relationships to relate input to output. This method imitates the behaviour of the real system using these relationships, which usually have nothing to do with real processes in the system. The system is not described in all of its details and functionality; it is treated as a black box.

The second approach, which is employed in this thesis, tries to physically explain the behaviour of the real system by mathematical modelling. In this case, some questions must be answered. Which and how many elements are present? How are they linked? How do they influence each other? Furthermore, a huge quantity of data and information about the elements must be available, and often this is not the case.

Using this information, the dynamic system behaviour can be simulated even for conditions not observed in the past. The system is treated as a glass box, where all of its elements and processes are schematized, and where the mutual interactions of the elements are taken into account in a holistic vision of the problem. Past and future system observations come into play at a later stage known as validation. Validation is the key by which it is determined if the system has been correctly schematized.

Simulation techniques join system modelling and computer science in order to obtain, in a virtual environment, the system behaviour over time.

The simulation models are usually composed of a set of data, Boolean logic, tables, and algebraic and differential equations, all linked to each other.

2.2 Literature Review

Different works (articles, Ph.D theses, books) present in the literature have been analysed. In fact, most of the relevant works have been produced by scientists at three universities: the research branch in marine modelling and simulation at Norwegian University of Science and Technology (NTNU), Delft University of Technology (TU Delft), and Genova University (UNIGE).

In particular, Fossen from NTNU wrote three comprehensive books [23–25] about the equations of motion and propulsion control systems for ocean vehicles. In these books, the mathematical basis and the main steps to study ship motion are well explained. Fossen also dedicated some detailed sections for control systems of ship motion. Two Ph.D theses developed in NTUN have been considered [33, 40] that deal with the modelling of propeller hydrodynamic forces and the local control system. In particular, the latter is focused on the propeller thrust estimation in four-quadrants operations.

In the literature are also several works about ship manoeuvrability. In particular, Ankudinov [11] proposed a modular mathematical approach for real time manoeuvring simulation; Kijima [30], studied roll motion; Brix [18] wrote regarding manoeuvring technical problems.

With regard to the rudder tests data, an active research group is located in Southampton; several works have been produced [31, 32] in which the rudder behaviour downstream of the propeller has been studied, proposing different mathematical formulas to evaluate interferences between the hull and the propeller.

The most studied topics include ship propulsion, the main engines, and auxiliary systems. However, most of the works currently in the literature deal only with particular propulsive components or with a particular ship system without taking into account the behaviour of the whole ship. Propeller pitch change mechanisms have been thoroughly studied in several works [12, 29, 44] from the point of view of mechanics, hydraulic system, and acting loads.

Gas Turbine dynamics analysis can be found in some works [14, 35, 37], and of particular note, the works of Rana and Rubis also deal with the turbine control system.

Few studies on the ship simulation, including propulsion plant, manoeuvring model, and control system, are reported in literature [16, 38].

In the present thesis, the propulsion simulation of a particular CODLAG system will be addressed and for which no information is present in literature as only three of these systems have been installed (on the Finnjet ferry, on the German Navy F125 frigate, and on Italian-French Navy Frigate FREMM). The modelling and simulation of such systems have been popular topics at Genoa University for the past fifteen years. Different propulsion plant simulation models (ferries, merchant ships, pleasure boats, and navy vessels) have been developed and published [5, 7, 13, 15]. In particular, the Cavour project [2, 3, 6] has been the best example of the effectiveness of simulation techniques.

2.3 Ship Dynamics

The simulation model will be a software platform that allows the study of the vessel behaviour during transient conditions (acceleration, deceleration, etc) and during steady state conditions (constant speed navigation) as well as the analysis of the mutual interaction between all the elements involved. To reach this goal, three completely different ship macro systems were joined together to adequately describe the global ship behaviour: the ship manoeuvrability, the propulsion plant, and the control system.

Each macro system is composed of different elements; each of these elements have been schematized and modeled using the differential equations that govern their physical behaviour and represent their functions.

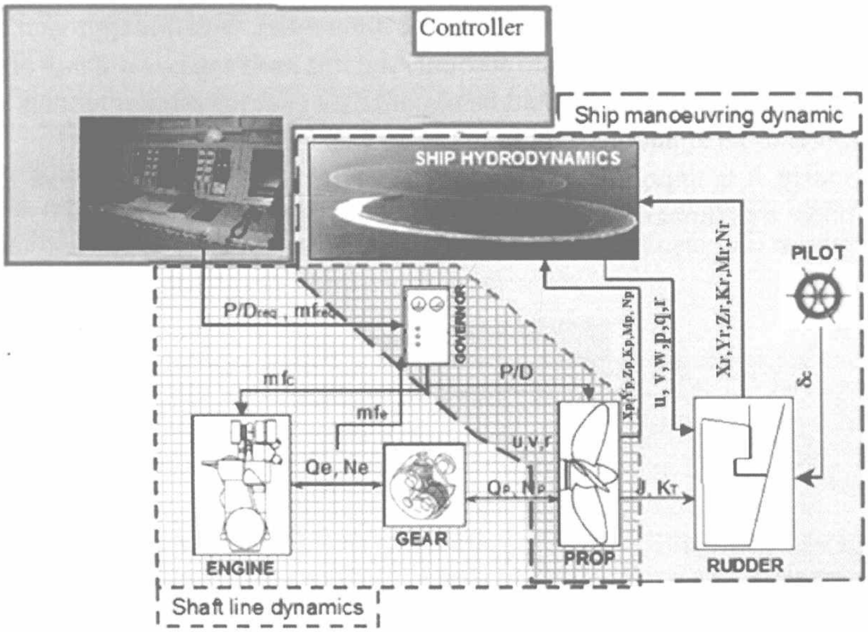

Figure 2.1: Ship Simulation Platform

The subdivision adopted in Table 2.1 is not completely accurate, because it is impossible to define the element membership to a specific macro area, and some systems are borderline. For example, the propeller can be seen associated with the manoeuvrability as it provides the thrust required to achieve a given ship speed, but it can also be included in the plant propulsive system because it determines the engine load.

The different sub models have been studied and developed with different degrees of detail. The simplest way to schematize a system is by using a table of parameters and algebraic equations that identify the system behaviour in steady state conditions.

Table 2.1: Simulator scheme

MACRO - SYSTEMS	SUB - SYSTEMS
Manoeuvrability	Hull Rudder Appendages Propeller
Propulsion Plant	Main Engine Gearbox Shaft line
Control System	Propulsion Control System

Usually most of the needed data comes from system manufacture trials. The complex and more realistic approach, used for the most of the elements, is to model the system with its physical equations, both algebraic and differential. With this approach, a large set of parameters must be taken into account, and this itself can be a difficult obstacle.

An intermediate approach could be obtained by merging tabular models and algebraic/differential equations to produce a quasi-static model.

Obviously, it is important to take into account the computational cost that increases (more than linearly) with the model complexity (Fig. 2.2).

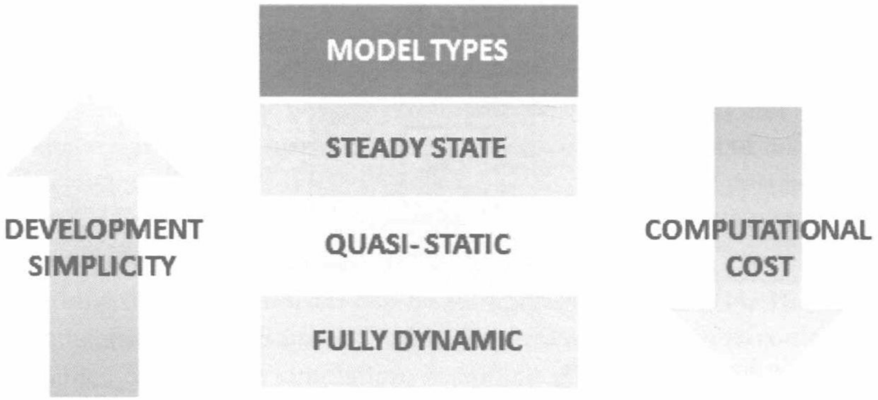

Figure 2.2: Simplicity vs. computational cost

2.3.1 Rigid Body Dynamics

The first macro system mentioned was the manoeuvrability, as the aim is to study the vessel's motion as a rigid body with six degrees of freedom (surge, sway, heave, roll, pitch, and yaw). In order to study the vessel dynamics, some simplifications need to be introduced: the ship is considered to be a rigid body; a constant displacement is assumed, so it is possible to apply the Newton-Euler formulation as follows:

$$(M_{RB} + M_A)\,\dot{\nu} = C_{RB}(\nu)\nu + D_L\nu + D_{NL}(\nu)\nu + G(\eta)\eta + \tau_P + \tau_R$$

Where:

M_{RB} and M_A are the inertia and added mass matrices, respectively
C_{RB} and G the Coriolis and restoring mass matrices, respectively
D_L and D_{NL} are the linear damping and non linear damping matrices, respectively
τ_P and τ_R are the propeller and rudder forces and moments vectors, respectively
$\dot{\nu}$ is the acceleration vector
ν is the velocity vector
η is the position vector

All the elements that appear in the motion equation are explained in detail in Chapter 4.

The crucial task has been to evaluate the right side of the equation. In particular, the hydrodynamic forces are the most difficult to evaluate with a standardized methodology valid for each vessel type.

The rigid body differential equation has been developed in matrix form and gives information about the ship acceleration, velocities (both linear and rotational), and ship position in terms of trajectory and attitude angle.

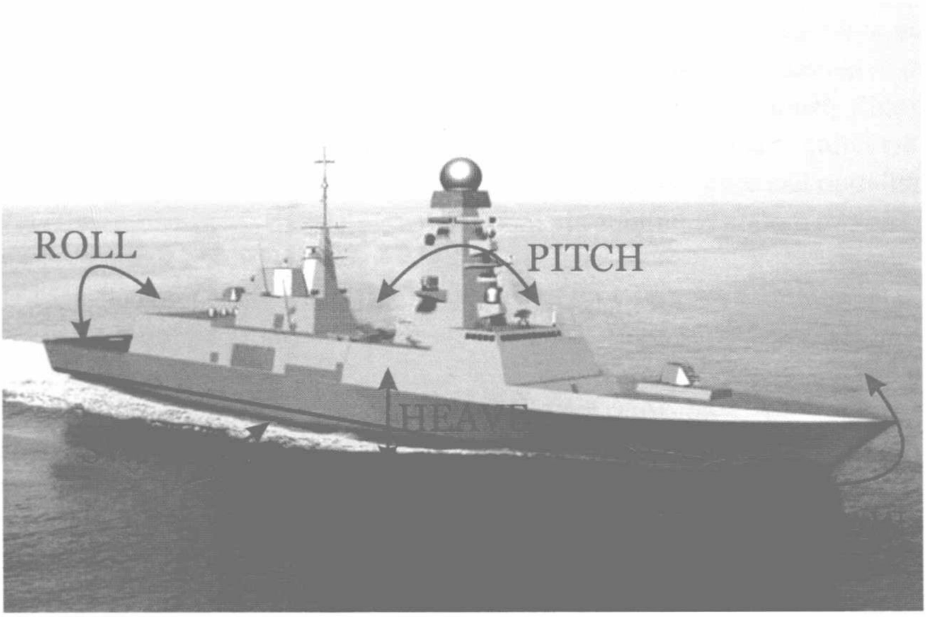

Figure 2.3: Six degrees of freedom

2.3.2 Propulsion plant dynamics

The propulsion plant is the second macro system studied, and its contribution to the global ship behaviour is considerable.

It produces the required thrust, with the highest efficiency possible, to overtake hydrodynamic drag. The propulsion plant has been decomposed into the following main elements: main engines and their governors, the gearbox, the thrust and other bearings, the shaft line, and the two controllable pitch propellers.

A large number of variables are required to represent the propulsion plant dynamics, including ship speed, rpm, propeller pitch angle, and fuel supply. In a modern propulsion plant, all these variables are managed by the propulsion control system.

It is hypothesized that the propulsion plant dynamics are mainly affected by the engines dynamic and the transmission lines dynamic; thus, both have been taken into account.

The main engines (i.e. gas turbine, electric motor, and diesel engine) dynamics can be charged to their thermodynamic characteristic and to the electronic control effects.

The main engine modelling and the main assumptions employed are reported in Chapter 3.

The transmission line studied in this work has two degree of freedom: the shaft line revolution regime and the propeller pitch angle. With respect to traditional transmission lines, this gives a greater operational flexibility.

The dynamics of the propeller pitch is governed by the load acting on the propeller blade and by the dynamics of the pitch actuating mechanism. For the last mechanism, a detailed mathematical model has been developed to include both the blade hydraulic piston motion equation and the dynamic pressure change inside the piston actuating chamber. To evaluate the loads acting on the propeller blade, a rigorous formulation has been developed.

The two motion equations are reported herein.

$$\ddot{\varphi}(t) = \frac{1}{I_b}\left(Q_{hyd}(t) + Q_S(t) + Q_{-\Phi}(t)\right)$$

Where:

$\ddot{\varphi}$ is the blade angular acceleration

$Q_{-\Phi}$ is the torque due to the interaction forces between propeller blade and blade bearing

Q_{hyd} is the hydraulic torque

Q_s is the total spindle torque acting on the blade

I_b is the moment of inertia of the blade about the spindle axis $\underline{f}_3$

$$m_m \ddot{x}_{pist}(t) = A_1 p_1(t) - A_2 p_2(t) - B_p \dot{x}_{pist}(t) + \sum_{i=1}^{Z} \Phi_i(t)$$

Where:

m_m is the total mechanism mass

$\ddot{x}_{pist}$ is the piston acceleration

A_1 and A_2 are the yoke areas of the astern chamber and of the ahead chamber, respectively

p_1 and p_2 are the pressures inside the two chambers

B_p is the damping coefficient

$\sum_{i=1}^{Z} \Phi_i$ are the interaction forces between each blade and the bearing

Z is the blade number

To evaluate the inside pressure, the mechanism is proposed in the following formula:

$$\dot{p}_{oil}(t) = \left(q_i(t) - C_{ip} p_{oil}(t) - A\dot{x}_{pist}(t)\right) \frac{B}{V(t)}$$

Where:

p_{oil} is the pressure

q_i is the volumetric flow in

C_{ip} represents the leakage coefficient

Agg is the piston area

Bgg is the oil Bulk modulus

$V(t)$ is the chamber volume

A detailed explanation of the propeller load and the propeller pitch actuating mechanism behaviour is reported in Chapter 6.

The second degree of freedom of the system is the shaft line rotational regime.

The shaft line has been modelled using the Lagrangian equation, which provides the rotational propeller speed ω.

$$I_s \dot{\omega}_s(t) = Q_{eng}(t) - Q_{fric}(t) - Q_P(t)$$

Where:

I_s is the transmission line polar inertia

$\dot{\omega}_s$ is the shaft line acceleration

Q_{eng} is the engine torque

Q_p is the required propeller torque

Q_{fric} is torque due to friction

The shaft lines equation is a scalar equation, and, once solved, gives information about the acceleration and revolution regimes of the shaft lines. It is also possible to know the instantaneous position of the propeller blade. For a comprehensive description of the shaft line model and behaviour, see Paragraph 3.2.

In the case of a twin-propelled ship, the two shaft lines are considered independently; thus, two equations should be implemented, one for each shaft line.

This becomes necessary because, during ship manoeuvring, an asymmetrical propeller behaviour is experienced. In this implementation, the system is being represented in a more realistic way.

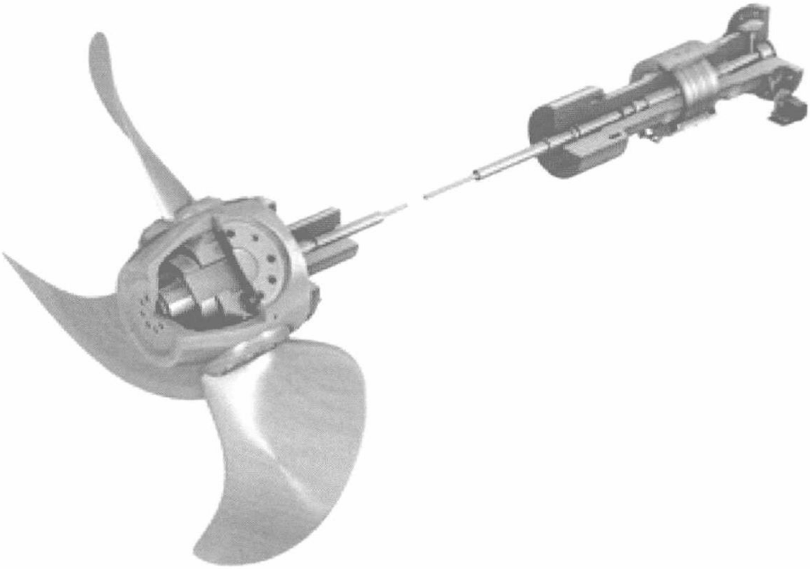

Figure 2.4: Shaft line overview

2.3.3 Control system

All modern ships have installed electronic controllers in order to assist the crew in handling the ship safely and efficiently.

A modern control system is a fully integrated system (ship supervisor) covering many aspects of the ship operation that include the propulsion plant operation, power management operation on the auxiliary engines, auxiliary machinery operation, cargo on-and-off-loading operation, navigation, and administration of maintenance and purchasing of spare parts.

Within the large group that composes the ship supervisor, in this thesis, only the propulsion control system has been studied and designed.

The aim of the propulsion control system is to '*translate*' the operator will into a suitable machinery signal (setpoint) respecting all constraints (torque max, rpm max, fuel consumption and so on) for all navigation modes.

Most of the parameters are controlled by a P.I.D. algorithm; the command signal (output) is obtained by comparing operator requests with the data from the various models, giving the propulsion plant a well-defined dynamic.

An example of P.I.D. algorithm is shown below:

$$u(t) = K_P e(t) + K_I \int_0^t e(t)\,dt + K_D \frac{d}{dt} e(t)$$

Where:

$u(t)$ is the setpoint
$e(t)$ is the error between the reference and the actual value
K_P is proportional gain
K_I is integral gain
K_D is derivative gain

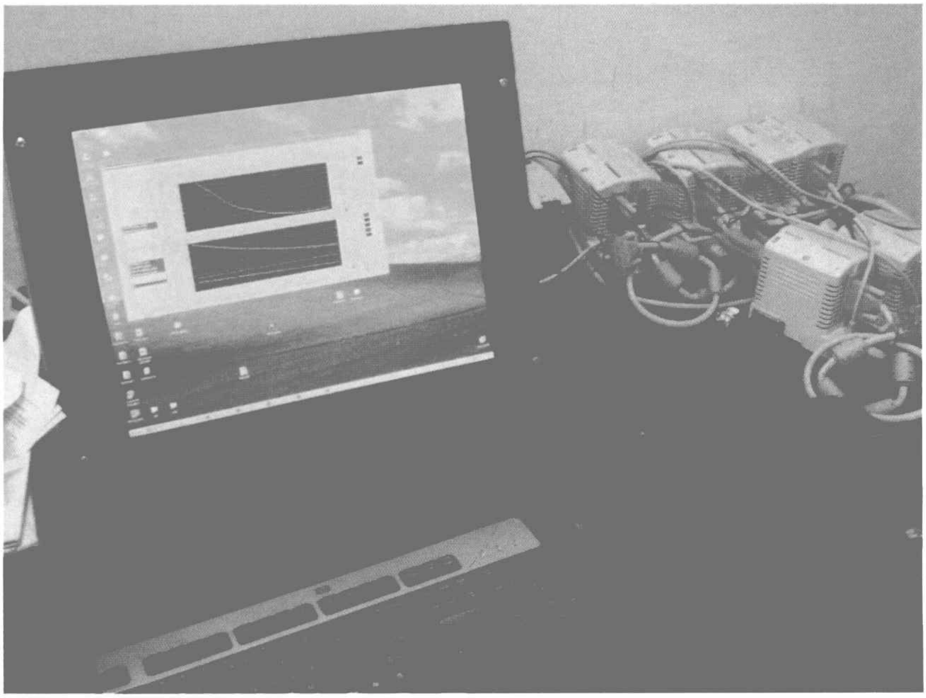

Figure 2.5: Example of propulsion controllers

A combination of P.I.D. algorithms are used, for instance, to generate the setpoint for the two propulsion degrees of freedom (shaft line revolution regime and propeller pitch angle).

The control system dynamics is not only supported by the P.I.D. algorithm; it is also influenced by a set of logics, thresholds, Boolean state, and truth table. For example, two innovative logics for emergency manouevring have been developed: *Slam Start* and *Crash Stop*.

The combination of all these elements produces the propulsion control system dynamics.

For the complete description of the ship propulsion control system, see Chapter 4.

2.4 System of Systems

The peculiarity of this work, as previously announced, is a system engineering approach to bring together all disciplines involved to represent a unified view of the system. This creates the need to implement many differential equations. From a mathematical point of view, the problem can be summarised by solving the following second order differential equations system (only the main equations are reported):

$$\begin{cases} (M_{RB}+M_A)\,\dot{\nu} = C_{RB}(\nu)\nu + D_L\nu + D_{NL}(\nu)\nu + G(\eta)\eta + \tau_P + \tau_R \\ \ddot{\varphi}(t) = \dfrac{1}{I_b}\left(Q_{hyd}(t) + Q_S(t) + Q_{-\Phi}(t)\right) \\ m_m\ddot{x}_{pist}(t) = A_1p_1(t) - A_2p_2(t) - B_p\dot{x}_{pist}(t) + \sum\limits_{i=1}^{Z}\Phi_i(t) \\ \dot{p}_{oil}\,(t) = \left(q_i(t) - C_{ip}p_{oil}(t) - A\dot{x}_{pist}(t)\right)\dfrac{B}{V(t)} \\ I_s\cdot\dot{\omega}_S\,(t) \;=\; Q_{eng}\,(t) - Q_{fric}\,(t) - Q_P(t) \\ u_i\,(t) = K_P\cdot e(t) + K_I\cdot\int e\,(t)\,dt + K_D\cdot\dfrac{d}{dt}e(t) \end{cases}$$

Solving this system is difficult and time consuming due to the large number of variables involved. This system was developed into a software environment able to solve it in the time domain. Thanks to modern computational power, this system can be solved an infinite number of times in order to predict the ship dynamics with different initial and boundary conditions.

Another no less important *'system'* included to the simulation platform is the human factor; this kind of *'system'* cannot be mathematically expressed. Incorporating the human interaction into the simulation loop is essential to have more realistic predictions about the ship dynamic behaviour under real conditions.

In Fig. 2.6 the connection between all simulation platform macro systems and elements are shown. On top, the human figure that handles the system is addressed. The control system *'translates'* and processes the input into a working point for the machinery. The propulsion plant allows the system to achieve the human request.

In order to better understand the figure, each sub-system is represented by black circles and the straight lines represent mutual interactions.