ROLL MODEL FOR CONTROL OF A FAST FERRY

Joaquín Aranda, José Manuel Díaz, Rocío Muñoz
Dpto. Informática y Automática. UNED. Madrid. Spain

ABSTRACT

An analysis of the rolling dynamic of a fast ferry has been carried out. The analysis consist of the identification of a continuous linear model. Data are provided from the simulation program PRECAL. Two methods has been used for the identification: genetic algorithms for a first optimization and a non linear least square algorithm with constraints applied in the frequency domain. Bode plots are computed, graphed and compared with the experimental data.

KEYWORDS

Measurement, stability, actuators, block diagram, constraints, dynamic behaviour, frequency measurements, frequency response, least squares method.

INTRODUCTION

One of the objectives in the design and build of high speed crafts is passenger comfort and vehicle safety. Vertical accelerations associated with roll, pitch and heave motions are the cause of motion sickness.

Previous researches of the work group have studied heaving and pitching motion ([1]) and modeled actuators and designed control methods, like PID ([2]), robust or QFT control ([3]), in order to achieve heave and pitch damping and with satisfactory results.

Now it is necessary to obtain a roll model, and the control of the roll movement together with pitch and heave control.

A scaled physical model (1:25) is used to experiment in the towing tank in CEHIPAR (Madrid, Spain). Test with diverse types of waves, ship speeds and heading wave has been made to analyze the dynamic of the fast ferry. Also CEHIPAR has a program simulation PRECAL, which reproduces a specified conditions and uses a geometrical model of the craft to predict its dynamic behavior.

This research correspond to an analysis of rolling motion for a further control design. The first step in this study is building a mathematical model of the dynamical system.

Models can be obtained by different techniques and methods. There are many publications related to the ships modelling ([4], [5]).

In this work modelling is obtained from system identification method. The research tries to identify a continuous linear model of rolling motion. In addition, model of wave to roll moment and roll moment to roll are identified.

Further researches are directed to control design of roll damping, actuators modelling, and analysis of motion coupling in more than one degree of freedom.

IDENTIFICATION METHODOLOGY

In this paper the employed method follows the scheme of classical system identification ([6], [8]), used for the pitch and heave movement in previous works.

Data used for the identification are provided from the PRECAL simulation program ([9]). Experimental simulations are made with various types of waves and ship speed. Research is restricted to rolling motion, regular waves with frequencies between 0.393 and 1.147 rad/s, 90 degrees of wave heading, and 20, 30 and 40 knots ship speed.

System is excited by the wave and total exciting moment and roll motion are the responses. Measurements in frequency domain are given. Thus, generated data result in moment amplitude [KNm/m] and phase [deg], and roll amplitude [deg/m] and phase [deg] for each type of wave, and therefore for a specific encounter frequency.

A frequency analysis is made for obtaining a transfer function model. The scheme in block diagrams is as follows

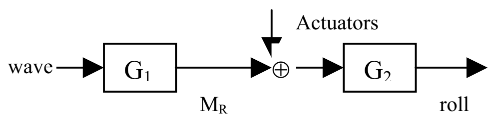


Figure 1. Block diagram of the system

This block diagram is equivalent to

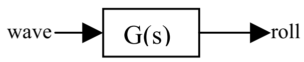


Figure 2. Equivalent blocks diagram of the system

It follows that

$$G(s)=G_1(s)\cdot G_2(s) \qquad (1)$$

Several transfer functions has been modeled. Firstly, transfer function G(s) from wave to roll is identified. Secondly, transfer function $G_1(s)$ from wave to roll moment is identified. Finally the transfer function $G_2(s)$ from roll moment to roll is estimated by considering equation (1).

Determining transfer function

Magnitude and phase data of roll moment and roll motion are graphed in Bode plots for each encounter frequency ω_{ei} and for each speed. These points are used to determine the transfer function so that the Bode diagram fits these experimental data. These data can be expressed as

$$\begin{aligned} G(j\omega_{ei}) &= \mathrm{Re}(G(j\omega_{ei})) + j\cdot\mathrm{Im}(G(j\omega_{ei})) \\ G_1(j\omega_{ei}) &= \mathrm{Re}(G_1(j\omega_{ei})) + j\cdot\mathrm{Im}(G_1(j\omega_{ei})) \end{aligned} \qquad (2)$$

ω_{ei} is the encounter frequency whose expression is

$$\omega_e = \omega_0 - \frac{\omega_0^2}{g} U\cdot\cos\beta \qquad (3)$$

where ω_0 is the wave frequency (rad/s), g the gravity acceleration (m/s^2), U the speed of ship (m/s) and β the angle between heading and wave direction (rad).
Data necessary to identify G_2 are calculated from the simulation data by using expresion (1) in frequency domain.

General expression of the estimated transfer function can be written in the following form

$$\hat{G}(s) = \frac{x_{n+m+1}s^{m} + x_{n+m}s^{m-1} + \ldots.. + x_{n+2} + x_{n+1}}{\left[s^2 + 2sx_1 + \left(x_1^2 + x_2^2\right)\right]\cdots\left[s^2 + 2sx_{npc-1} + .. + \left(x_{npc-1}^2 + x_{npc}^2\right)\right]\left(s + x_{npc+1}\right)\cdots\left(s + x_{npc+nps}\right)} \quad (4)$$

For the criterion of fit, a parameter vector **P** is defined

$$\mathbf{P} = (x_1,.., x_{npc}, x_{npc+1},.., x_{npc+nps}, x_{n+1},.., x_{n+m+1}) \quad (5)$$

P is determined so that it minimises a cost function J, whose expression is

$$\begin{aligned} J(\mathbf{P}) &= J_{real}(\mathbf{P}) + j \cdot J_{imag}(\mathbf{P}) \\ J_{real}(\mathbf{P}) &= \sum_{i=1}^{N}\left[\mathrm{Re}\left(G(j\omega_{ei})\right) - \mathrm{Re}\left(\hat{G}(j\omega_{ei}, \mathbf{P})\right)\right]^2 \quad (6) \\ J_{imag}(\mathbf{P}) &= \sum_{i=1}^{N}\left[\mathrm{Im}\left(G(j\omega_{ei})\right) - \mathrm{Im}\left(\hat{G}(j\omega_{ei}, \mathbf{P})\right)\right]^2 \end{aligned}$$

Two methods are used to carry out the fit: a non linear least squares with constraints method and genetic algorithms for optimisation ([7]).

System stability is a restriction to be considered in the fitness. In addition, a priori basic knowledge of ship dynamic states that amplitude of G must tend to zero at low encounter frequencies.

To beginning with the identification, a set of candidate models must be selected. Thus, number of poles and zeros are going to be defined. Several structures are tried, and finally the model with the least value of the cost function J is selected as the best model.

Identifying wave to roll transfer function. The global transfer function from wave to roll motion is known as G(s). In this case only is necessary the non linear least squares method to carry out the fit.

Identifying wave to roll moment transfer function. Then, the first block $G_1(s)$ in figure 1 is identified. Firstly an optimisation by genetic algorithms is used to find a vector **P** close to the global optima. Then, non linear least squares method is applied by using the genetic algorithm solution as initial values.

Identifying roll moment to roll transfer function. Finally, block G_2 in figure 1 is identified. Non linear least squares is the method used . Stability is the only restraint to be considered.

Methodology followed in this case is different. The idea is a new identification of Ĝ(s) by forcing Ĝ(s) to have the same poles and zeros as $\hat{G}_1(s)$.

Thus, $\hat{G}_2(s)$ will be determined so that the resultant product transfer function $\hat{G}_1(s)\cdot\hat{G}_2(s)$ were a good model of the global transfer function Ĝ(s) from wave to roll. Now the cost function is

$$J_1(\mathbf{P}) = J_{real1}(\mathbf{P}) + j\cdot J_{imag1}(\mathbf{P})$$

$$J_{real1}(\mathbf{P}) = \sum_{i=1}^{N}\left[\mathrm{Re}(G(j\omega_{ei}) - \mathrm{Re}(\hat{G}_{12}(j\omega_{ei},\mathbf{P}))\right]^2 \quad (7)$$

$$J_{imag1}(\mathbf{P}) = \sum_{i=1}^{N}\left[\mathrm{Im}(G(j\omega_{ei}) - \mathrm{Im}(\hat{G}_{12}(j\omega_{ei},\mathbf{P}))\right]^2$$

where

$$\hat{G}_{12}(j\omega,\mathbf{P}) = G_1(j\omega)\cdot\hat{G}_2(j\omega,\mathbf{P}) \quad (8)$$

RESULTS

Wave to roll motion model Ĝ(s)

Representation of the experimental points in Bode plots demonstrates that frequency response at different ship speed are very similar. Therefore, only one model is required.

Table 1 shows different considered model structures (m,n,nps), and the value of the cost function *J* for speed 20, 30 and 40 knots. *m* is the number of zeros, *n* is the total number of poles, and *nps* is the number of simple poles.

Table 1. Cost function *J* for different structures and 20, 30 and 40 knots

(m,n,nps)	J 20 knots	J 30 knots	J 40 knots
(4,5,1)	2.46	30.27	180.53
(6,7,3)	1.15	28.74	174.30
(7,8,2)	0.47	44.46	224.84
(6,9,5)	0.45	44.44	224.52

The parameter vector **P** and transfer function are determined for each model structure. These all models give very similar Bode plots in the frequency range of interest, so this is a proof that these must reflect features of the true system. Structure with minimum *J* is selected as the best model.

Finally, structure (6,9,5) is selected, and the estimated transfer function is given by equation (9).

$$\hat{G}(s) = \frac{785.8s^6 - 339.5s^5 + 369.3s^4 - 3011s^3 - 1587s^2 - 527.s}{s^9 + 25.13s^8 + 134.2s^7 + 450.4s^6 + 1157s^5 + +1810s^4 + 1976s^3 + 1682s^2 + 900s + 198.7} \quad (9)$$

Figure 3 presents the Bode plots of the estimated transfer function and the simulation true data.

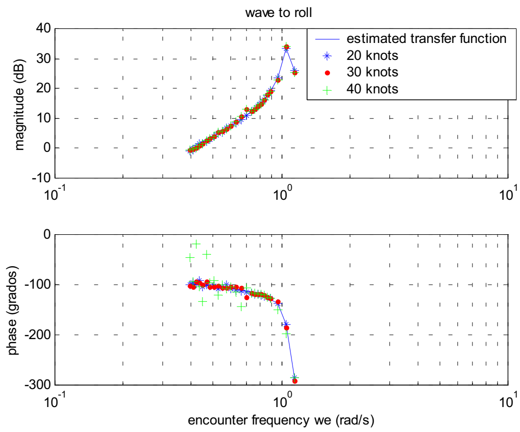


Figure 3.Bode plot of Ĝ(s) and experimental data

Wave to roll moment transfer function $\hat{G}_1(s)$

Firstly, genetic algorithms method is applied in order to find and optimal initial values. Then, least square method is used to achieve an accurate fitness.

Table 2 shows different model structures (m,n,nps), and the value of the cost function *J* for each speed.

Table 2. Cost function *J* for different structures and 20, 30 and 40 knots

(m,n,nps)	J 20 knots	J 30 knots	J 40 knots
(2,2,2)	$7.30 \cdot 10^6$	$8.44 \cdot 10^6$	$9.11 \cdot 10^6$
(3,3,1)	$2.04 \cdot 10^5$	$1.14 \cdot 10^6$	$2.01 \cdot 10^6$

Structure with minimum J is selected as the best model.The chosen model is (3,3,1). The estimated transfer function is given by equation (10).

$$\frac{-5397s^3 - 970s^2 - 448.3s}{s^3 + 1.044s^2 + 0.4261s + 0.002104} \quad (10)$$

Figure 4 presents the Bode plots of the estimated transfer function and the simulated true data. It is shown that the determined transfer function agrees data quite good.

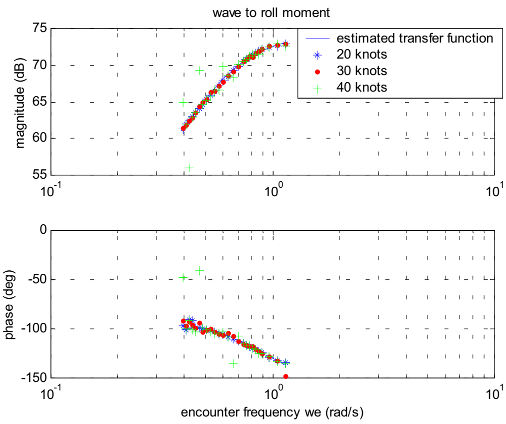


Figure 4. Bode plot of $\hat{G}_1(s)$ and experimental data.

Roll moment to roll transfer function $\hat{G}_2(s)$

Non linear least square method is used. Table 3 presents several structures for the roll moment to roll transfer function $\hat{G}_2(s)$ and the value of cost function J_1. Structure with the minimum J_1 is chosen as the best model.

In this case, structure (3,3,1) is the final selected model for $\hat{G}_2$. The estimated transfer function is given by equation (11) and figure 5 represents the Bode plot with the simulation true data.

Table 3. Cost function J_1 for different structures and 20, 30 and 40 knots

(m,n,nps)	J 20knots	J 30knots	J 40knots
(3,3,1)	0.368039	0.375501	0.38511
(3,4,2)	0.369947	0.369045	0.38441

$$\frac{-3.4\cdot10^{-4}s^{3}-1.1\cdot10^{-4}s^{2}+7.3\cdot10^{-4}s^{1}+2.32\cdot10^{-3}}{s^{3}+3.253s^{2}+1.329s+3.646} \quad (11)$$

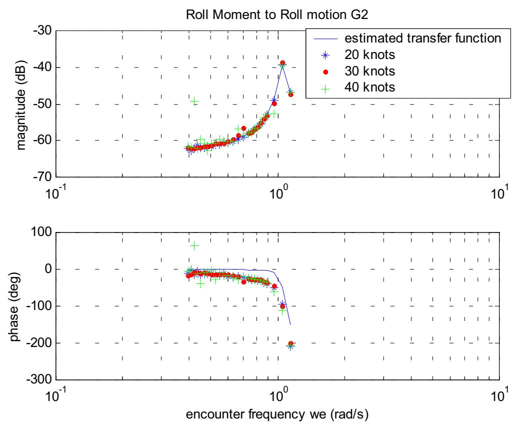


Figure 5. Bode plot of $\hat{G}_2(s)$ and experimental data

Once transfer function $\hat{G}_2$ is determined, Bode plot of the product $\hat{G}_1\cdot\hat{G}_2$ is graphed and compared to the experimental data. It is shown that the fitness is quite good. Figure 6 presents this Bode diagram.

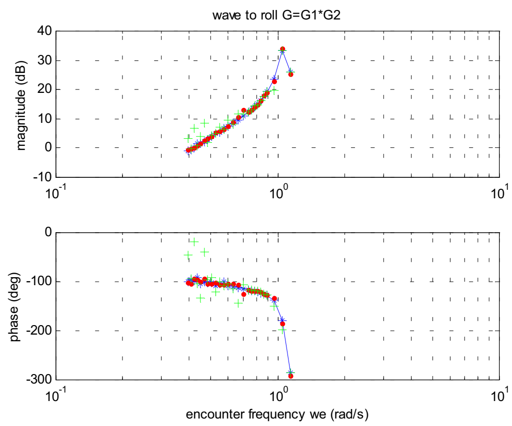


Figure 6. Bode of $\hat{G}_1(s)\cdot\hat{G}_2(s)$ and experimental data

CONCLUSIONS

In this research an analysis of the roll motion of a fast ferry has been carried out. The interest has been restricted to 90 degrees wave heading.

The analysis has been consisted of the identification of a continuous linear model of the system. Measured data with PRECAL simulation program are given. Roll moment and roll responses in the frequency domain are the resultant data. Several model structures and orders have been defined.

Genetic algorithms and non linear least squares with constraints methods applied in the frequency domain has been used as a criterion of fit to compute the best model.

Obtained model's properties are examined. Bode plots are computed, graphed and compared with experimental data. It is seen that estimated model describes data information. Models which best agree with the experimental data are selected.

Firstly, global model $\hat{G}(s)$ of roll motion is identified. Then, two transfer functions, from wave to roll moment ($\hat{G}_1(s)$) and from roll moment to roll ($\hat{G}_2(s)$) are identified. It is demonstrated that the product of $\hat{G}_1(s)\cdot\hat{G}_2(s)$ is capable of describing the global system.

REFERENCES

[1] CRUZ, J.M DE LA, J. ARANDA, B. DE ANDRÉS, P. RUIPÉREZ, J.M. DÍAZ, A. MARÓN. Identification of the vertical plane Motion Model of a High Speed craft by Model Testing in Irregular waves. *CAMS Proceeding Volume*. (K.Kijima, TI. Fossen) Pergamon Press. 257-262.

[2] ARANDA, J., J.M. DÍAZ, P. RUIPÉREZ, T.M. RUEDA, E. LÓPEZ. Decreasing of the motion sickness incidence by a multivariable classic control for a high speed ferry. *CAMS ProceedingVolume*. Pergamon Press.

[3] ARANDA, J., J.M DE LA CRUZ, J.M. DÍAZ, S. DORMIDO CANTO .QFT versus classical gain scheduling: study for a fast ferry. *15th IFAC World Congress b'02.*

[4] FOSSEN, T.I. *Guidance and Control of Ocena Vehicles*. John Wiley & sons. 1994

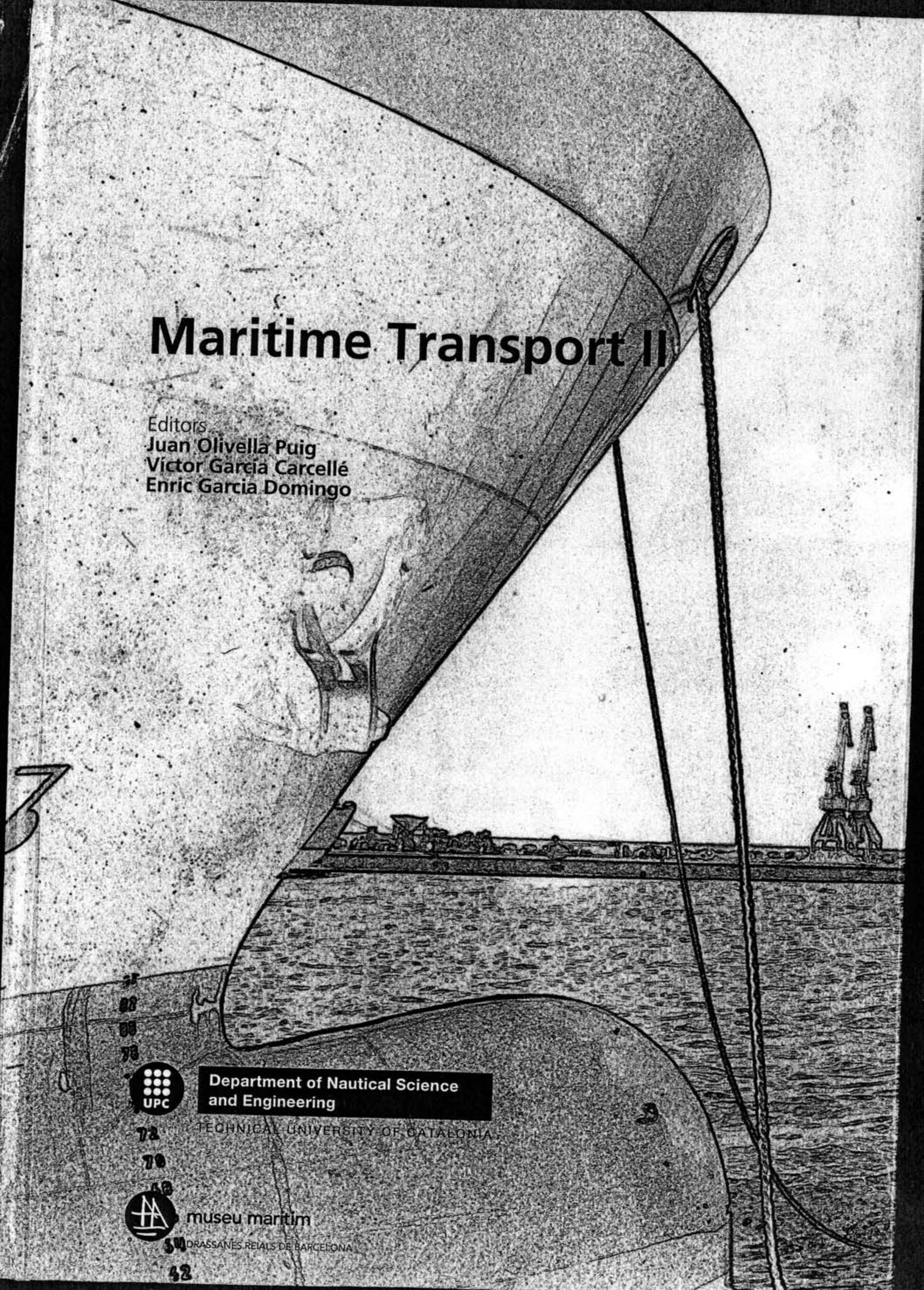
[5] LEWIS, E.V., *Principles of Naval Architecture*. Volume III. Society of Naval Architects and Marine Engineers.1989

[6] LJUNG, L., *System Identification: Theory for the User*. Prentice Hall. 1989

[7] MICHALEWICZ, Z. *Genetic Algorithms + Data Structure= Evolution Programs.*Third, revised and extender Edition. Springer. 1999

[8] SÖDERSTRÖM, T. AND P. STOICA *System Identification*. Prentice Hall. 1989

[9] BAZÁN. NATIONAL COMPANY . *Sea behaviour tests of the Turbo Ferry TF-120*. OTI-2086-CM-1. 1995



Maritime Transport II

Editors
Juan Olivella Puig
Víctor Garcia Carcellé
Enric Garcia Domingo

UPC
Department of Nautical Science and Engineering
TECHNICAL UNIVERSITY OF CATALONIA

museu marítim
DRASSANES REIALS DE BARCELONA

Second International Conference on Maritime Transport and Maritime History

MARITIME TRANSPORT 2003

With the support of:

Sponsored by:

INSTITUTO DE NAVEGACIÓN DE ESPAÑA

Amb el suport del Departament d'Universitats, Recerca i Societat de la Informació de la Generalitat de Catalunya

SCI UPC, 2003 (7049)

Legal deposition: B - 45323 - 2003
ISBN: 84 - 7653 - 839 - 1
Printed to Barcelona Digital S.L.