COMPARISON OF THE VERTICAL DYNAMIC MODELS OF A FAST FERRY WITH ACTUATORS AND WITHOUT ACTUATORS

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Abstract

An analysis of the vertical dynamic model of a fast ferry with actuators has been carried out. The research corresponds to heaving and pitching motions. The analysis consist of the identification of a continuous lineal model with actuators and a comparison with a model without actuators. Experimental data are provided from tests made with a replica of the ferry in regular waves, heading see and 40 knots. Height wave, heave motion and pitch motion in different frequencies are the measured data. These data are used to make a frequency analysis and to obtain a transfer function model. A non-linear least square algorithm with constrained applied in the frequency domain has been used. Low frequency constrained for heave and pith was considered. Bode plots are graphed, and zeros and poles of the estimated transfer function are calculated and compared with the estimated model without actuators. It is shown how the vertical dynamic of the fast ferry changes.

Introduction

One of the objectives in the design and built of high speed crafts is the passenger comfort and the safety of the vehicle. Vertical accelerations associated with roll, pitch and heave motions are the cause of motion sickness. Roll damping is easily to obtain. In order to reduce heaving and pitching motion, anti-pitching devices and pitch control methods must be considered.

The first step in this study is building mathematical models of the dynamical system.

Models can be obtained by different techniques and methods. There are many publications related to the ships modelling (1), (2). There a theoretical study has been carried out, and non linear models in six degrees of freedom are obtained from the equations of the rigid body partially immersed in water.

Obtaining a very accurate mathematical model is very complicated and costly. In addition, it often increases the complexity of the control algorithm.

In this work modelling is obtained from system identification method. (3). This method does not need a previous knowledge of the system structure and it is based on observed system data. A scaled physical model is used, and several test are made in the towing tank of the CEHIPAR (Madrid, Spain) (8) with different types of waves. Actuators are the antipitching devices. Actuators are two active control surfaces, one T-foil in bow, and two flaps in stern.

This research tries to identify a continuous linear model of the vertical dynamic of the fast ferry with actuators at rest. Once this final model is obtained, this dynamic is compared with the vertical dynamic model of the fast ferry without actuators, that it was estimated from a set of simulated data generated by the PRECAL program, which reproduces the same conditions fo the experiments and uses an geometrical model of the ship to predict its dynamic behaviour(5)

Identification Methodology

Input-Output data

In this paper the employed method follows the scheme of classical systems identification (3) (4).

A scaled replica (1:25) is used to experiment in the towing tank in CEHIPAR (Madrid, Spain) (8). Tests are restricted to heaving and pitching motions, heading sea and 40 knots speed. Actuators are positioned at rest point.

Experiments are made with various types of waves. Waves can be regular or irregular, and they are characterized by a certain amplitude and frequency. Regular waves with frequencies between 0.57 and 0.89 rad/s are used for the identification of models.

System is excited by the wave (input) and heave and pitch motion are the responses (outputs). Experimental data result in temporal series of wave height (m), heave movement (m) and pitch movement (deg). Each temporal series takes long for 75-85 seconds and the sampling time is 0.05 s, and it corresponds to a type of wave, and therefore to an specific frequency.

Thus, two transfer functions will be identified (see Figure 1)

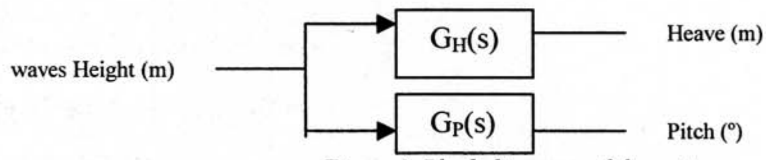

Figure 1. Block diagrams of the system

- $G_H(s)$: transfer function from wave height (m) to heave motion (m).
- $G_P(s)$: transfer function from wave height (m) to pitch motion (deg).

A frequency analysis is made for obtaining a transfer function model. Although the input is a regular wave, it contains various components in frequency.

Therefore, first of all an approximation to sinusoidal series have to be made. The fitted signals can be expressed in the following form

$$u_{wave} = A_{wave} \cdot \cos(\omega_e \cdot t + \varphi_{wave})$$
$$y_{heave} = A_{heave} \cdot \cos(\omega_e \cdot t + \varphi_{heave})$$
$$y_{pitch} = A_{pitch} \cdot \cos(\omega_e \cdot t + \varphi_{pitch})$$

where

A_{wave}, A_{heave}, A_{pitch} : amplitudes of the input u_{wave} (m) and the outputs heave y_{heave} (m) and pitch y_{pitch} (°).
φ_{wave} , φ_{heave}, φ_{pitch} are the phases of wave height, heave and pitch respectively.
t: time,
ω_e is the encounter frequency, whose expression is

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

where

ω_0 : wave frequency (rad/s)
g : acceleration of gravity (m/s^2)
U: total speed of ship (m/s)
β: the angle between the heading and the direction of the wave (rad).
In this particular case, U=40 knots and β = 180 °.

Identification procedure

Once the temporal signals of the input and the two outputs are approximated, frequency response functions for heave and pitch can be determined.

Expressions of the gain and phase of these frequency functions are the following

$$G_H(j\omega_{ei}) = \frac{A_{heave}(j\omega_{ei})}{A_{wave}(j\omega_{iei})}$$
$$\arg(G_H(j\omega_{ei})) = \varphi_{heave}(j\omega_{ei}) - \varphi_{wave}(j\omega_{ei})$$

$$G_P(j\omega_{ei}) = \frac{A_{pitch}(j\omega_{ei})}{A_{wave}(j\omega_{ei})}$$
$$\arg(G_P(j\omega_{ei})) = \varphi_{pitch}(j\omega_{ei}) - \varphi_{wave}(j\omega_{ei})$$

Thus, magnitude and phase of heave and pitch are calculated and graphed in Bode plots for each encounter frequency ω_{ei}. These point are used to determine the transfer function of heave and pitch responses so that their Bode diagram fits these experimental data, that can be expressed as,

$$G_H(j\omega_{ei}) = \mathrm{Re}(G_H(j\omega_{ei})) + j\cdot\mathrm{Im}(G_H(j\omega_{ei}))$$
$$G_P(j\omega_{ei}) = \mathrm{Re}(G_P(j\omega_{ei})) + j\cdot\mathrm{Im}(G_P(j\omega_{ei}))$$

A non linear least squares with constraints method is used to carry out the fit.

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

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

where
m: the number of zeros,
n: the total number of poles,
npc: the number of conjugated complex poles
nps: the number of singles poles.

For the criterion of fit, a parameter vector P is defined
$P = (x_1, x_2, x_3, .., x_{npc-1}, x_{npc}, x_{npc+1}. \ldots\ldots, x_{npc+nps})$

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

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

A priori basic knowledge of ships dynamic shows two constraints to be considered in the identification

1. Gain of $G_H(s)$ must tend to zero al low frequencies of encounter.
2. Gain of $G_P(s)$ must tend to one al low frequencies of encounter.

In addition, models must to be stables.

Defining model structure

First step in the identification is to select a set of candidate models, that is, the model structure. In this case, number of poles and zeros are going to be defined. An approximated figure can be given by the continuous linear model without actuators. In general the dynamic of the actuators adds one pole and one zero.

Several structures are tried, and finally the best model is selected after validation.

Initial values

Initial values for the parameters vector P have to be given to the optimization algorithm. Two different type are used, random numbers and fixed numbers.

Random values are found between a certain range. Upper limit is 15 and lower limit is 0. Fixed values are given by the model of the ship dynamic process plus actuators dynamic (6) obtained by SIMULINK. In this case, number of poles and zeros will be fixed obviously.

Models Validation

Once the best model for each model structure is determined, a validation to select a particular model in the set must to be made. The criterion of the validation is based on the information on the data, and shows how well the model fits the data. Bode plots, zero-pole plots, and model simulation are techniques that displays the model properties in terms of quantities that have more physical meaning than the parameter themselves.

Validation consist of running a simulation with the real input and comparing the simulated outputs $\hat{y}_H(t)$, $\hat{y}_P(t)$ with the actual measured output $y_H(t)$, $y_P(t)$ for the same input. For this, data that was not used to built the model are selected. In this particular case, temporal series measured in irregular waves and see states SSN=4,5,6 are used.

Simulated and true output are graphed and compared. Also, mean quadratic error are calculated

$$e = \frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2$$

where i is the number of measured points.

With this, it is seen if the model is capable of describing the system.

Final model selected is the one that best reflects the properties of the true, unknown system, and gives the least value of e.

Comparing Dynamics Models

A continuous linear model of the dynamic of the fast ferry without actuators was determined (5). Now it is compared with the continuous linear model of the dynamic of the ferry with actuators.

Both frequency functions of the models are computed, and presented as a Bode plot.

Poles and zeros of the models are also computed and graphed.

Models of the ferry with actuators

Tables 1 and 2 shows, for the model with actuators, encounter frequency, and magnitude and phase of the frequency response for heave and pitch respectively. These are calculated from measured true data, in the given wave frequency. Figures 2 and 3 shows the Bode plots.

Table1.Magnitude and phase of the frequency response of HEAVE movement in different frequencies.

	wave 18	wave 19	wave 20	wave 21	wave 22	wave 23	wave 2[illegible]
ω_e (rad/s)	2.5726	2.3101	2.0794	1.8747	1.7190	1.5792	1.2545
magnitude(db)	-35.9134	-34.4850	-20.5209	-12.2539	-6.3607	-3.7050	-0.2539
Phase(°)	-152.6851	-31.2370	33.1615	71.7501	109.7593	134.4226	208.0670

Table2.Magnitude and phase of the frequency response of PITCH movement in differents frequencies

	wave 18	wave 19	wave 20	wave 21	wave 22	wave 23	wave 2[illegible]
ω_e (rad/s)	2.5726	2.3101	2.0794	1.8747	1.7190	1.5792	1.2545
magnitude (db)	-32.6680	-14.7365	-8.2746	-3.2245	0.3622	2.1348	4.8434
Phase(°)	-141.7549	-86.8674	-55.1736	-27.2686	-3.6125	18.2582	88.8603

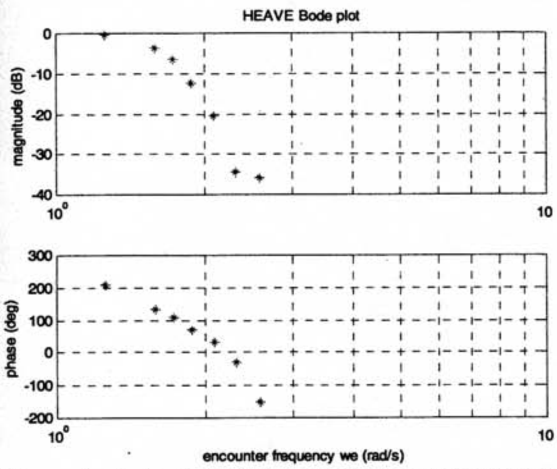

Figure 2. Bode plot of the measured data for HEAVE movement

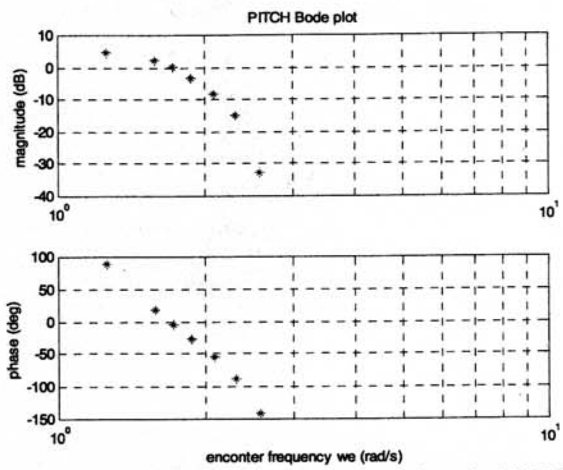

Figure 3. Bode plot of the measured data forPITCH movement

Table 3 shows different defined model structures (m, n, nps) for *heave* movement, and the value of the cost function J and mean quadratic error for see states SSN=4,5,6. *m* is the number of zeros, *n* is the total number of poles, and *nps* is the number of simple poles. Random and fixed initial conditions of the parameters vector P are differentiated.

Table 3. Model structure, cost function J and mean quadratic error e2m for HEAVE motion.

	(m,n,nps)	Cost function J	e (m^2) SSN=4	e (m^2) SSN=5	e (m^2) SSN=6
Random initial values of P	(5,6,0)	$3.38\cdot10^{-3}$	0.0036	0.0288	0.2012
	(5,6,2)	$3.35\cdot10^{-3}$	0.0036	0.0287	0.1994
	(6,7,1)	$3.09\cdot10^{-3}$	0.0058	0.0393	0.1683
	(6,7,3)	$4.01\cdot10^{-3}$	0.0047	0.0336	0.1274
	(6,7,5)	$3.39\cdot10^{-3}$	0.0035	0.0275	0.1977
Fixed initial values of P	(9,11,1)	0.0416	0.0044	0.0314	0.1492

The parameters vector P and transfer function are calculated 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.

In the particular case of (5,6,2), that is, five zeros, six poles and two of them single poles, estimated transfer function is

$$\hat{G}_H(s) = \frac{0.2516s^5 - 0.2094s^4 + 3.497s^3 + 3.961s^2 + 10.77s + 29.8}{s^6 + 6.664s^5 + 22.19s^4 + 48.41s^3 + 66.94s^2 + 63.12s + 29.8}$$

Figure 4 presents the Bode plots of the estimated transfer function and the measured true data.

Figure 5 shows the simulation of $\hat{G}_H$ response $\hat{y}_H(t)$ to real data (irregular wave, SSN=5) and the measured output $y_H(t)$ of the system.

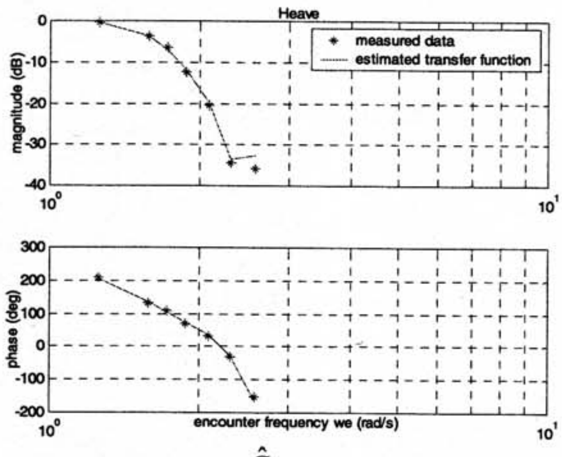

Figure 4. Bode plot of $\hat{G}_H(s)$ and experimental data

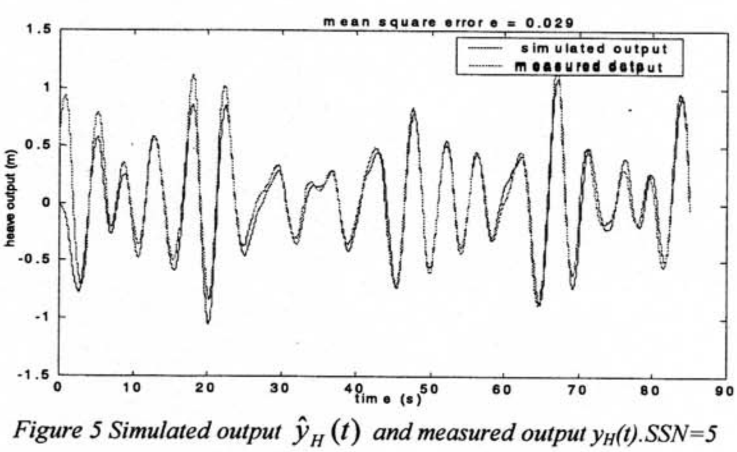

Figure 5 Simulated output $\hat{y}_H(t)$ and measured output $y_H(t)$.SSN=5

Table 4 shows different considered model structures (m, n, nps) for *pitch* movement, and the value of the cost function J and mean quadratic error for see states SSN=4,5,6. *m* is the number of zeros, *n* is the total number of poles, and *nps* is the number of simple poles. Random and fixed initial conditions of the parameters vector P are differentiated.

Table 4. Model structure, cost function J and mean quadratic error e2m for PITCH motion.

	(m,n,nps	Cost funct on J	e(°)^2 SSN=4	e (°)^2 SSN=5	e (°)^2 SSN=6
Random initial values of P	(5,7,1)	$6.49\cdot10^{-3}$	0.0348	0.0946	0.5256
	(5,7,3)	$5.47\cdot10^{-3}$	0.0108	0.0813	0.3384
Fixed initial values of P	(5,8,4)	$9.46\cdot10^{-3}$	0.0094	0.0653	0.3677

The parameters vector P and transfer function are calculated for each model structure. Values of the cost function are very similar. Bode plots of these different structures are graphed. In the same graph are drawn the experimental data. These all models give very similar Bode plots in the frequency range of interest. The estimate of the obtained transfer functions agrees data quite good.

In the particular case of the transfer function $\hat{G}_P(s)$ determined with structure (5,8,4) with known initial values, is the following

$$\hat{G}_P(s) = \frac{43.25s^5 - 201.7s^4 + 301.1s^3 - 1505s^2 - 83.92s}{s^8 + 22.11s^7 + 180.2s^6 + 727.4s^5 + 1707s^4 + 2645s^3 + 2684s^2 + 1589s + 393.8}$$

Figure 6 presents the Bode plots of the estimated transfer function and the measured true data.

Figure 7 shows the simulation of $\hat{G}_P(s)$ response $\hat{y}_P(t)$ to real data (irregular wave, SSN=5) and the measured output $y_P(t)$ of the system.

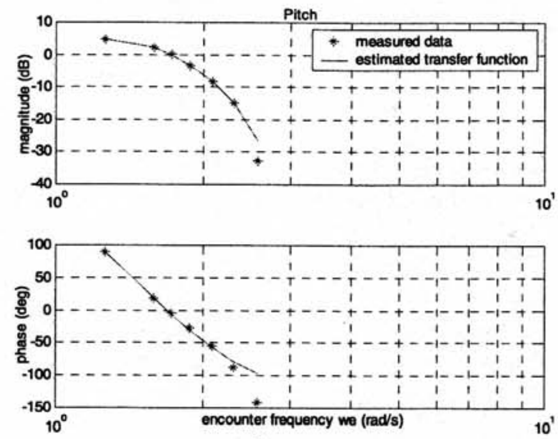

Figure 6 *Bode plot of* $\hat{G}_P(s)$ *and experimental data*

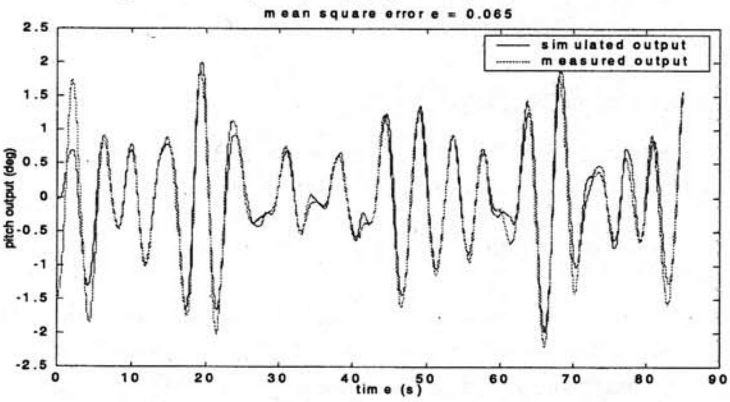

Figure 7 Simulated output $\hat{y}_P(t)$ *and measured output* $y_P(t)$*.SSN=5*

Comparing dynamic with actuators and without actuators

Table 7 shows poles and zeros computed from the estimated model $\hat{G}_H(s)$ for the dynamic of the system with actuators, and poles and zeros of the model of the dynamical system without actuators $\hat{G}_{Hs}(s)$ (5). Also natural frequency ω_n and damping factor δ are computed and presented.

In Figure 8 poles and zeros of both models are graphed.

Table 7. Poles and zeros of HEAVE model with actuators GH(s) and with no actuators GHs(s)

$G_H(s)$ with actuators			$G_{Hs}(s)$ without actuators			$G_H(s)$ with actuators			$G_{Hs}(s)$ without actuators		
Poles	δ	ω_n	Poles	δ	ω_n	Zeros	δ	ω_n	Zeros	δ	ω_n
-2.62	1.00	1.14	-0.23+1.73i	0.67	0.33	1.19+3.28i	-0.34	3.49	-0.87+3.62i	0.23	3.73
-1.01+1.73i	0.28	1.57	-0.23-1.73i	0.67	0.33	1.19-3.28i	-0.34	3.49	-0.87-3.62i	0.23	3.73
-1.01-1.73i	0.28	1.57	-0.45+1.25i	0.34	1.33	0.08 2.38i	-0.03	2.38	0.95+3.24i	-0.28	3.38
-0.44+1.51i	0.50	2.01	-0.45-1.25i	0.34	1.33	0.08-2.38i	-0.03	2.38	0.95-3.24i	-0.28	3.38
-0.44-1.51i	0.50	2.01	-0.22+0.24i	0.13	1.75	-1.71	1.00	1.71	0.20	-1.00	0.20
-1.14	1.00	2.62	-0.22-0.24i	0.13	1.75						

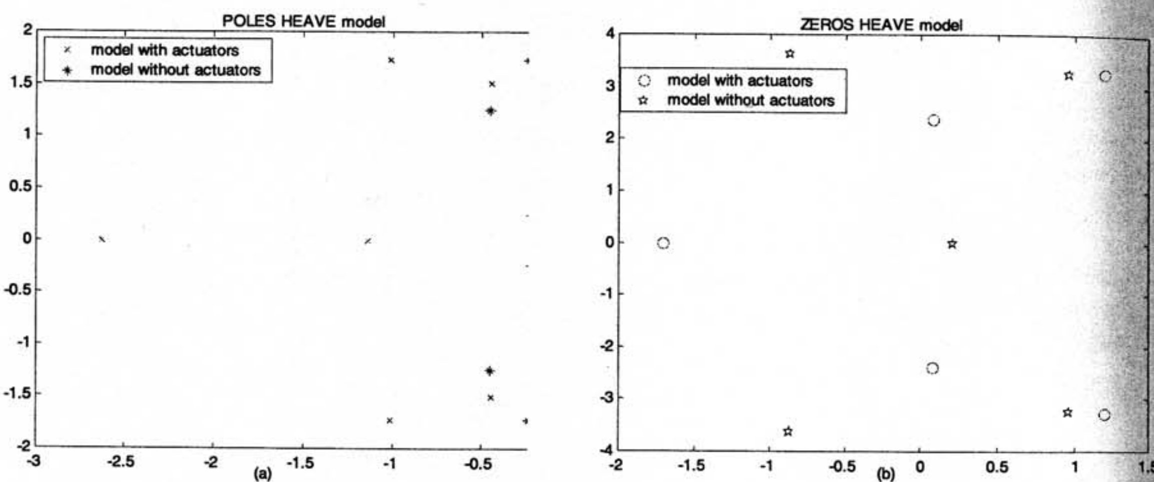

Figure 8. Poles(a) and zeros (b) of HEAVE model with actuators and without actuators

Table 8 shows poles and zeros computed from the estimated model $\hat{G}_P(s)$ for the dynamic of the system with actuators, and poles and zeros of the model of the dynamical system without actuators $\hat{G}_{Ps}(s)$ (5). Also natural frequency ω_n and damping factor δ are computed and presented.

In Figure 9 poles and zeros of both models are graphed.

Table 8. Poles and zeros of PITCH model with actuators $G_p(s)$ and with no actuators $G_{Ps}(s)$

$G_P(s)$ with actuators			$G_{Ps}(s)$ without actuators			$G_P(s)$ with actuators			$G_{Ps}(s)$ without actuators		
Poles	δ	ω_n	Poles	δ	ω_n	Zeros	δ	ω_n	Zeros	δ	ω_n
-9.55	1.00	9.55	-0.59+1.68i	0.33	1.78	0	Inf	0	0	Inf	0
-5.23	1.00	5.23	-0.59-1.68i	0.33	1.78	7.19	-1.00	7.19	-6.75	1.00	6.75
-3.50	1.00	3.50	-0.29+1.59i	0.18	1.61	0.053+2.74i	-0.019	2.74	0.20+3.48i	-0.057	3.48
-0.50+1.45i	0.32	1.54	-0.29-1.59i	0.18	1.61	0.053-2.74i	-0.019	2.74	0.20-3.48i	-0.057	3.48
-0.50-1.45i	0.32	1.54	-0.93+0.03i	0.99	0.93	-0.0415	1.00	0.041			
-1.09+0.22i	0.98	1.11	-0.93-0.03i	0.99	0.93						
-1.09–0.22i	0.98	1.11									
-0.64	1.00	0.64									

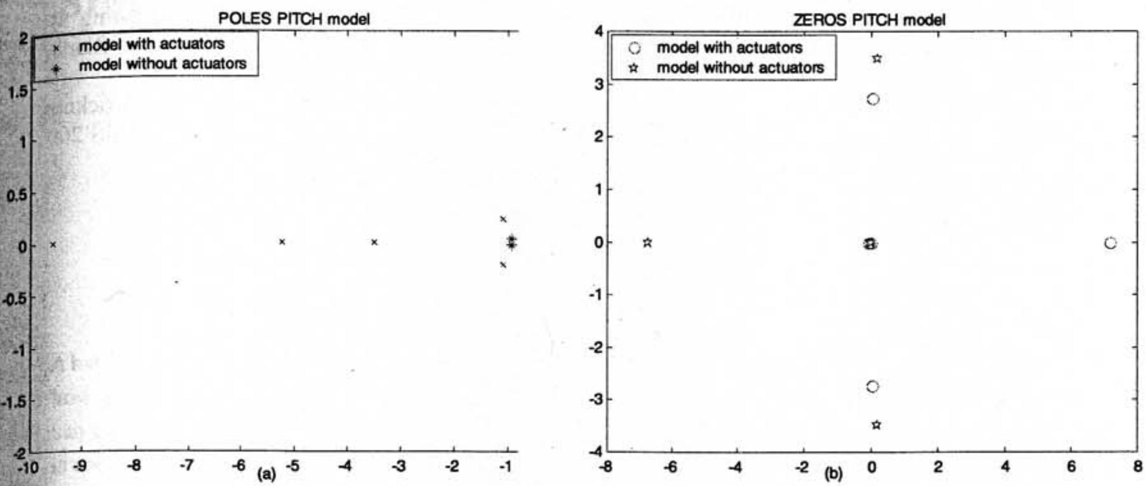

Figure 9.Poles (a) and zeros (b) of PITCH model with actuators and without actuators

Conclusions

In this research an analysis of the vertical dynamic of a fast ferry with actuators has been carried out. The interest has been restricted to heaving and pitching motions, heading see and 40 knots speed.

The analysis has been consisted of the identification of a continuous linear model of the system with actuators, and a comparison with the system without actuators.

Input-output measured data are given. Input are wave height and outputs are heave and pitch movement. Several model structures and orders have been defined, and both random and fixed initial values has been considered. A non linear least squares with constraints method applied in the frequency domain has been used as a criterion of fit to compute the best model in the model structure.

A priori knowledge of ships dynamic give two low frequency constraints to be considered.

Obtained model's properties are examined. Bode plots and model simulations are computed and graphed. It is seen that estimated models are capable of describing information data. G_H tends to one and G_P tends to zero at low frequency.

Models which best agree with the experimental data are selected.

Final model of heave and pitch are compared with the continuous model of the system without actuators. Zeros and poles are plotted. Also natural frequency and damping factor are calculated.

It is shown that heave and pitch models with actuators decrease both natural frequency and damping factor. This is traduced in reduction of heave and pitch response. In conclusion, a bit movement damping has been achieve, and consequently vertical accelerations have been reduced.

Acknowledgements

This development was supported by CICYT of Spain under contract DPI 2000-0386-C03-01.

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3rd. International Congress on Maritime Technological Innovations and Research

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I.S.B.N.: 84-8373-492-3
Depósito Legal/Lege Gordailua: BI-2879-02

Impresión/Inprimatzea:
Servicio Editorial/Argitalpen Zerbitzua UPV/EHU