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Development of a Control-Oriented Model of the Vertical Motions of a Fast Ferry

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As a main part of a research study on the control of active flaps and a T-foil of a high-speed ferry, a control-oriented model of vertical motions of the ship has been developed. The objective of the control is to improve comfort, decreasing the impact of heave and pitch motions. We have experimental data from a towing tank institution and simulations with PRECAL. The model is based on a decomposition of the physic phenomena into two main aspects: the coupling of the ship with distance between waves and the dynamics of a semisubmerged mass. The model can be handled with MATLAB-SIMULINK, which is useful for studying control strategies. The model shows good agreement (model validation) with the experimental and simulated data for regular and irregular waves. The article shows a methodology, based on MATLAB tools, for obtaining control-oriented models from computer-aided design (CAD)–based programs. That means that the control-oriented model can be derived from the ship design, even before the ship is built.

Introduction

IN FAST-FERRY–BASED passenger transportation, speed is most important. To achieve speed, many solutions are under way, such as the use of aluminum hulls. But there are vertical accelerations that cause seasickness and create structural risks, so speed must be reduced, unless the ship has the means to alleviate these accelerations. In the case we are dealing with, active control surfaces—transom flaps and a T-foil—are used to counteract the vertical motions due to sea waves. The problem to be solved is to move the control surfaces in the most effective way. That means an analysis in the context of automatic control.

In general, the automatic control study of a problem requires having a mathematical model of the plant to be controlled. With this model, nonrisk tests of control strategies can be tried, and specifications of control parameters (for instance, proportional integral differential [PID] controller tuning) can be easily refined.

For a given plant (in this case, a ship), several kinds of models can be elaborated, according to the objectives of study. For example, a small-scale replica for a towing tank, a computer-assisted design/manufacturing (CAD/CAM) model for hydrodynamic studies on computer, or mathematical models of diverse nature as static or dynamic aspects are mainly considered. For the automatic control perspective, interest is centered on the dynamic responses of the plant to stimuli: for instance, the response of the ship to sea waves. Because models focus on certain aspects, they usually apply simplifications and admit limits on the valid conclusions that can be reached.

A main objective of our research has been to find a mathematical model of the ship's vertical motions, pitching and heaving, with head seas. The model must be control oriented. The best way to get a reliable model, for different work conditions, is to consider the physics of the problem. Taking this approach, a satisfactory control-oriented model has been obtained, being also useful for a better understanding of the ship behavior.

The scientific literature offers several works of interest for this research. The fundamental knowledge is in the books of Lloyd (1989), Lewis (1989), and Fossen (1994). Key aspects of the ship motions are considered in Korvin-Kroukovski (1955) and Korvin-Kroukovski and Jacobs (1957) for regular waves, and completed in Salvesen et al (1970). The article of Ewing and Goodrich (1967), on the influence of wave spectra and ship length, presents interesting clues for our modeling purposes. In Van Sluijs and Gie (1972) we find a set of curves describing the vertical motions of frigates, which are relevant (as fast ships) for comparison. Concerning the problems related to speed, the article of Lewis (1959) makes a good account, considering also actuators to alleviate vertical motions. The article of Ferdinande and De Lembre (1970) describes the behavior of a ferry similar to the ship pertaining to our research, only that our ship is aluminum, and the ferry studied by Ferdinande

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and De Lembre is a conventional one. In the contribution of Skorupka and Perdon (1993), we get opportune remarks about passenger comfort. Anonymous references ("126m Long Spanish fast ferry launched" 1996, "Silvia Ana" 1998) and the contribution of Moret et al (1993) have design details of the fast ferry we are dealing with. The contribution of De la Cruz et al (1998) presents a discrete model identified by time series analysis of the response to irregular waves.

To have a specific target for our research, a fast ferry operating between Denmark and Norway during the European summer has been selected. Using a 1/25 scaled-down replica, some series of experiments have been performed by a towing tank institution (Canal de Experiencias Hidrodinamicas de El Pardo [CEHIPAR], Madrid). The experimental results obtained constitute the basis to validate our model. In addition, CEHIPAR can supply simulated data, by using the computer program PRECAL. Using a CAD description of the hull, PRECAL predicts the ship's motions for regular waves, giving also information on hydrodynamic coefficients, forces, and moments. This information has been very useful in developing the control-oriented model.

MATLAB is a "de-facto" standard for the automatic control studies on computer (Shahian & Hassul 1993; Hanselman & Littlefield 1997). As a part of the MATLAB environment, SIMULINK paves the way to developing models by combining building blocks that are displayed as drawings in a Windows screen (Dabney & Harman 1998). The connections between blocks help one to see the interactions in the model (and the principles of the model). With SIMULINK there is a very convenient framework for automatic control studies: once a model is depicted, simulations can be run, and behaviors of the plant (controlled or not) can be observed. In our case, a SIMULINK expression of our model has been obtained that makes it easy to connect the control actuators (flaps, T-foil) and to analyze the results of different automatic control strategies.

In summary, this article describes how to obtain from the results of a CAD-based program such as PRECAL control-oriented models in MATLAB-SIMULINK. The results are validated with experimental data.

The "Methodology of research" section shows the organization of this article, highlighting the main steps of the research.

Methodology of research

The article focuses on a fundamental part of a research study on improving comfort in a fast ferry. In particular, seasickness is contrary to comfort and is caused by vertical accelerations. In consequence, heave and pitch vertical motions must be attenuated, using active actuators (flaps and T-foil in our case) and designing a controller to command them. It is necessary, for the design and tuning of the controller, to have a control-oriented model (COM) of the problem. *For convenience to the research objectives, the COM will* consist of a set of transfer functions (the concept of transfer function will be explained in the next section). This COM is also needed to study stability and robustness of the controlled system, that is, the ship with actuators and controller. The purpose of this article is to obtain a COM of the full-scale ship. A computer fluid dynamic (CFD) program has been used as the starting point of the research. With the data obtained by the CFD program, it has been possible to get a satisfactory COM model. Experiments with a scaled-down replica of the ship has been done to validate the data provided by the CFD and to validate the COM of the ship. At the end of the research, experiments with actuators and control action have been done to validate simulated results, too.

Figure 1 shows a diagram with the main steps of the modeling methodology described in the article. It is interesting to explain these steps, as a guide for the article contents. They are the following:

1. The starting data are the gains and phases provided by a CFD program. In this case, PRECAL has been used because it was available at CEHIPAR institution.
   - A mesh of the real dimensions hull and its main characteristics has been programmed on PRECAL.
   - A set of experiments with head seas and regular waves has been simulated on PRECAL. Several ship speeds (20, 30, and 40 knots) and several wavelengths have been considered.
   - PRECAL computes the gains and phases of this vessel for each ship speed and wavelength. With these data, it is possible to plot curves of heave force, pitch moment, heave motion, and pitch motion, versus wavelengths of the regular waves. The curves are the initial information required to determine transfer functions of waves to heave force, waves to pitch moment, waves to heave motion, and waves to pitch motion.
2. Several steps are necessary to obtain the COM from the data provided by PRECAL.
   - Waves to heave force and waves to pitch moment data are given with respect to the wave frequency. It is necessary to change them to encounter frequency. COMs are a function of the excitation frequency, equivalent to encounter frequency in this case.
   - The phases generated by PRECAL are not causal because they are computed with respect to the wave measured at the center of gravity of the ship. However, the wave starts to cause a ship motion when it arrives at the bow. Therefore, the phase must be measured just from this moment. The phases generated by PRECAL must be recomputed with respect to the bow.

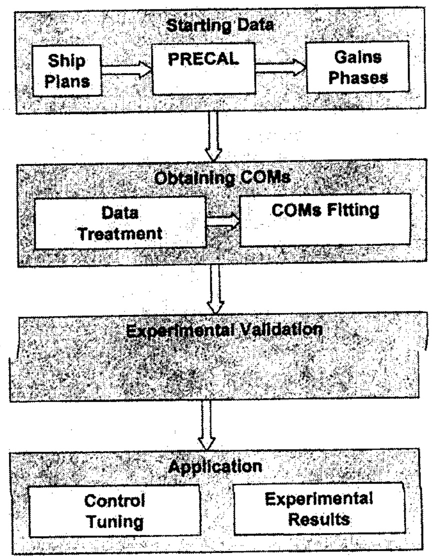

Fig. 1 Methodology of this article

- A linear COM is identified from the data: the gains and phases are fitted by transfer functions. It is shown that it is possible to obtain simple transfer functions with good agreement in a wide range of frequencies. Four transfer functions (waves to heave force, waves to pitch moment, waves to heave motion, and waves to pitch motion) are obtained for each speed condition.
3. Experimental validation of the COM. A scaled-down replica of the ship has been used for experimental tests at CEHIPAR basin. The records of the experiments are scaled up to real ship dimensions.
   - Regular wave experiments with the scale replica have been done to validate the gains and phases data generated by PRECAL.
   - Irregular wave experiments with the scale replica have been done to validate the identified COMs. So, the models have been obtained with regular waves and have been validated with irregular waves. The results corroborate that linear models are good enough for the research purposes.
4. Applications of COMs. Some controller studies and results are briefly described.

Basic structure of a control-oriented model

A model architecture must be defined for a complete model of the ship with actuators and control. Figure 2 shows this architecture. It is based on decomposition into waves to forces and forces to motions, inspired by the structure of the information given by PRECAL. The model of the ship's vertical dynamic behavior, denoted as waves to motions in the figure, is formed with four blocks. Two of the blocks give the forces generated by waves (waves to forces). These blocks are waves to heave force (WtoHF) and waves to pitch moment (WtoPM). The other two blocks give the motions caused by the forces. These blocks are heave force to heave motion (HFtoH) and pitch moment to pitch motion (PMtoP).

The structure of waves to motions provides an easy and natural way of including the action of the control and the actuators. In fact, the actuators should counteract the forces and moments generated by waves. Figure 2 shows the complete architecture, coupling a generator of waves and models of sensors, controller, and actuators to the waves to motions model of the ship's behavior. The actuators must generate lift force opposite to the waves heave force and a moment opposite to the waves pitch moment.

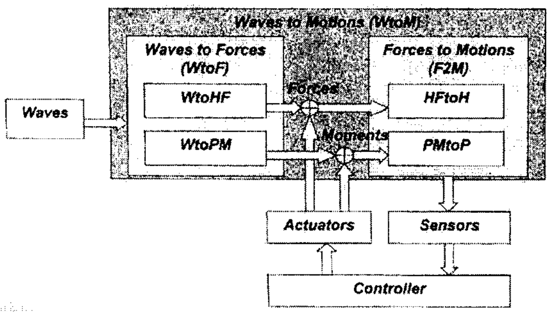

Fig. 2 Architecture of the complete model. HFtoH = heave force to heave motion; PMtoP = pitch moment to pitch motion; WtoHF = waves to heave force; WtoPM = waves to pitch moment

The architecture of the complete model can be easily translated to SIMULINK diagrams, for control studies.

In view of building this architecture, the main research task is to obtain mathematical expressions for the WtoHF, WtoPM, HFtoH, PMtoP blocks. PRECAL does not provide us with forces to motions data; however, it is possible to deduce these data, as will be described in the "Treatment of data" section.

There are several alternatives for the mathematical expression of control-oriented models. In this case, waves can be considered approximately as a sinusoidal input, with a frequency of encounter, to the plant. It seems natural to use transfer functions for the models, because transfer functions correspond to studies in the frequency domain. This domain has many advantages for control analysis (Kuo 1987). Given a system with a single input $u(t)$ and a single output $y(t)$, the transfer function of the system is the relation showed by equation (1):

$$G(s) = \frac{Y(s)}{U(s)} \tag{1}$$

where $Y(s)$ is the Laplace transform of the output, $y(t)$, and $U(s)$ is the Laplace transform of the input, $u(t)$. The transfer function $G(s)$ is dimensionless and is a quotient of polynomials in s (that is the Laplace operator). Knowing the expression of $G(s)$ is sufficient to be able to calculate the response of the system to any input. The response of the system to sinusoidal input is easily determined by a simple substitution of s by $j\omega$ (where j is the imaginary unit and ω is frequency in rad/s) in the expression of $G(s)$. The response of a system to sinusoidal input covering a range of frequencies is called frequency response of the system and is typically studied plotting gain, $G = |G(j\omega)|$, and phase, $\gamma = \angle G(j\omega)$, versus frequency of the sinusoidal input. These graphical representations are very useful for control design. In this paper the complex notation, $G \cdot e^{j\gamma}$, is used, too. PRECAL gives us the necessary data to obtain transfer functions. The frequency of the input signal is the frequency of encounter with waves.

The ship and data obtained with PRECAL

The target of this research is an aluminum fast ferry. Figure 3 shows a photograph of the ship.

Table 1 summarizes the main characteristics of the ship and the scaled-down dimensions of the replica made by CEHIPAR. The replica will be used to validate this research.

The ship characteristics have been programmed on PRECAL, and it has been used to reproduce on computer the experiments with regular waves. The characteristics of the simulated experiments are shown in Table 2.

Along this research it was found that the conventions used by naval engineers for the signs of phases are different from the convention used by control engineers. For control engineers, negative phase means time delay and positive phase a prediction of the future. In this article the convention of control engineers is used. PRECAL provides us the frequency response data shown in Figs. 4 and 5.

All the plots are referenced to the frequency of encounter. Because PRECAL data about waves to heave force and waves to pitch moment are given with respect to wavelengths, it has been necessary to calculate the corresponding frequencies of encounter.

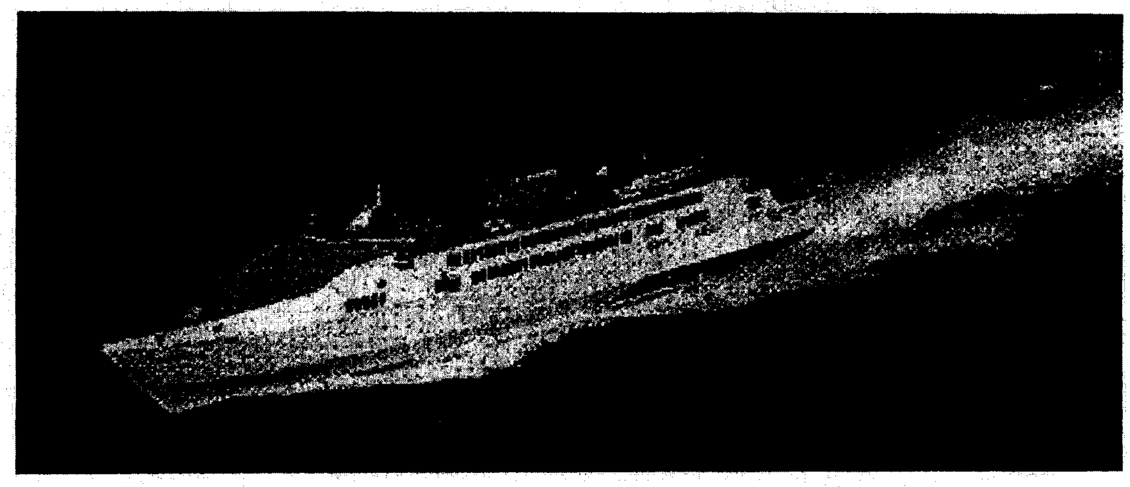

Fig. 3 Photograph of the ship

Table 1 Characteristics of the ship

Characteristic	Ship	Replica
Length	110 m	4.4 m
Beam	14.696 m	0.588 m
Draught	2.405 m	0.096 m
zcog	7.6 m	0.304 m
Deadweight	475 tons	
Power	4 × 5,650 kW	
Load	1,250 passengers	
	230 cars	
	4 buses	
Speed	40 knots	

Table 2 Regular waves characteristics

λ/Lpp	H (m)	T (s)
0.35	0.963	4.966
0.51	1.403	5.994
0.70	1.925	7.023
0.80	2.200	7.508
0.91	2.503	8.007
1.03	2.833	8.519
1.15	3.163	9.001
1.28	3.520	9.496
1.42	3.905	10.002
1.72	4.730	11.008
2.04	5.610	11.989
2.40	6.600	13.003
2.78	7.645	13.995
3.19	8.773	14.992
3.63	9.983	15.992

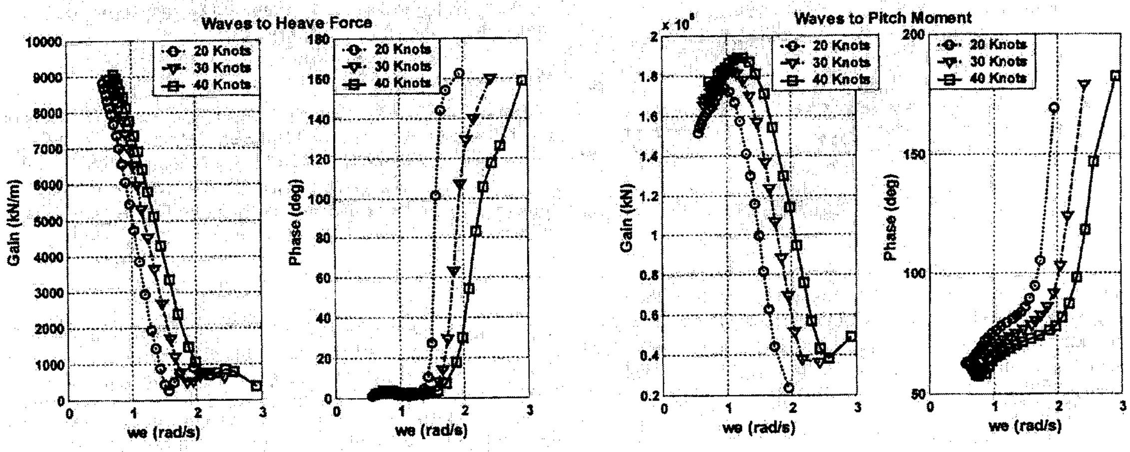

Fig. 4 Waves to forces frequency response

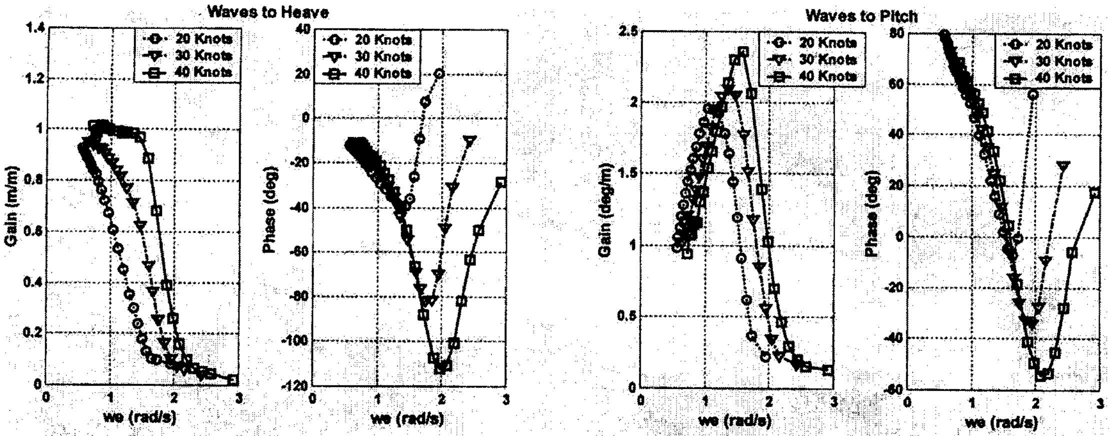

Fig. 5 Waves to motion frequency response

Treatment of data: correction of phases

Transfer functions must be causal. That means that the order of the numerator polynomial must be less than the order of the denominator polynomial. This causality is reflected in the phases of transfer functions. In the case of the ship, the input to the plant (the waves) should be considered in the moment when it interacts with the ship (not waiting until the waves to reach the center of gravity of the ship). Because the conventional way of studying the ship's motions takes the center of gravity as reference, the PRECAL phases for waves to forces and waves to motions are noncausal.

To get causal relationships, a correction of phases has been applied, moving the reference to the bow. The time for a head wave to move from the bow to the center of gravity is calculated, and time is expressed as phase. This phase is subtracted from the PRECAL phase. The equations for this correction process are as follows:

$$V_w = \frac{g}{\omega_w} \tag{2}$$

$$V_e = V_{ship} + V_w \text{ (for head seas)} \tag{3}$$

$$\lambda_w = \frac{2\pi g}{\omega_w^2} \tag{4}$$

$$\omega_e = \frac{2\pi V_e}{\lambda_w} \tag{5}$$

$$\gamma_{bow} = \gamma_{cog} - \omega_e \frac{d_{bow-cog}}{V_e} \tag{6}$$

where V_w is the speed of the waves, g is the gravity acceleration, ω_w is the wave frequency, V_e is the ship speed relative to the wave, V_{ship} is the speed of the ship, λ_w is the length of the wave, ω_e is the encounter frequency, γ_{bow} is the phase of the wave measured on the bow, γ_{cog} is the phase of the wave measured on the center of gravity, and $d_{bow-cog}$ is the distance from the bow to the center of gravity.

Figure 6 shows the corrected phase of waves to forces and waves to motions. These may be compared with Figs. 4 and 5.

Obtaining the models

There are powerful tools offered by MATLAB that are useful for obtaining the models in the form of transfer functions. In particular the invfreqs routine, which is included in the signal toolbox, is a fast way for mean squares fitting of a transfer function to frequency domain data. Some initial guess of the order of the transfer function denominator helps to find the best fitting. In the case of the gains and phases we are handling, the slope of the curves gives an indication of the minimum order of the denominator.

Given a transfer function, the roots of the denominator are called poles, and the roots of the numerator are called zeros. Poles with positive real parts imply instability. Unstable poles are undesirable. Looking at frequency response plots, complex poles are related to resonance peaks and zeros to valleys.

Using invfreqs, the task of obtaining models has been achieved in two steps: First, the models for the waves to forces are obtained, and then the models for the forces to motions. This has been done for 20, 30, and 40 knots (a total of 12 transfer functions). In the following, only the results for 40 knots will be shown (the method is also easily applied for the other speeds).

Waves to forces models

The application of invfreqs to the corrected gains and phases of the waves to forces data is fairly direct, with fast results. The appendix contains a MATLAB program for this purpose. Figure 7 shows the fitting of a transfer function for waves to heave force.

According to the best fitting, as shown in Fig. 7, the model of waves to heave force at 40 knots is the following transfer function, equation (7):

$$G_{WtoHF}(s) = \frac{F_3(s)}{w(s)} = \frac{698\,s^5 + 724.8\,s^4 + 15{,}840\,s^3 + 5{,}948\,s^2 + 59{,}260\,s - 1{,}913}{s^6 + 1.93\,s^5 + 9.135\,s^4 + 10.81\,s^3 + 17.02\,s^2 + 7.537\,s + 2.984} \tag{7}$$

where $F_3(s)$ is the Laplace transform of the heave force and $w(s)$ is the Laplace transform of the wave measured just when it catches the bow up.

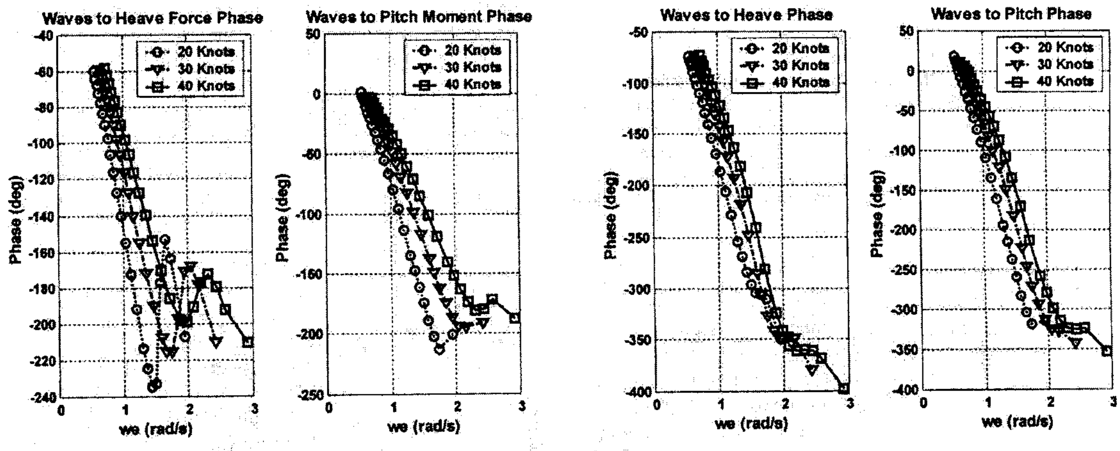

Fig. 6 Corrected phase of waves to forces and waves to motions

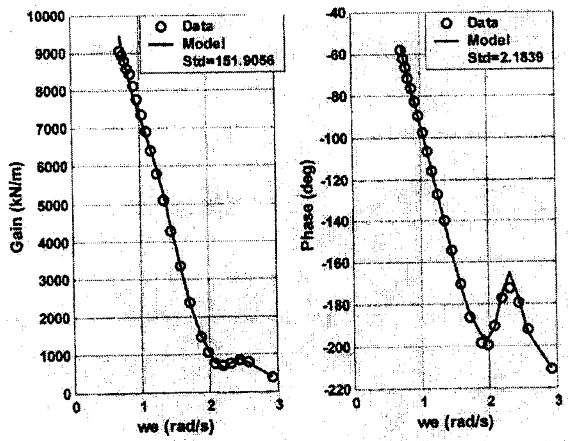

Fig. 7 Fitting of waves to heave force model

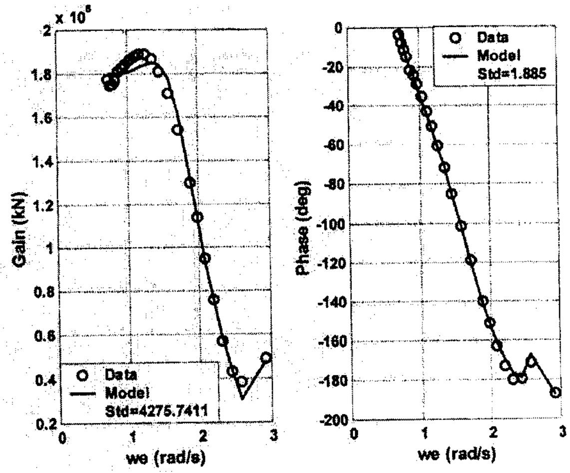

Fig. 8 Fitting of waves to pitch moment model

Table 3 Poles and zeros of the waves to heave force model

Poles	Frequency	Zeros	Frequency
−0.2375 ± 2.3581 i	2.37 rad/s	− 0.1591 ± 2.1906 i	2.20 rad/s
−0.4750 ± 1.3666 i	1.45 rad/s	− 0.3760 ± 4.1855 i	4.20 rad/s
−0.2521 ± 0.4361 i	0.50 rad/s	+0.0321	0.03 rad/s

Table 4 Poles and zeros of the waves to pitch motion model

Poles	Frequency	Zeros	Frequency
−0.1237 ± 2.7486 i	2.75 rad/s	−0.1090 ± 2.6370i	2.64 rad/s
−0.5115 ± 1.6893 i	1.77 rad/s	−19.2149	19.21 rad/s
−0.7026	0.70 rad/s	+0.2708	0.27 rad/s
−0.5530	0.55 rad/s		

Table 3 shows the values of the zeros and poles of this transfer function. There are no poles with a positive real part, meaning no unstability problems. The poles with 2.37 rad/s frequency correspond to a small resonance peak (between 2 and 3 rad/s) in Fig. 7.

Figure 8, equation (8), and Table 4 correspond to the waves to pitch moment model.

The transfer function obtained for waves to pitch moment at 40 knots is the following, equation (8):

$$G_{WtoPM} = \frac{F_5(s)}{w(s)} = \frac{32{,}780\,s^4 + 628{,}200\,s^3 + 193{,}200\,s^2 + 4{,}289{,}000\,s - 1{,}189{,}000}{s^6 + 2.526\,s^5 + 12.92\,s^4 + 22.75\,s^3 + 38.53\,s^2 + 32.93\,s + 9.166} \quad (8)$$

where $F_5(s)$ is the Laplace transform of the pitch moment and $w(s)$ is the Laplace transform of the wave measured just when it catches the bow up.

Table 4 shows the values of the zeros and poles of this transfer function. Again, there are no poles with a positive real part, meaning no instability problems. The poles with 1.77 rad/s frequency correspond to the big gain peak (between 1 and 2 rad/s) in Fig. 8.

It is possible to obtain a simpler approximate model, by cancellation of poles and zeros at high frequencies (disregarding the small peaks at the bottom of the curves).

Forces to motions models

Although PRECAL does not give data about forces to motions, it is possible to obtain it by manipulating the other information given by PRECAL. Let us consider the following expression (9), where $G_{WtoM}(s)$ is the waves to motions transfer function, $G_{WtoF}(s)$ is the waves to forces transfer function, $G_{FtoM}(s)$ is the forces to motions transfer function:

$$G_{WtoM}(s) = G_{WtoF}(s) \cdot G_{FtoM}(s) \Rightarrow G_{FtoM}(s) = \frac{G_{WtoM}(s)}{G_{WtoF}(s)} \quad (9)$$

If we represent the gain (G) and phase (λ) as complex numbers, as $G \cdot e^{\lambda j}$, it is easy to obtain the G_{FtoM} transfer function by division of gains and subtraction of phases. In this way, we can plot the data points of G_{FtoM}, and use invfreqs for fit the transfer function in the complex domain.

Figure 9 shows the fitting for force to heave motion model, and Table 5 the zeros and poles map of the transfer function (again, some pole-zero canceling could be applied).

The transfer function obtained for heave force to heave motion at 40 knots is equation (10):

$$G_{HFtoH}(s) = \frac{X_3(s)}{F_3(s)} = \frac{-4.315 \cdot 10^{-5} s^3 + 2.779 \cdot 10^{-4} s^2 - 2.046 \cdot 10^{-4} s + 1.526 \cdot 10^{-3}}{s^4 + 0.7057 s^3 + 8.507 s^2 + 3.437 s + 16.66} \quad (10)$$

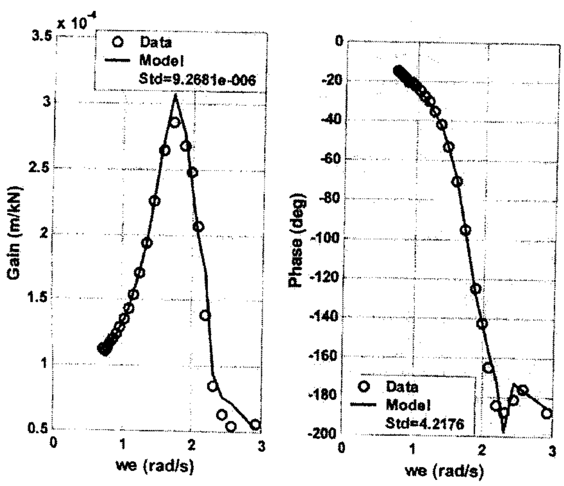

Fig. 9 Fitting of heave force to heave motion model

Table 5 Poles and zeros of the heave force to heave motion model

Poles	Frequency	Zeros	Frequency
−0.0666 ± 2.2940 i	2.30 rad/s	−0.0508 ± 2.3244 i	2.33 rad/s
−0.2862 ± 1.7553 i	1.78 rad/s	+6.5418	6.54 rad/s

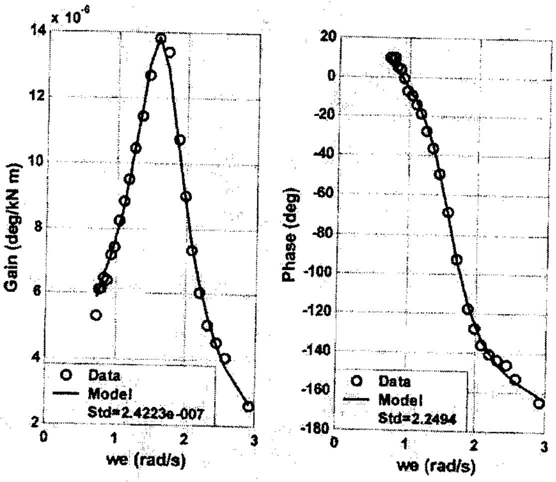

Fig. 10 Fitting of pitch moment to pitch motion model

Table 6 Poles and zeros of pitch moment to pitch motion model

Poles	Frequency	Zeros	Frequency
−0.3481 ± 1.6196 i	1.66 rad/s	+18.9632	18.96 rad/s
−0.5341	0.53 rad/s	−0.1613	0.16 rad/s

where $X_3(s)$ is the Laplace transform of the heave motion and $F_3(s)$ is the Laplace transform of the heave force.

Figure 10 and Table 6 show the results for pitch moment to pitch motion model.

The transfer function of pitch moment to pitch motion is the following, equation (11):

$$G_{PMtoP}(s) = \frac{X_5(s)}{F_5(s)} = \frac{-8.626 \cdot 10^{-7} s^2 + 1.622 \cdot 10^{-5} s + 2.639 \cdot 10^{-6}}{s^3 + 1.231 s^2 + 3.116 s + 1.466} \quad (11)$$

where $X_5(s)$ is the Laplace transform of the pitch motion and $F_5(s)$ is the Laplace transform of the pitch moment.

Once the four models at 40 knots have been obtained, these models can be combined, according to the structure of Fig. 2, to get the model of pitch and heave motions with any input of waves.

The models are very good for the range of encounter frequency ([0.7, 3] rad/s) used for the fitting. This range covers the frequencies for sea state number (SSN) 4, 5, and 6 at 20, 30, and 40 knots. It is really strange to think that a fast ferry with passengers could affront more than SSN5 (at 40 knots and SSN5, this could mean around 50% of passengers will vomit). On the other hand, ships with lengths around 100 m do not have problems with SSN3 or less. So, the ship will work in this range of frequency, and the models are very good for this range.

It is known that pitch and heave motions are coupled (Havelock 1955). The waves to motions data given by PRECAL contain this coupling. In consequence, this coupling remains implicitly as part of the forces to motions models, equations (10) and (11). A more refined data fitting, with higher-order transfer functions, would show more explicitly the coupling in the form of common complex poles.

Of course, the behavior of the ship is nonlinear. However, the obtained results (as shown in Figs. 11 and 12) are well approximated by linear models. For the control community, it is not essential that the model is perfect, because it is assumed that model parameters will change, and there will be also unmodeled dynamics due to passengers' distribution and weight, presence of wind, changes in water density, changes in sea spectra, and so forth. All these uncertainties are precisely the basis of the robust control approach, which is able to design controllers that withstand perturbations and parameter changes.

Validation

An extensive series of experiments have been done, with the 1/25 scaled-down replica, to validate several results of the research. Both regular and irregular waves have been generated, and the seakeeping tests have been done with speeds corresponding to 20, 30, and 40 real scale knots.

The main experimental information has been obtained in a tank (150 × 30 × 5 m) with a wave generator of 60 blades. The scaled-down replica is moved by a computerized planar motion carriage (CPMC); heave and pitch motions are free; and surge, roll, yaw, and sway motions are not allowed. There is a set of sensors in the replica, connected to data-processing systems on the CPMC. Wave height, and vertical elevation and acceleration in five frames of the ship are measured with the sensors. The experimental data are digitized and saved as computer data files. With these data files, the temporal evolution of the measured variables can be recovered and analyzed, for instance, to obtain the gains and phase diagrams. Figure 13 shows a picture of the replica during experiments in CEHIPAR.

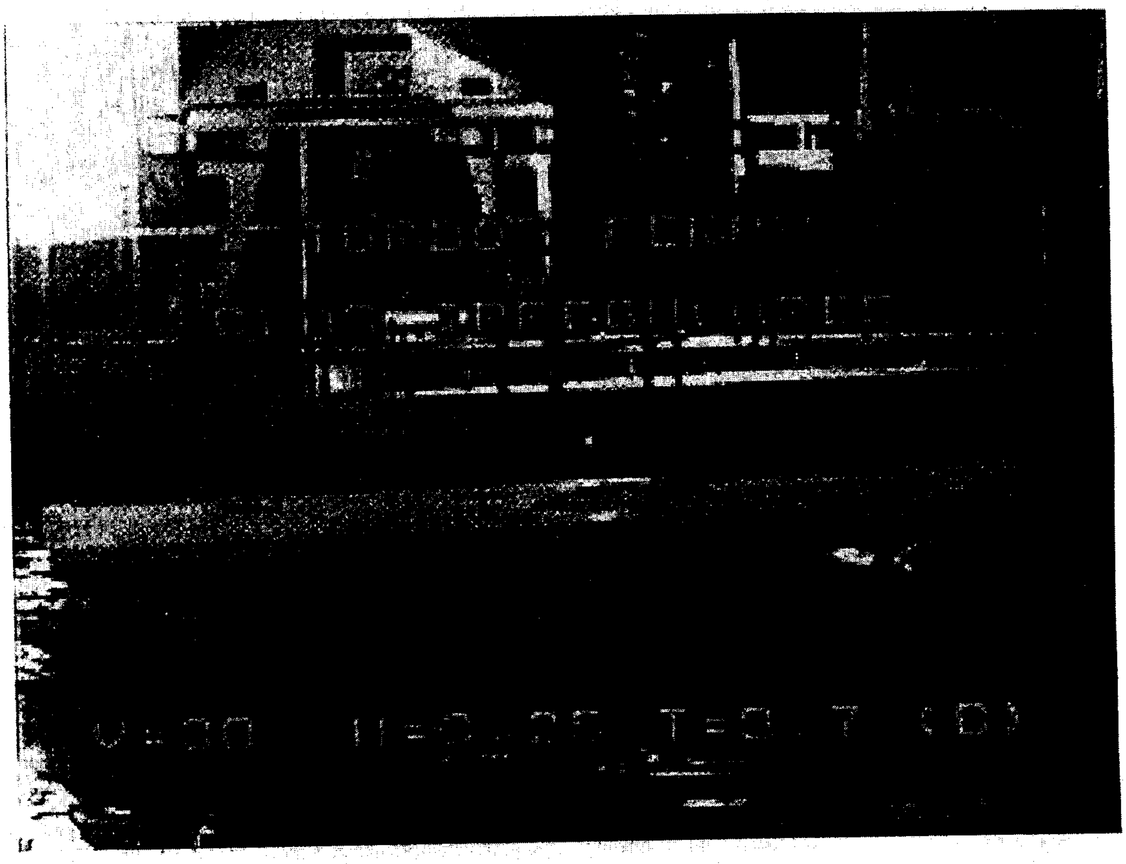

Fig. 11 Photograph of the experiments

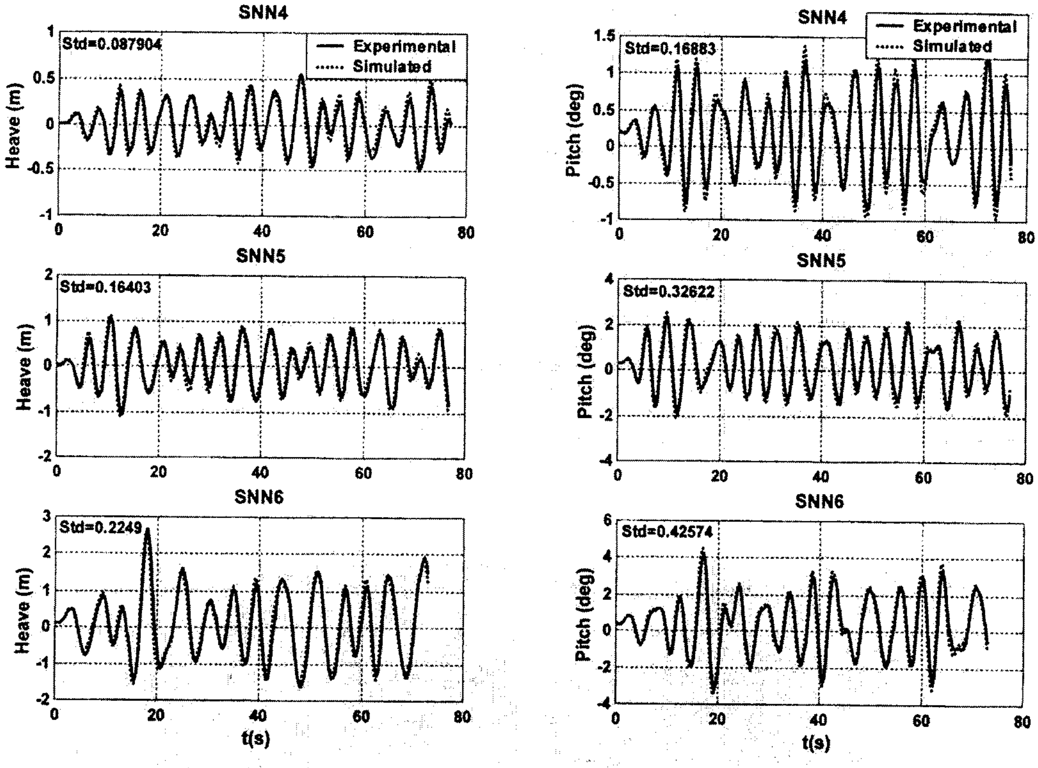

Fig. 12 Vertical motions validation

The following validation tasks have been achieved:

- Experiments with the regular waves of Table 2. The results have been compared with the gain and phase data given by PRECAL, for the same waves of Table 2. The results of this validation have been satisfactory: the data calculated by PRECAL agree with experiments in the frequency range of this study. Because there are 15 wavelengths and three ship speeds, a set of 45 runs of the replica along the basin has been done for this validation.
- Experiments with irregular waves (Table 7), corresponding to the JONSWAP spectrum. This spectrum has been selected because the fast ferry selected for the research operates in coastal waters. The objective of the experiments with irregular waves is to validate the models for the normal operation of the ship.

The same waves of the CEHIPAR experiments with the replica (as saved on computer files), are applied to the model. Figures 11 and 12 compare the experimental and the modeled motions and accelerations. Both figures represent the behavior at the real scale of the ship. For the complete record of waves and responses, the agreement between the replica and the model is good enough (more than sufficient for control design). Of course, there are differences, due to nonlinearities and bias, but this has few implications for control efficacy. What it is important is that phases are well captured (there is no delay between experimental data and model), because it is crucial that actuators must be synchronized to the effects of waves.

Application

There has been throughout the paper an insistence on the use of the models, just described, for control purposes. Therefore, it is interesting to devote a section to a brief overview of the control part of this research. The aspects covered after the development of the ship's vertical dynamics model were the following:

- Development of actuators models
- Development of a simulation environment for safe control design studies
- Establishment of control optimization criteria
- Design of an optimal control, using the simulation environment
- Inclusion of actuators and control in the scaled replica
- Experimental validation at CEHIPAR of the optimal control design.

The complete set of research tasks needed around 3 years of computer and experimental work. A brief description of the main aspects is presented next.

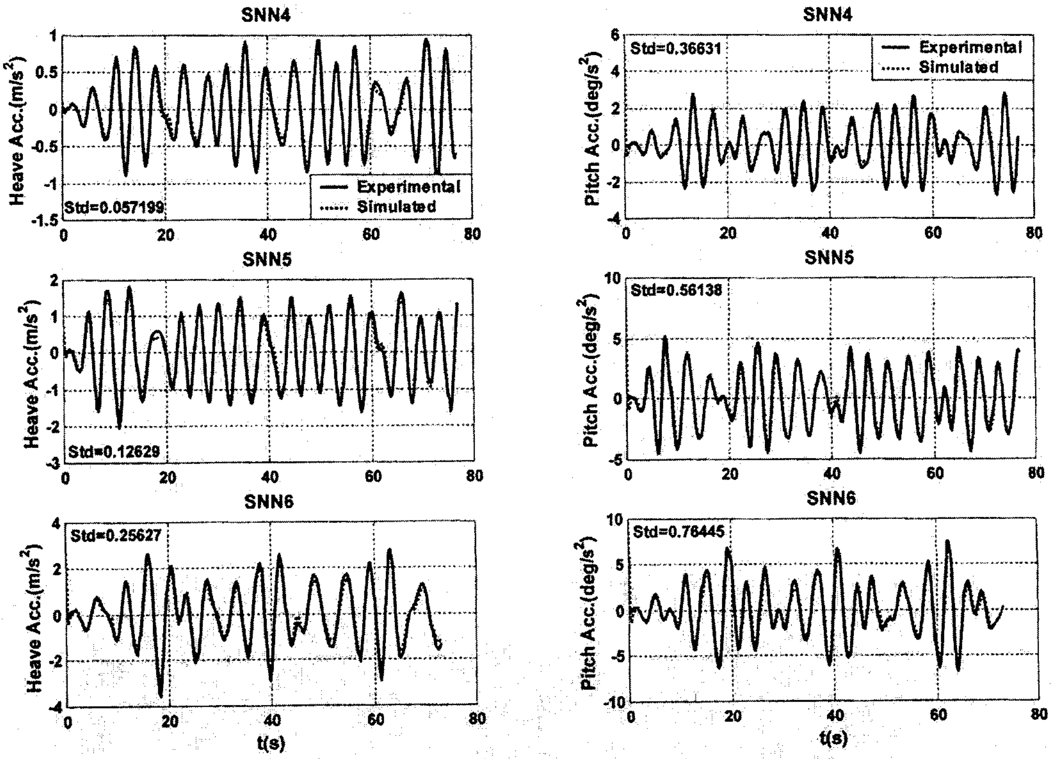

Fig. 13 Vertical acceleration validation

Table 7 Irregular waves experiments

SSN	H (m)	T (s)
4	1.90	8.8
5	3.25	9.7
6	4.50	12.4

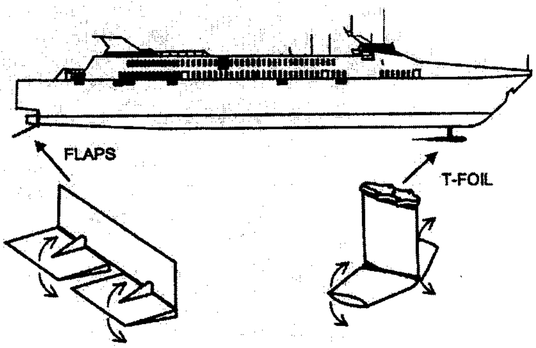

Fig. 14 Adding flaps and T-foil to the fast ferry

Models of the actuators

The actuators considered in this research are two transom flaps and a T-foil. The actuators can move by means of hydraulic cylinders. The T-foil has two moving wings. Figure 14 shows where the actuators are placed.

These actuators will give lift force, as a function of the actuator's angle α and the fluid's speed U, according to equation (12):

$$F_L = \frac{1}{2} \rho A \frac{\partial C_L}{\partial \alpha} U^2 \alpha \tag{12}$$

where A is area of the actuator, ρ is the water density, and C_L is the lift coefficient.

The angle α is with respect to the water flow. We can measure the angle β of the actuator with respect to the ship keel. At any time, the ship itself has an angle φ with respect to the waterline. From the model of ship's motions, we can determine φ. By adding β and φ, we can obtain in real time α.

Experiments were carried out, using in this case a 300 m long channel with calm waters at CEHIPAR, to determine the coefficients for the flaps and the T-foil (Esteban et al 2000). Notice that the equation of lift force is nonlinear. There are limit angles for the actuators; beyond them lift force decreases. Usually, the actuators are moved by hydraulic cylinders. There will be a limit on the maximum speed the cylinders can move. The dynamic of the hydraulic cylinders can be modeled with an integrator block with two saturations, one at the input (for rate limit) and other at the output (for β angle saturation). A local feedback loop has been devised. This loop, which includes hydraulic cylinders and actuators, forms the actuator subsystem. The input of the subsystem is the desired actuator's angle β_{ref}, and the outputs are the heave force and pitch moment (easily computed from F_L) being applied to the ship (Fig. 2). The model also considers efficacy loss when actuators emerge, and computes accumulated cavitation.

Simulation environment for control design

All the models have been expressed as SIMULINK blocks. The main reason is that SIMULINK offers important facilities for simulation and control study. SIMULINK is an interactive simulation development tool, based on the use of blocks. There is a set of blocks (linear and nonlinear functions) that can be selected with the mouse, and connected according to the structure of Fig. 2. To make the complete model more realistic, several observations from experiments were translated to the SIMULINK model. Noise from sensors was recorded from experiments and included in the model.

Simulation is to run experiments on models. In this case, all the excitations used by CEHIPAR, regular and irregular waves, were recorded as seen by the replica. The excitation block in the simulation includes these records. A menu window is devised for the user to select any combination of waves and speed. Once the excitation is specified, the experiment (the same run at CEHIPAR) can be carried out, and the behavior of the ship can be observed on the computer screen and recorded on disk. The visualization capabilities of SIMULINK, and the GUI interface of MS-Windows, were very useful in developing an interactive simulation environment (Fig. 15).

Aspects of the control design

The main objective of the research is to alleviate vertical accelerations. Thinking about passengers, it is important to avoid seasickness. The research of O'Hanlon and McCawley (1974) links seasickness to the amplitude of vertical accelerations with a frequency around 0.17 Hz. This research established the motion sickness incidence (MSI) index and a mathematical model. The MSI

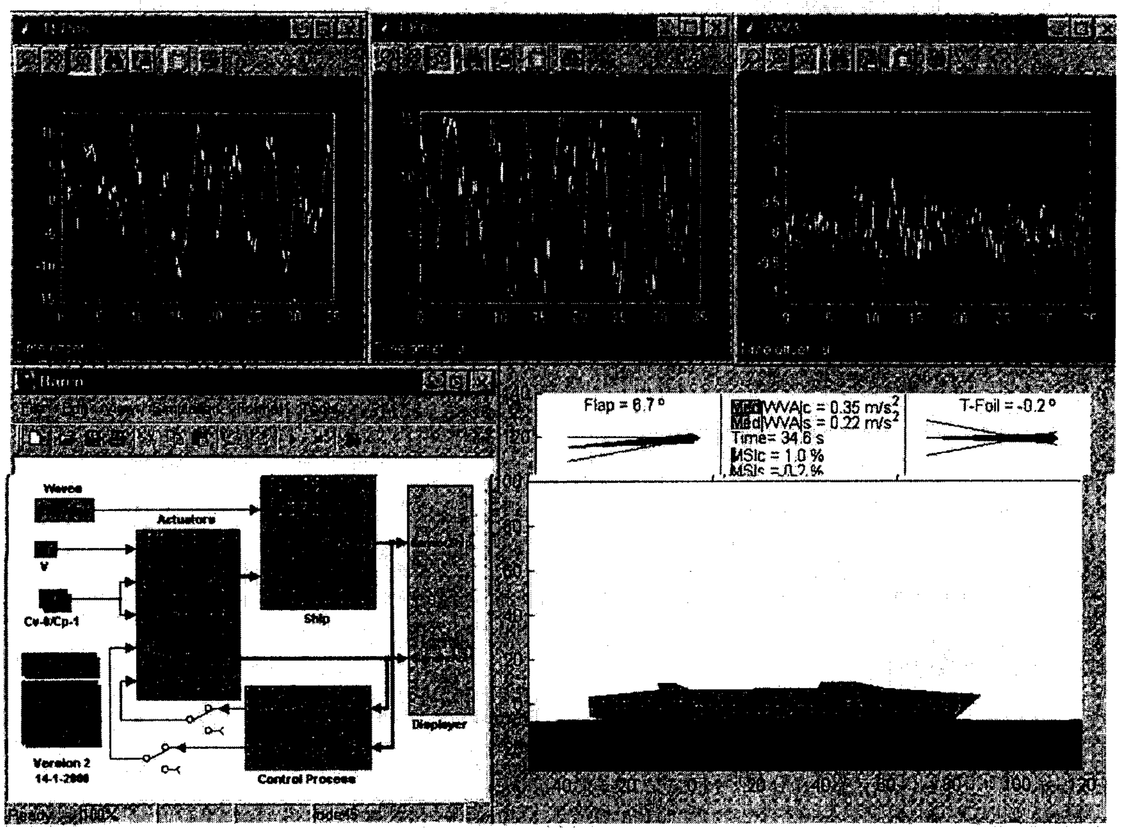

Fig. 15 Simulation environment

index is the percent of passengers who will be sick (vomiting) after 2 hours of sailing. When the actuators move, to counteract the effect of incident waves, there will be secondary effects. One is mechanical fatigue, and this is a reason to save motions of actuators (for instance, when waves are small enough to be ignored). Another issue is cavitation, which is related to speed and the angle of attack, and that can destroy the actuators. Cavitation should be minimized. Indeed, there are clear reasons to avoid slamming and deck wetness. All these criteria constitute a multiobjective optimization problem to be considered for the control design.

The simulation environment calculates and records, for any experiment, a set of indexes measuring the accumulated cavitation effect, the wear of actuators due to motions, the time actuators remain at angle limits, the MSI, and the number of bow emergences.

An accelerometer was put at the worst place for passengers, near the bow. There the MSI reaches its maximum value. The acceleration measured there is denoted as worst vertical acceleration (WVA). This signal is the input signal used by the controller. The output of the controller is a desired actuator's angle β_{ref}, which in turn is given as control input to the actuators subsystem (the subsystem generates a lift force to reduce the WVA).

Part of the accelerometer output is noise. A filter has been designed to eliminate noise that is out of the frequency band of ship motions. In the real ship, sensors will be the same, and the noise due to mechanical vibrations will be of lower frequency, but the frequency of ship motions will be lower, too (the filter can be easily redesigned). An interesting difference between the scaled-down replica and the ship is that there will be vibrations in the ship due to machinery. The filter will be also useful to avoid this noise.

Experimental validation: control results

The scaled replica was equipped with transom flaps and a T-foil. An embedded computer on board, a complete set of sensors, and computer interface electronics for handling signals and actuators power were added. Several runs in the CEHIPAR basin were done with the replica + actuators + control, for irregular waves corresponding to SSN4, 5, and 6, and at 20, 30, and 40 knots. It was corroborated that predicted control efficacy was coincident with the experimental results.

The results of the optimal controller are fairly good, especially for high speeds. For instance, at 40 knots and SSN4, the MSI is reduced from 7.98% without the stabilization system to 0.05% with the optimized stabilization system. Moreover, the videos taken during experiments at CEHIPAR show that slamming was completely suppressed.

Figure 16 compares experimental results in irregular waves for the replica without actuators with fixed actuators and with moving controlled actuators.

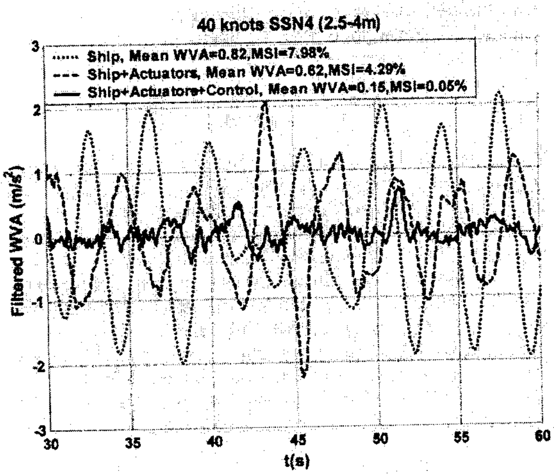

Fig. 16 Experimental results

Conclusions

Vertical accelerations of fast ships, due to waves, can be alleviated by moving actuators and a well-designed control of the actuator motions. A good model of the vertical motions of the ship is required for analytical and simulated development of the actuators control.

From both experimental and simulated data, a control-oriented model of fast-ferry vertical motions has been elaborated. The model expression is in the form of transfer functions. Transfer functions exhibit clear advantages for automatic control analysis and can be translated to SIMULINK block diagrams, to build simulation environments.

The model has been developed for pitch and heave motions and heading seas. The experimental basis is a series of tests made by CEHIPAR with a replica of the ship and the results of the program PRECAL. The same experiments made with the replica, as recorded on computer files, allow us to validate the model obtained, with satisfactory results.

Other parts of the research, concerning actuators, control design, and experiments, are described in De la Cruz et al (2004), Esteban et al (2000), Esteban et al (2001), Aranda et al (2001), Polo et al (2001), and Giron-Sierra et al (2001).

The article shows a methodology, based on MATLAB tools, for developing control-oriented models of ship motions, using experiments and CAD-based programs.

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References

126m Long Spanish fast ferry launched. 1996 *Ship and Boat International*, September, 19.

Aranda, J., Diaz, J. M., Ruiperez, P., Rueda, T. M., and Lopez, E. 2001 Decreasing of the motion sickness incidence by a multivariable classic control for a high speed ferry, *Proceedings*, IFAC International Conference, Control Applications in Marine Systems, July, Glasgow, UK.

Dabney, J. B., and Harman, T. L. 1998 *The Student Edition of SIMULINK*, Prentice-Hall, Englewood Cliffs, NJ.

De La Cruz, J. M., Aranda, J., Giron-Sierra, J.M., Velasco, F., Esteban, S., Diaz, J.M., and Andres-Toro, B. 2004 Improving the comfort of a fast ferry, *IEEE Control Systems Magazine*, 24, 2, 47.

De La Cruz, J. M., Aranda, J., Ruipérez, P., Díaz, J. M., and Maron, A. 1998 Identification of the vertical plane motion model of a high speed craft by model testing in irregular waves, *Proceedings*, IFAC Conference, Control Applications in Marine Systems, October, Fukuoka, Japan, 277.

Esteban, S., De Andres, B., Giron-Sierra, J. M., Polo, O. R., and Moyano, E. 2001 A simulation tool for a fast ferry control design, *Proceedings*, IFAC International Conference, Control Applications in Marine Systems, July, Glasgow, UK.

Esteban, S., De La Cruz, J. M., Giron-Sierra, J. M., De Andres, B., Diaz, J. M., and Aranda, J. 2000 Fast ferry vertical acceleration reduction with active flaps and T-foil, *Proceedings*, IFAC International Symposium on Maneuvering and Control of Marine Craft, August, Aalborg, Denmark, 233–238.

Ewing, G. A., and Goodrich, G. J. 1967 The influence on ship motions of different wave spectra and of the ship length, *Transactions of the Royal Institution of Naval Architects*, **109**, 47.

Ferdinande, V., and De Lembre, R. 1970 Service-performance and seakeeping trials of a car-ferry, *International Shipbuilding Progress*, **17**, 196, 361.

Fossen, T. I. 1994 *Guidance and Control of Ocean Vehicles*, John Wiley, New York.

Giron-Sierra, J. M., Esteban, S., De Andres, B., Diaz, J. M., and Riola, J. M. 2001 Experimental study of controlled flaps and T-foil for comfort improvement of a fast ferry, *Proceedings*, IFAC International Conference, Control Applications in Marine Systems, July, Glasgow, UK.

Hanselman, D., and Littlefield, B. 1997 *The Student Edition of MATLAB*, Prentice-Hall, Englewood Cliffs, NJ.

Havelock, T. 1955 The coupling of heave and pitch due to speed of advance, *Transactions of INA*, **98**, 246.

Korvin-Kroukovsky, B. V. 1955 Investigation of ship motions in regular waves, *Transactions of the Society of Naval Architects and Marine Engineers*, **63**, 386.

Korvin-Kroukovski, B. V., and Jacobs, W. R. 1957 Pitching and heaving motions of a ship in regular waves, *Transactions of the Society of Naval Architects and Marine Engineers*, **65**, 590.

Kuo, B. C. 1987 *Automatic Control Systems*, Prentice-Hall, Englewood Cliffs, NJ.

Lewis, E. V. 1959 Increasing the sea speed of merchant ships, *Transactions of the Society of Naval Architects and Marine Engineers*, **67**, 757.

Lewis, E. V. 1989 *Principles of Naval Architecture*, Society of Naval Architects and Marine Engineers, Jersey City, NJ.

Lloyd, A. R. J. M. 1989 *Seakeeping: Ship Behaviour in Rough Weather*, A.R.J.M. Lloyd, Hampshire, UK.

Moret, J. A., Perez De Lucas, A., and Tejedor, J. L. 1993 Fast ferry MESTRAL: a reliable answer in fast ferry design, *Proceedings*, FAST'93, December, Yokohama, Japan, 1269.

O'Hanlon, J. F., and McCawley, M. E. 1974 Motion sickness incidence as a function of frequency and acceleration of vertical sinusoidal motion, *Aerospace Medicine*, 45, 366.

Polo, O. R., Esteban, S., Maron, A., Grau, L., and De La Cruz, J. M. 2001 Control code generator used for control experiments in ship scale model, *Proceedings*, IFAC International Conference, Control Applications in Marine Systems, July, Glasgow, UK.

Salvesen, N., Tuck, E. O., and Faltinsen, O. 1970 Ship motions and sea loads, *Transactions of the Society of Naval Architects and Marine Engineers*, **78**, 250.

Shahian, B., and Hassul, M. 1993 *Control System Design Using MATLAB*, Prentice-Hall, Englewood Cliffs, NJ.

Silvia Ana: results of first year's service. 1998 *Ship and Boat International*, January/February, 15.

Skorupka, S., and Perdon, P. 1993 Comfort inquiry and motion measurement during commercial passenger service on the French S.E.S. Agnes 2000, *Proceedings*, FAST'93, Yokohama, Japan, December, 1.

Van Sluijs, A., and Gie, T. S. 1972 Behaviour and performance of compact frigates in head seas, *International Shipbuilding Progress*, **19**, 210, 35.

Appendix

This MATLAB program obtains a transfer function that fitted to a frequency response.

```
%ga: gains;
%ph: phases (deg). Negative phase means to be delayed;
%w: frequencies of encounter (rad/s);
OrdN=5; %(Numerator order, selected by the user)
OrdD=6; %(Denominator order, selected by the user)
%Fitting using least squares
cmp=ga.*exp(j*ph*pi/180);
[B,A]=invfreqs(cmp,w,OrdN,OrdD);
sysc=tf(B,A), %Make a LTI system
%Plotting and Evaluating the RAO and Phase
[mf,ff]=bode(sysc,w); mf=squeeze(mf)f=squeeze(ff);
figure;
subplot(1,2,1)+ot(w,ga,'o',w,mf,'-')pid on;
subplot(1,2,2)+ot(w,ph,'o',w,ff,'-')pid on;
```