FREQUENCY-DOMAIN MODEL OF FAST FERRY VERTICAL MOTIONS

Segundo Esteban[1], Jesus M. de la Cruz[1], Jose M. Giron-Sierra[1], Bonifacio de Andres[1], Luis Grau[2]

[1] *Dept. Arquitectura de Computadores y Automatica, Universidad Complutense de Madrid.*
Ciudad Universitaria, 28040 Madrid. Spain.
Tf:34913944387; Fax:34913944687; e-mail: segundo@dacya.ucm.es

[2] *Dept. Informatica y Automatica, Universidad Nacional de Educacion a Distancia*

SUMMARY: The negative effects of vertical motions can limit the speed of fast ships. By means of active control surfaces, it is possible to alleviate vertical motions. But these surfaces should move in a suitable way, according to a control strategy. To design this strategy, a good control-oriented model of the vertical dynamics of the ship is welcome. Our research deals with the frequency-domain modelling of a high-speed aluminium-made ferry. The model is used to design the control to improve comfort, decreasing the impact of heave and pitching motions. MATLAB has been used to formulate the model, to provide a suitable environment for control studies. The model development is based on experimental data from a towing tank institution, and simulations with PRECAL. The results obtained, the model, shows good agreement with the experimental and simulated data for regular and irregular waves. As an application example, the model is used for the design of a PID controller for active flaps and a T-foil.

INTRODUCTION

Speed is important for fast-ferries. But there are vertical motions with negative consequences for the comfort of passengers and for the ship behavior. Speed must be reduced, unless the ship has the means to counteract the effect of waves. In the case we are dealing with, the ship actually has several active control surfaces for such purpose. The problem to be solved is to move in the most effective way the control surfaces. To analyze this problem, in order to find a good control method, we need a mathematical model of the pitching and heaving motions of the ship, in response to waves. A suitable approach for the model is in the form of transfer functions.

With transfer functions, several control alternatives (for instance, the conventional PID) can be tested on computer, and tuned for the best performances. Taking from experiments digitized data of the waves, it is possible to predict on computer what will be the vertical motions of the ship at several speeds.

Our research concerns a specific ship, with head seas. Using a small scale replica, a series of experiments have been performed by a towing tank institution (CEHIPAR: Canal de Experiencias Hidrodinamicas de El Pardo, Madrid). The experimental results obtained constitute the basis to establish the model. In addition, the scientific literature provides the pertinent elements for analysis. The fundamental aspects are studied in the books of Lloyd (1), Lewis (2) and Fossen (3). Specifics on ship motions are considered in Korvin-Kroukovski (4), Korvin-Kroukovski and Jacobs (5) for regular waves, and completed in Salvesen, Tuck and Faltinsen (6). With regard to the problems related to speed, the article of Lewis (7) makes a good account, including actuators to alleviate vertical motions.

The paper begins with a short description of the ship, the experimental data and the analysis based on physics. Then, by means of decomposition into two main blocks, the model is developed. Finally, the model is validated. The results obtained are satisfactory, as demonstrated with several comparisons between actual and predicted dynamic behaviors of the ship.

Since MATLAB is a "de-facto" standard for the automatic control studies on computer (8), the model is developed in MATLAB. References (9,10,11,12) describe our previous work about vertical motions of the ship.

1. BASIS OF THE MODELLING

1.1. The Ship

The target of our research is a fast-ferry working in La Plata and in the Baltic Sea. She is a mono-hull aluminium-made ship. Figure 1 shows a photograph of the ship, and figure 2 depicts a lateral view.

Figure 1: photograph of the ship

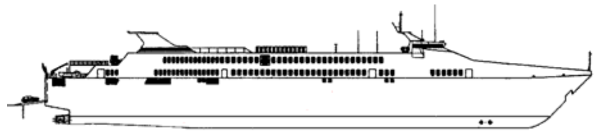

Figure 2: lateral view

Table 1 summarizes the main characteristics of the ship, and the scaled-down dimensions of the replica made by CEHIPAR.

Characteristics	Ship	Replica
Length	110 m	4.4 m
Beam	14.696 m	0.588 m
Draught	2.405 m	0.096 m
Zcg	7.6 m	0.304 m
Deadweight	475 Tons	
Power	4x5650 kW	
Load	1250 Passengers 230 Cars 4 Buses	
Speed	40 Knots	

Table 1: Characteristics of the ship

1.2. Experimental Data

Making use of the CEHIPAR facilities, a replica, with the dimensions given in table 1, has been built, and several experimental studies have been performed.

The main experimental information has been obtained in a pool (150x30x5 m.) with a wave generator of 60 blades. The replica is moved by a CPMC (Computerized Planar Motion Carriage). There is a set of sensors in the replica, to measure vertical motions. The experimental data obtained by the sensors, are digitized and saved as computer files. With these data files, the temporal evolution of the measured variables can be recovered and analyzed

The experimental design accomplished comprises tests for both regular and irregular waves, at speeds of 20, 30 and 40 knots. For regular waves, 15 different values of wavelengths have been generated. The tests with irregular waves have been done for sea states SSN4, 5 and 6.

There are computer programs that, starting from the geometry of the hull, can predict heaving and pitching motions. Actually, CEHIPAR has PRECAL: one of these programs. Taking advantage of PRECAL, a set of predictions has been calculated and used as complementary data for the model development.

1.3. Analysis based on Physics

The chief phenomenon observed as a basis for the modeling, is the coupling between the ship length and the distance among consecutive waves. When the ship rests on two or more waves, there will be small heaving and pitching motions. But, increasing the distance between waves removes the relief of the ship, and vertical accelerations become significant. In any case, the forces exerted by the waves, originate effects that will depend on the dynamic characteristics of the ship (a semi-submerged body in motion).

From the point of view of physics, we can start with the equations given by Lloyd (1) for vertical motions:

$$(m_{33} + a_{33})x_3'' + b_{33}x_3' + c_{33}x_3 + a_{35}x_5'' + b_{35}x_5' + c_{35}x_5 = \\ = (F_3 U)_{\gamma 3} \qquad (1)$$

$$(m_{55} + a_{55})x_5'' + b_{55}x_5' + c_{55}x_5 + a_{53}x_3'' + b_{53}x_3' + c_{53}x_3 = \\ = (F_5 U)_{\gamma 5} \qquad (2)$$

The right-hand sides of the equations are the forces exerted by the waves. The left-hand sides of the equations constitute a model of the response of the ship (vertical motions) to these forces. Notice the coupling between both equations (1) and (2), according to ij coefficients. The notation is as follows:

- m_{33} is the mass of the ship.
- m_{55} is the moment of inertia related to the pitch.
- a_{ij} is the added mass.
- b_{ij} is the damping coefficient.
- c_{ij} is the restoring coefficient.
- U is the input (waves).
- F_i is the gain of the model Waves-to-Forces.
- γ_i is the phase of the model Waves-to-Forces.

The program PRECAL provides the values of the equations coefficients for a specified set of frequencies of encounter. Some of the coefficients remain fixed, and are given by Table 2. Others do change, as depicted in figures 3,4,5 and 6. The fact that some parameters change with ship's speed and the frequency of encounter, indicates that we are in the presence of non-linearities. However, linear models are most useful for control study, so we shall select the adequate linear model for each work condition.

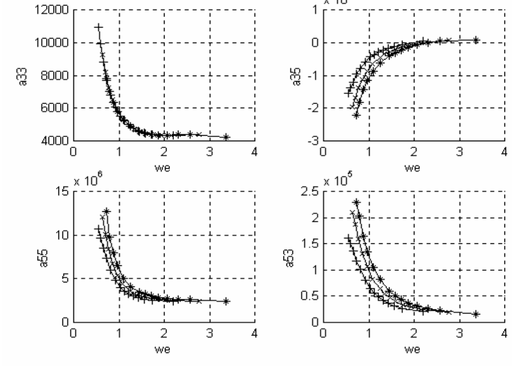

Figure 3: Added mass.

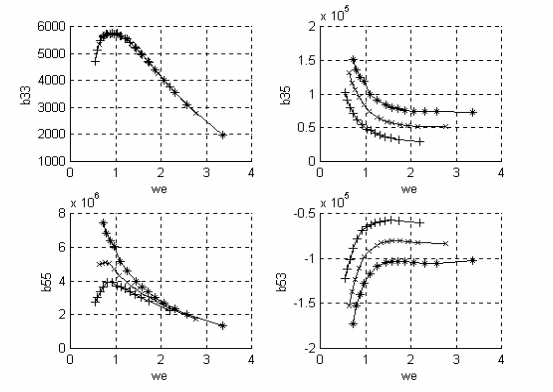

Figure 4: Damping coefficients.

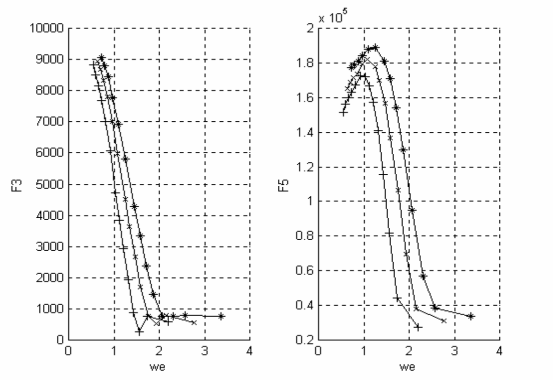

Figure 5: Force and Moment RAOs.

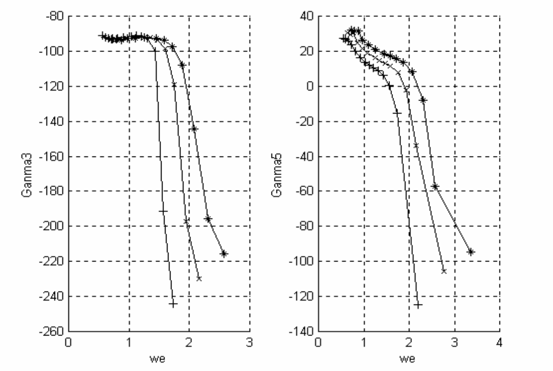

Figure 6: Force and Moment phases.

Coefficient	Value
m_{33}	1770
m_{55}	1339100
c_{33}	12128
c_{55}	8419000
c_{35}	-22857
C_{53}	-22857

Table 2: Fixed parameters

It is our experience that better results are obtained if, instead of considering the phases of the forces with respect to the c.o.g., center of gravity, these phases are referred to the bow.

2. MODEL DEVELOPMENT

Based on equations (1) and (2), the model can be considered as composed of two main blocks connected in series, as depicted in the diagram of figure 7. One of the blocks (denoted as "Waves-to-Forces") corresponds to the right-hand sides of the equations. The other block ("Forces-to-Ship") corresponds to the left-hand sides of the equations.

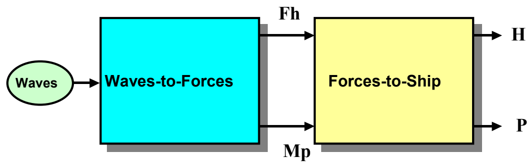

Figure 7: Block diagram of the model

2.1.Modelling of the 'Waves-to-Forces' Block

As depicted in the diagram of figure 8, the block "Waves-to-Forces" is decomposed into two single-input single-output blocks, which correspond to the transfer functions WFH(s) and WMP(s), to be determined. The transfer function WFH(s) models the vertical force on the c.o.g. due to waves. The transfer function WMP(s) models the pitching moment due to waves.

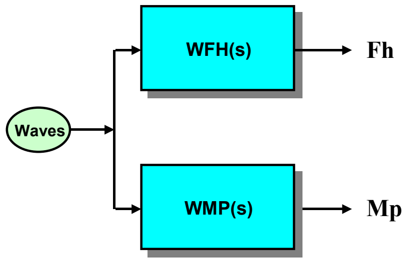

figure 8: Decomposition of "Waves-to-Forces"

Abrupt changes are observed when plotting the amplitude and phase of forces and moments, against frequency of encounter (figures 5 and 6). Trying to adjust with transfer functions reveals as a difficult task. A set of combinations of complex-conjugate poles and zeros has been tried, with poor results: when amplitude is adjusted, phase fails, and vice-versa.

To cope with these difficulties, a novel approach was devised. The idea is to model by a manageable set of discrete elements, along the hull, the Froude-Krylov forces (predominant at low and medium frequencies of encounter). Hence, a shift-register is stated, to keep the profile of the waves along the hull. The wave that strikes the bow, is the wave that enters the shift-register. Each stage of the shift-register contains a sample of the profile of the waves. The same sampling period that is used by CEHIPAR, to save experimental data into computer files, is employed by the shift register: 0.25 sec. Figure 9 shows a diagram of the approach.

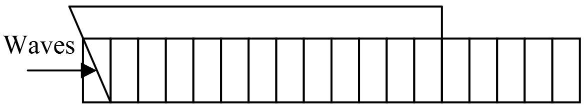

Figure 9: Keeping a record of waves along the hull.

The wavelength and the frequency of waves, in deep waters, have the following relationship:

$$\lambda = \frac{2 \cdot \pi \cdot g}{w_0^2} \qquad (3)$$

This equation guide us to evaluate how many shift-register stages are sufficient for our modeling purposes. From the information given by the shift-register, heave force is easy to calculate. For the pitch moment, distances of each stage to the c.o.g. are considered, as radii.

Once adjusted the shift-register model to the amplitudes and phases given by PRECAL, the next task is to deduce a linear model. First, the shift-register is described as a discrete transfer function. The order of the discrete transfer function will be the number of stages of the shift register. This number is a function of the ship's speed, the frequency of waves and the length of the ship. For instance, taking V = 30 knots, and w_o = 0.62 rad/s, the transfer functions of heave and pitch, both have 11 poles at the origin, and 10, 11, zeros respectively. By means of the Tustin approximation (see for instance Ogata (13)), equivalent continuous transfer functions can be obtained.

This procedure has been applied for the dominant frequencies of waves for sea states SSN4, 5 and 6. It has been verified that the models obtained for each dominant frequency, can be chained to cover the entire frequency range of interest, with a good agreement to the data.

The order of the continuous transfer functions are somewhat excessive for analysis work. There are MATLAB functions intended for model order reduction , that can be useful to get a more manageable, simplified model. Specifically, the functions "balreal" and "modred" allow us to obtain a good approximation by transfer functions of 4th order:

$$WFH(s) = 2408 \cdot \frac{s^4 - 3.48s^3 + 24.56s^2 - 16.10s + 58.77}{s^4 + 3.92s^3 + 9.61s^2 + 12.11s + 6.63} \qquad (4)$$

$$WMP(s) = 66180 \cdot \frac{-s^4 + 5.40s^3 - 10.87s^2 + 35.56s - 15.76}{s^4 + 3.97s^3 + 9.97s^2 + 12.39s + 6.87} \qquad (5)$$

Figures 10 and 11 show a comparison of the original transfer functions (11th order), and the approximated transfer functions (4th order), by plotting the amplitude of the functions against frequency of encounter.

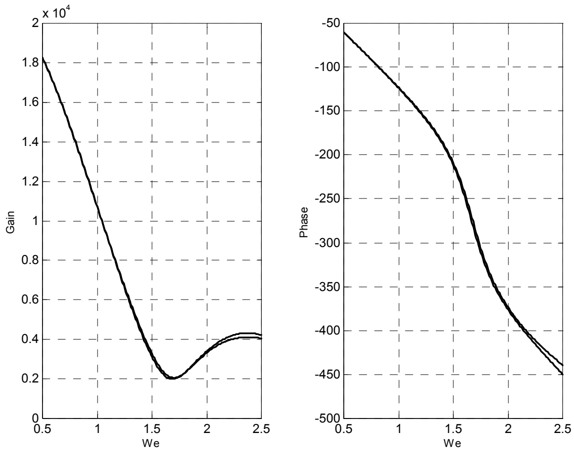

Figure 10: Original (__) and approximated(_ _) WFH.

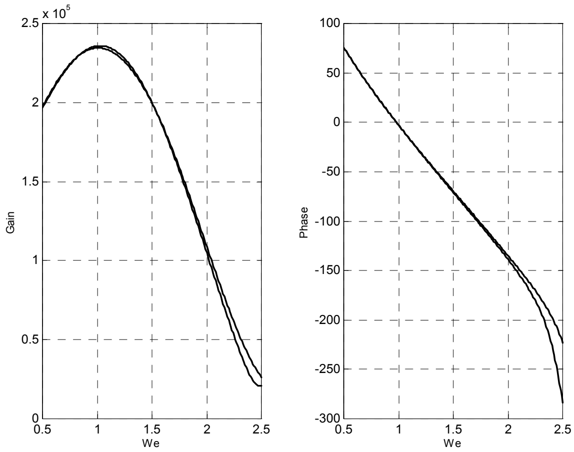

Figure 11: Original (__) and approximated (_ _) WMP.

The curves of figures 10 and 11 show a good agreement for the frequencies of interest, with the differences appearing at high frequencies. In consequence, the approximation can be considered as satisfactory for our purposes.

The continuous transfer functions obtained, constitute a model of "Wave-to-Forces". The data provided by PRECAL, about the forces for different frequencies of encounter, allow us to validate the model. Figures 14 and 15 show plots of the PRECAL data points and the curves corresponding to the continuous transfer functions for a velocity of 30 Knots. The figures display the curves as three parts: each part corresponds to a transfer function (a transfer function for SSN4, other for SSN 5, and the last for SSN6). A good agreement is noticeable for the frequencies (medium and low) of interest. For the high frequencies, difraction forces, not considered by the shift-register model, become more important and the curves differ a little from the data points.

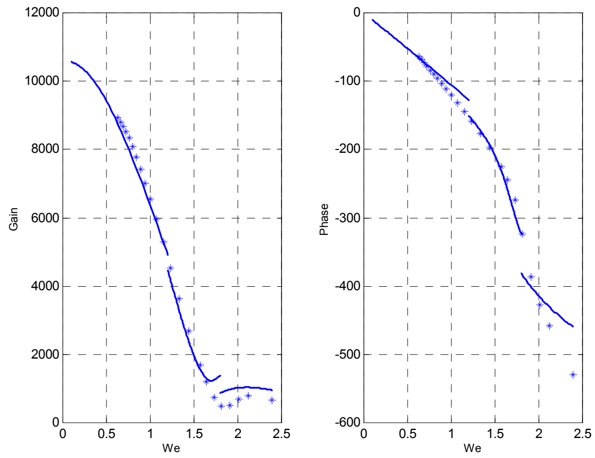

Figure 14: Comparison of data and model WFH

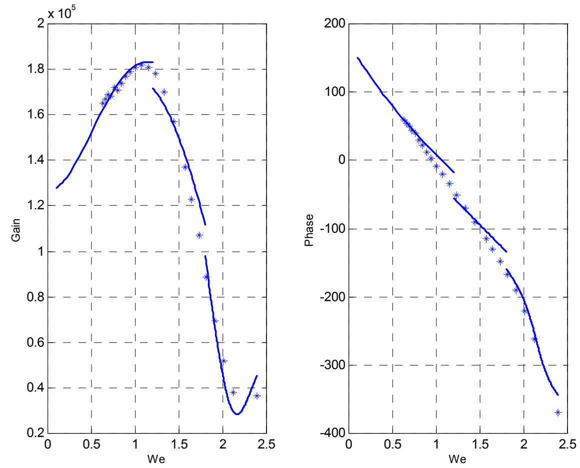

Figure 15: Comparison of data and model WMP.

2.2. Modelling of the 'Forces-to-Ship' Block

From the left-hand sides of equations (1) and (2), it is easy to obtain a state-space version, by assigning the following state variables:

$$z_1 = x_3, z_2 = x_3', z_3 = x_5, z_4 = x_5' \quad (6)$$

With these variables, and decoupling the equations, the following expression is obtained:

$$\begin{bmatrix} z_1' \\ z_2' \\ z_3' \\ z_4' \end{bmatrix} = A \bullet \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} + B \bullet \begin{bmatrix} (F_3U)_{\gamma 3} \\ (F_5U)_{\gamma 5} \end{bmatrix} \quad (7)$$

In this expression there are terms concerning not only direct effects (for instance pitching moment on pitch motion), but also cross-couplings (for instance, pitching moment on heave motion). It is interesting to distinguish each effect, and this is possible with the help of the "ss2tf" MATLAB function. Using this tool, It is easy to obtain a decomposition of the "Forces-to-Ship" block into four single-input single-output blocks (each one a transfer function). Figure 16 shows a diagram of the decomposition.

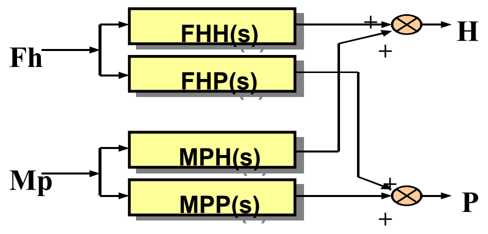

Figure 16: Decomposition of "Forces-to-Ship"

The connections between the four blocks of the model, clearly show the direct effects and the cross-couplings. The four transfer functions of the model, are the following:

$$FHH(s) = 1.21 \cdot 10^{-4} \cdot \frac{s^2 + 0.62s + 1.05}{s^4 + 1.31s^3 + 3.10s^2 + 1.63s + 1.53} \quad (8)$$

$$FHP(s) = 1.42 \cdot 10^{-6} \frac{-s + 0.24}{s^4 + 1.31s^3 + 3.10s^2 + 1.63s + 1.53} \quad (9)$$

$$MPP(s) = 1.24 \cdot 10^{-7} \cdot \frac{s^2 + 0.69s + 1.47}{s^4 + 1.31s^3 + 3.10s^2 + 1.63s + 1.53} \quad (10)$$

$$MPH(s) = 1.66 \cdot 10^{-6} \frac{s + 0.21}{s^4 + 1.31s^3 + 3.10s^2 + 1.63s + 1.53} \quad (11)$$

3. VALIDATION OF THE MODEL

The complete model is a cascade connection of the "Waves-to-Forces" model and the "Forces-to-Ship" model (figure 7).

To validate the complete model, the same waves of the CEHIPAR experiments with the replica (as saved on computer files), will be applied to the model. Then, the responses of the replica, and the model, to the same waves, will be compared.

Figures 17 and 18 show a part of the results. The figures display the temporal response of the replica and of the model for a velocity of 30 knots and a SSN of 5. For the complete record of waves and responses, the agreement between replica and model is really good. In particular, pitch is very well modeled for every combination of ship speeds and sea states. Heave is also very well modeled for sea states 5 and 6; for state 4 there are slight errors for the small waves (for these waves, even the experimental measurements contain significant errors).

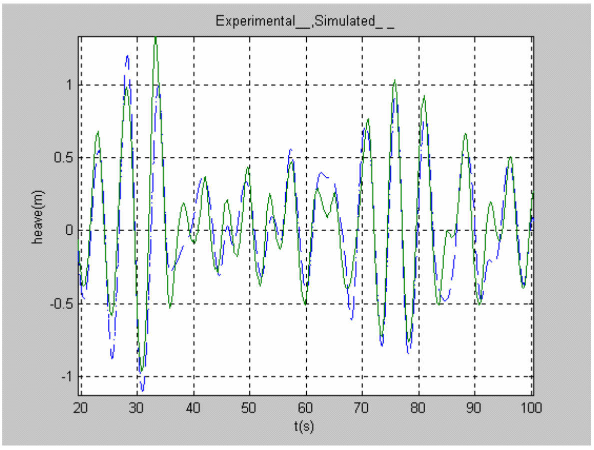

Figure 17: Heave validation.

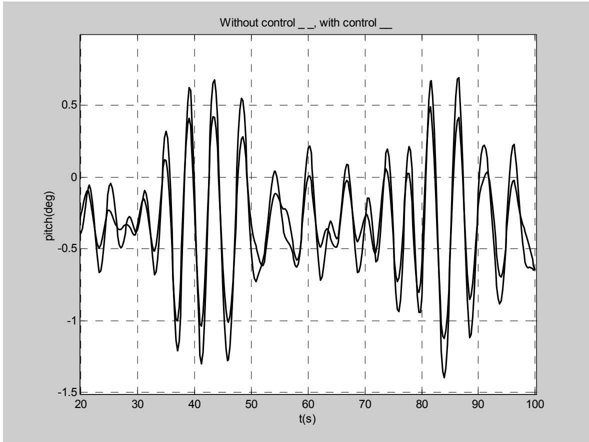

Figure 20: Effect of control on pitching.

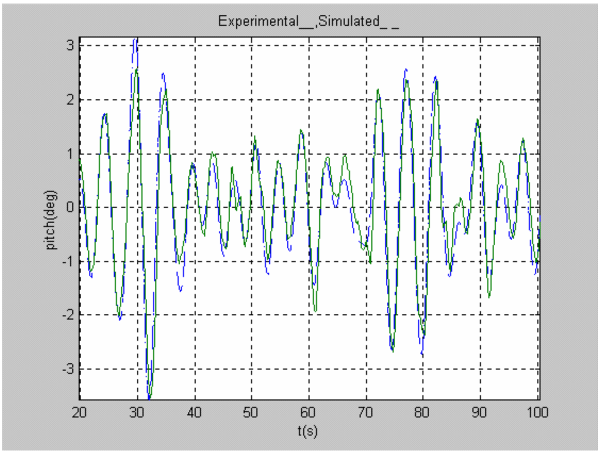

Figure 18: Pitch validation.

4. STUDY OF A PID CONTROL

A first study of what can be expected from actuators and PID control has been accomplished. Figure 19 shows a diagram of the system that has been analyzed: it is a feedback connection, including the model of the ship. This structure can be easily translated to a MATLAB program, and used to test and tune the PID.

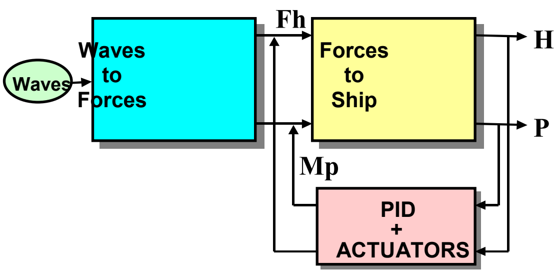

Figure 19: Diagram of the ship under PID control

The actuators considered are transom flaps and a T-foil near the bow. Both actuators can move, under PID control, to counteract the effect of waves. Figure 20 shows the attenuation of pitch motions at 30 knots and SSN4 by a well-tuned PID.

5. CONCLUSIONS

From both experimental and simulated data, and based on physics principles, a control oriented model of a fast-ferry has been elaborated.

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.

The model is now in use for control design purposes. First results for a conventional PID, transom flaps and a T-foil have been presented. These results are a reference, for further control improvement.

ACKNOWLEDGEMENTS:

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