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NEURO-FUZZY MODELLING OF A FAST FERRY VERTICAL MOTION

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Abstract: A neuro-fuzzy system has been developed to model the behaviour of a fast ferry. The sources of the available knowledge are the physical laws of the vertical dynamics of the craft, and some experimental and simulated data of the ship performance in regular waves. The non-linear model has been obtained by applying adaptive neurofuzzy inference. It is focus on the vertical motion of the craft, both heave and pitch. The modelling problem is complex and the results are original, and have been proved satisfactory for regular waves. *Copyright © 2002 IFAC*

Keywords: Neuro-Fuzzy Modelling, Marine Systems, Vertical Motion, Ship Control, MIMO.

1. INTRODUCTION

Ship motion is a complicated issue to model. Dealing with high-speed crafts, the description of their behaviour is very complex because of the strongly non-linearities. The model of the system changes with the ship speed and the Sea State in a non-linear way. Some of its parameters are coupled, and others are variable. Although some simplifications can be applied, there is still some uncertainty, which is difficult to deal with.

Because all of this, an accurate and general mathematical model is difficult to achieve. In addition, the uncertainty that comes from the sea waves encourages to deal with wide broad models, which can incorporate knowledge about the system.

Therefore, developing a non-linear fuzzy model seems an adequate solution to incorporate the available experimental knowledge about the ship behaviour. On the other hand, fuzzy logic allows us to deal with the uncertainty that involves these kind of complex processes. As far as we know, there has been no previous fuzzy models of these marine systems.

The research deals with a fast ferry called “Silvia Ana”. Currently, the ferry Silvia Ana works in La Plata and in the Baltic Sea. The craft has an aluminium-made deep V hull, and the following characteristics: 110 m length, 14.696 m beam, 2.405 m draught, 475 tons dead weight, 1250 passengers (Anonymous, 1996), (Anonymous, 1998).

The main goal of dealing with these systems is to stabilise the motion of the craft for some purposes such as improve the comfort of the passengers, maintaining the speed. The main impact on the behaviour in this aspect is caused by the vertical acceleration, both heave and pitch motions. The vertical acceleration originates the seasickness, which can be measured by an index, the MSI (Motion Sickness Incidence). In order to control this system and reduce the vertical acceleration, a model is needed. Then, some appendages such flaps and T-foils can be added to counteract the motion due to the sea waves.

The model consists of three fuzzy inference systems (FIS), which provide the amplitude and phase of the vertical motion (heave and pitch), and the final pitch moment of the ship, as a function of the modal wave frequency, the ship speed and the heading angle.

These FIS are implemented by applying adaptive neuro-fuzzy techniques to the experimental and simulated data which have been collected and provided by CEHIPAR (Cehipar, 1998), a specialised towing tank. Although the experimental environment can be considered to be different from that in the Baltic Sea, the normal sailing conditions (small or moderate waves) are not so different.

The paper is organised in 4 sections. Section 2 presents the general equations for ship motion, remarking the role of some coefficients and the coupling between heave and pitch motions. Section 3 shows a description of the ferry behaviour based on experimental data, and deals with the development of the model, by applying adaptive neuro-fuzzy techniques. Some results show the performance of the model. Section 4 summarizes the conclusions.

2. SHIP DYNAMIC

Understanding the dynamic of the system in a qualitative way is essential in order to develop a fuzzy model. Many aspects of the ship behaviour depend on the general laws of fluid flow. The main source of knowledge is always a deep knowledge of the physics of the problem. An extensive and rigorous literature on this subject has been worked out. The key issues of the ships motion are considered in Lloyd (1998), Lewis (1989) and Fossen (1994).

The ship is not only under the influence of the waves, wind, ocean currents, etc., but also its own inertia, the added mass, the hydrodynamic damping, and the stiffness forces. The system of six general linearised equations that describes the physical motion of the craft for small amplitude motions in regular waves can be written (Lloyd, 1998),

$$\sum_{j=1}^{6}\left(A_{ij}\frac{d^2 x_j}{dt^2}+b_{ij}\frac{dx_j}{dt}+c_{ij}x_j \right)=F_{\omega_{i0}}\sin(\omega_e t+\varphi_i), \quad (1)$$

$$i=1,\ldots,6$$

where each one of the three terms on the left-hand side of the equation refers to the inertia, the damping and the stiffness forces, respectively. The ship has linear accelerations, $\ddot{x}_1$, $\ddot{x}_2$, and $\ddot{x}_3$ *m/s*^{2}, and angular accelerations, $\ddot{x}_4$, $\ddot{x}_5$, and $\ddot{x}_6$ *rad/s*^{2}.

The excitation amplitude, $F_{\omega io}$, and the phase, φ_i, are given by,

$$F\omega_{i0}=\delta_o\sqrt{(c_i-a_i\omega_e{}^2)^2+(b_i\omega_e)^2} \qquad (kN)$$

$$\tan\varphi_i=\frac{b_i\omega_e}{c_i-a_i\omega_e{}^2}$$

where δ_o is the wave amplitude.

The encounter frequency, ω_e, is defined as the frequency at which the ship and a train of regular waves meet. It is a function of the frequency of the waves, ω_o, the speed of the craft, U, and the heading angle, μ, angle relative to the direction of propagation of a train of regular waves. The formula in deep water is given by (Lloyd, 1998),

$$\omega_e=\omega_o-\frac{\omega_o{}^2}{g}\mathrm{U}\cos\mu \quad (rad/s) \qquad (2)$$

The wave modal frequency, ω_0, can be obtained by Pierson-Moskowitz spectrum formula, where $H_{1/3}$ is the observed significant height of the waves,

$$\omega_0=0.4\sqrt{\frac{g}{H_{1/3}}}=\frac{1.2526}{\sqrt{H_{1/3}}} \quad (rad/s) \qquad (3)$$

In addition, simulated data about the ship motion in ideal regular waves have been provided by CEHIPAR and computed by using the computer program PRECAL (based on finite elements). In this way, some estimated values of the frequency of the waves are listed in Table 1.

Table 1: Modal wave frequency estimated

Estimated values of the frequency of the waves based on the observed height of the waves

Pierson-Moskowitz spectrum		*slope 50*		*slope 40*		*slope 30*	
H1/3	w0	H50	w0	H40	w0	H30	w0
0,050	5,6029	0,770	1,2652	0,963	1,2652	1,283	1,2652
0,300	2,2874	1,122	1,0482	1,403	1,0482	1,870	1,0482
0,875	1,3393	1,540	0,8947	1,925	0,8947	2,567	0,8947
1,875	0,9149	1,760	0,8369	2,200	0,8369	2,933	0,8369
3,250	0,6949	2,002	0,7847	2,503	0,7847	3,337	0,7847
5,000	0,5603	2,266	0,7375	2,833	0,7375	3,777	0,7375
7,500	0,4575	2,530	0,6981	3,163	0,6981	4,217	0,6981
11,500	0,3694	2,816	0,6617	3,520	0,6617	4,693	0,6617
14,000	0,3348	3,124	0,6282	3,905	0,6282	5,207	0,6282
		3,784	0,5708	4,730	0,5708	6,307	0,5708
		4,488	0,5241	5,610	0,5241	7,480	0,5241
		5,280	0,4832	6,600	0,4832	8,800	0,4832
		6,116	0,4490	7,645	0,4490	10,193	0,4490
		7,018	0,4191	8,773	0,4191	11,697	0,4191
		7,986	0,3929	9,983	0,3929	13,310	0,3929

Based on these values, the modal frequency may also be estimated by means of $H_{1/3}$ when using the expression,

$$\omega_0=1.1103/\sqrt{H_{1/3}} \quad (rad/s) \qquad (4)$$

which is very similar but a little lower than (3). From now on, this modal frequency as defined in (4) will be used to characterise the Sea State Number (SSN), according to the World Meteorological Organisation (WMO). The experimental data corresponding to frequencies close to each modal frequency are grouped and related to one specific SSN. The behaviour of the system for a fixed SSN can be associated with sinusoidal signals, whose frequencies are the modal wave frequencies.

Figure 1 shows the encounter frequency vs. the modal frequency of the waves (for different ship speed). These data have been obtained by substituting the data provided by CEHIPAR into (4) for ω_o and applying (2) to calculate ω_e. As it can be seen, it reaches negative values for speed larger than 20 knots in following seas and high modal frequencies (SSN 5, 4 and 3).

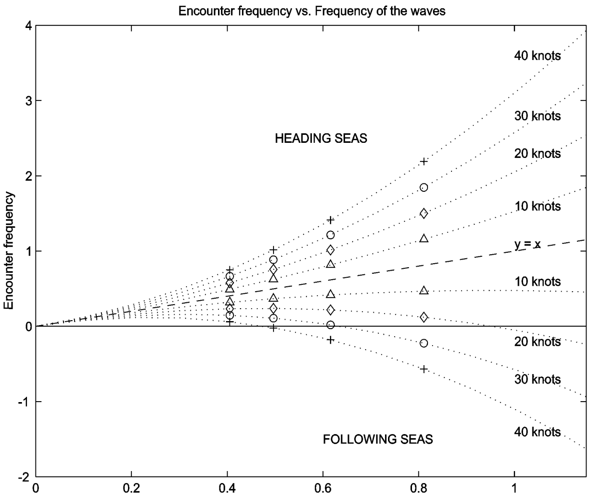

Fig. 1: Encounter frequency vs. wave frequency

The relationship between ω_e and U$\cos\mu$ (the component of the velocity of the ship in the direction of wave propagation) is plotted in Figure 2, for different wave frequencies. In this figure, negative values of U$\cos\mu$ mean heading sea. As it shows, for a fixed SSN and in head waves, increasing the ship speed causes a linear increment in the encounter frequency. On the other hand, for fixed SSN and following seas, the encounter frequency falls linearly if speed increases. In this case, although the positive and larger values of the factor Ucosμ, the encounter frequency can reach negative values.

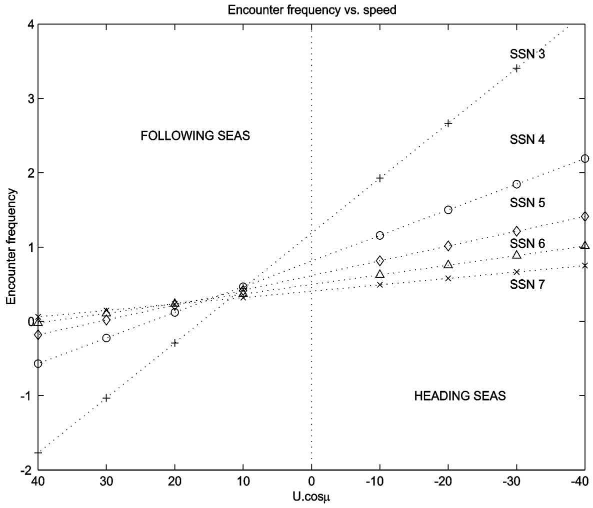

Fig. 2: Encounter frequency vs. Ucosμ

Going back to (1), the coefficients (local inertia, damping and stiffness) are not constant, and depend on the wave frequency (or the wavelength), the ship speed and the hull shape.

Being *m* the total mass in tonnes and *I* the mass moments of inertia of the ship, the acceleration coefficients A_{ij} consist of the inertia mass ($A_{ij} = m_{ij} + a_{ij}$, $i = j = 1, 2, 3$), and the added mass ($A_{ij} = I_{ij} + a_{ij}$, $i = j = 4, 5, 6$), which depends also on the heading angle. It is needed to remark that this system performs with large inertial forces (Figure 3).

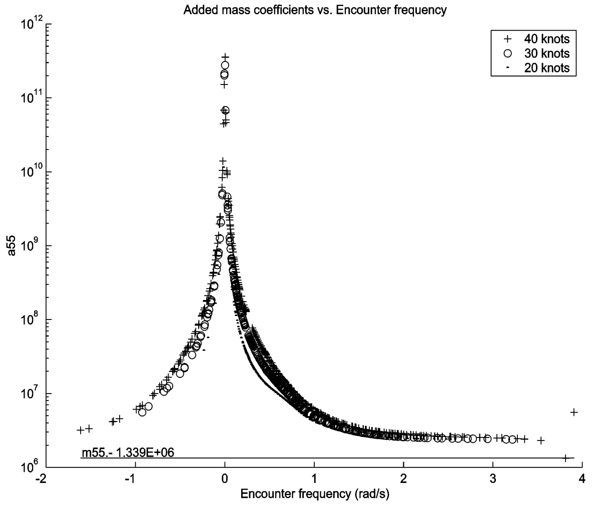

Fig. 3: Added mass coefficients vs. ω_e frequency

If the real mass of the ship is represented as m_{55} or I_{55}, the figure shows that, at $\omega_e \approx 2$ rad/s, the added or virtual mass, a_{55}, is twice the real mass (2.08 times), and it increases when decreasing ω_e to 0 rad/s. For example, at 40 knots, the added mass is 4.33, 20.34 and 20.01 times I_{55} when $\omega_e = 1.0158$, 0.5030 and –0.5080 *rad/s*, respectively. That means that the frequency range of interest will be around 1 *rad/s*, where the largest vertical acceleration is reached, as it will be shown in Section 3.

When plotting the behaviour of the damping coefficients, b_{55}, the maximum is reached at frequency $\omega_e \approx$ 0-1 *rad/s*.

Since the model is focused on particular aspects, certain simplifications can be applied. Based on experimental data and the port/starboard symmetry of the craft, some of the coefficients have been found to be zero or negligible and other are constant. The motions that remain coupled are pitch and heave. Therefore, the initial study is focused on heave and pitch motions with heading sea.

3. NEURO-FUZZY MODELLING

A qualitative understanding of the behaviour of the ship helps to develop the model. The more interesting observed aspect is the coupling of the ship length and the distance between consecutive waves, as it is reflected in the literature. In fact, if the ship lies on two or more waves, there will be small heave and pitch motions. In the same way, increasing the distance between waves removes the relief of the ship. Then, 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.

Recasting system (1), the equations for heave ($j = 3$) and pitch ($j = 5$) motions can be seen as,

$$(m_{33}+a_{33})\ddot{x}_3(t)+b_{33}\dot{x}_3(t)+c_{33}x_3(t)=F_{30}\sin(\omega_e t+\varphi_3)$$
$$(I_{55}+a_{55})\ddot{x}_5(t)+b_{55}\dot{x}_5(t)+c_{55}x_5(t)=F_{50}sin(\omega_e t+\varphi_5)$$

Solving the system with initial conditions $x_j = 0$, $\dot{x}_j = 1$ (Ziegler, 1968) for different ship speed values and different encounter frequencies, it is possible to prove that the steady state solution for the pitch signal are sinusoidal functions,

$$x_5(t)=x_{50}\sin(\omega_e t+\varphi_5) \qquad (5)$$

$$\ddot{x}_5(t)=-x_{50}\omega_e^2\sin(\omega_e t+\varphi_5)=-\omega_e^2 x_5(t) \qquad (6)$$

where x_{50} is the maximum pitch amplitude and φ_5 is the phase. The same type of solution can be found for heave motion. These equations will be used to obtain the graphics of the ship behaviour when applying the experimental data supplied by Precal (x_{50}, φ_5, x_{30}, φ_3).

3.1 *Qualitative Behaviour of Pitch Motion*

To get some insight into the model, pitch excitation, F_{50}, and pitch acceleration, x_5, are represented as a function of the encounter frequency for different ship speed. The experimental design accomplished (Cehipar, 1998) consists of tests for regular waves, at speed of 20, 30 and 40 knots, and different sea state codes (ω_o = {0.3930 to 1.1470 rad/s}). Applying subtractive clustering and training the fuzzy inference system, a first approximation of a general fuzzy model is obtained for each case. For instance, Figure 4 and Figure 5 show the behaviour of the ship (dashed: experimental data, solid: FIS) at 40 knots.

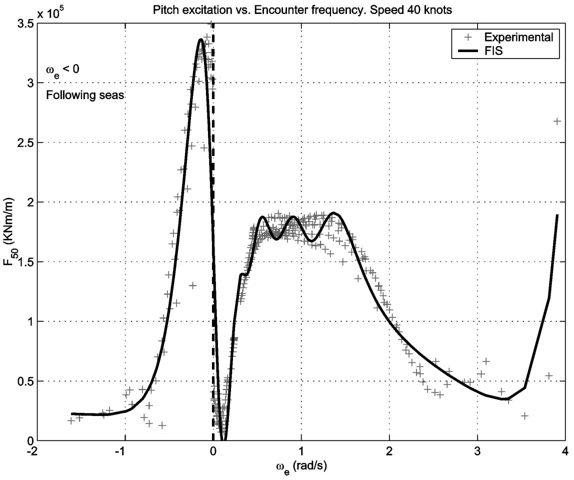

Fig. 4: Pitch excitation vs. encounter frequency

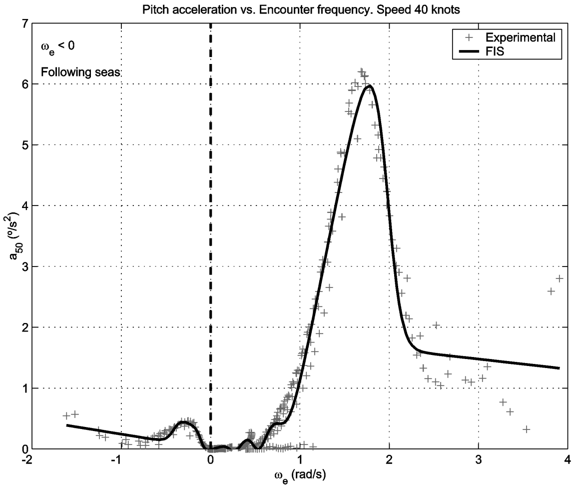

Fig. 5: Pitch acceleration vs. encounter frequency

From all graphics of the experiments, it can be concluded that:

- Excitation signals reach a maximum around $\omega_e \approx 1$ rad/s for positive values of the encounter frequency. There is also a peak at $\omega_e \approx 0$ rad/s for following seas. These maximum are left shifting when ship speed increases. The shape is an inverted parabola in both cases, meaning that excitation forces decrease for large frequencies (positive or negative).

- The shape of the pitch acceleration is similar, but it reaches its maximum at 1.5 rad/s. For negative values of the encounter frequency, the acceleration is almost zero. The expected values range for the acceleration is 0 - 7 $^{o}/s^2$, which matches with the predictions of the model described in Esteban, *et al.* (1999).

Figure 6 and Figure 7 show an example of an interpolation of the ship behaviour obtained by the FIS, when pitch excitation and pitch acceleration are represented as a function of the encounter frequency for a fixed Sea State of 5 (a group of modal frequencies, 0.5710 to 0.6980).

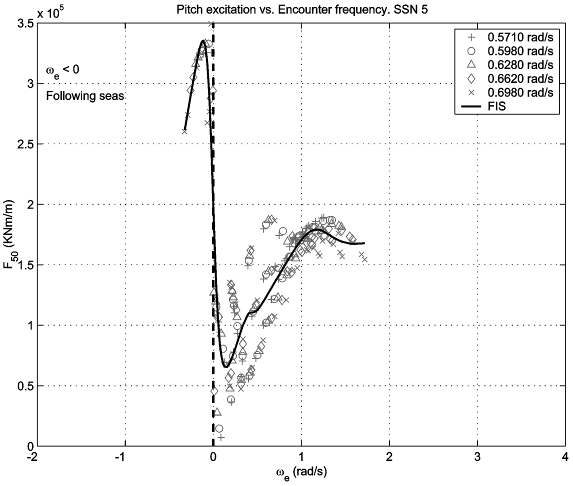

Fig. 6: Pitch excitation vs. encounter frequency

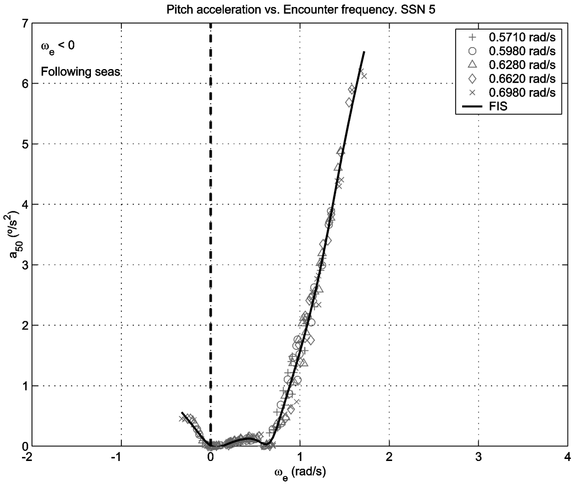

Fig. 7: Pitch acceleration vs. encounter frequency

It is interesting to notice the way acceleration grows at 1 rad/s, although the excitation is larger at other frequencies.

In conclusion, Figure 8 illustrates the values of the pitch acceleration given by the experimental data vs. the encounter frequency for different SSN. The data have been chosen for a particular case in which modal frequency belongs to that SNN. Figure 9 shows this variable vs. ship speed, for different SNN. For high frequencies, SSN of 5, 6 and 7, the experimental data are scant because of the difficulty of the measurement.

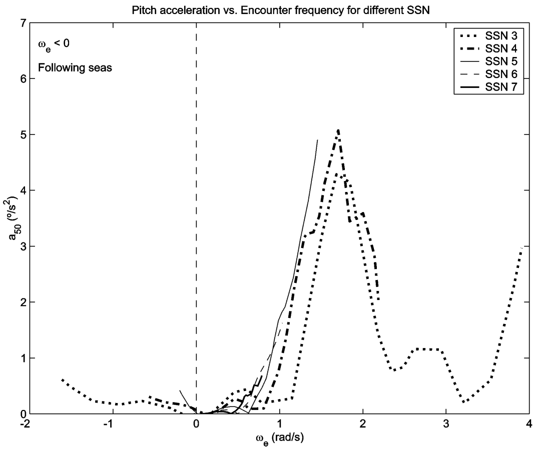

Fig. 8: Pitch acceleration vs. encounter frequency

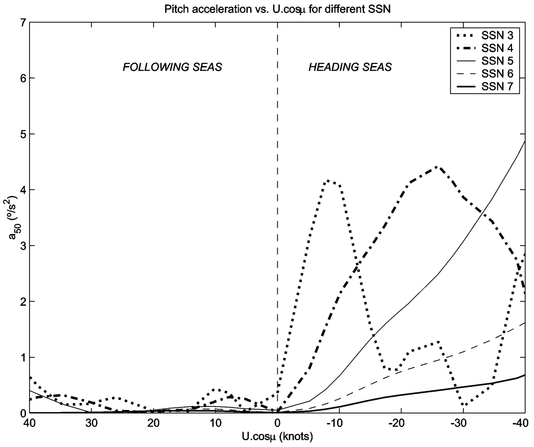

Fig. 9: Pitch acceleration vs. Ucosμ

3.2 *Neuro-Fuzzy Model*

The available knowledge about the ship behaviour comes from the analysis of the experimental data that has been shown above and the study of the equations of motion of the ship and the solution of those equations (Section 2). The knowledge involved in the model comes from the data, and the model learns by neuro-fuzzy techniques from these data. The rules are generated by the Fuzzy Inference System (FIS) based on the available experimental results.

The model that has been developed emulates the total pitch moment of the ship, i.e., the one caused by the final pitch acceleration, not only by the external excitations (because the forces caused by the waves are filtered by the ship and so its moment does not necessarily fit the total moment). For example, at 40 knots for following seas, -negative values of ω_e frequency-, the pitch acceleration is almost zero despite the large excitation forces (Figures 4 and 5).

These results are summarise in Table 2, which shows a comparison between the excitation forces, F_{50}, for different sea state codes and the total pitch moment.
For each wave frequency, the maximum pitch acceleration has been selected. The excitation values, F_{50}, comes from Cehipar (1998), and the total pitch moment has been obtained by calculating Ix_5, where the inertia torque I is I_{55} = 1.399.100 Tonnes/m² plus the “added mass”, a_{55}. The pitch acceleration, x_5, is obtained by (6) taking into account the value of the pitch amplitude, x_5, for the corresponding ω_e.

Table 2: Comparison between the maximum pitch excitation force and the total pitch moment

SSN	ω_0	Uxcosμ	ω_e	I_{55}	a_{55}	$accel_{50}$	F_{50}	Pitch moment
3	1,0480	-10,35	1,6445	1.339.100	3.130.000	5,1002	135.900	397.819
3	1,1470	-10,35	1,8615	1.339.100	2.888.000	4,7853	111.400	353.042
4	0,7380	-34,64	1,7277	1.339.100	3.021.000	6,1341	152.200	466.793
4	0,7600	-28,28	1,6170	1.339.100	3.172.000	6,0215	161.900	474.097
4	0,7850	-28,28	1,6993	1.339.100	3.056.000	6,1968	153.100	475.350
4	0,8100	-28,28	1,7835	1.339.100	2.960.000	5,8939	142.600	442.238
4	0,8370	-20,00	1,5720	1.339.100	3.248.000	5,5107	158.200	441.186
4	0,8650	-20,00	1,6500	1.339.100	3.122.000	5,9595	151.400	464.011
4	0,8950	-20,00	1,7354	1.339.100	3.012.000	6,0081	142.500	456.259
4	0,9650	-15,00	1,6977	1.339.100	2.775.000	4,8019	122.100	344.801
5	0,5710	-40,00	1,2551	1.339.100	4.135.000	3,1113	189.100	297.256
5	0,5980	-40,00	1,3484	1.339.100	3.797.000	3,8888	186.900	348.600
5	0,6280	-40,00	1,4555	1.339.100	3.491.000	4,8812	181.200	411.487
5	0,6620	-40,00	1,5816	1.339.100	3.231.000	5,9006	170.800	470.652
5	0,6980	-38,64	1,6855	1.339.100	3.074.000	6,2014	158.600	477.649
6	0,4650	-40,00	0,9187	1.339.100	7.020.000	1,1031	182.600	160.938
6	0,4830	-40,00	0,9725	1.339.100	6.544.000	1,2948	184.100	178.140
6	0,5030	-40,00	1,0339	1.339.100	5.655.000	1,6418	186.500	200.421
6	0,5240	-40,00	1,1001	1.339.100	5.049.000	2,0055	188.000	223.596
6	0,5460	-40,00	1,1715	1.339.100	4.511.000	2,4622	189.100	251.402
7	0,3930	-40,00	0,7171	1.339.100	12.640.000	0,4828	177.200	117.790
7	0,4060	-40,00	0,7519	1.339.100	10.830.000	0,6043	174.600	128.351
7	0,4190	-40,00	0,7874	1.339.100	9.721.000	0,6683	175.100	129.009
7	0,4340	-40,00	0,8292	1.339.100	8.799.000	0,7873	176.700	139.310
7	0,4490	-40,00	0,8720	1.339.100	7.935.000	0,8836	181.100	143.022

The fuzzy model of the ship has three inputs: the sea state (given by the modal frequency of the waves), the ship speed and the heading angle. Each of them has been represented by five membership functions uniformly distributed in their corresponding universe of discourse. The output variables are the heave and pitch motions (both, amplitude and phase), and the final pitch moment, as it is shown in Figure 10.

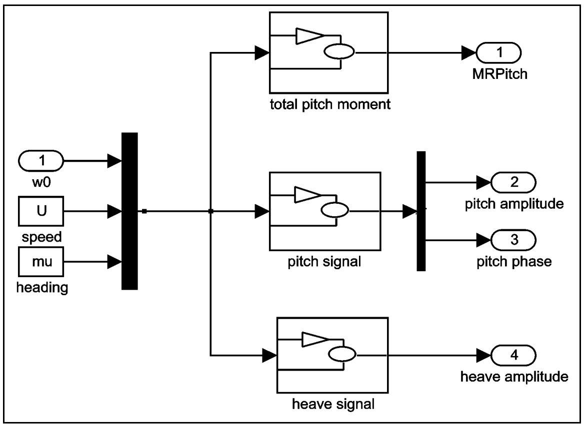

Fig. 10: Fuzzy model of the ship

Block structure of the pitch and the heave systems are similar. They consist of some functions to estimate the signal amplitude, the phase, and to obtain the encounter frequency by applying (4). Their outputs are the inputs of a S-function that calculates the output signals (heave, x_3, pitch, x_5, or even pitch moment, M_5, with the corresponding inputs). See Figure 11 for pitch signal.

These functions, designed to calculate the pitch and heave amplitude and phase, are implemented by means of a FIS Sugeno-type, with three inputs and a linear function as an output. These kind of fuzzy systems are computational efficient as well as they assure the continuity of the output surface. They have been trained applying ANFIS learning strategies.

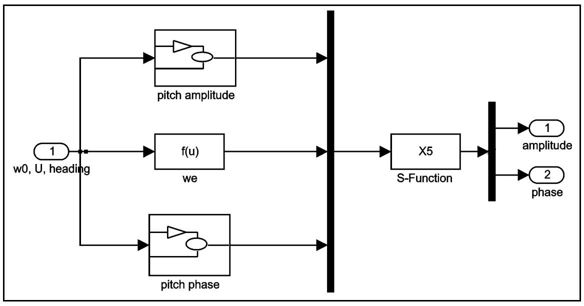

Fig. 11: Block of the pitch signal

The neuro-fuzzy model has been tested by introducing a block of simulated regular waves as an input to the model. Figure 12 shows the results of the model working at 40 knots, SSN 5 (ω_o = 3.78 m) and heading seas (μ = 180 º). The encounter frequency in this case is 1.255 rad/s (upper graphic). The behaviour of the fuzzy model is compared to the experimental model obtained by Precal (Esteban, *et al.*, 1999) for the same conditions. The comparison shows a good result.

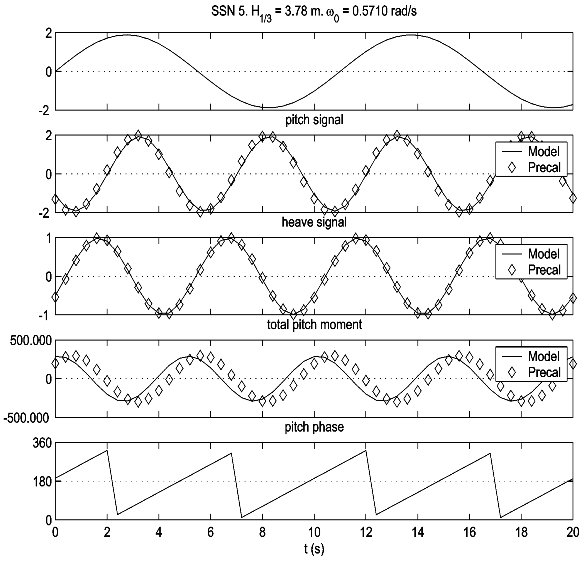

Fig. 12: Comparison between fuzzy model results and the experimental model obtained by Precal

It must be taken into account that the neuro-fuzzy model is a general one in the sense that can be apply for any condition, whereas the other models that have been developed consist of a set of different models for each application point (wavelength, speed, etc.).

The fuzzy model fits very well at SSN of 4, 5 and 6. For lower and higher sea state the experimental data are more scattered and that makes fitness more difficult. For SNN lower than 4 there is no problem of stabilization with the ship, and for SNN larger than 6, the ferry could hardly travel. The results are then very encouraging in the range of interest.

The model has been also tested for irregular waves, but results must be refined mainly due to the phase.

4. CONCLUSIONS

A neuro-fuzzy model has been obtained for a fast ferry vertical motion. Based on physical principles, experimental and simulated data, and qualitative knowledge, a neuro-fuzzy inference system has been applied to estimate the non-linear model. The model has been developed for pitch and heave motions and heading seas, using as inputs the Sea State, the ship speed and the heading angle.

Using a small replica, a series of experiments have been performed by a specialised towing tank institution, CEHIPAR, and the obtained experimental results are available to validate the NF-model. In addition, CEHIPAR can supply simulated data by using the computer program PRECAL. Actually, a set of simulated data has been essential to develop the NF-model.

The neuro-fuzzy model shows good pattern with experimental and simulated data for regular waves, for different sea states, and has been compared with other model with satisfactory results. The modelling problem is complex and the results are original.

This control-oriented model has been developed in order to apply some neuro-fuzzy control strategies (López and Santos, 2002).

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