Amplitude, Phase and Frequency Fuzzy Controllers of a Fast Ferry Vertical Motion

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Abstract. Based on the physical study of the behaviour of a fast ferry, a fuzzy controller has been developed to control the vertical motion of the craft. The sources of the expert knowledge for designing the controller are the experimental data of the performance of this ship in regular waves, the description of the vertical dynamics of the craft, and the model of the actuators (flaps and T-foils). Amplitude control and a phase and frequency fuzzy controllers have been implemented. The results have been simulation tested in regular waves and have been proved successful.

1 Introduction

Nowadays, shipping has some advantages such as safety, big capacity of transport, gentleness, etc., that makes it an efficient way of travelling for some purposes. But one of its drawbacks is the speed, especially if it is compared with other means of transport. Hence, the crafts are now made out of material, as aluminium, that makes them faster, or they are shaped to reduce the friction with the waves, etc.

In fact, this research deals with a TF-120 fast ferry that has an aluminium-made deep V hull. It is working in La Plata and in the Baltic Sea since more than five years. The high-speed ship, which is called “Silvia Ana”, is described in [1], [2].

The main problem of dealing with these fast systems is to stabilise the motion of the craft, not only for passenger transport but also for other purposes, whilst maintaining the speed. The main impact on the behaviour in this aspect is caused by the vertical motion that originates the seasickness To improve the stability of the ship by reducing the vertical acceleration, a fuzzy controller has been developed.

The motivation of using fuzzy logic comes from the fact that the model of the ship motion is complex and strongly non-linear, and some assumptions have to be made to carry out its development. Because of this lack of accuracy and the need of dealing with uncertainty, a fuzzy controller seems an adequate approach. On the other hand, expert knowledge is available to be incorporated to the controller.

This paper is focused on the control of the pitch acceleration by moving some appendages, such as flaps and T-foils, which can be added to the fast ferry. Two different sets of rules have been designed for different control purposes: to control the amplitude of the opening angle of the control surfaces, and to reduce the phase between the actuator oscillation and the pitch moment. The controllers have been successfully tested in regular waves.

The paper is organised as follows: Section 2 describes the motion of the craft by the equations of the movement, remarking on the coupling of the components of the vertical acceleration. Section 3 presents the model of the actuators and the control actions they can provide. Section 4 deals with the design of the amplitude and the phase and frequency fuzzy controllers, which are tested by some simulation experiments. The conclusions bring us to the end.

2 Behaviour of the Craft

Understanding the behaviour of the ferry is essential in order to design the fuzzy controller as a knowledge-based system. The most significant variables for studying the behaviour of the craft are the encounter frequency, which depends on the modal frequency of the waves, the ship speed, and the advance direction of the waves.

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 wave,

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

We will work in terms of this modal frequency to characterise the State Sea Number (SSN), according to the World Meteorological Organisation (WMO).

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_0, 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 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 ship motion can be studied as a rigid solid with six degrees of freedom. 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 [3],

$$\sum_{j=1}^{6}\left(A_{ij}\frac{d^2 x_j}{dt^2} + b_{ij}\frac{dx_j}{dt} + c_{ij}x_j \right) = F_{\omega i_0}\sin(\omega_e t + \varphi_i),\ \ i = 1,\ldots,6\ (kN)\ . \quad \textbf{(2)}$$

where the three terms on the left hand refer to the inertia, the damping, and the stiffness forces, respectively. The excitation amplitude, $F_{\omega io}$, and the phase, φ_i, are functions of the wave amplitude, δ_o, the coefficients, and ω_e.

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. Being m the total mass in tonnes and I the moment of inertia of the ship, the acceleration coefficients A_{ij} consist of the mass plus the added mass ($A_{ij} = m_{ij} + a_{ij}$, $i = j = 1, 2, 3$), and the inertia moment plus added inertia ($A_{ij} = I_{ij} + a_{ij}$,

$i = j = 4, 5, 6$), which depends also on the heading angle. It is worth noting that this system performs with large inertial forces [4].

The coefficients (local inertia, damping and stiffness) are not constant, and depend on the wave frequency (the wavelength), the ship speed, and the hull shape. Since the model is focused on particular aspects, certain simplifications are 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 the vertical ones (pitch and heave).

Solving the system [5], for different ship speed values and different encounter frequencies, it is possible to prove that the steady state solution for the pitch motion ($j = 5$ in (2)) is a sinusoidal function,

$$(I_{55} + a_{55})\ddot{x}_5(t) + b_{55}\dot{x}_5(t) + c_{55}x_5(t) = F_{50}\sin(\omega_e t + \varphi_5)\ . \tag{3}$$

$$x_5(t) = x_{50}\sin(\omega_e t + \varphi_5)\ . \tag{4}$$

and the pitch acceleration is then,

$$\ddot{x}_5(t) = -x_{50}\omega_e{}^2\sin(\omega_e t + \varphi_5) = -\omega_e{}^2 x_5(t)\ . \tag{5}$$

where x_{50} is the maximum pitch motion amplitude and φ_5 is the phase.

In order to validate the model, experimental data are available at speed 20, 30 and 40 knots, for different heading angles (0 to 180º, every 15º) and several modal waves frequencies (25 values between SSN3 and SSN7). These data have been provided by CEHIPAR [6], a specialised towing tank, working with a small replica of the ferry. In addition, by using the computer program PRECAL (based on finite elements), simulation results are available.

Taking into account the added mass coefficients and some other data provided by CEHIPAR about the pitch excitation, F_{50}, and the pitch amplitude, x_{50}, it is possible to obtain the pitch acceleration by applying (5).

Therefore, the total pitch moment produced by the pitch acceleration is calculated using the ship inertia torque, I_{55} = 1.339.100 Tons/m^2. **Table 1** shows a comparison between the maximum pitch excitation force, F_{50}, and the total pitch moment, $I\ddot{x}_5{}^2$, where $I = I_{55} + a_{55}$, for different SSN and heading seas. In general, the moment is higher than F_{50}, except for SSN 7.

Table 1. Maximum pitch excitation force and the total pitch moment, for different SSN

SSN	ω_0	U	μ	ω_e	a_{55}	$accel_5$	F_{50}	$I*accel_5{}^2$
3	1.1470	40	105	1.8615	2,888,000	4.7853	111,400	353,042
4	0.8950	40	120	1.7354	3,012,000	6.0081	142,500	456,259
5	0.6980	40	165	1.6855	3,074,000	6.2014	158,600	477,649
6	0.5460	40	180	1.1715	4,511,000	2.4622	189,100	251,402
7	0.4490	40	180	0.8720	7,935,000	0.8836	181,100	143,022

These results will be considered in Section 4 to design the qualitative controller.

3 Actuators

The strategy of employing stabiliser fins has been used in other cases [7]. The control surfaces originate lift forces that will be applied to counteract the vertical motion.

The actutaros are two flaps at stern and a T-foil at bow, working underwater. Their physical characteristics and position are shown in **Table 2**. The motion of the flap is limited upward (0º to 15º). The wings of the T-foil can freely move upward and downward (-15º to 15º).

Table 2. Physical characteristics of the actuators

	stern flap	bow t-foil
area (m^2)	11	13,5
maximum angle (º)	15	+15/-15
lift coefficient ($kN/º/m^2/knot^2$)	9,19E-03	6,90E-03
rotational max. speed (º/s)	13,5	13,5
distance to the cog (m)	41,6	58,4

Given a ship speed, U, the lift force only depends on the actuator angle, α, and it is expressed for any control surface (flap, *f*, or T-foil, *T*) as,

$$L_{[f\,|\,T]} = \rho\, S_{[f\,|\,T]}\, U^2\, (dC_L/d\alpha)_{[f\,|\,T]}\, \alpha_{[f\,|\,T]} = k_{[f\,|\,T]}\, \alpha_{[f\,|\,T]} \quad . \tag{6}$$

where $\rho = 1.025$ MTm/m^3, and the flap and T-foil values of the lift coefficient, $(dC_L/d\alpha)_{[f\,|\,T]}$, and their areas, S, are listed in **Table 2**.

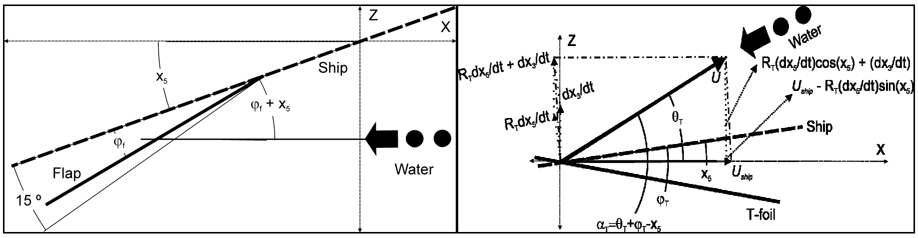

Fig. 1. Flap *(left)* and T-foil (*right*) motion

The flap and T-foil working angles, α, are (**Fig. 1.**),

$$\alpha_f = \varphi_f + x_5 \quad . \tag{7}$$

$$\alpha_T = \theta_T + \varphi_T - x_5 \quad . \tag{8}$$

where φ_f and φ_T are the flap and T-foil theoretical opening angles, respectively. The term $(x_5 - \theta_T)$ is, regarding the T-foil, the angle between the lift force, L, and the normal line to the longitudinal axis of the ship (see **Fig. 1**).

Therefore, the total moment of the actuators is,

$$CMP = CMF + CMT = R_f L_f + R_T L_T \quad . \tag{9}$$

The values of the operating radio of the fins, R_f and R_T, are listed in **Table 2**; L_f and L_T are calculated by (6) taking into account (7, 8). Substituting these values into (9) and recasting the equation, the vertical moment due to these control surfaces is obtained. This pitch moment caused by the lift forces of the actuators is applied to counteract the total pitch moment of the ship.

Thus, the maximum pitch correction (CMP) that it is possible to achieve, in the most general case, can be calculated as:

$$CMP = CMPF + CMPT + CMPM \;. \tag{10}$$

where CMPM refers to the proper pitch motion of the ship. Hence, woking with the physical dimension of the ship,

$$CMPF = 4.33\mathrm{U}^2\left(\left(\frac{1}{2}\varphi_{fMAX} + x_{5MAX}\right)\sin(\omega_e t) + \frac{1}{2}\varphi_{fMAX}\right). \tag{11}$$

$$\begin{aligned} CMPT = 5.84\Big[&\left(0.51\mathrm{U} - .0009\pi^2 x_{5MAX}^2 \omega_e \sin(2\omega_e t)\right)^2 + \\ &(0.32\pi x_{5MAX} + x_{3MAX})^2 \omega_e^2 \cos(\omega_e t)^2 \Big]\left(\left(\frac{1}{2}\varphi_{TMAX} - x_{5MAX}\right)\sin(\omega_e t)\right). \end{aligned} \tag{12}$$

$$\begin{aligned} CMPM = 5.84\Big[&(0.51\mathrm{U} - .0009\pi^2 x_{5MAX}^2 \omega_e \sin(2\omega_e t))^2 + \\ &(0.32\pi x_{5MAX} + x_{3MAX})^2 \omega_e^2 \cos(\omega_e t)^2 \Big]\theta_T \;. \end{aligned} \tag{13}$$

with

$$\theta_T = \frac{180}{\pi}\arctan\left(\frac{(0.32\pi x_{5MAX} + x_{3MAX})\omega_e \cos(\omega_e t)}{0.51\mathrm{U} - .0009\pi^2 x_{5MAX}^2 \omega_e \sin(2\omega_e t)}\right). \tag{14}$$

where x_{3MAX} and x_{5MAX} are the maximum amplitude for heave and pitch motions, and φ_{fMAX} and φ_{TMAX} are the maximum angles that the flaps and T-foil can reach. These angles have been calculated for different ship positions, and considering the constraints imposed by the physical characteristic of the control surfaces. Therefore, the maximum angle of the actuators in a semi-period, at 13.5 º/s, will be,

$$\varphi_f \max = \min\left(15,\ 13.5\frac{\pi}{|\omega_f|}\right); \qquad \varphi_T \max = \min\left(30,\ 13.5\frac{\pi}{|\omega_T|}\right).$$

assuming that the flap is oscillating at rate ω_f and the T-foil at ω_T.

If we want this correction to be effective, the actuators should oscillate at the same rate than the pitch. For this reason, ω_f and ω_T should be the same than the encounter frequency, ω_e. **Table 3** shows the maximum angle that it is possible to achieve for different encounter frequencies. As a conclusion, in the range of frequencies we are interested in (1-2 rad/s), the flap amplitude can reach 15º, but the T-foil amplitude is bounded and does not always reach the desirable angle.

Substituting these angles into equations (11-14), the pitch corrections (CMP) are shown in the last column of **Table 3**. MMP is the maximum pitch moment ($I*accel_5^2$ in **Table 1**) without actuators.

Table 3. Maximum angles that it is possible to achieve and maximum pitch correction

SSN	ω_0	U	μ	ω_e	φ_f	φ_t	X_{30}	X_{50}	CMPF	CMPT	CMPM	CMP	MMP
3	1.1470	40	105	1.8615	15.00	22.78	0.61	1.38	110,018	23,436	8,464	90,025	353,042
4	0.8950	40	120	1.7354	15.00	24.44	0.77	2.00	113,798	23,866	11,304	97,036	456,259
5	0.6980	40	165	1.6855	15.00	25.16	0.75	2.18	114,575	24,108	12,296	98,984	477,649
6	0.5460	40	180	1.1715	15.00	30.00	0.99	1.79	113,937	31,487	6,039	99,578	251,402
7	0.4490	40	180	0.8720	15.00	30.00	1.02	1.16	111,097	33,772	2,125	95,087	143,022

As we can infer from these values, for large sea state codes the craft is moving mainly because of the waves, and so the pitch moment is small. We must assure that the actuator correction does not exceed the pitch moment of the ship. It is also possible to notice that the correction provided by the flaps is stronger than the T-foil's.

4 Fuzzy Controllers Design

A fuzzy controller has been developed to reduce the vertical motion of the craft. To get some rules for the controller, a qualitative analysis of the ship behaviour has been carried out. The more interesting observed aspect of the behaviour is the coupling of the ship length and the distance between consecutive waves [8].

Pitch acceleration is represented in **Fig. 2** for different speeds and sea state codes.

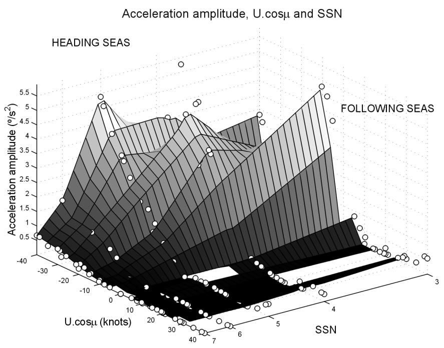

Fig. 2. Pitch acceleration vs. Ucosμ for different SSN

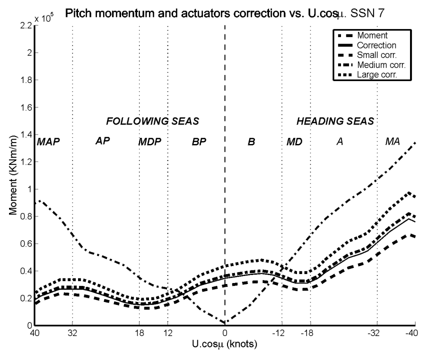

Fig. 3. Design of the amplitude controller rules

From **Fig. 2**, it is possible to say that, with following seas, the ship motion is quite stable. In fact, despite the large excitations, for SSN 3 and SSN 7 in particular, the pitch moment is small for any speed.

For heading sea the situation is more complex. When Sea State code of 3 (wave height ≈ 1 m), the pitch moment is small at any rate except around 10 knots, where the encounter frequency (1.93 rad/s) and the natural oscillation frequency (1.84 rad/s) are very closed. For SSN 4 the situation is quite similar, and the pitch peak is now at speed of 20 knots, where the encounter frequency and the undamped oscillation are 1.50 rad/s and 1.74 rad/s, respectively.

For SSN 5 ($H_{1/3} \approx 2.5$-4 m), the pitch moment reaches its maximum values because there is an interaction between the waves and the ship. SSN 6 ($H_{1/3} \approx 5$ m) is similar but the interaction waves-ship is smaller, and so the pitch moment decreases. When SSN 7, the waves are quite high and the ship moves on the wave; the pitch moment is small. Therefore, we are going to focus on SSN of 4, 5 and 6, with heading sea.

So, an amplitude controller and a phase and frequency controller have been designed. In both cases, the fuzzy controller is implemented as a Mamdami controller with COA defuzzyfication method.

4.1 Amplitude Controller

The two chosen input variables are the Sea State (i.e., the significant observed wave height, $H_{1/3}$, or the modal wave frequency, ω_0), and the ship speed (including the advance direction, i.e., U$\cos\mu$).

The output variable is the pitch correction expressed as the maximum angle of the actuators: $\varphi = \{0 \text{ to } 15\}^{o}$, (4 sets), with labels None (no correction), Small, Medium and Large correction. The angle of the T-foil is double φ if possible. The membership functions of inputs and output variables are non-uniform.

The universe of the input variable Sea State is: $\omega_0 = \{1.19 \text{ to } 0.41\}$ *rad/s,* (5 fuzzy sets), with labels SN_i, where *i* means the sea state code corresponding to that modal frequency. The speed is defined over $U\cos\mu = \{-40 \text{ to } 40\}$ knots, (8 sets), with labels MA (very high), A (high), MD (medium), B (low), in head waves, and MAP (very high), AP (high), MDP (medium), BP (low), with following seas.

The set of rules has been defined considering the previous analysis and the corresponding pitch moment correction available at that frequency (**Table 3**). For example, working at SSN 7, **Fig. 3** shows the maximum possible correction (solid line) and the pitch moment (dashed line). The absolute value of the corrected moment should not be larger than the final moment. Otherwise, the actuators should be disturbing the system and causing an increment in the pitch. Hence, the rules are shown in **Table 4**.

Fig. 4 shows the control surface of the flap control. The controller seems satisfactory in the sense that, for following seas and low speed, no correction is applied; for SSN 5 and SSN 6, the maximum correction (15º) is supplied. The action of the actuator is focused on the sea states 4, 5 and 6, and speed larger than 10 knots.

The control is always feasible (does not saturate the actuator). On the other hand, the moment correction is smaller than the final moment (does not disturb the system). **Fig. 5** compares, for SSN 6, the pitch moment and the corrected moment.

For testing the amplitude controller, a model of the moment generated by the waves has been simulated. When applying the fuzzy controller, the results are encouraging. For example, estimated pitch without actuators (solid) and corrected pitch (dashed) are shown in **Fig. 6** for SSN 5 (3.25 m wave height).

Table 4. Amplitude fuzzy controller Rules

φ		U.cosμ							
		MAP	AP	MDP	BP	B	MD	A	MA
SSN	3	None		Large					None
	4	Large		None		Large			
	5	Large	None	Large	None		Large		
	6	Large	Small			None	Large		
	7	Large			None		Large		

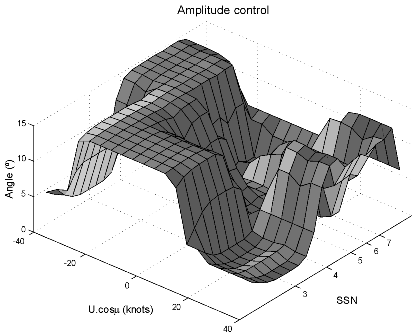

Fig. 4. Amplitude control for the flap

4.2 Phase and Frequency Controller

As it has been said, the fuzzy system should also control the oscillation frequency of the actuators, so that it will be the same than the frequency of the pitch signal x_5, in order to cancel the difference of phase: $\omega e = \omega_f = \omega_T$.

This frequency and phase controller can change the actuator frequency by, i) Increasing the maximum opening angle, i.e., reducing the oscillation frequency of the actuators; ii) Decreasing the maximum opening angle to increase the oscillation frequency.

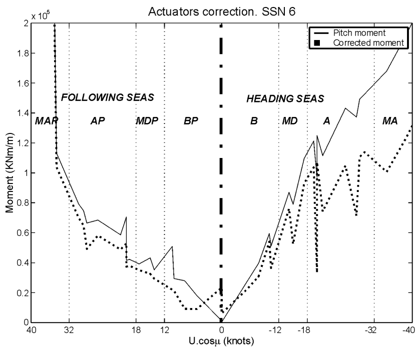

Fig. 5. Pitch moment (*solid*) and Corrected moment (*dashed*)

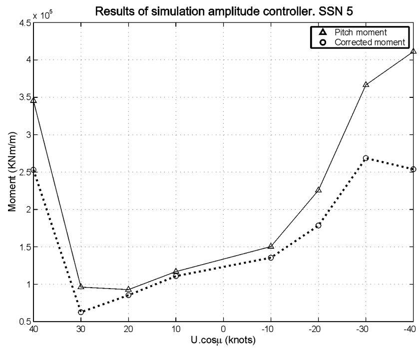

Fig. 6. Results of simulation

As regarding to the phase, different cases can be studied, i) Actuator is phase lagged behind pitch ($+\delta_o$). The opening angle will be reduced. ii)Actuator is ahead in phase ($-\delta_o$). The opening angle will be increased.

The constraints on the actuators are: the potential maximum angle ($\varphi_{max} \leq 15^o$ or 30^o), and the rotational speed, $d\varphi_{max}/dt \leq 13.5^o/s$.

The target is to control the opening angle. The two chosen input variables are the phase error, δ_o, and the initial angle, φ_i (i.e., the output angle of the amplitude controller). The output is the final angle. The membership functions of these variables are not evenly distributed. The labels for the output angle mean: MP (very small), P (small), M (medium), A (high) and MA (very high).

Small angles (high frequencies) are not significant because they do not cause large corrections in the pitch moment (that means a small phase between actuators and waves). On the other hand, it sounds difficult to correct a high frequency oscillatory motion in a little while, with such large inertia. Taking this into account, the set of rules is given in **Table 45**.

The control surface is shown in **Fig. 7**. As it is supposed to do, for small initial angles (around 0º) the controller does not correct the phase, but for large angles, these are modified according to the rules.

Table 5. Rules

Output angle		Phase error				
		Very Advanced	Advanced	Ok	Lag	Very lag
Input angle	N	N				
	MP	MP	P	MP	N	MP
	P	P	A	P	N	P
	M	M	MA	M	N	M
	A	A	MA	A	N	A
	MA	MA	MA	MA	N	MA

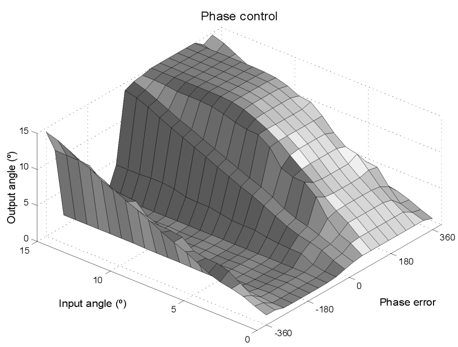

Fig. 7. Phase control

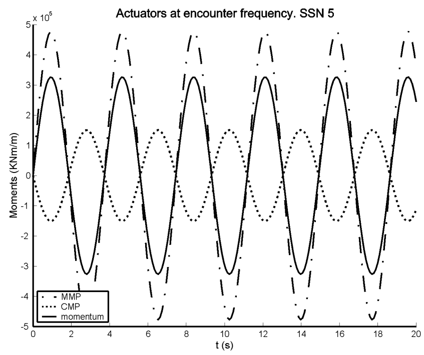

Fig. 8. Actuators operating at encounter frequency

For instance, **Fig.8** shows the actuators operating at the encounter frequency for Sea State code 5 (wave height ≈ 2.5-4 m). Dashed lines represent the initial pitch moment MMP (without actuators), and the correction supplied for the actuators (CMP), and the continuous line is the final pitch moment. The total pitch moment has been notably reduced.

5. Conclusions

In this paper, fuzzy control has been applied to reduce the vertical acceleration of a fast ferry. As it is well known, the vertical acceleration of the ship is the main cause of the seasickness. Consequently, reducing the pitch acceleration in a fast ferry improves the conditions of the shipping and enlarges the operational range.

To stabilise the motion of the ferry, some control surfaces have been added to the craft. The fuzzy controller controls the movement of these fins, flaps and T-foils, so that to reduce the total pitch moment of the craft.

To achieve this moment correction, the fuzzy systems works on the actuators by controlling their opening angles (amplitude) and the phase and frequency of the oscillation. By varying them, it is possible to decrease the impact of the pitch acceleration on the total moment of the craft.

These fuzzy controllers has been tested for different sea states and ship speeds. The results in regular waves are satisfactory, and there is a considerable reduction of the vertical acceleration.

Acknowledgements

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References

1. Anonymous: 126 m Long Spanish Fast Ferry Launched. Fast Ferries, Sept (1996) 19-20.
2. Anonymous: Silvia Ana: Results of First Year's Service. Ship&Boat Int., Jan/Feb (1998) 15-16.
3. Lloyd, A.R.J.M.: Seakeeping: Ship Behaviour in Rough Water. 1st edn Ellis Horwood, RPM, Sussex, UK. (1998)
4. López, R., Santos, M.: Neuro-Fuzzy modelling of a fast ferry vertical motion. IFAC 15th World Congress, Barcelona, 2002.
5. Ziegler, H.: Principles of Structural Stability. Blaisdell Publishing Company (1968)
6. CEHIPAR: Informe OTI-2135-CM-2 de los resultados del programa de comportamiento en la mar "Precal" del Ferry TF-120 para investigación de control. Canal de Experiencias Hidrodinámicas del Pardo (1998). <www.cehipar.es>
7. Dallinga, R.P.: Hydrodynamical Aspects of the Design of Fin Stabilizers. Trans. RINA (1993) 189-200.
8. Fossen, T.I.: Guidance and Control of Ocean Vehicles. John Wiley, N.Y. (1994)