AMPLITUDE, PHASE AND FREQUENCY FUZZY CONTROLLERS OF A FAST FERRY VERTICAL MOTION

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Keywords: Fuzzy Control, Marine Systems, Vertical Ship Motion, Hydraulic Actuators.

Abstract:

Based on the study of the behaviour of a fast ferry, Mamdani-type fuzzy systems have been developed to control the vertical motion of the craft. The sources of the knowledge for designing the controllers 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 some actuators (flaps and T-foils) that have been added to the craft. Amplitude, phase and frequency fuzzy controllers have been implemented to control the working angles of the fins in order to reduce the vertical acceleration of the ferry, which is the main cause of the seasickness. The controllers have been simulation tested in regular waves and the results are encouraging. Consequently, by reducing the pitch motion of the fast ferry, the sailing conditions are improved and the operational range is enlarged.

1 Introduction

Nowadays, shipping presents 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 the drawbacks is its low speed, especially if it is compared with other means of transport. Actually, the crafts tend to be made out of material, as aluminium, that makes them faster, or they are shaped to reduce the friction with the waves, etc.

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 seven 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 the comfort of the passengers 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 system 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 system seems an adequate approach [11]. 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 –it has been shown that the other vertical component, the heave acceleration, does not contribute so significantly in the motion [6]- by moving some appendages, such as flaps and T-foils, which have been added to the fast ferry. Two different sets of rules have been designed for different purposes: i) to control the amplitude of the opening angle of the control surfaces, and ii) 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 the vertical components of the acceleration. Section 3 presents the model of the actuators and the 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 variable when studying the performance of the craft is the encounter frequency, ω_e, 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 wave modal frequency, ω_0, can be obtained by Pierson-Moskowitz spectrum formula (1), a prediction technique used to calculate the wave spectra [10, 5]. $H_{1/3}$ is the observed significant height of the wave.

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

This modal frequency will be used to characterise the Sea State Number (SSN), according to the World Meteorological

Organisation (WMO) which in 1970 agreed the standard sea state code [12, 7]. Each sea state number corresponds to a range of significant wave heights. Its use is well established and widespread in the seafaring community.

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 equations that describes the physical motion of the craft for small amplitude motions in regular waves can be written [7],

$$\sum_{j=1}^{6}\left(A_{ij}\frac{d^2x_j}{dt^2}+b_{ij}\frac{dx_j}{dt}+c_{ij}x_j\right)=F_{\omega io}\sin(\omega_e t+\varphi_i), \quad \text{for } i=1,\dots,6 \tag{2}$$

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 [8].

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 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 can be considered constants.

Solving the system of motion equations [13] 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 frequencies (25 values between Sea State numbers of 3 and 7, i.e., the corresponding wave frequencies). These data have been provided by CEHIPAR [3], a specialised towing tank, working with a small replica of the ferry. In addition, simulation results are available by using the computer program PRECAL (based on finite elements), for the same experiments.

Taking into account the added mass coefficients and 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 U = 40 knots, different SSN and heading seas. In general, the moment is higher than F_{50}, except for SSN 7.

SSN	ω_0	μ	ω_e	$a_{55}10^3$	$\ddot{x}_5$	F_{50}	$I.\ddot{x}_5^2$
3	1.147	105	1.8615	2,888	4.7853	111,400	353,042
4	0.895	120	1.7354	3,012	6.0081	142,500	456,259
5	0.698	165	1.6855	3,074	6.2014	158,600	477,649
6	0.546	180	1.1715	4,511	2.4622	189,100	251,402
7	0.449	180	0.8720	7,935	0.8836	181,100	143,022

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

These results will be considered in Section 4 to design the rules of the heuristic controller.

3 Actuators

The strategy of employing stabiliser fins has been used in other cases [4, 6]. The control surfaces originate lift forces that will be applied to counteract the vertical motion.

The actuators 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).

	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

Table 2: Physical characteristics of the actuators

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

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

where ρ = 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.

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

$$\alpha_f = \varphi_f + x_5 \quad (7)$$

$$\alpha_T = \theta_T + \varphi_T - x_5 \quad (8)$$

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. 1b).

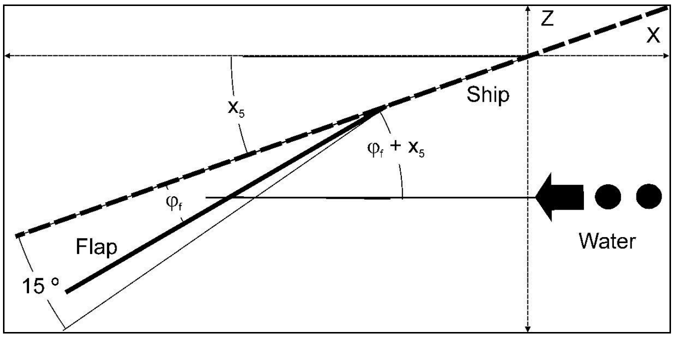

Fig. 1a. Flap motion

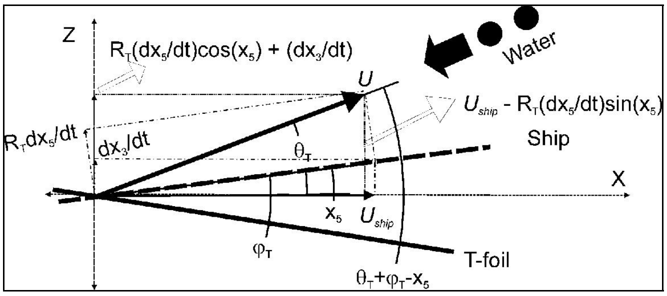

Fig. 1b. T-foil motion

Therefore, the total moment of the actuators is,

$$MP = MF + MT = R_f L_f + R_T L_T \quad (9)$$

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

$$CMP = CMP_F - CMP_T + CMP_M \quad (10)$$

where CMPM refers to the proper pitch motion of the ship, and taking into account that flaps and T-foil work in opposite directions. Hence, working with the physical dimension of the ship, the moment correction of the flap CMP_F (11), of the T-foil CMP_T (12), and the pitch motion of the ship CMP_M (13) are given by the expressions,

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

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

$$CMP_M = 5.84\left[(0.51\mathrm{U} - .0009\pi^2 x_{5MAX}^2 \omega_e \sin(2\omega_e t))^2 + (0.32\pi x_{5MAX} + x_{3MAX})^2 \omega_e^2 \cos(\omega_e t)^2\right]\theta_T \quad (13)$$

with

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

where x_{3MAX} and x_{5MAX} are the maximum amplitude for heave and pitch motion, and φ_{fMAX} and φ_{TMAX} are the maximum angles that the flaps and the T-foil can reach. Considering the constraints imposed by the physical characteristic of the control surfaces, the maximum angle of the actuators in a semi-period at 13.5 °/s will be,

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

assuming that the flap oscillates 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, i.e., at the frequency of the system ω_e. For this reason, ω_f and ω_T should be the same than the encounter frequency, ω_e. Table 3 shows the maximum angles φ_f and φ_T that are possible to achieve for different encounter frequencies. As a conclusion, in the range of frequencies we are interested in, the flap amplitude φ_f reaches 15°, but the T-foil amplitude φ_T is bounded and does not always reach the desirable angle.

Substituting these angles into equations (11-14), the pitch corrections (CMP) provided by the actuators are shown in the second last column of Table 3. MMP is the maximum pitch moment ($I.x_5^2$ in Table 1) without actuators.

SSN	3	4	5	6	7
ω_0	1.1470	0.8950	0.6980	0.5460	0.4490
U	40	40	40	40	40
μ	105	120	165	180	180
ω_e	1.8615	1.7354	1.6855	1.1715	0.8720
φ_f	15	15	15	15	15
φ_T	22.78	24.44	25.16	30.00	30.00
x_{30}	0.61	0.77	0.75	0.99	1.02
x_{50}	1.38	2.00	2.18	1.79	1.16
CMP_F	110,018	113,798	114,575	113,937	111,097
CMP_T	23,436	23,866	24,108	31,487	33,772
CMP_M	8,464	11,304	12,296	6,039	2,125
CMP	95,047	101,236	102,763	88,489	79,036
MMP	353,042	456,259	477,649	251,402	143,022

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

SSN	3	4	5	6	7
Δ(%)	26	21	25	42	60

Summarizing the average improvement for each SNN

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. It is also possible to notice that the correction provided by the flaps is stronger than the one originated by the T-foil.

4 Fuzzy Controllers Design

A fuzzy system has been developed to reduce the vertical motion of the craft by controlling the actuators. To get some rules for the controller, a qualitative analysis of the ship dynamics 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 [5].

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

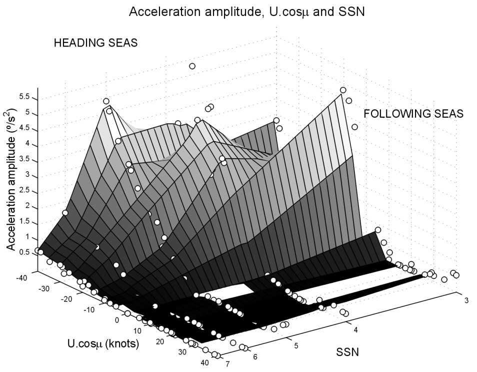

Fig. 2. Pitch acceleration vs. Ucosμ for different SSN

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 20 knots speed, where the encounter frequency and the undamped oscillation are 1.57 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 will focus on SSN of 4, 5 and 6, with heading sea.

So, an amplitude fuzzy control system and a phase and frequency controller are designed. In both cases, the fuzzy controller is implemented as a Mamdani system (that is, rule based systems [9]) 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 equivalent modal wave frequency, ω_0), and the ship speed (including the advance direction, i.e., Ucosμ*)*.

The universe of the input variable Sea State is: ω_o = {1.19 to 0.41} *rad/s,* (5 fuzzy sets), with labels SN_i, where *i* means the sea state code corresponding to that particular range of modal frequencies. The speed is defined over Ucosμ = {-40 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 output variable is the pitch correction expressed as the maximum angle of the actuators: φ = {0 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 the input and output variables are non-uniformly distributed.

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 would be disturbing the system and causing an increment in the pitch. For instance, at this sea state of 7, for low speed (both following and heading seas), no correction might be applied as this would deteriorate the behaviour of the system and, on the other hand, high speed requires large action to decrease the moment. Hence, the rules are shown in Table 4.

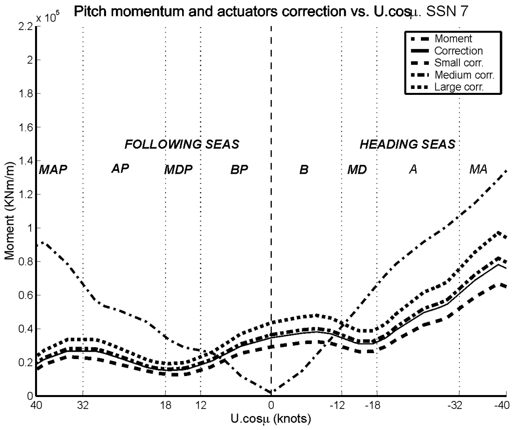

Fig. 3. Design of the amplitude controller rules

<table>
<tr><th colspan="2" rowspan="2">φ</th><th colspan="8">U.cosμ</th></tr>
<tr><th>MAP</th><th>AP</th><th>MDP</th><th>BP</th><th>B</th><th>MD</th><th>A</th><th>MA</th></tr>
<tr><td rowspan="5">SSN</td><td>3</td><td colspan="2">None</td><td colspan="5">Large</td><td>None</td></tr>
<tr><td>4</td><td colspan="2">Large</td><td colspan="2">None</td><td colspan="4">Large</td></tr>
<tr><td>5</td><td>Large</td><td>None</td><td>Large</td><td colspan="2">None</td><td colspan="3">Large</td></tr>
<tr><td>6</td><td>Large</td><td colspan="3">Small</td><td>None</td><td colspan="3">Large</td></tr>
<tr><td>7</td><td colspan="3">Large</td><td colspan="2">None</td><td colspan="3">Large</td></tr>
</table>

Table 4: Amplitude fuzzy controller Rules

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.

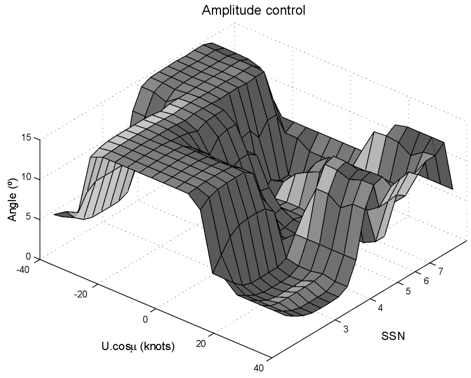

Fig. 4. Flap amplitude control surface

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.

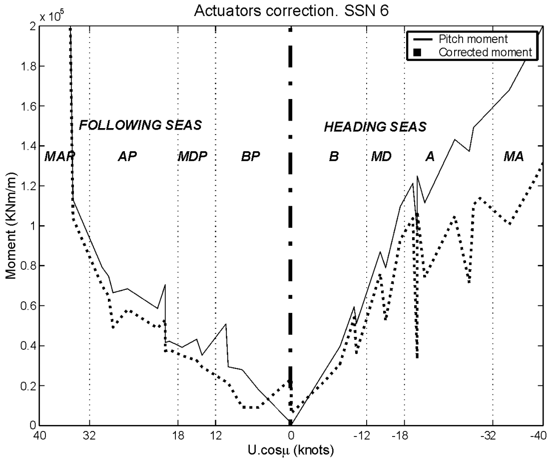

Fig. 5. Pitch moment (*solid*) and Corrected moment (*dashed*)

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

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 they had the same frequency than the pitch signal x_5, in order to cancel the difference of phase, i.e., $\omega_e = \omega_f = \omega_T$.

This fuzzy 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.

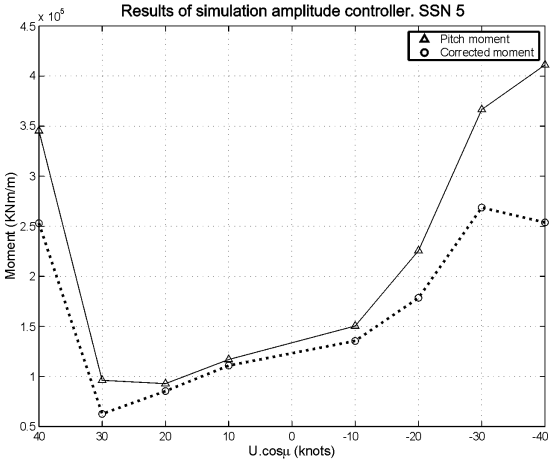

Fig. 6. Results of simulation

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 maximum angle is $\varphi_{max} \leq 15^o$ for the flap or 30º for the T-foil, and rotational speed, $d\varphi_{max}/dt \leq 13.5^o/s$.

The target is to effectively control the working angle. The two input variables are the phase error, δ_o, and the initial angle, φ_i (i.e., the output of the amplitude controller). The output is the final real 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 that into account, the set of rules is given in Table 5.

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

Table 5: Phase and frequency control rules

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, it is modified according to the rules.

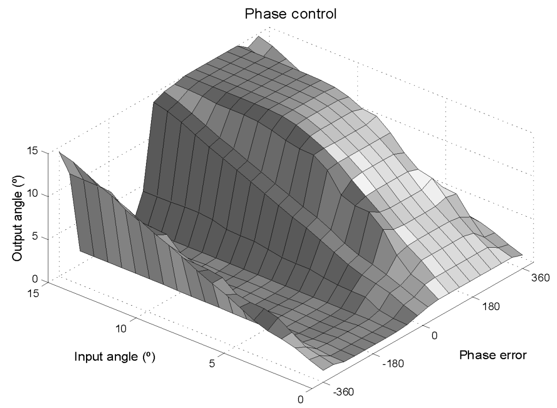

Fig. 7. Phase control

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

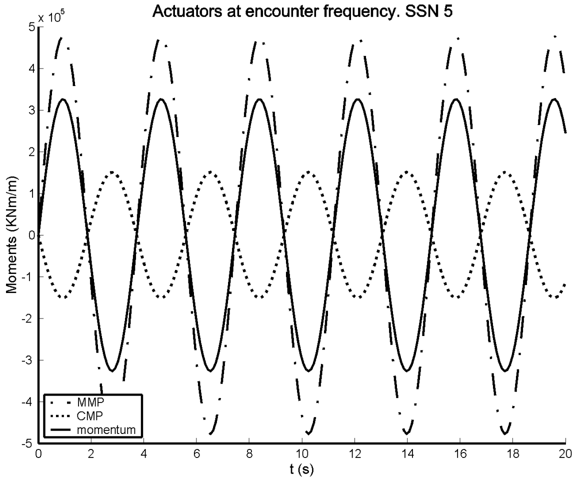

Fig. 8. Actuators operating at the encounter frequency

This controller is going to be experimental tested with a small replica of the ship. Other fuzzy Sugeno-type controllers have been applied in real time with satisfactory results [14].

5. Conclusions

In this paper, fuzzy control has been applied to reduce the vertical motion 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 sailing conditions and enlarges the operational range.

To stabilise the motion of the ferry, some control surfaces have been added to the craft. The fuzzy system controls the movement of these fins, two flaps and a T-foil, so that to reduce the total pitch moment of the ship. To achieve this moment correction, the fuzzy controller 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 simulation tested for different sea states and ship speeds. The results in regular waves are encouraging, and there is a considerable reduction of the vertical acceleration.

Acknowledgements

Authors would like to thank the support of the CICYT Spanish Committee (Project TAP97-0607-C03-01) and the collaboration of the CEHIPAR staff.

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