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# Fuzzy control of the vertical acceleration of fast ferries

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**Abstract**

This paper shows the design and implementation of a fuzzy control system used to reduce the vertical motion of a TF-120 fast ferry. The system increases the comfort of the passengers and crew by reducing the main cause of seasickness. The aim of this controller—which is based on a fuzzy model of the ship behaviour—is to decrease the pitch acceleration by controlling the position of some actuators and varying their working angles. Experiments have been carried out on a ship scaled-down replica. The motion sickness incidence has been evaluated and results have proved to be highly satisfactory.


*Keywords:* Fuzzy control; Marine systems; Stabilization; Vertical motion; Hydraulic actuators

## 1. Introduction

Stability is an important issue to be considered when handling marine systems. The main problem when dealing with fast ferries is to reduce the motion of the ship. This is not only to improve the comfort of the passengers and crew but also to make it safer while maintaining speed.

In this paper, a fuzzy controller has been designed and implemented in order to reduce the vertical motion of a high-speed craft. The goal is to minimize the motion sickness incidence (MSI) which is an index used to measure seasickness. Seasickness is caused mainly by the impact of vertical oscillations. The MSI (O'Hanlon & McCawley, 1974) provides a useful measurement of the impact of this acceleration on the passengers, and therefore helps to evaluate the controller.

The fuzzy controller is focused on reducing pitch acceleration. The neuro-fuzzy system controls the working angles of some control surfaces—two flaps at stern and a T-foil at bow—that have been added to the craft to create lift forces that will be applied to counteract the pitch motion.

The motivation for using a fuzzy controller is due to the uncertainty that comes from the waves and the sea state, and the complexity and strongly non-linear nature of the system itself. On the other hand, data and knowledge are available to be incorporated into the system.

One of the main sources for modelling and control is the collected experimental data of the performance of a high-speed ship on regular waves. These data have been obtained by carrying out some experiments with a small replica of the ship in a specialized towing tank, CEHIPAR (El Pardo Model Basin) (CEHIPAR, 2003). The physical studies of the vertical dynamics of the ship and the model of the actuators have also contributed useful information to the development of the fuzzy system.

The proposed controller is based on a neuro-fuzzy model of the ship (López & Santos, 2002) that has been developed in order to try different control strategies. The neuro-fuzzy model has been generated by applying fuzzy inference to the set of data provided by Precal, a facility of CEHIPAR.

The controller has been tested both in a simulation environment, in regular and irregular waves, and by carrying out some real-time experiments with a scaled-down replica.

Although other types of controllers have been designed for this marine system (Aranda, de la Cruz, Díaz, & Dormido Canto, 2002a; Aranda, Revilla, Díaz, &

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Ruipérez, 2002b; de la Cruz et al., 2004; Esteban et al., 2000; Girón-Sierra, Katebi, de la Cruz, & Esteban, 2002), the fuzzy control results are encouraging and can be applied in a wider range of sailing conditions.

The paper is structured as follows. Section 2 summarizes the principal aspects of the available neuro-fuzzy model of ship behaviour. Section 3 presents the actuators to be controlled. In Section 4, the design of the fuzzy controller is explained. Experimental results using the replica are shown and discussed in Section 5. Finally, conclusions are drawn with regard to the proposed controller.

## 2. Neuro-fuzzy model

The research deals with a TF-120 fast ferry called "Silvia Ana", an aluminium-made craft with a deep V hull. Its main characteristics can be found in Anonymous (1996, 1998).

Using a small replica of the fast ferry, a series of experiments have been performed by the towing tank institution, CEHIPAR, and have been computed by a numeric program called Precal. Precal is a program based on a CAD description of the hull that predicts the motion of the ship with regular waves. The collected experiment results (CEHIPAR, 1998), and the knowledge of the physics of the problems with marine systems and waves (Fossen, 1994; Lewis, 1989; Lloyd, 1989), allowed for the development of a neuro-fuzzy model by applying fuzzy inference (López & Santos, 2002).

The model focuses on the vertical acceleration both heave and pitch, of the marine system. The structure of the model consists of three inputs:

(i) the *sea state number* (SSN), according to the World Meteorological Organization (WMO)—given by the modal frequency, $\omega_o$, or the wavelength—which can be calculated observing the wave height,
(ii) the *ship speed*, $U$,
(iii) the *heading angle*, $\mu$, angle relative to the direction of propagation of a train of regular waves.

The outputs are the heave and pitch amplitude and phase, and the total pitch moment.

The fuzzy non-linear model has been tested in simulation and shows very similar results to those of the simulated data in regular waves. Fig. 1 shows an example of the output of the simulation model (solid line) for regular waves of 3.78 m height (SNN of 5), $U = 40$ knots and heading angle $\mu = 180°$. Regular waves have been used for simulation testing of the model as this is the only available simulation data provided by Precal (the computer tool of the towing tank). The model given by Precal is also shown in this figure (dashed line).

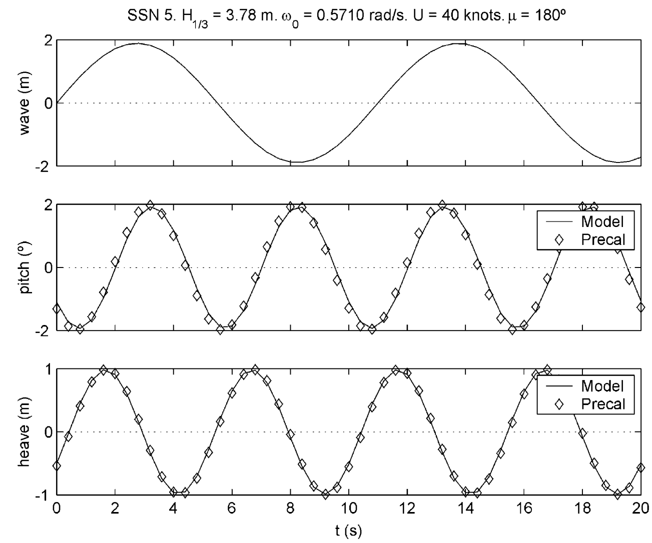


Fig. 1. Model simulation results (solid line).

One of the main advantages of this model is that it is a general one, in the sense that it can be applied to any marine system condition, whereas other models that have been developed (Aranda, Muñoz, & Díaz, 2002c; de la Cruz et al., 2004) consist of a set of different models for each application point (wavelength, speed, etc.). Its structure allows for connecting to different types of controllers. More details about the model can be found in López and Santos (2002).

## 3. Characteristics of the actuators

The actuators provided to the system will be used to reduce the vertical motion of the ship by using the lift forces that are caused when varying their opening angles. The expression of this force is (Lloyd, 1989)

$$L = \rho S U^2 \frac{dC_L}{d\alpha}\alpha, \quad (1)$$

where $C_L$ is the lift coefficient, $\rho$ is the fluid density (1.025 MTm/m$^3$), $S$ is the area of the control surface, $U$ is the ship speed, and $\alpha$ is the working angle of the actuator. For a fixed ship speed, $U$, the lift force depends only on the working angle, $\alpha$.

The characteristics and positions of the two added flaps at stern and the T-foil at bow are shown in Table 1. These control surfaces work underwater.

## 4. Fuzzy control

The final implemented controller is a fuzzy-PID type. The inputs are the normalized signals of the error, $e$, change in error, d$e$, and the accumulative value of the error, $ie$. The error is defined as the difference between

Table 1
Physical characteristics of the actuators

| | Flap | T-foil |
|---|---|---|
| Area ($m^2$) | 11 | 13.5 |
| Maximum angle (deg) | 15 | ±15 |
| Lift coefficient ($kN/^\circ/m^2/knot^2$) | 9.19E−03 | 6.09E−03 |
| Rotational max. speed ($^\circ$/s) | 13.5 | 13.5 |
| Distance to the c.o.g. (m) | 41.6 | 58.4 |
| Distance to the bow (m) | | 10 |

the pitch acceleration of the ship, $a_{15}$, and the desired value, i.e., zero. That means the error is the value of the vertical acceleration, $e = a_{15}$, which is to be eliminated. Although it is not physically possible to completely eliminate the vertical oscillations, the results were better when the system was forced to minimize the acceleration to the greatest extent possible.

The outputs are the working angles of the actuators, both the flap and the T-foil. In fact, two different controllers have been implemented, one for the flap and another for the T-foil. The structure is the same, and the only difference is the output range. The motion of the flap is limited upward [0, 15]° and the wings of the T-foil can freely move upward and downward [−15, 15]°.

The purpose was to obtain a set of input and output data of the system, in order to obtain a criterion function of the acceleration. By applying genetic algorithms, this function (acceleration) will be minimized. The knowledge obtained from this optimization is included in the rule base of a fuzzy controller by applying fuzzy inference.

As there was not prior knowledge about the system behaviour, a conventional Mamdani fuzzy PD with a crisp integral action (fuzzy PD + *I*) was chosen to avoid steady-state error (Chun-Tang & Ching-Cheng, 1997). In the case that there are only harmonic disturbances, this integral action is not needed. In fact, that was the case with this system, which has a sinusoidal dynamic.

The fuzzy inference system (FIS) that implements the initial PD fuzzy controller for the control surfaces was a Mamdani type, with inputs: error, $e$, and change in error, d$e$; and the output, $u$, is the angle of the corresponding actuator. The seven membership functions of each of these variables are triangular, and evenly distributed. The input universe of discourse is $[-1, 1]$ and the output range is $[-15, 15]^\circ$ for the T-foil, and $[-7.5, 7.5]^\circ$ for the flaps. The linguistic labels for all the variables are: NB, N, NS, Z, PS, P, PB (P: positive; N: negative; Z: zero; B: big; S: small). The rule base is summarized in Table 2. The maximum and the product are used for applying fuzzy inference, and the defuzzification method is the centre of gravity. The control output of the fuzzy PD is shown in Fig. 2.

The scaling factors of the input and output variables are $Kf_p$, $Kf_d$, $Kf_i$, and $Kf_u$ for the flap, and $Kt_p$, $Kt_d$, $Kt_i$, and $Kt_u$ for the T-foil. These gains of the controller have been tuned by applying genetic algorithms.

Table 2
Fuzzy rules for PD control

| | Error | | | | | | |
|---|---|---|---|---|---|---|---|
| | *NB* | *N* | *NS* | *Z* | *PS* | *P* | *PB* |
| *Derror* | | | | | | | |
| *NB* | NB | NB | N | N | NS | NS | Z |
| *N* | NB | N | N | NS | NS | Z | PS |
| *NS* | N | N | NS | NS | Z | PS | PS |
| *Z* | N | NS | NS | Z | PS | PS | PS |
| *PS* | NS | NS | Z | PS | PS | P | PS |
| *P* | NS | Z | PS | PS | P | P | PB |
| *PB* | Z | PS | PS | P | P | PB | PB |

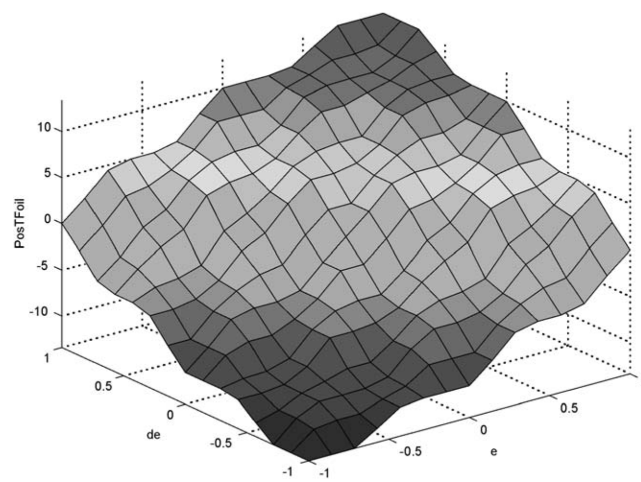


Fig. 2. Control surface of the fuzzy PD.

Several simulations with different gain values were run in order to minimize the error. This error, the vertical acceleration, is computed at the worst place of the craft, i.e., 40 m to the c.o.g. of the ship, where the seasickness is the strongest. It is called worst vertical acceleration (WVA) because at that point the vertical acceleration is the largest. As it is not possible to predict the value of the acceleration, and there is no prior knowledge about its value, an algorithm has been proposed to compute the normalized error. The modified version of the one presented in Jantzen (1998) follows:

1. Set maximum_error to 0.
2. Compute the error as the value of the pitch acceleration (WVA).
3. If the absolute value of the error is larger than the maximum error, then set maximum_error to the absolute value of error.
4. Normalize the error by dividing it by maximum_error.
5. Go to step 2.

During the simulations a cost function is evaluated to obtain the quality of the set of parameters. This function is a weighted acceleration given by

$$a = (a_{4,40} + 3a_{5,40} + 2a_{6,40})/6,$$

where $a_{i,j}$ is the acceleration for sea state $i$ at speed $j$. This criterion function has taken into account that the only available experimental data provided by CEHIPAR are the results at 40 knots speed, SSN 4, 5, and 6, and heading seas ($\mu = 180°$).

Genetic algorithms have been used to obtain the set of eight gains of the controller. Up to 300 generations of 300 individuals have been run in an MPP machine (SGI Origin 2000). More than 180,000 simulations have been executed in 21 different processors, by using parallelization techniques. Each chromosome had 16 genes and the values for the cross operator and mutation probability were 0.8 and 0.008, respectively.

After recording all this data, two new fuzzy systems were generated by applying subtractive clustering, one for the flap and another for the T-foil. The structure of each system is now a PID-like, and the fuzzy controllers are Sugeno type. The reason for working now with a Sugeno-type controller is because this makes sets of data available to train the system, and minimize the error function (to reduce the acceleration). Very efficient techniques (ANFIS: adaptive neural fuzzy inference system) are available for this kind of fuzzy systems.

The steps to obtain the final fuzzy-PID controller are shown in Fig. 3. The initial controller is a Mamdani fuzzy PD, with a crisp integral action, which is tuned by genetic algorithms. When working with the data provided by this controller, subtractive clustering is applied in order to obtain a new FIS. This fuzzy system is now a PID-like controller. It has been proven that it is equivalent to the previous fuzzy PD + $I$ with the tuned gains.

Simulation tests have been run with the new fuzzy-PID algorithms. The gains of this new scheme have been tuned by genetic algorithms, following the same procedure. The final values that have been obtained for these parameters are given in Table 3.

Because the signals are sinusoid, some of the gains involve a phase shift. Using these values, simulations

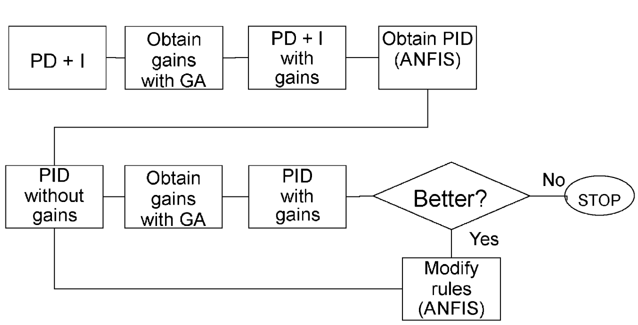


Fig. 3. Steps to obtain the fuzzy-PID controller.

Table 3
Controller gains

| | | | |
|---|---|---|---|
| *Flap* | | | |
| $Kf_p$ | $Kf_u$ | $Kf_d$ | $Kf_i$ |
| −1.0000 | −1.0000 | 0.0006 | 14.9977 |
| *T-Foil* | | | |
| $Kt_p$ | $Kt_d$ | $Kt_i$ | $Kt_u$ |
| −1.0000 | 0.0003 | 14.9995 | −1.0000 |

have been then carried out to obtain data for the training of the new FIS. The results reflect the system working under minimal vertical acceleration conditions.

More simulations that take into account all the available data have been carried out, obtaining new values for the parameters and generating new FIS. For each epoch, the acceleration is checked to assure that its value is smaller than the previous one, and so the system is improving. This procedure has been repeated until no further improvement was obtained. The final results were the two Sugeno-type fuzzy systems for controlling the flap and the T-foil, with three inputs and an output, the fin position (Fig. 4). The generated systems have a small number of function rules. The fact that the systems are simple helps to run them on-line. On the other hand, the results show that superior performance need not be linked with a large number of rules, but rather to the quality of these rules.

Simulation results with this controller predicted an improvement over the 47% for SSN 4, up to 37% for SSN 5, and 19% for SSN 6 in the pitch decrement. The real-time experiments with the replica, as it will be presented in the next section, in some cases reached greater reduction of the acceleration for those sea states.

## 5. Experiment results

### 5.1. Experiment environment

The experiments have been carried out in the Model Basin (CEHIPAR, 2003). Its Ship Dynamic Laboratory is fitted with large facilities for the testing of ships and propeller models.

The experiments were performed in a basin 152 m long, 30 m wide, and 5 m deep. The snake-type wavemaker of 60 flaps permits the generation of waves with the following characteristics:

- Regular waves from 1.7 to 15 m in length.
- Long-crested, irregular waves with a maximum significant height of 0.4 m.
- Short-crested waves with a maximum directional angle of 60°.

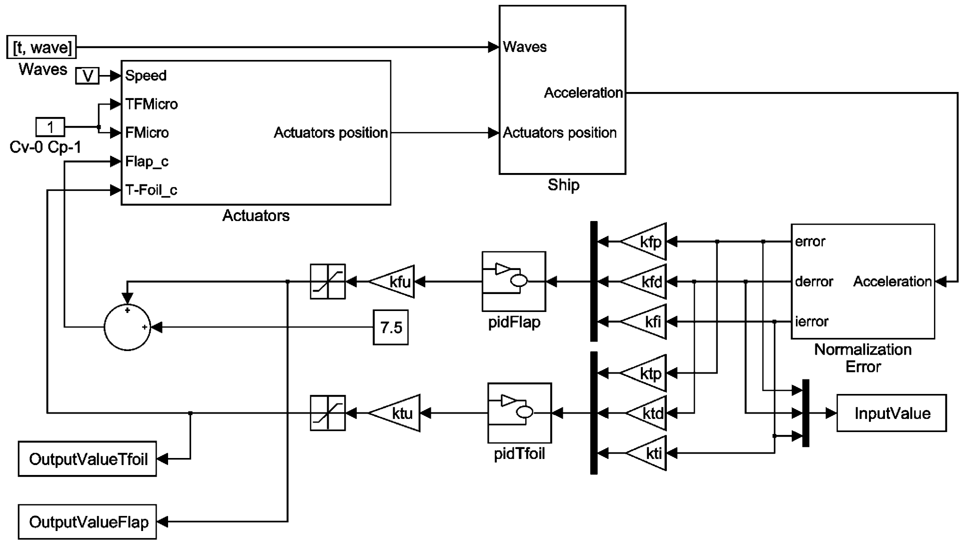


Fig. 4. Fuzzy-PID controllers.

Together with the wave generation equipment, the Laboratory of Ship Dynamics also used the computerized planar motion carriage (CPMC) for model testing. Its basic function is to reproduce, with high precision, any horizontal motion of the ship at sea.

The measured data taken from sensors are: heave, pitch, height of incident wave, drag forces (port and starboard), and vertical accelerations at several places of the ship.

A scaled-down replica ($\frac{1}{25}$) of the TF-120 ferry was provided by CEHIPAR, and used for the experiments. The replica is 4.5 m long. The sensors located on the replica measure the acceleration at several points. A T-foil near the bow and two transom flaps have been added (Figs. 5 and 6).

A step motor of 0.18° precision per pulse is used to move each of the fins. According to the real dimensions of the ship, 13.5°/seg wings rotation speed corresponds with the maximum speed rotation provided by the motors: 67.5°/s.

An industrial PC, fixed to the carriage, is used to test on-line the different control strategies with the scaled-down replica. The trials have to be performed in a short time without interruption, so a suitable software tool has been developed that allows changing some control characteristics (Polo, Esteban, Maron, Grau, & de la Cruz, 2001) on-line. A visual CASE tool for real-time automatic control code generation, called EdROOM, runs under Windows and makes the redesign of the control program easier. The software has a graphic interface for displaying the main variables in real time. The data are recorded and analyzed.

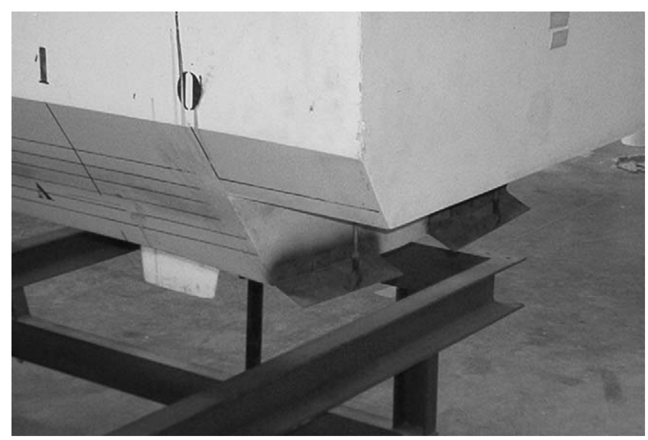

Fig. 5. View of the replica with the flaps at stern.

Fig. 6. View of the replica with the T-foil at bow.

### 5.2. Experiment results

To evaluate the efficiency of the fuzzy controller on the scale replica described in Section 5.1, the figure used is the WVA, i.e., the place on the ship where the passenger suffers the most acceleration. For this value, the MSI is obtained by applying the expression given by de la Cruz (2000). The MSI is a function of the average WVA and the encounter frequency.

The reduction of the WVA and the MSI has been calculated by computing the difference between those values without controlling the actuators, and when using the fuzzy control algorithm to move them.

Some first runs were done by setting the actuators to a fixed position, and not allowing them to move. These are considered reference runs. In general terms, it has been proved that the fixed actuators alone are extremely effective in attenuating the WVA (Aranda et al., 2002c). Moving the fins with a control system makes this reduction greater. Also, the action of the controlled actuators helps to eliminate the slamming that can be noticed in the experiments without appendages.

The fuzzy controller has been tested for irregular waves, heading sea, and SSN of 4, 40 knots speed, and SSN of 5, 30 and 40 knots speed.

These experiment results, together with the simulation results that had been previously obtained, and the reference runs, are summarized in Table 4.

The simulation results do not take into account the proper action of the shape of the ferry, particularly at stern, where the flap is placed. So the real results are better than the simulation ones. In any case, the uncontrolled WVA and MSI results from simulation are included in Table 4 in order to compare them with the simulation results without control.

It seems that the higher the speed, the more effective the actuators.

It is worth noting that the control algorithm was not trained for SSN 5 and speed of 30 knots. Although no simulation data were available in that case for the tuning, the improvement is also very satisfactory under those conditions. That means there is a single sub-optimal set of gains that can be used for any speed, with a slight difference in comparison to the optimal ones.

The experiments with the replica were carried out for all the different SNN and speeds, and some of the most relevant results are presented below. In particular, the results for 40 knots are selected since this is the most competitive speed. The chosen sea state is 5, although SSN over 4 may motivate cruise cancellation. The results prove that when being controlled, the actuators increase the feasibility of the shipping.

For instance, Fig. 7 shows the pitch acceleration signal $a_{15}$ ($^\circ/s^2$) without controlling the control surfaces (dashed line), and the same vertical acceleration when controlling the fins by the fuzzy algorithm (solid line). The acceleration measured is the WVA.

Fig. 8 presents, as a representative example for sea state 5 and 40 knots, the height of the wave (SSN), and the pitch motion. Fig. 9 shows the position of the control surfaces in that case. As can be seen, the actuators follow the control law without saturation.

Experiment results show that the fuzzy controller outstandingly reduces the vertical moment, and consequently the MSI. In some cases, this attenuation reaches 95% of the MSI (due to a 65.7% reduction of pitch acceleration).

Table 4
Experiment results

| | SSN 4, 40 knots | SSN 5, 30 knots | SSN 5, 40 knots |
|---|---|---|---|
| *WVA ($^\circ/s^2$)* | | | |
| Simulation | | | |
| Without control | 0.5492 | | 1.2180 |
| With control | 0.2962 | | 0.7705 |
| Improvement | 46.07% | | 36.74% |
| Experiment | | | |
| Without control | 0.6069 | 0.9031 | 0.9900 |
| With control | 0.2079 | 0.6673 | 0.5832 |
| Improvement | 65.74% | 26.11% | 41.09% |
| *MSI* | | | |
| Simulation | | | |
| Without control | 3.2427 | | 35.5171 |
| With control | 0.5924 | | 19.2531 |
| Improvement | 81.73% | | 45.79% |
| Experiment | | | |
| Without control | 4.0844 | 27.5710 | 27.5444 |
| With control | 0.1843 | 17.7692 | 12.0813 |
| Improvement | 95.49% | 35.55% | 56.14% |

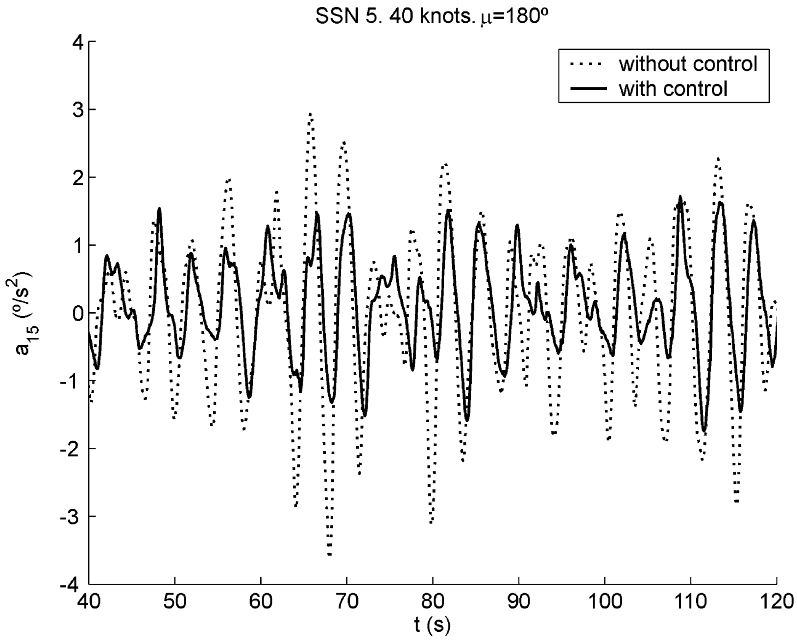


Fig. 7. Pitch acceleration (SSN 5, 40 knots, heading 180°).

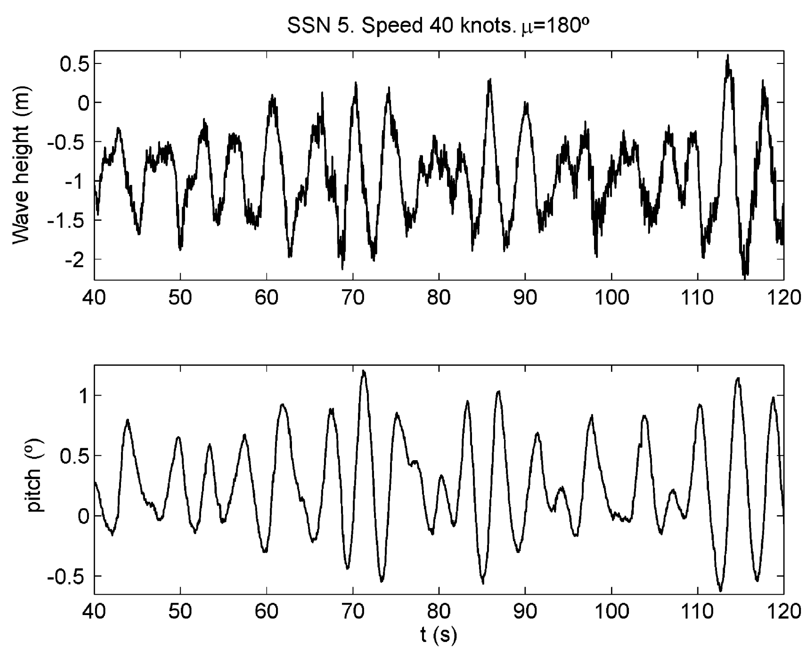


Fig. 8. Wave height and pitch motion (SSN 5, 40 knots, heading 180°).

## 6. Conclusion

This paper deals with the necessity of stabilizing the motion of a fast ship. It has been proved that seasickness is related, in a cumulative form, to vertical accelerations. So, a new controller is proposed to attenuate the pitch acceleration of the craft and therefore to improve the comfort and the safety of sailing.

A neuro-fuzzy non-linear model of the Tf-120 fast ferry has been previously obtained. Based on that control-oriented model, a fuzzy control system has been designed and implemented to stabilize the vertical motion of the ship. The fuzzy system controls the working angles of some appendages (transom flaps and a T-foil near the bow) that have been coupled to the craft. By studying the operation of the actuators, the

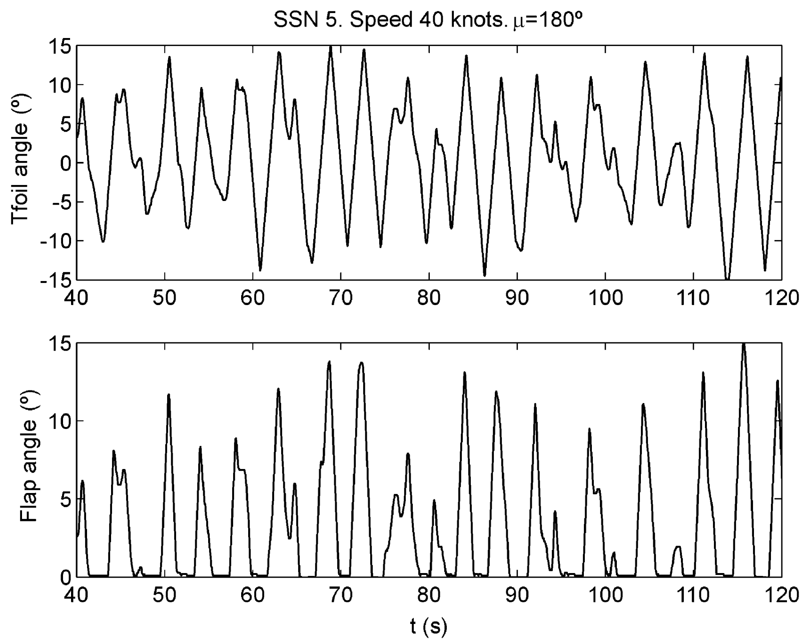

Fig. 9. Actuators movement. SSN 5 (speed 40 knots, heading 180°).

maximum pitch correction of the total pitch moment has been calculated.

The fuzzy controller has been tuned by applying GA, minimizing a criterion function defined in terms of the vertical acceleration. With these controller parameters, a fuzzy inference system has been generated to apply it to the control surfaces.

This controller works under any marine system conditions (speed, sea state, etc.).

The performance of the controller has been simulation tested in regular and irregular waves. Also, real-time experiments have been carried out on a scaled-down replica of the ship and the most relevant results are presented. The efficiency of the fuzzy control on the actuators has been experimentally confirmed.

The results are highly satisfactory: there is a considerable reduction of the vertical acceleration and, therefore, of the motion sickness incidence (MSI) in all the operational conditions. Therefore, as the normal sailing conditions (small or moderate waves) mean low pitch acceleration, reducing the vertical motion by means of this control strategy increases the operational range of the ship and its ability to carry passengers.

Although fuzzy controllers have been widely used before, as far as we know, the application of this strategy to reduce the vertical motion of fast ferries is novel.

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