PREDICTIVE PERTURBATION CANCELLING FOR SEAKEEPING IMPROVEMENT OF A FAST FERRY

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Abstract

Fast ships have speed limitations due to vertical motions. These motions induce sea-sickness, degrading the comfort of passengers. The research considers a fast ferry with transom flaps and a T-foil. A suitable control must be found to move these actuators to counteract the effect of waves in the most effective way. As a result of the research already done, models of the ship and the actuators have been developed. With these models, a simulation environment has been established. Different controllers can be tested on this environment. To get a reference, a study of PID control has been accomplished. Due to the characteristics of the problem, predictive control was supposed to be a better solution. A development of predictive control has been done for this case and tested on the environment. The results for 20, 30 and 40 knots shows good improvement over the PID reference.

1 Introduction

The vertical motions of fast ships have negative consequences that limit the speed. It is not only a matter of structural damage or safety risks. When the frequency of vertical motions are around 1 rad/sec, they contribute in a cumulative way to sea-sickness of the passengers. This is important for fast ferries, where passengers' comfort is a factor of competitiveness.

From some years ago, our research deals with a particular fast ferry, with the following characteristics: monohull, aluminium-made, 110m. length, 1250 passengers. The ship has transom flaps and a T-foil. These control actuators can move to counteract the effect of waves. The objective of our research is to control the motion of the actuators in the most convenient way. First results are encouraging: there is a significant improvement of comfort. This is important for established cruises and for opening new possibilities. Actually, most of the cruises are limited to short distances, because the incidence of sea-sickness on passengers.

After a strong work to get a model of the complete system, a simulation environment has been developed for control studies. The model is a combination of a model of the ship dynamics, and a model of the actuators. An extensive experimental work has been accomplished to get the required data, using a scaled-down replica of the ship. The main steps of this part of the research has been described in [1,2,3], in these references a complete, fairly complex model of the ship is presented (this paper is based on this model). The pertinent background literature is [4,5,6,7].

Our previous participation in the project Garteur [8], related to aeroplane control, gave us useful experience for several aspects of our research with ships. For instance, the analysis of the flaps and the T-foil forces was made taking into account the physics of a wing (into water). Also, we recognised the potential of predictive control [9], and it was a motivation to investigate its application to the ship.

With the results of our previous research with a fast ferry, we have all we need to evaluate the performances of predictive control for this application. The simulation environment is open to include any controller, for testing purposes. In addition, PID control has been studied as a first step to establish a reference. An optimal tuning of the PID has been established, and the results has been recorded for comparison with other control methods [10]. The question is whether it can be improved with a control strategy based on predicting and cancelling perturbations.

The paper begins with a short description of the models and the simulation environment. Then, the paper focus on the control problem: by predicting perturbations a new control scheme is developed, which counteracts the predicted perturbations. This predictive control is developed for the fast ferry case. Using the simulation environment, the predictive control is evaluated and compared with the PID. The results are encouraging. The paper concludes with a look to future aspects to be considered in this research.

2 Models and simulation environment

With the services of a towing tank institution (CEHIPAR: Canal de Experiencias Hidrodinamicas de El Pardo, Madrid), experimental data were obtained and recorded for speeds of 20, 30 and 40 knots. Both regular and irregular waves were generated. 15 different wavelengths were tested for regular waves. Irregular waves reproduced sea states SSN 4, 5 and 6. The research is restricted to head sea. MATLAB-SIMULINK is used to formulate the models. The model of the vertical motions of the ship was established considering first principles and decomposing into two main blocks: the generation of forces and moments by the waves, and the motions due to these forces and moments. Figure 1 shows the SIMULINK diagram of this model.

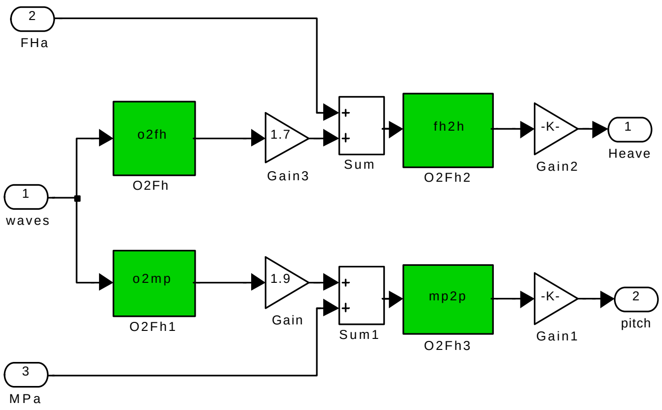

Fig. 1: Model of vertical motions of the ship

The model of the actuators was developed considering submerged wings, and includes the dynamic characteristics of the hydraulic cylinders moving the actuators. Figure 2 shows the SIMULINK diagram of the model. Notice that there are outputs with information about cavitation and bow emergence (this information is useful to evaluate control performances).

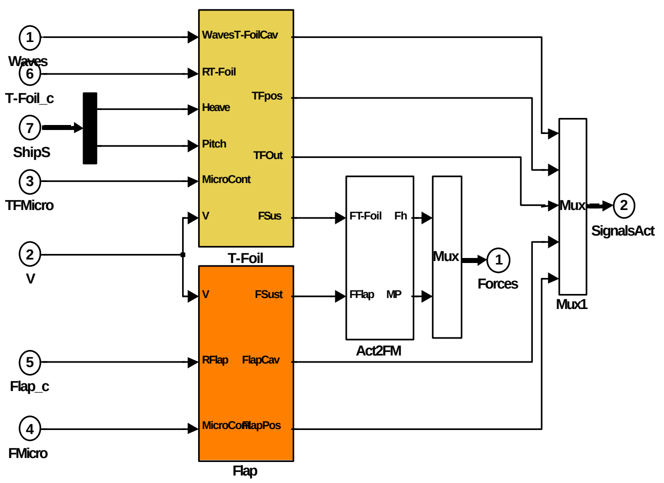

Fig. 2: Model of the actuators

Since the models were developed using MATLAB-SIMULINK, it was easy to couple them to get the model of the complete system. The model is non-linear and fairly complex. With this model a simulation environment was established, with facilities to include any controller and study its performances. Figure 3 shows the main screen of the simulation environment.

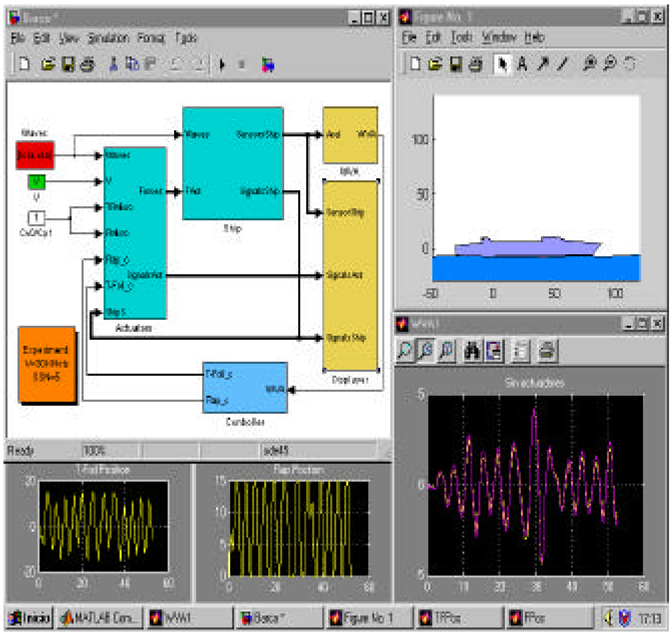

Fig. 3: Main screen of the simulation environment

3 The control problem

The studies about sea-sickness conclude that it is originated by vertical accelerations, with frequencies around 1 rad/sec. It is a cumulative effect along time. Our simulation environment can measure the vertical acceleration at any point of the ship. To define a criterion to be optimised by the control, we selected the passengers in the worse position on the ship, near the bow. We denote the vertical acceleration there as WVA (Worse Vertical Acceleration). This acceleration is due mainly to pitching, and should be reduced by the control action. Actually, the bow itself is not a place for humans: vertical accelerations at high speed may be around 1g.

The objective of the control is to minimise sea-sickness incidence. That means to decrease WVA. There are 9 conditions to be considered combining three speeds (20, 30 and 40 knots) and three sea states (SSN4, 5 and 6). The control must work well in the 9 conditions.

Presently, the actuators can only have a limited effect. Nevertheless, the smoothing of vertical accelerations that we can obtain with these actuators, do have a significant good impact on sea-sickness. Figure 4 shows a lateral view of the ship with the actuators.

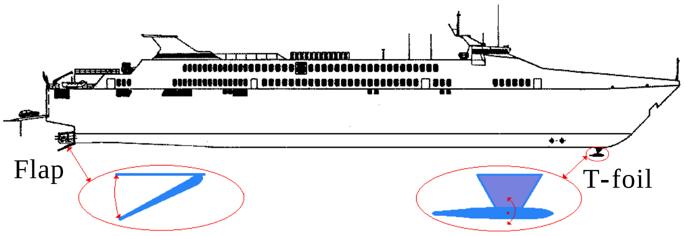

Fig 4: Lateral view of the ship with flaps and T-foil

4 Predictive control of the ship

The novel concept for the control is to predict the perturbations, and use this prediction for a more effective reduction of the accelerations due to perturbations. Standard predictive control distinguishes two types of perturbations: measurable and non-measurable. A standard predictive control uses the present measurable perturbations. Our design goes further: measurable perturbations will be predicted, and the predictions will be used in the control law. Let us denote this type of control as "Predictive PREPER".

As a first development, we designed a predictive control not including in analytic form the dynamics of the ship with actuators. This is due to the complexity and nonlinearity of this dynamics. The gains of the controller will be tuned by means of Genetic Algorithms. The cost function to be minimised is the mean WVA. Figure 5 shows a diagram of the control system.

An important parameter to be decided is the prediction horizon. In our case, the flaps can move a maximum of +15º and the T-foil between –15º and +15º. Both can move at a maximum speed of 13.5º/sec. The sampling period used to control the ship is 0.25 sec. With 1 sec. we can move the actuators near the limit, equivalent to 4 sampling periods. So we take 4 sampling periods as the prediction horizon.

To get prediction models a simple idea was applied: to shift the phase of the waves the required number of sampling periods, to get the future wave. The model considers the present wave as input, and the future wave as output. By means of the MATLAB tool IDENT, the model is identified. Table 1 presents some of the models obtained for several combinations of sea state and prediction distances.

V=30 Knots	SNN=4	SNN=5	SNN=6
1 Period=0.25 s	$\frac{1.732\ z - 0.8799}{z}$	$\frac{1.83\ z - 0.9465}{z}$	$\frac{1.884\ z - 0.977}{z}$
2 Period=0.50 s	$\frac{2.02\ z - 1.41}{z}$	$\frac{2.334\ z - 1.663}{z}$	$\frac{2.545\ z - 1.811}{z}$
3 Period=0.75 s	$\frac{1.973\ z - 1.646}{z}$	$\frac{2.481\ z - 2.08}{z}$	$\frac{2.913\ z - 2.412}{z}$
4 Period=1.00 s	$\frac{1.777\ z - 1.738}{z}$	$\frac{2.348\ z - 2.239}{z}$	$\frac{2.98\ z - 2.746}{z}$

Table 1: Prediction models

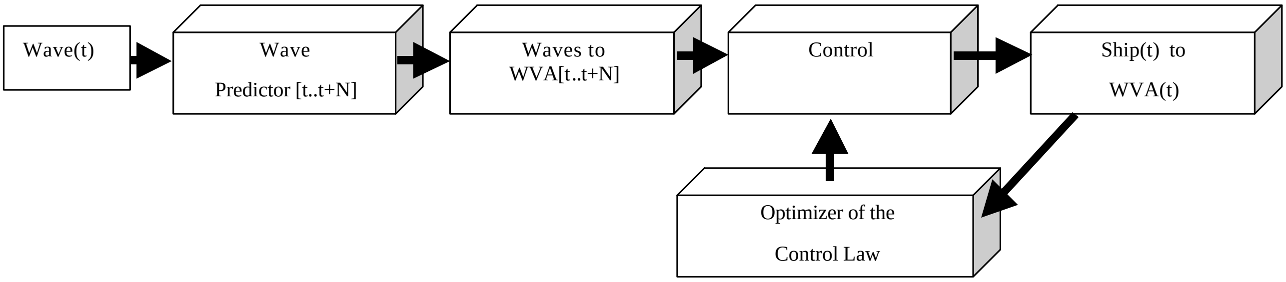

Fig 5: Block diagram of the control system

4.1 Prediction of the Perturbations

As the ship advances, she encounters a series of waves. These waves are the perturbations, originating vertical accelerations. Both the sea state and the ship speed have influence on the characteristics of the perturbations. Our experience is that measuring the height of waves with respect to the ship waterline (relative height) leads to simpler models of perturbations, than using absolute measurements of the height of waves. This is also true when predicting perturbations. In consequence, we selected relative height for the predictions: positive values are assigned to waves surpassing the waterline at the bow. An important advantage of using relative height is that it can be easily measured in the ship (for instance, with ultrasonic sensors).

In the standard Predictive control a model for one prediction is applied N times to get the N-future prediction. This method implies a cumulative error. Figure 6 shows the prediction for the next second (four predictions).

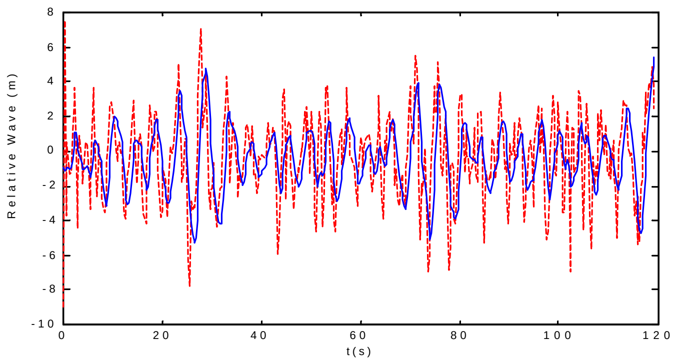

Fig.6: Standard waves prediction method

It is more accurate to identify one model for the first prediction, another (different) model for the second prediction, and so on (in this case we use four predictions, so we have four models). Figure 7 shows the good effect of this approach compared to the standard one (figure 6).

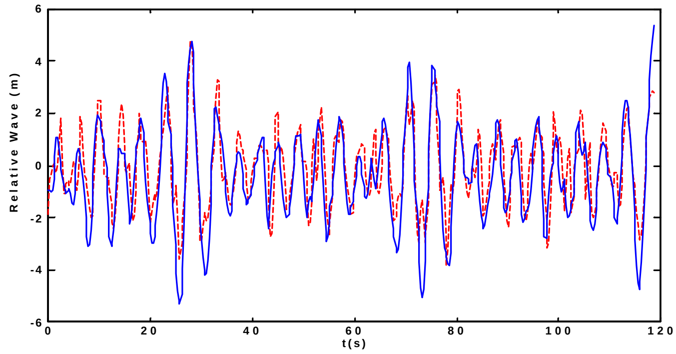

Fig. 7: New waves prediction method.

Once we have a prediction of the future waves, if we obtain a model relating waves and WVA we can predict ship motions.

4.2 Waves to WVA Model

As a result of our previous research we have models of the ship vertical motions. But these models consider absolute measurements of the height of waves. Since we are now considering relative heights, we have to find new models of the ship vertical motions. Using again IDENT and the temporal series of sampled data about waves (given by the CEHIPAR experiments) and WVA (generated by the simulation environment), ARX models have been obtained. As a result of the approach (taking relative heights), the models of the ship motions are very simple: of second order. This to be compared with the order 28 of the same model using absolute heights. For example, the model for 30 knots and SSN5 is now:

$$\frac{-0.03435z^2 + 0.1055z}{z^2 - 1.725z + 0.9245} \qquad (1)$$

Figure 8 shows a validation of this model, comparing measured ship motions and the predicted by the model. The result is fairly good.

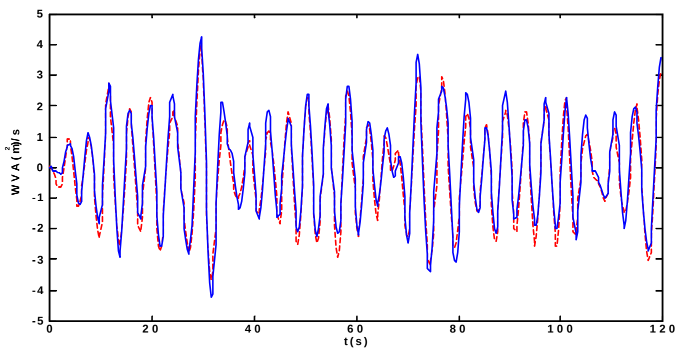

Fig. 8 : Validation of the model Wave2WVA

4.3 Structure of the Controller

It is a very simple controller. A proportional gain applied to the different predictions and an adjustable trim of the flap. Figure 9 shows a SIMULINK diagram of the controller.

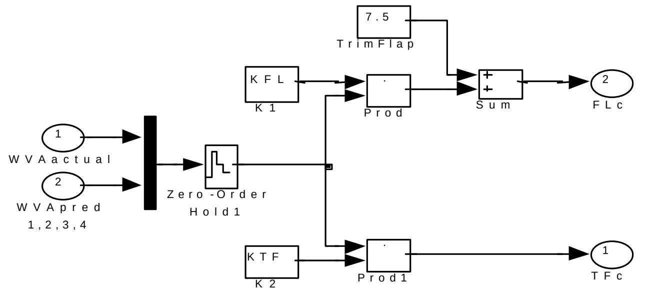

Figure 9: SIMULINK diagram of the controller

Notice that the present WVA is added to the vector of predictions, since it contains information of interest for the control. The ZOH is included since the plant is continuous time.

4.4 Controller Tuning

The tuning of the controller has been accomplished with Genetic Algorithms. The criterion optimised is the mean WVA. Figure 10 shows a plot of the optimisation evolution. With a Pentium 500 Mz. the generation 100 is reached in 30 minutes.

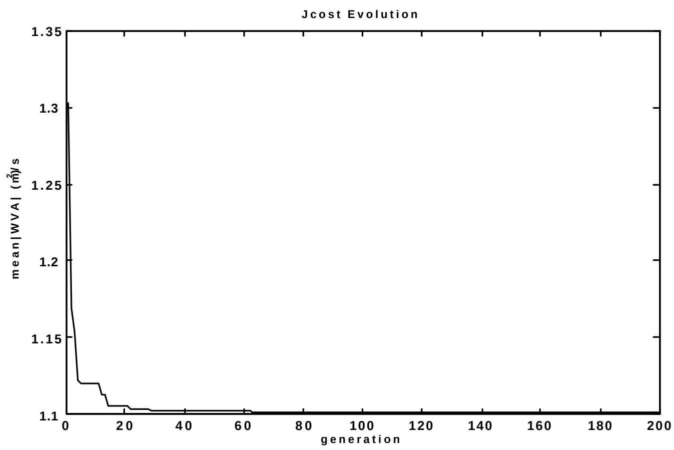

Fig 10: The optimization evolution along GA generations

4.5 Results

Table 2 presents a comparison of an optimal PD and the new predictive control for the same case. The predictive control performs better than the PD since it has a clear effect on eliminating vibrations of the actuators. Taking into account that the ship with flaps and T-foil is an under-actuated system, the results are satisfactory indeed.

	No Control	PD	PD Improv.	PRED	PRED Improv.	PRED vs PD
WVA(m/s^2)	1.3033	1.1199	14.07%	1.1008	15.54%	1.47%
Vibration/s	0	3.72	______	0.98	______	73.66%

Table 2: Comparison of PD and predictive control

Figure 11 shows how the T-Foil motion with the PD controller has a lot of vibrations (dangerous for the hydraulic system), while with the predictive controller is clearly more smooth.

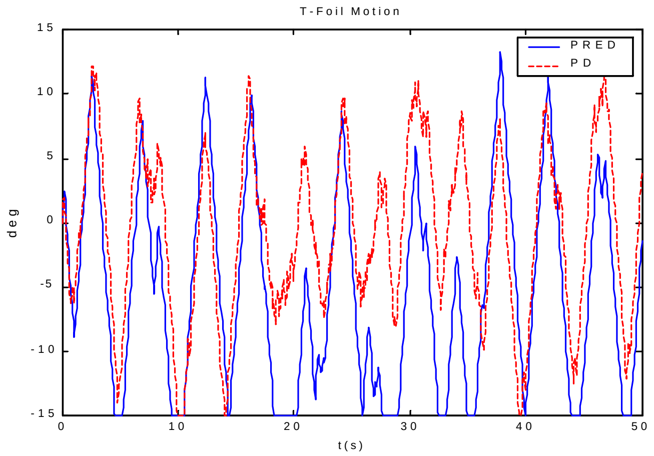

Fig 11: Motion of the T-Foil

All the results shown in figures 6 to 11 corresponds to 30 knots and SSN5. Our complete study includes the design of the controllers for the other conditions (20 and 40 knots, SSN 4 and 6: a total of 9 combinations). The results obtained for each case are similar to the results presented here.

5 Conclusions

A control method based on the prediction of perturbations has been developed and applied to a fast ferry. By means of flaps and a T-foil, moved under control, vertical accelerations can be smoothed, with a significant improvement of passengers comfort. The results of the new control methods are compared with an optimal PD, and in every case the new control performs better.

In the future more elaborate schemes will be considered in the control law. Some experiments in CEHIPAR are now being prepared to confirm the results.

Acknowledgements

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