CLASSICAL CONTROLLERS TO REDUCE THE VERTICAL ACCELERATION OF A HIGH-SPEED CRAFT

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Abstract

This article describes the tuning of various digital control structures by means of genetic algorithms with the aim of reducing the vertical acceleration of a high-speed craft in order to decrease Motion Sickness Incidence (MSI). The objective pursued in designing each one of these controllers was to obtain good performance for a craft speed of 40 knots and for sea-state 4. To tune the ship controllers the Simulink model was used. The variable controlled was the vertical acceleration measured in the position of the "worst passenger" (WVA), which is also the cost function to be minimized in the genetic algorithm. It is found that these controllers provide a significant vertical acceleration and MSI reduction for the studied case.

1 Introduction

Passengers and crew comfort and the safety of vehicles on board are two of the problems to be dealt with in the design and development of a high-speed craft. Pitching an heaving motions related with the vertical acceleration of the craft are the main causes of discomfort and seasickness among passengers and crew on board.

This paper presents the design of various classical digital controllers with a view to reducing the vertical acceleration of the high-speed craft, the TF-120 (figure 1). With this reduction, the motion sickness incidence is also lowered, leading to an increase in comfort for both passengers and crew.

The tuning of the controllers has been carried out using genetic algorithms to minimise the vertical acceleration measured at the "worst passenger" position. The simulation results are shown in several tables, which indicate the control parameter values, the reduction in vertical acceleration and the improvement in the motion sickness incidence. Here are also shown graphics in which the vertical acceleration and the MSI reduction can be seen.

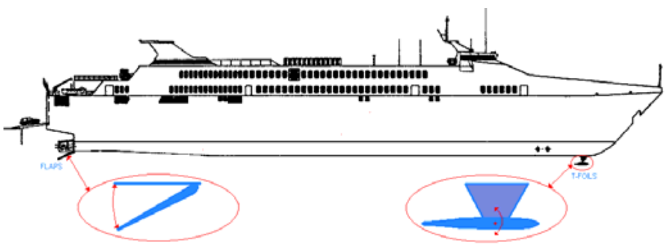

Figure 1: High-speed craft TF-120

2 Mathematical model of the vessel

In order to simulate the vertical movement of the craft, the TF-120, the Simulink model developed in the CICYT DPI2000-0386-C03 project was used. This has a modular design and allows the movement of the different controllers to be simulated simply by appropriately modifying the control module. In each simulation, a single controller is tuned for a craft speed of 40 knots and for sea-state 4.

The vertical dynamics of the craft is composed of various continuous linear SISO models which were identified from PRECAL data [1,2,3], corrected at bow, at speed of 40 knots. These identified models are four transfer functions which relate wave height with heave force and pitch momentum, heave force with heave movement and pitch momentum with pitch movement.

The system has two actuators [4], a T-foil and a flap. The model of these actuators has been designed as a block which has as inputs: a) the position of the T-Foil, b) the position of the flap, c) heave movement, and d) pitch movement; and as outputs: a) heave force, and b) pitch momentum.

The encounter frequency depends on the sea and the ship's speed. It may happen that a certain speed clearly increases the MSI, and slowing down could be necessary. In those cases, the use of the actuators have the benefit of counteracting the effect of waves, avoiding the MSI increase and making still possible to sustain a high-speed.

The Simulink model of the high-speed craft used is presented in figure 2.

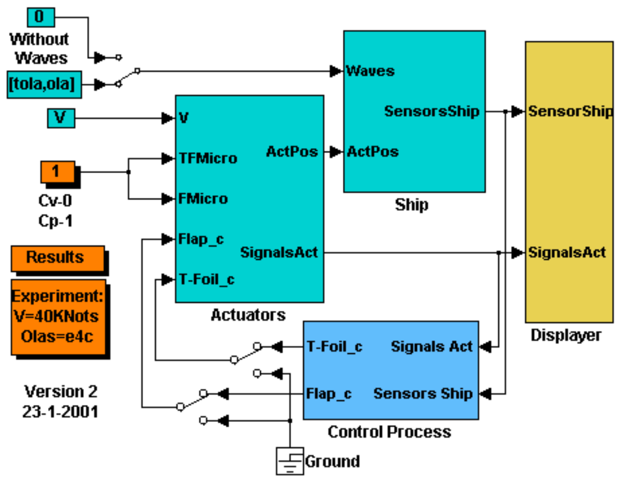

Figure 2: Simulink Model

3 Control problem

3.1 System Block Diagram

The feedback system includes the controller block which will be made up of two controllers: the $G_{C(F)}$ controller acts on the flap to reduce the acceleration in the heave component, and the $G_{C(TF)}$ acts on the T-foil to reduce the acceleration in the pitch component. The variable to control is the vertical acceleration measured 40 metres forward from the centre of gravity (WVA). The block diagram of the referred system is:

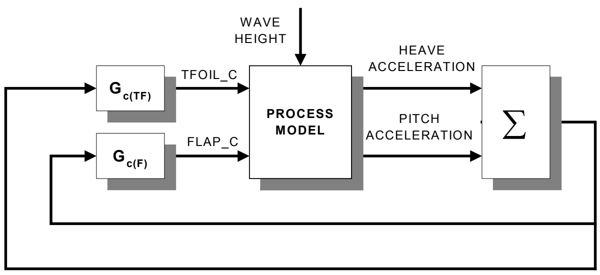

Figure 3: Control Schema

3.2 Specifications

The main aim in the design of the controller [5] is to increase passenger comfort. The minimisation of the mean vertical acceleration is obtained using the heave and pitch accelerations as follows:

$$
\begin{aligned}
acv40(t_i) &= a_{VH}(t_i) + a_{VP}(t_i) = \\
&= \frac{d^2 heave(t_i)}{dt^2} - 40\frac{\pi}{180}\frac{d^2 pitch(t_i)}{dt^2}
\end{aligned} \tag{1}
$$

It also achieves a reduction in the motion sickness incidence. Lloyd [6] tells O'Hanlon and McCaully found MSI (percentage of passengers getting sick after two hours of motions) can be quantified by the following expression:

$$
MSI = 100\left(0.5 \pm erf\left(\frac{\pm \log(|\ddot{s}_3| / g) \pm \mu_{MSI}}{0.4}\right)\right) \tag{2}
$$

with $|\ddot{s}_3|$, vertical acceleration at the chosen point (40 metres to bow of the c. g.) and

$$
\mu_{MSI} = -0.819 \pm 2.32\,(\log_{10} \omega_e)^2 \tag{3}
$$

where ω_e is the dominant encounter frequency with waves.

Figure 4 shows MSI plots for different encounter frequencies and values of vertical accelerations. Notice that the worst frequency for passengers is around 1.07 rad/sec and was the acceleration increases so does the number of sea-sicken persons.

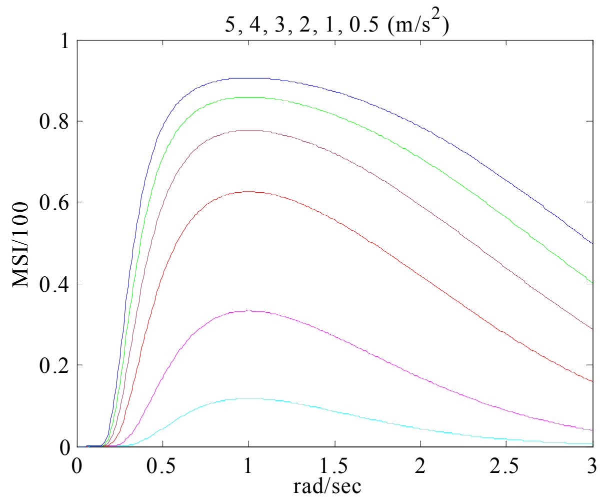

Figure 4: MSI/100 vs. encounter frequency for several mean values of vertical acceleration

3.3 Controllers

The following classical digital controller types have been implemented:

Standard PD:

$$
G_C(z) = k_p + k_d\frac{z-1}{Tz} \tag{4}
$$

Where k_p and k_d are the proportional and derivative constants and T is the sampling period. The value of T should be sufficiently small, so that the digital approximation of the continuous controller is adequately accurate.

PID with forward-rectangular integration (PIDfi):

$$G_C(z) = k_p + k_d \frac{z-1}{Tz} + k_i \frac{Tz}{z-1} \qquad (5)$$

Where k_i is the integral constant.

PID with backward-rectangular integration (PIDbi):

$$G_C(z) = k_p + k_d \frac{z-1}{Tz} + k_i \frac{T}{z-1} \qquad (6)$$

PID with trapezoidal integration (PIDti):

$$G_C(z) = k_p + k_d \frac{z-1}{Tz} + k_i \frac{T(z+1)}{2(z-1)} \qquad (7)$$

3.4 Tuning the Controllers

Genetic algorithms (GAs) [7] have been used to obtain optimal tuning of the controllers.

Genetic algorithms form an optimisation technique which acts on a population of defined individuals through a chromosome formed by binary genes. The GA acts on the chromosomes using selection, crossover and mutation operators for a specific number of generations. In order to quantify the aptitude of the individuals, an objective function, Φ, is maximised. The starting point is an initial population, P(0), formed by p individuals. Some genetic operators are applied to this population to modify it probability to create a new population, P(1). The process is repeated over a given number of generations T. The successive generations, P(t) being obtained. The solution is obtained among individuals of the last generation P(T).

Figure 5 shows a flow diagram of a simple GA. To make the flow diagram easier to understand, a short summary of the terminology and the operators used is presented.

Fitness: The measurement of the aptitude of the individuals of a population is performed by means of the evaluation of the values of the objective function Φ. The aptitude of the population corresponding to any one given generation can be expressed by:

$$\Psi_t = \sum_{i=1}^{p} \Phi_{it} \qquad (8)$$

Selection operator: It is considered that the dimension of the population remains constant during the selection process. Each individual i of a population P(t) is assigned a selection probability based on the measurement of its aptitude

$$s_{it} = \frac{\Phi_{it}}{\Psi_t} \qquad (9)$$

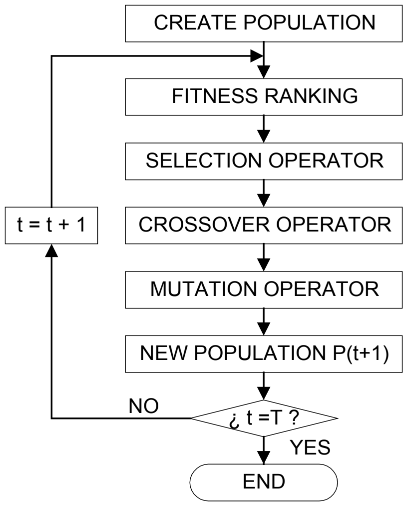

Figure 5: Basic genetic algorithm

The operator selects at random the individuals from the population P(t) in keeping with the probabilities s_{it}, generating a new population P'(t+1) with a greater Ψ_t value.

Crossover operator: This operator is applied to the intermediate population P'(t+1) from a specified crossover rate ($0<r_c<1$). For each individual from P'(t+1) a random number ($0<r_i<1$) is generated and if $r_i<r_c$ it is selected for the crossover. Thus, an even number of individuals (parents) is selected and by selecting a random point in its strings, the chromosomes are combined giving rise to two new descendants (new population P''(t+1))

Mutation operator: This operator alters the population P''(t+1) at random, inverting one or more bits of the string of some chromosome, using a mutation probability r_m. The mutation is introduced in an attempt to guarantee that any point in the search space can be reached and to prevent the GA from getting stuck at a local optimum.

The values of the crossover and mutation rates affect the convergence characteristics of the method, depending on the problem and the algorithm concerned.

In order to obtain the optimum controller parameters using GAs, the Simulink model for the ship has been used, minimizing the cost function WVA.

A summary of the results obtained is presented in Tables 1 and 2. It can be observed that the greatest reduction in vertical acceleration occurs in the case of PD controller. Good results are also obtained with PID controllers.

Controllers type	*WVA (m/s^2)*
PD	0.269951
PIDfi	0.272782
PIDbi	0.272699
PIDti	0.278298

Table 1: WVA

		k_p	k_d	k_i
PD	*T-foil*	42.20	3.71	0
	Flap	19.85	35.01	0
PIDfi	*T-foil*	49.68	6.90	2.33
	Flap	14.85	83.53	7.86
PIDbi	*T-foil*	45.69	8.44	1.096
	Flap	0.526	20.08	1.78
PIDti	*T-foil*	45.223	1.807	0.148
	Flap	26.98	95.78	4.47

Table 2: Controller parameters

4 Simulations

To simulate the ship TF-120 vertical acceleration and MSI reduction results, the Simulink model has been used for a craft speed of 40 knots and sea-state 4. Tables 3 y 4 present a summary of the results obtained with the controllers studied. Here, it can be observed a good reduction in vertical acceleration and MSI with all the PD and PID controllers.

	WVA without controller	*WVA with controller*	*WVA reduction (%)*
PD	0.5639	0.2633	53.3
PIDfi	0.5639	0.2691	52.3
PIDbi	0.5639	0.2653	53.0
PIDti	0.5639	0.2693	52.2

Table 3: Percentage of Improvement in WVA

	MSI without controller	*MSI with controller*	*MSI Reduction (%)*
PD	3.4560	0.4090	88.2
PIDfi	3.4560	0.4386	87.3
PIDbi	3.4560	0.4192	87.9
PIDti	3.4560	0.4397	87.3

Table 4: Percentage of Improvement in MSI

In figures 6 to 11 are shown the graphics for the mean vertical acceleration, actuators position (T-foil and Flap) and MSI for PD and PID with backward-rectangular integration. These controllers were chosen because they provide to the ship smaller vertical accelerations and less actuators saturation. In the graphics can be seen that the best results are obtained with the PID controller due to the fact that the same reduction of MSI is achieved with a lesser amplitude of flap movement

Trials with a scale model in irregular waves have been carried out in the towing tank of CEHIPAR (Canal de Experiencias Hidrodinámicas de El Pardo, Madrid, Spain). The results obtained confirm the Simulink model simulations.

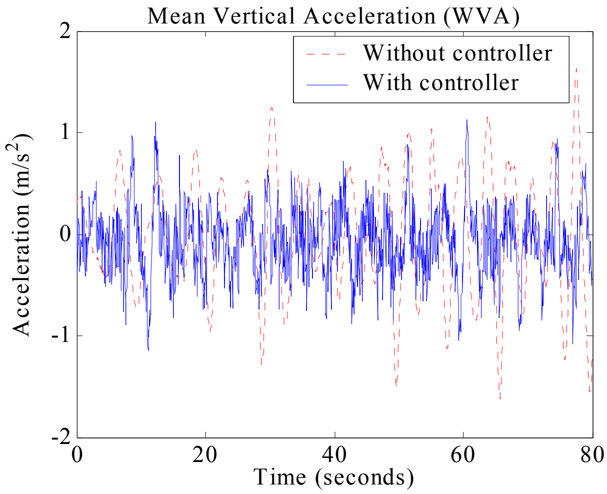

Figure 6: Mean vertical acceleration (PD controller)

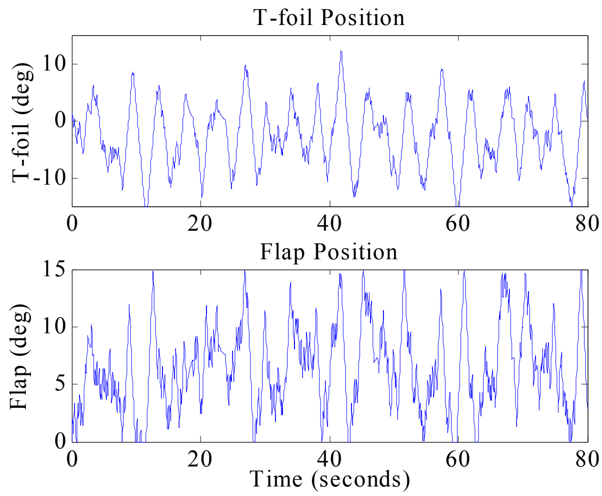

Figure 7: T-foil and Flap position (PD controller)

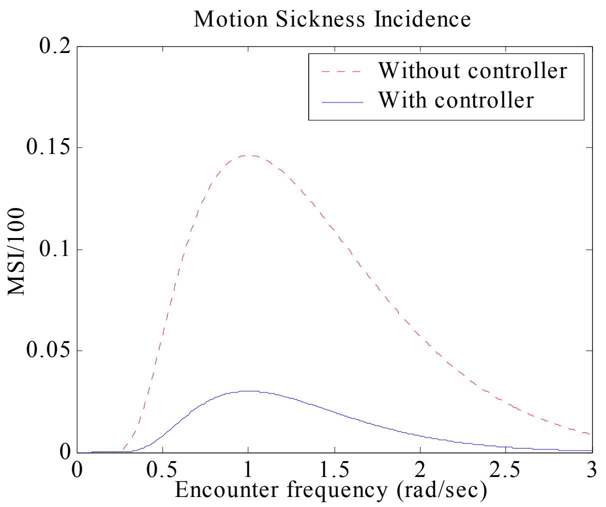

Figure 8: Motion Sickness Incidence (PD controller)

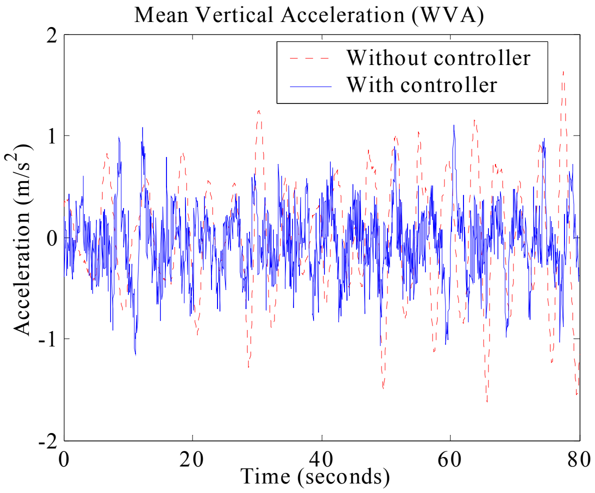

Figure 9: Mean vertical acceleration (PID controller)

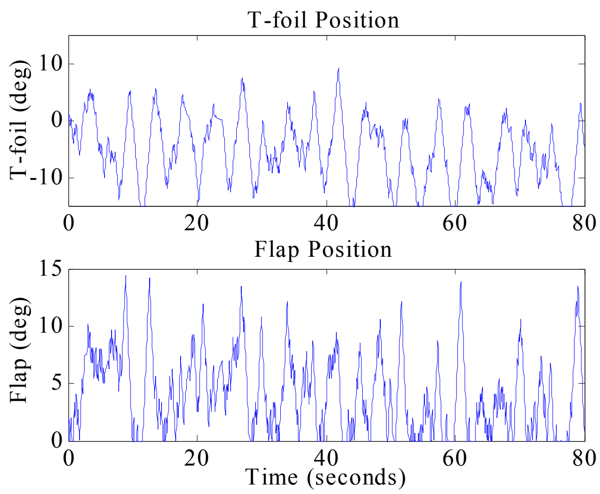

Figure 10: T-foil and Flap position (PID controller)

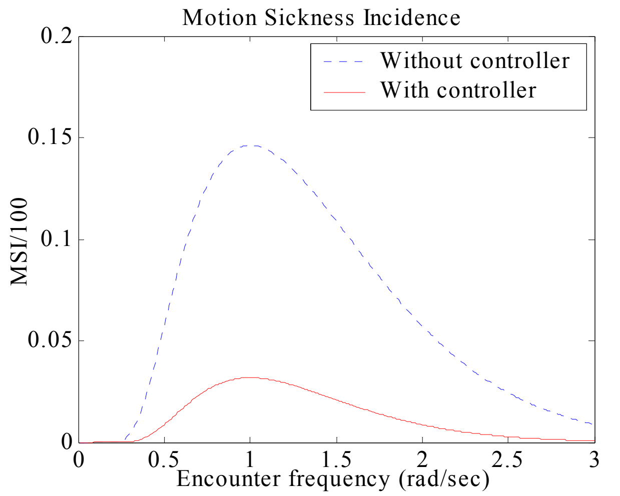

Figure 11: Motion Sickness Incidence (PID controller)

5 Conclusions

We have shown the tuning of several classical controllers. The optimum values of the controller parameters were found by GAs. The Simulink model referred to the ship has been used for controller parameters optimisation.

The simulation tests were realized using the Simulink model with two of the controllers tuned. It has been found that using classical digital controllers tuned by GAs an important reduction has been achieved in the vertical acceleration (and, consequently, in the motion sickness incidence) with almost all of the controllers studied.

Acknowledgements

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