CLASSICAL CONTROLLERS FOR A HIGH-SPEED CRAFT

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ABSTRACT

This article describes the tuning of various classical 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 all speeds (20, 30 and 40 knots) and sea conditions (4 and 5). 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 several controllers provide a significant reduction. This study will be used in the future for comparison with robust intelligent controllers that are currently being designed.

KEYWORDS
Ship Control, Ship Model, High Speed Craft, Heave Stabilization, Pitch Stabilization, Genetic Algorithms.

INTRODUCTION

This paper presents the design of various classic controllers with a view to reducing the vertical acceleration of the high-speed craft, the TF-120. 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 (GAs) to minimise the vertical acceleration measured at the "worst passenger" position. The 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.
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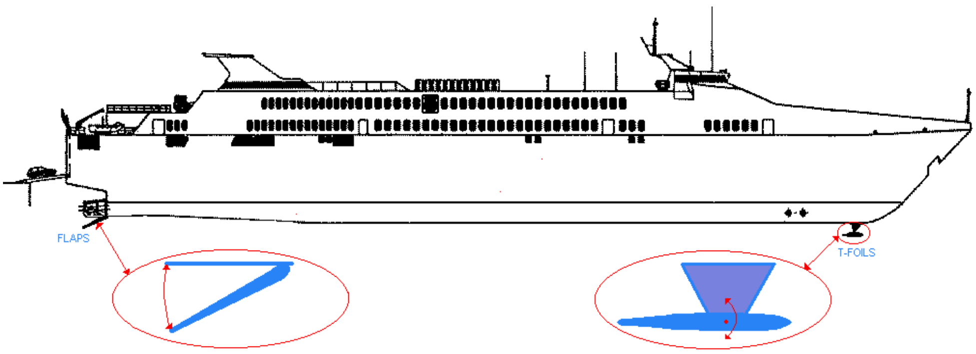
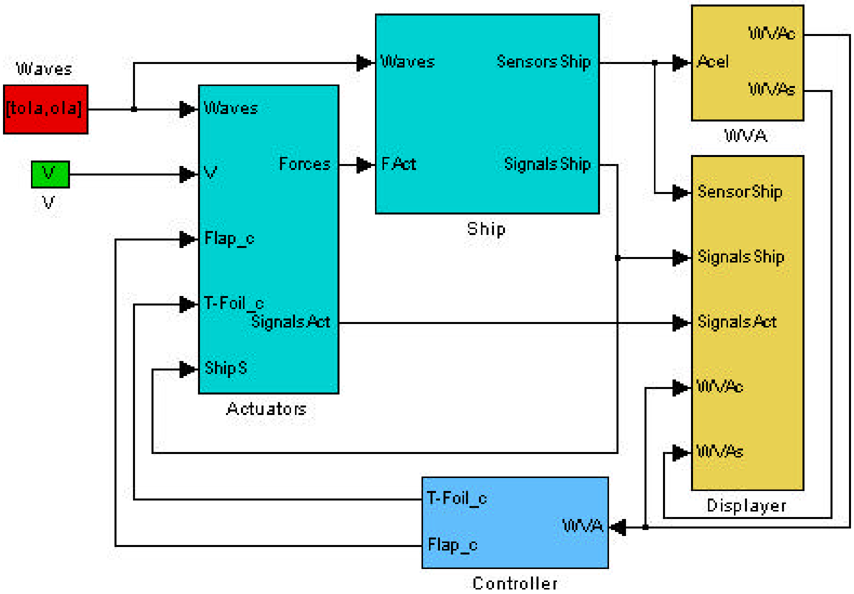


MATHEMATICAL MODEL

In order to simulate the vertical movement of the craft, the TF-120, the Simulink model developed in the CICYT TAP97-0607 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 the craft speeds of 20, 30 and 40 knots and for sea-states 4 and 5.
The vertical dynamics of the craft is composed of various continuous linear SISO models which were identified from PRECAL [1], [2], [3] data, corrected at bow, at speeds of 20, 30 and 40 knots. These models are given by the transfer functions which relate wave height with heave force (w2hf) and pitch momentum (w2pm) and the heave force with the heave movement (hf2h) and the pitch momentum with the pitch movement (pm2p).
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 vertical dynamic model together with the actuators is:

Fig. 1. System Model

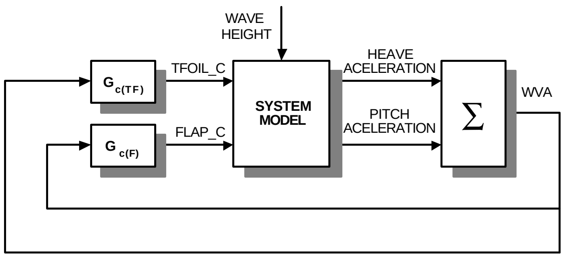


CONTROL PROBLEM

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 from to bow from the centre of gravity (WVA). The block diagram of the referred system is:

Fig. 2. Control Schema



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:

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

It also achieves a reduction in the motion sickness incidence (MSI) which can be quantified by the following expression:

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

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

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

Controllers

The following classical controller types have been implemented:

Standard PID: $G_C(s) = kp \dfrac{a\,Ti\,Td\,s^2 + [Ti + (a+1)Td]s + 1}{Ti\,s\,(a\,Td\,s + 1)}$ (4)

Standard PD: $G_C(s) = kp \dfrac{(a+1)Td\,s + 1}{a\,Td\,s + 1}$ (7)

First Order Controller: $G_C(s) = kp \dfrac{s+z}{s+p}$ (10)

Lead Controller: $G_C(s) = kp \dfrac{s + \frac{1}{T}}{s + \frac{1}{a\,T}}$ (11)

Lead-lag controller: $G_C(s) = kp \dfrac{\left(s + \frac{1}{T1}\right)\left(s + \frac{1}{T2}\right)}{\left(s + \frac{a}{T1}\right)\left(s + \frac{1}{a\,T2}\right)}$ (12)

for $0.05 < a < 0.95$.

Both the series and parallel forms of the PID and PD controllers have also been implemented.

Tuning the controllers

Genetic algorithms have been used to obtain optimal tuning of the controllers.

Genetic algorithms (GAs) [6] form an optimisation technique which acts on a population of defined individuals through a chromosome formed by binary genes. The GA act 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 is maximised Φ. The starting point is an initial population P(0), formed by p individuals. Some genetic operators are applied to this population to modify it probabilistically 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).

The cost function in the genetic algorithm is MejWVA = WVA (without controller) – WVA (with controller) (equivalent to minimising WVA with controller).

SIMULATIONS

Tables 1 and 2 present a summary of the results obtained with the controllers studied. Here, it can be observed that the greatest reduction in vertical acceleration and MSI occur in the case of the first order controller. Good results are also obtained with a lead-lag controller.
Although PID controllers also achieve a good reduction in MSI, better in fact than that obtained with Standard and Series PD, Parallel PD get better results without the possible problem of integral saturation. The position of the poles and zeroes of the Parallel PD controller is very similar to that obtained for the first order controller..

Table 1: Controller Parameters

		K	Zeros	Poles
Standard PD	T-foil	1123	- 0.047	- 0.518
	Flap	941.6	- 0.0624	- 0.686
Parallel PD	T-foil	159.15	- 10.30	- 10.99
	Flap	13.63	- 0.147	- 0.551
Series PD	T-foil	1496.3	- 5.882	- 58.823
	Flap	929	- 9.091	- 90.91
Standard PID	T-foil	50.8842	- 125.65 - 0.173	0 -1.93
	Flap	17.32	- 0.783 - 0.0126	0 - 0.621

Parallel PID	T-foil	71.967	- 8.27 - 0.057	0 -0.685
	Flap	51.67	- 0.602 - 0.001	0 - 0.5936
Series PID	T-foil	609.3	- 0.478 - 0.085	0 - 0.854
	Flap	450.1	- 50 - 0.99	0 - 9.901
Lead controller	T-foil	149.30	- 0.053	- 0.0812
	Flap	59.63	- 0.0754	- 0.0877
Lead-lag controller	T-foil	133.11	- 0.09 - 0.104	- 0.077 - 0.1224
	Flap	148.42	- 3.33 - 33.33	- 0.533 - 208.33
First order controller	T-foil	130.66	- 14.74	-11.09
	Flap	22.61	- 2.60	- 0.17
Second order controller	T-foil	143.11	- 1.11 - 4.62	- 10.43 - 0.05
	Flap	94.07	- 19.24 -17.93	- 15.39 - 15.90

Tabla 2: Mean Percentage of Improvement in WVA and MSI

	MejWVA (%)	MejMSI(%)
Standard PD	16.04	25.7
Parallell PD	18.73	29.54
Series PD	17.34	27.57
Standard PID	18.52	29.45
Parallel PID	18.27	29
Series PID	18.40	29.04
Lead controller	17.88	28.34
Lead-lag controller	18.79	29.54
First order controller	19.22	30.19
Second order controller	18.53	29.47

As a sample of the results obtained, the graphs for the cases of a craft speed of 40 knots (SSN 4 & 5) and a first order controller which represent a comparison between the vertical heave acceleration pitch and mean vertical acceleration of the craft without controller and with controller, shown both as a function of time and of frequency. Finally the passenger motion sickness incidences when sailing without controller and with controller are compared .

Fig. 4. Time series of heave and pitch acceleration.

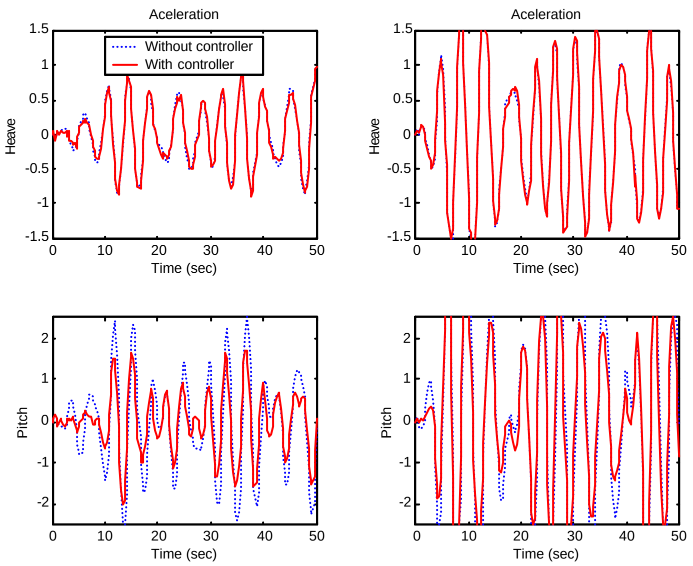
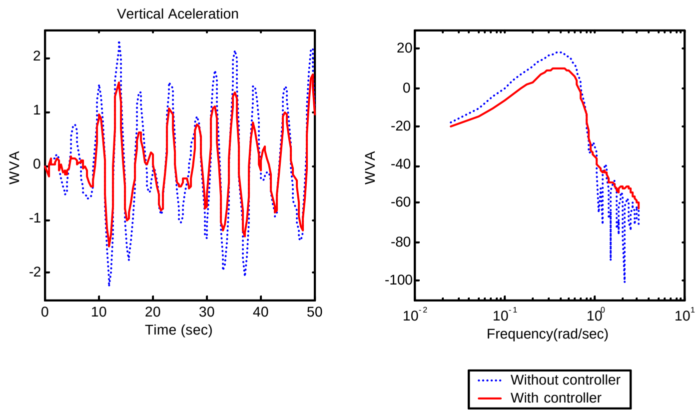


Fig. 5. Time series and Bode Diagram of WVA (40/4, 40/5)



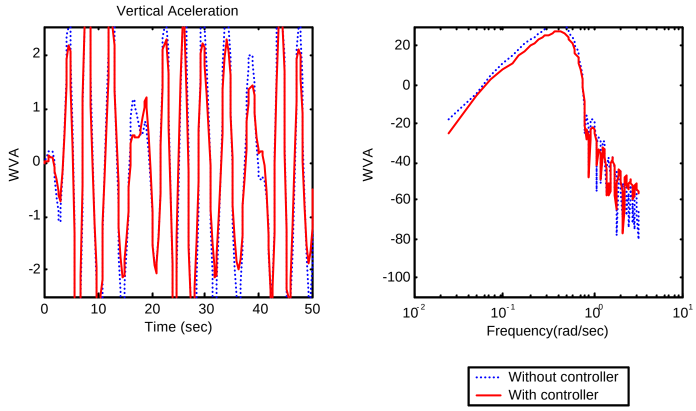
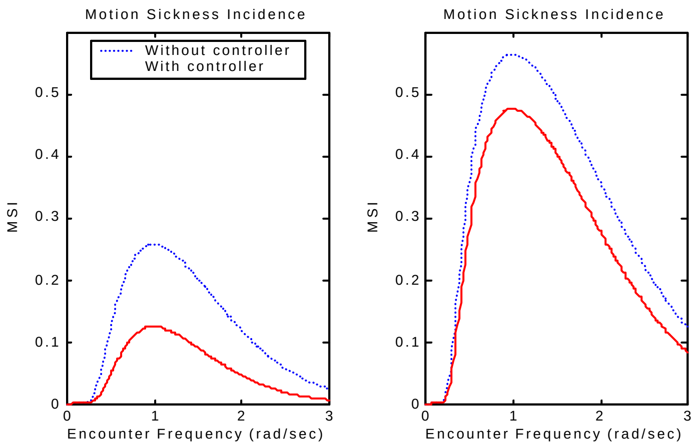


Fig. 6. Motion sickness incidence



Tables 3 and 4 show the results obtained with the first order network adjusted with the same values (sv) for all the craft speeds and sea-states and those obtained when the network is specifically tuned for each case.

Since, for all simulations, the best results are obtained for 4e4 conditions (speed 40 knots, SSN 4) and 3e4 (speed 30 knots, SSN 4) these cases bear the most weight in the mean cost function. Thus, the controllers adjusted specifically for these conditions have very similar parameter values. In any case, the improvement obtained with the specifically tuned controllers is not very great in comparison with that of the controller adjusted with the same values for all cases.

Table 3: Controller Parameters

		K	Zeroes	Poles
First order controller	T-foil	130.66	- 14.74	-11.09
	Flap	22.61	- 2.60	- 0.17
2e4	T-foil	104.92	- 18.07	- 2.04
	Flap	71.32	- 5.02	- 0.11
2e5	T-foil	77.06	- 1.6	- 0.05
	Flap	126.05	- 3.74	- 0.01
3e4	T-foil	121	- 15.44	- 9.58
	Flap	31.83	- 3.8	- 0.05
3e5	T-foil	54.022	- 19.65	- 11.28
	Flap	84.06	- 1.55	- 0.038
4e4	T-foil	134.05	- 17.44	- 11.11
	Flap	26.05	- 2.12	- 0.07
4e5	T-foil	139.16	- 12.88	- 11.71
	Flap	22.79	- 2.64	- 0.025

Table 4: Percentage of Improvement in WVA and MSI

	MejWVA (%)	MejMSI (%)
2e4 sv	8.15	15.45
2e4	10.1196	19.0787
2e5 sv	5.20	7
2e5	6.4022	8.6380
3e4sv	31.49	60.27
3e4	32.3459	61.5762
3e5 sv	14.74	15.91
3e5	14.85	16.05
4e4 sv	36.98	64.77
4e4	37.2419	65.1307
4e5 sv	18.76	17.72
4e5	19.00	18.10

CONCLUSIONS

With the craft model used for the tuning, a single controller has been found in all cases for all craft speeds (20, 30 and 40 knots) and sea-states (4 and 5). Using 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 and, most significantly, with the first order controller.

With the first order controller, it has been shown that by designing a controller for each speed and sea-state, slight improvements are achieved in the reduction of vertical acceleration and MSI. It can be appreciated in the graphs that the greatest reduction in the vertical acceleration of the craft is due to the reduction in the pitch acceleration. In some cases, the reduction in the heave acceleration is practically unnoticeable.

ACKNOWLEDGEMENTS

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