MULTIOBJECTIVE CONTROL OF FLAPS AND T-FOIL IN HIGH-SPEED SHIPS

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Abstract: Fast sea transportation of passengers must considered safety and comfort requirements. Due to waves, there are heaving and pitching motions. These motions originate sea-sickness and can have negative effects on the ship. By means of submerged actuators, vertical motions can be smoothed. This paper considers the real case of a fast ferry with a T-foil and flaps. This is a control problem that also has to consider cavitation and possible fatigue of the actuators' system. In consequence there is a multiobjective optimization problem, controlling a non-linear system. A Multiobjective Genetic Algorithm is designed and applied to the case. The research obtains satisfactory results.

Keywords: marine systems, ship control, multiobjective optimisations, control applications.

1. INTRODUCTION

Nowadays passenger comfort has become an important issue in the world of sea transportation. In particular, vertical -heave and pitch- motions of ships, in response to waves, are related with sea-sickness. There are several ways to smooth these motions. For instance by means of submerged appendages, designed to counteract the waves effect.

This paper is concerned with the control of two transom flaps and a T-foil in a high-speed ship, figure 1. These appendages are actuators that move wave after wave. There is a control problem: to move the actuators in the most effective way, considering the dynamics of the ship and the actuators. Due to the use of dynamic cylinders, the actuators have rate limits. Since the actuators are submerged wings, there are angle limits for its lifting action. All that puts nonlinear characteristics into the control problem.

A replica was built for experiments on a basin with a wavemaker. Direct observation of many series of experiments, using several control alternatives, showed a tendency for excessive efforts of the actuators (they move even for negligible waves). Many motions of the actuators mean mechanical fatigue. Also, the onset of cavitation (eroding the appendages) was noticed when large actuator motions were used.

The complete scenario calls for a multiobjective design of the control, considering comfort, control efforts and cavitation. This is an interesting context (Miettinen, 1999), where our experience with multiobjective Genetic Algorithms (Besada-Portas, *et al.*, 2001) can be exercised. But the Multiobjective design problem must be adequately specified: this is a crucial point of the research.

The paper begins with a description of the control problem, highlighting the main aspects. Then the mathematical specification of the multiobjective control optimisation is presented. Afterward the method to find the control solution with Genetic Algorithms is briefly explained. Then the paper shows how the method is applied to our case. Good results are obtained and presented in several figures. The paper ends with some conclusions.

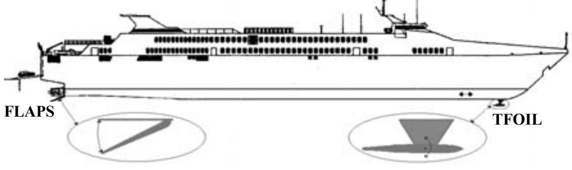


Fig. 1. Position of the T-foil and the flaps.

2. THE CONTROL PROBLEM

The fast ferry selected for the research is an aluminium-made deep-V monohull ship, with 110m. length, 1200 passengers, and a speed of 40 or more knots. It was built by Bazan (now Izar). A scaled down (1/25) was built for experiments in CEHIPAR (Canal de Experiencias Hidrodinamicas de El Pardo, Madrid), a towing tank institution. The research is concerned, as a first step, with head seas. The replica has been used in a basin with wavemaker, with a set of regular waves of different wavelengths and irregular waves corresponding to coastal waters (JONSWAP spectra, SSN4, 5 and 6) (Fossen, 1994).

A series of experiments has been accomplished to determine a mathematical model of the pitching and heaving motions (Esteban et al., 2000a). This model is internally decomposed into coupled linear blocks (transfer functions) and it is expressed in SIMULINK. Since information of actuators was scarce, the approach was to accomplish the entire cycle of design, (implementing, testing and modelling), using the replica. The model is non-linear, as it takes into account rate and angle limits (Esteban et al., 2000b). It is also implemented in SIMULINK. Using the models of the ship and the actuators, together with records of the waves generated at CEHIPAR, a complete simulation environment has been developed (Esteban et al., 2001). Different control strategies can be easily studied in this environment, with reliable results.

Due to the complexity and the nonlinearities of the system (the ship with actuators), it is very difficult to accomplish analytical control studies. But the simulation environment can be used to "tune" any control strategy, by searching methods. As a natural choice to start with, the PID has been subject to study in this case. Other control alternatives have been also tested, with slight better results. Since the actuators have a limited influence on the ship vertical motions (the forces and moments exerted by the waves can be enormous), there is little hope for significant improvements due to a particular control strategy. But, in any case, the important point is to have the control obeying, as far as possible, several optimal criteria.

3. OBJECTIVES TO BE OPTIMIZED

The main objective is to minimize sea-sickness. Another objective is to avoid cavitation. The third objective is not to use excessive control efforts. These objectives must be specified in mathematical terms. Let us proceed orderly.

3.1 Sea-sickness.

The basic references (for instance (Lloyd, 1998)) give credit to experimental studies (O'Hanlon, MacCawley, 1974) which relate sea-sickness with vertical accelerations of certain frequencies. The MSI ("Motion Sickness Incidence") index was defined as the percentage of passengers getting sick after two hours of motions. A mathematical model of the MSI was obtained, with the following expression (1):

$$MSI = 100 \cdot \left[0.5 \pm \mathrm{erf}\left(\frac{\pm \log_{10}(|\ddot{s}_3| / g) \mp \mu_{MSI}}{0.4} \right) \right] \quad (1)$$

where $|\ddot{s}_3|$ is the r.m.s. vertical acceleration in a chosen place (MAA), and:

$$\mu_{MSI} = -0.819 + 2.32(\log_{10} \omega_e)^2 \quad (2)$$

where ω_e is the dominant pulsation of encounter with waves.

Figure 2 shows some plots of MSI versus the frequency of encounter and the r.m.s. values of the vertical accelerations. Notice that the worst pulsation for humans is around 0.16 Hz. (about one wave each six seconds).

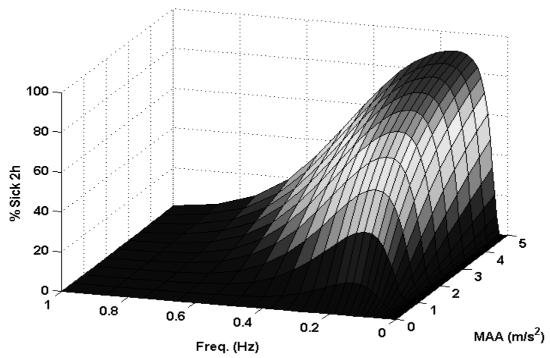


Fig. 2. MSI vs. w_e and MAA.

The frequency of encounter 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.

Passengers sit in different places in the ship. Near the bow the vertical accelerations are bigger than near the c.o.g. of the ship. Thinking about what kind of information about the current MSI should be given to the captain, it is clear that a weighting must be applied to get an "average" MSI. During experiments with the replica, five accelerometers were used, in five different places. By a study of the passengers' distribution on the ship, the following weights were determined, figure 3.

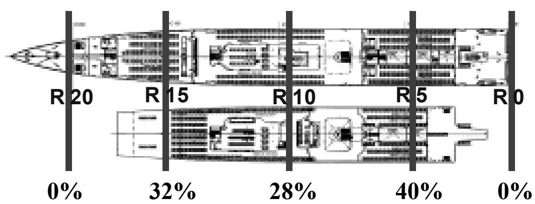


Fig. 3. Location and weight of accelerometers.

The first objective to be minimised is (3)

$$J_1 = \sum_i weightC_i \cdot MSI_i \quad \text{with } i = \{0,5,10,15,20\} \tag{3}$$

3.2 Cavitation.

The phenomenon of cavitation appears in certain conditions that depend on pressure, fluid speed, angle of attack and dimensions of the actuators. Figure 4 shows the conditions for cavitation in terms of angle of attack versus fluid speed.

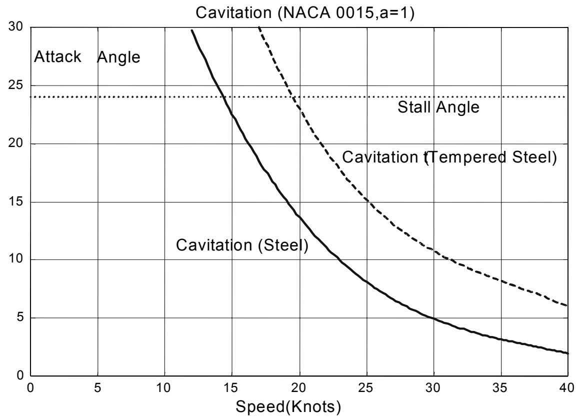


Fig. 4. Cavitation curves.

Considering the characteristics of the actuators designed during the research, two objective functions J_2 and J_3 were defined (to be minimised), according to the following equations:

- For the T-foil (4):

$$\begin{aligned} CavTF &= \begin{cases} AngCavTF & \text{If } AngCavTF > 0 \\ 0 & \text{If } AngCavTF \leq 0 \end{cases} \\ \text{where } & AngCavTF = |AngTF| - AngMaxCav \\ & AngMaxCav = 0.025 \cdot V^2 - 2 \cdot V + 43 \\ J_2 &= \overline{CavTF} \end{aligned} \tag{4}$$

CavTF is the instantaneous cavitation, and J_2 is the mean value of this cavitation along the ship travel.

- For the Flaps (5):

$$\begin{aligned} CavFL &= \begin{cases} AngCavFL & \text{If } AngCavFL > 0 \\ 0 & \text{If } AngCavFL \leq 0 \end{cases} \\ \text{where } & AngCavFL = |AngFL| - AngMaxCav \\ & AngMaxCav = 0.025 \cdot V^2 - 2 \cdot V + 43 \\ J_3 &= \overline{CavFL} \end{aligned} \tag{5}$$

CavFL is the instantaneous cavitation, and J_3 is the corresponding mean value along the ship travel.

3.3 Control efforts

Hydraulic cylinders are used to move the T-foil and the Flaps. One of the main reasons for fatigue and malfunctioning of these cylinders and valves, is the cumulative effect of brisk motion reversings. They should be minimized. Brisk motions can be detected by a acceleration threshold. In this way, the following objective functions J_4 and J_5 can be defined:

- For the T-foil (6):

$$\begin{aligned} \lim &= 1.2\left[\frac{d(VelocityTF)}{dt}\right]_{start} \\ CSENTF &= \begin{cases} 1 & \text{If } \frac{d(VelocityTF)}{dt} > \lim \\ 0 & \text{If } \frac{d(VelocityTF)}{dt} \leq \lim \end{cases} \\ J_4 &= \overline{CSENTF} \end{aligned} \tag{6}$$

CSENTF is an instantaneous value, and J_4 is the corresponding mean value along the ship travel.

- For the Flaps (7):

$$\begin{aligned} \lim &= 1.2\left[\frac{d(VelocityFL)}{dt}\right]_{start} \\ CSENFL &= \begin{cases} 1 & \text{If } \frac{d(VelocityFL)}{dt} > \lim \\ 0 & \text{If } \frac{d(VelocityFL)}{dt} \leq \lim \end{cases} \\ J_5 &= \overline{CSENFL} \end{aligned} \tag{7}$$

CSENFL is an instantaneous value, and J_4 is the corresponding mean value along the ship travel.

Now, things are ready for multiobjective optimization. A special version of Genetic Algorithms will be used. Let us describe briefly the essence of the method.

4. MULTIOBJECTIVE GENETIC ALGORITHMS

Genetic Algorithms usually have two main aspects. One is the way to form successive populations, by using evolution operators. The other is the evaluation of individuals, in view of the objectives.

Based in our previous research, with results such a complete Toolbox (Besada-Portas *et al.*, 2001), a panmitic, elitist, with tight linkage Genetic Algorithm has been designed for the case. Crossover and mutation probabilities have been chosen according to other similar problems (Andrés-Toro *et al.*, 1999).

There are two main alternatives to handle multiobjective optimization problems. A simple way is the use of aggregating functions, forming a single objective function (for instance, by means of weights, exponentials, penalties, etc.). Pareto sets are the basis of a second alternative, with better avoidance of local minima. Priority levels can be considered (Fonseca and Fleming, 1998), to guide the evolutionary searching. This second alternative has been chosen for our case.

The encoding of the control optimization is done with a group of 6 real numbers inside an interval, which represent the parameters of the PID controllers (3 for the flaps, 3 for the T-foil

5. APPLICATION TO THE PROBLEM

According to the multiobjective fitness method, several priority levels are defined for the optimisation. It uses simultaneously all the information in all the levels, although improvements in the higher levels are more important than improvement in the lower ones. The method was relaxed to gain searching space for the lower levels. A 5% of tolerance is accepted for the MSI in order to get more important improvements at the lower objective levels. Other percentages of tolerances are also tested at middle objective levels, for instance a 2% in the cavitation. In this way, giving different values to percentages, some "tuning" knobs are introduced that constitute a control design method.

In this case, three priority levels are used. Figure 5 depicts a diagram with the objectives in each level. The first is devoted to minimize sea-sickness. The second to minimize cavitation. The third to minimise brisk changes in the motion of the actuators.

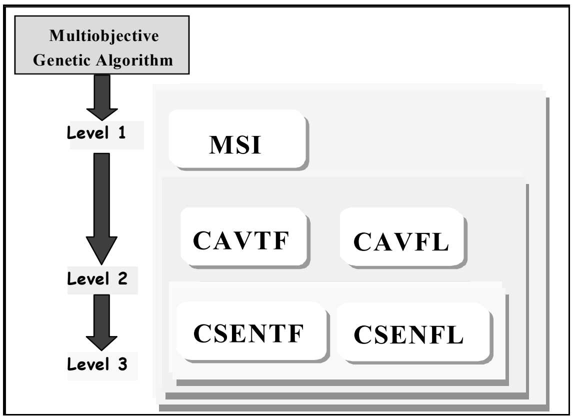


Fig. 5. Levels of the objectives hierarchy.

Let us take as example the optimization of a PD controller. In all the cases it was enough with sixty generations of the GA to reach a solution. Figure 6 shows an example of a typical multiobjective evolution. Figure 7 shows a 3D plot of the evolution at the first level (sea-sickness). Figure 8 shows the evolution of the cavitation of the T- foil and Figure 9 the evolution of the motion quality of the T-foil. The GA is initiated with a bad solution (actuators without control). At the very beginning, the Genetic Algorithm finds a good solution for the first level (marked as '1' in figure 6), but cavitation is too high. The evolution continues reaching another solution with better cavitation (marked as '2'). This solution has some derivative action that makes the actuators have many motion reversings (see figure 9). Now the evolution is guided to reach a solution (marked as '3') with better motion quality (the valley in figure 9). In this way a satisfactory solution, concerning all the objectives, has been found.

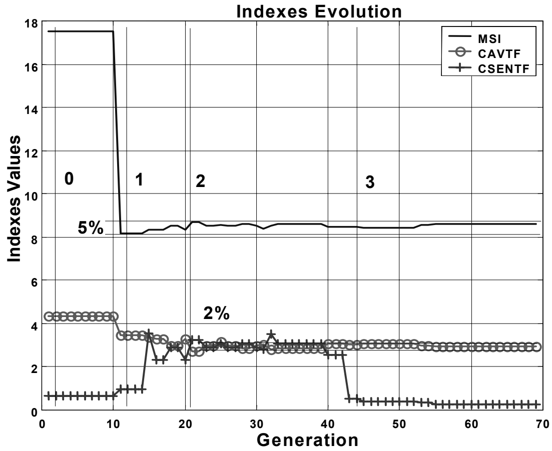


Fig. 6. Evolutionary multiobjective searching

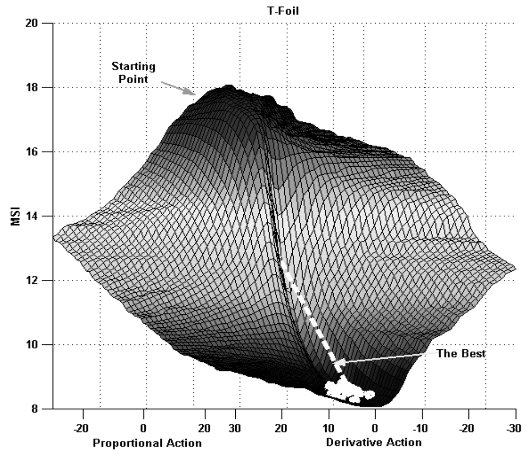


Fig. 7. MSI evolution

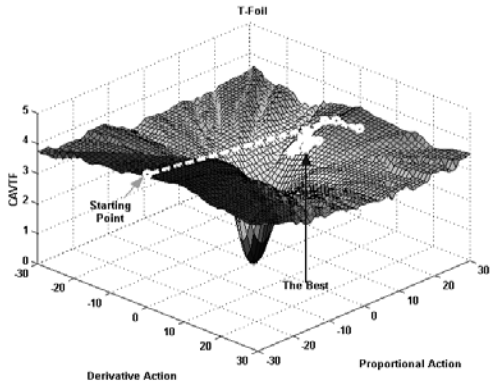


Fig. 8. Cavitation evolution

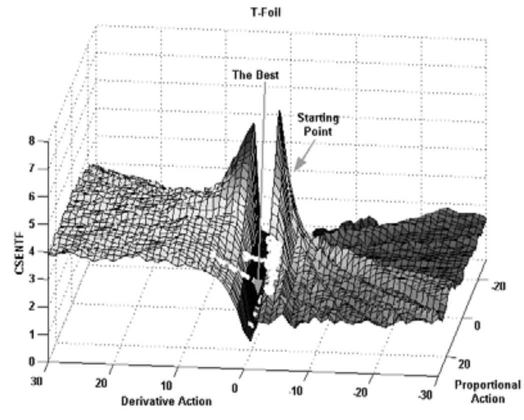


Fig. 9. Actuators vibration evolution.

Since this research considers two sea states (SSN4 and SSN5) and two ship's speeds (30 and 40 knots), four different cases were studied, and the best controller obtained for each of them. Additionally, the same GA, slightly modified was used for searching a common controller (unique tuning) for the four possible cases. The new GA uses a total of 16 objectives, divided in the same 3 levels and finds a Pareto-set of solutions.

6. RESULTS

In order to provide a visualisation mean for a rapid evaluation of multiobjective solutions, a special type of plotting has been chosen. Figure 10 shows an example. The vertical axis at the top is the normalised MSI (it is divided by the MSI without actuators). The two axes to the right correspond to the T-foil; the two axes to the left correspond to the flaps. Axes at the top are cavitations. Axes at the bottom are motion reversing.

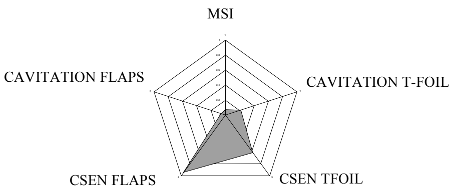


Fig. 10. Visualisation of a multiobjective solution.

Figure 11 compares the performance of control specifications for an optimal MSI (left column of plots), versus performances obtained with multiobjective optimisation (right column). The four cases are considered: SSN 4 and 30 Knots are the first row of two plots, the next rows below are SSN4-40 Knots, SSN5-30 Knots, SSN5-40 Knots. Notice that MSI values, in each case, are very similar for both controllers, but cavitations are clearly improved by the multiobjective solutions.

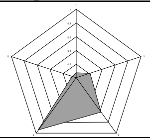
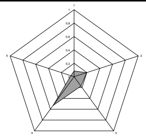
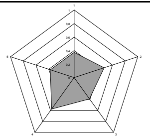
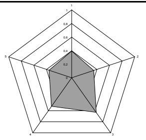
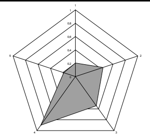
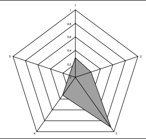
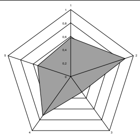
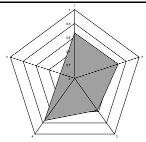
	Optimal MSI	Multi-Objective
SSN4-30		
SSN4-40		
SSN5-30		
SSN5-40		

Fig. 11. Mono-objective and multi-objective tuning.

It is interesting to have a visual impression of the effect of multiobjective optimisation concerning the motion quality of the actuators. Figure 12 compares the motion of the T-foil with and without minimisation of the vibrations. Smoother peaks are observed in the optimised curve.

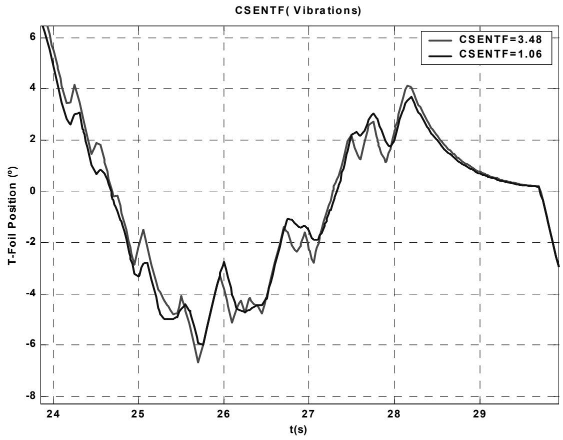


Fig. 12. Motion smoothing of the T-foil.

The following figures display the performances of several controllers. The controller A is the best common controller obtained when all the cases were considered simultaneously. The controller B is the multiobjective optimal for SSN4-30 Knots. The controller C is the same for SSN5-30 Knots, D is the same for SSN4-40 Knots, E is the same for SSN5-40 Knots.

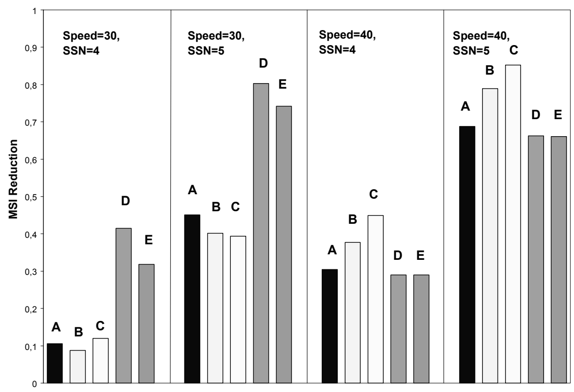


Fig. 13. Comparison of MSI for 5 controllers.

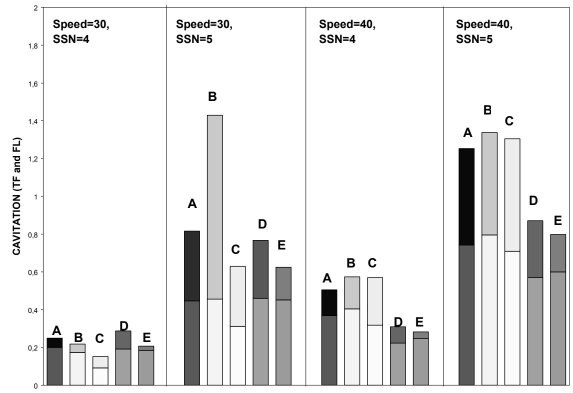


Fig. 14. Comparison of cavitation for 5 controllers.

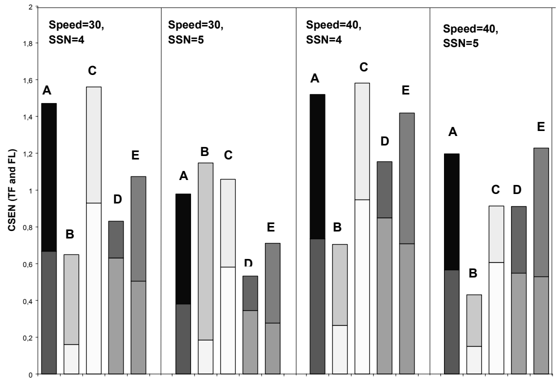


Fig. 15. Comparison of actuator vibrations for 5 controllers.

Figure 13 shows the MSI performances of the 5 controllers for the four cases considered. Notice that the common controller differs little from the best controller for each case. Figure 14 shows a comparison concerning cavitation. Each column is the sum of the cavitation of the T-foil (bottom) and the cavitation of the flaps (top). Figure 15 shows a comparison concerning motion quality.

7. CONCLUSIONS

This paper considers the multiobjective optimization of control for a high- speed passenger ship with T-foil and Flaps. The main objective is to increase comfort, by smoothing pitching and heaving motions. These vertical motions, due to waves, originate sea-sickness. The actuators must move wave after wave to counteract their effects. In certain conditions cavitation appears, eroding the actuators: cavitation must be minimized. Hydraulic cylinders are used to move the actuators. Brisk changes in the motion of the actuators shorten the life of the hydraulic system, so they also must be minimized.

All the objectives must be stated in mathematical terms, in order to apply optimization methods. This has been accomplished in the paper. On this basis, a Genetic Algorithm method has been designed and applied to the problem. The paper describes relevant aspects of how the evolutionary searching is guided through a multi-level scheme. Taking as example a PD controller, the paper presents a table of results for comparison of several alternatives. One is the mono-objective optimization, only looking at sea-sickness. The others are multi-objective optimizations.

Many other practical control problems, difficult to treat analytically, can be solved in a similar manner. Since Genetic Algorithms have to evaluate (many) solutions, it is important to get a (fast) simulation of the controlled system. This simulation can involve nonlinearities. Considering this point, the advice to use similar methods to other problems is to direct the effort toward two main aspects: a good simulation and an adequate formulation of the objectives. It is also interesting, when possible, to visualize the evolution.

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