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OVERVIEW OF A RESEARCH ON ACTUATORS CONTROL FOR BETTER SEAKEEPING IN FAST SHIPS

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Abstract: The paper is an overview of a research initiated seven years ago by three groups of three universities, under the auspices of a Spanish shipbuilder. The research aims to improve the seakeeping performances of fast ferries, by using moving appendages such transom flaps and T-foil. There is a problem of control design to move the actuators in adequate way, to counteract the effect of encountered waves. The research focuses on alleviation of seasickness. Several aspects have been covered along the research, motivating a long series of papers. The overview gives an ordered account of the main results, with the corresponding references. Main results concerning seasickness and navigation, prediction of seasickness during ship design, experimental modelling, control design and experimental verification, are presented.

Keywords: Overview, Ship control, Seakeeping, Human factors.

1. INTRODUCTION

With the advent of fast ferries the need of seakeeping improvement systems was realized. In particular, seasickness of passengers needs to be minimized. Scientific studies on seasickness, such (O'Hanlon and Mc Cauley, 1974), relate it to oscillatory vertical accelerations with a frequency around 1 rad/sec. Seakeeping improvement is also of military interest, looking for better crew and ship operational efficiency.

Years ago, under the auspices of a Spanish shipbuilder, a research started on the use of actuators such T-foil and transom flaps. The actuators should move to counteract the effect of encountered waves, alleviating the accelerations that cause sickness. A research team, of three universities, was formed to study the effect of such actuators and to control them. The research started considering head seas, letting for a second step the more general case of any heading with respect to waves.

The research has been fruitful, with many publications. Then, it seems useful to make now an overview of the results, highlighting the main aspects and pointing to the adequate references for more details. The name given to the research is CRIBAV (In Spanish:"Control Robusto e Inteligente de Barcos de Alta Velocidad"). A web page (CRIBAV, 1999) was established with videos of experiments.

In general, control studies begin with modelling, taking a long time, especially if there are experiments. Indeed, this has been the case in this research. Moreover, control designs have been also verified by experiments too. This paper starts with a description of the problem and its scientific context. Then, it focuses on the modelling task, beginning with data gathering. The paper continues with control design aspects. Then, the paper deals with present research activities, considering the 6 DOF case. Finally, conclusions are presented, with a view of future advances.

2. THE PROBLEM OF SEAKEEPING IMPROVEMENT USING ACTUATORS

Classically the main motion control topics concerning ships are related to the rudder. Simply because in many ships, the rudder is the only actuator for motion control. There are few papers in the scientific literature considering other actuators. However, it is interesting to quote some early initiatives on the use of antipitching fins (Abkowitz, 1959; Stefun, 1959; Vugts, 1967). Only recently some papers about moving appendages appeared, in connection with fast ferries (Haywood , et al., 1995; Ryle, 1998; Wu-Qiang and Zhu-Shun, 2002; Sclavounos and Borgen, 2004).

Figure 1 shows the case considered by CRIBAV. It is 126m. long fast ferry, aluminium made, deep-V monohull, capable of 40 knots speed (Anonymous, 1996). Two transom flaps and a T-foil near the bow were added to the ship.

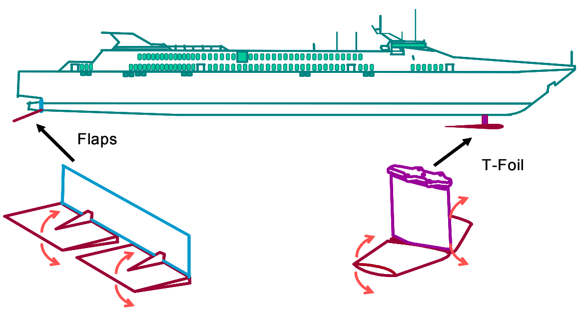

Fig. 1. Location of actuators on the ship

A first look to the control problem shows important peculiarities. The input causing ship motions are waves. When the ship's speed changes, added masses change, the frequency of encounter with waves shifts, and resonance peaks of the motions shift also. The plant to control is non-linear. Ship motions are coupled.

To simplify the research, three fixed ship's speeds were considered: 20, 30 and 40 knots. Regular sea waves were approximated as sinusoidal. This paves the way to consider transfer functions.

With head seas, only pitch and heave motions are relevant for the research (surge do not cause vertical accelerations).

Pitch moments and heave forces caused by sea waves are enormous. The actuators have limited authority, being unable to completely eliminate the vertical motions.

3. THREE FILTERS

Driving a car on certain roads could lead to vertical oscillations around 1 rad/sec., causing sickness. It can be avoided changing the speed. Same with ships (they can also change the heading).

An analogy of three filters can be established to calculate the percent of passengers becoming sick (Ewing and Goodrich, 1967). There are statistical descriptions of sea waves, according with a classification of sea states which tabulates ten different cases, from calm waters (Sea State Number 0, abbreviated as SSN 0), to phenomenal waves more than 14m high (SSN 9). The statistical distributions of waves across wave frequencies can be modelled as band-pass filters (one for each sea state). The vertical motions of the ship depend on the input frequency as another band-pass filter. Finally, the mathematical model of seasickness established in (O'Hanlon and Mc Cauley, 1974) can be seen as a band-pass filter, around 1 rad/sec. When the three filters have in common a certain frequency band, passengers become sick.

Based in the three filters analogy, a complete study of the impact of ship's speed and heading on passengers' seasickness has been done (Esteban, et al., 2005). This study has been preceded by a paper (Giron-Sierra, et al., 2003a) considering in general a ship, the wave wavelengths, and the speed and heading conditions putting the ship in resonance with excitation. This type of studies is useful for operational advice, to suggest changes in navigation parameters to avoid large motions and seasickness.

An interesting result has been derived in (Giron-Sierra, et al., 2004a), making possible to compute the percent of passengers becoming sick after two hours of sailing in certain conditions of sea state and ship's speed, using the frequency response of the ship (vertical accelerations). This frequency response can be determined from simulation tools, based on a CAD description of the ship's hull, before the ship was actually built. Consequently, it is possible to provide a tool helping to design ships with better seakeeping performances.

The result obtained is given by the following equation:

$$MSI = 100 \cdot e^{-0.42\,(SIA - 0.5)} \qquad (1)$$

where MSI (Motion Sickness Incidence) is the percent of passengers becoming sick after two hours of sailing, and SIA (Seasickness Impact Area) is the area of the of the frequency response of the coupled three filters.

Figure 2 shows the frequency response of the three filters for SSN5 and 40 knots ship speed. The figure includes the coupling of the three filters.

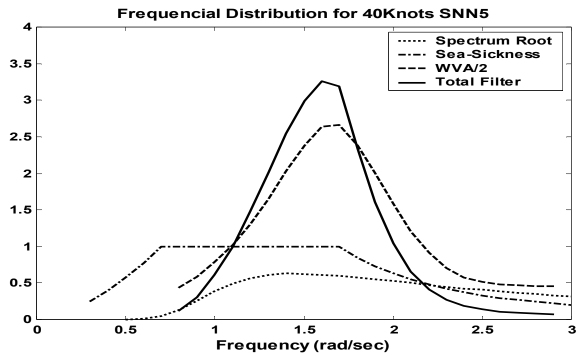

Fig. 2. The three filters and their intersection

A main result of the studies devoted to the three filters analogy, is to determine the frequencies of interest for actuators and control.

4. GETTING DATA FOR SHIP MOTION MODELLING

The research is based on two sources of data about ship motions in response to waves. One is a simulation program that, using a CAD description of the hull, gives the added masses, and the magnitude and phase of surge, heave, sway, roll, heave and yaw motions, together with the magnitude and phase of surge, heave and sway forces, and sway, roll and yaw moments. The program computes that information for regular waves. In this research a set of 25 wavelengths were selected, covering the frequencies of interest.

The other source of information is experimental. A 1/25 scaled down replica of the fast ferry was built. With the help of a large experimental facility ("CEHIPAR: Canal de Experiencias Hidrodinamicas de El Pardo") near Madrid, several series of experiments were carried on, using a 150m x 30m basin with a wavemaker. The replica was attached to a computerized planar motion carriage. Part of the experiments was devoted to reproduce the same cases treated by the simulation program: head seas, regular waves, 25 different wavelengths. Figure 3 shows photographs of the experimental facility and the replica:

Fig 3. The CEHIPAR facility and the replica

The computerized towing carriage is equipped with instrumentation for video recording, and for measurement of forces, moments and motions experienced by the replica. There are more details of the research design and the experiments in (Giron-Sierra, et al., 2001; De la Cruz, et al., 2001).

5. MODEL OF SHIP VERTICAL MOTIONS

The modelling task was initiated by using experimental data and standard identification methods (De la Cruz, et al., 1998). However it provides little insight, and brings some interpretation uncertainties.

A basis for first principles modelling of the ship motions is given by the following equations (Lloyd, 1998; Fossen, 2002):

$$
\begin{aligned}
&(m+a_{11})\ddot{x}_1 + b_{11}\dot{x}_1 = F_1 \\
&(m+a_{22})\ddot{x}_2 + b_{22}\dot{x}_2 + \\
&\qquad + a_{24}\ddot{x}_4 + b_{24}\dot{x}_4 + a_{26}\ddot{x}_6 + b_{26}\dot{x}_6 + c_{26}x_6 = F_2 \\
&(m+a_{33})\ddot{x}_3 + b_{33}\dot{x}_3 + c_{33}x_3 + \\
&\qquad + a_{35}\ddot{x}_5 + b_{35}\dot{x}_5 + c_{35}x_5 = F_3 \\
&a_{42}\ddot{x}_2 + b_{42}\dot{x}_2 + (I_{44}+a_{44})\ddot{x}_4 + b_{44}\dot{x}_4 + c_{44}x_4 + \\
&\qquad + a_{46}\ddot{x}_6 + b_{46}\dot{x}_6 + c_{46}x_6 = F_4 \\
&a_{53}\ddot{x}_3 + b_{53}\dot{x}_3 + c_{53}x_3 + (I_{55}+a_{55})\ddot{x}_5 + \\
&\qquad + b_{55}\dot{x}_5 + c_{55}x_5 = F_5 \\
&a_{62}\ddot{x}_2 + b_{62}\dot{x}_2 + a_{64}\ddot{x}_4 + b_{64}\dot{x}_4 + \\
&\qquad + (I_{66}+a_{66})\ddot{x}_6 + b_{66}\dot{x}_6 + c_{66}x_{66} = F_6
\end{aligned}
\tag{2}
$$

The equations suggest a model decomposition that is very convenient for control studies. Figure 4 shows a block diagram of the model structure, for pitch and heave motions. The Wave-to-Forces (or moments) blocks correspond to the right hand side of the equations. The Forces (or moments)-to-Motions blocks correspond to the left hand side of the equations.

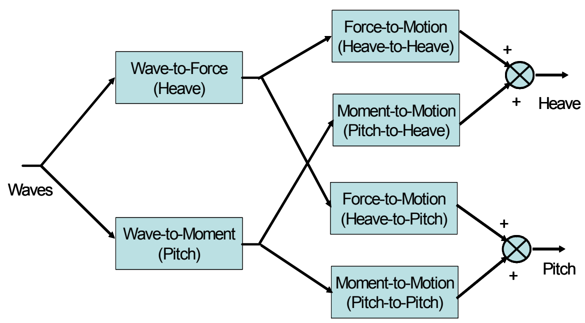

Fig 4. Block diagram of the model

Notice that the left hand side equations give enough information to establish transfer functions for the Forces-to-Motions blocks. However, the transfer functions for the Waves-to-Forces must be obtained by fitting data (obtained by simulation or experiments). An interesting way for modelling is the use of Genetic Algorithms, as it is described in (De Andres, et al., 2000; Aranda, et al., 2000). In (Esteban, et al., 2004b) a detailed procedure to obtain all transfer functions is described.

6. ACTUATORS

The dimensions, characteristics and location of the flaps and the T-foil were given by the technical advice of the Spanish shipbuilders. Not much was in the literature as a help for modelling the actuators. Therefore, they were considered as submerged wings, and the corresponding non-linear equations were considered. Scaled down flaps and T-foil were added to the replica. A series of experiments in a long channel established the lift force due to these actuators at several angles of attack. The parameters of the equations were fitted to the data, with good agreement. This part of the research is described in (Giron-Sierra, et al., 2002).

Figure 5 shows the expected efficiency of the actuators at ship's speeds of 20, 30 and 40 knots, eliminating part of the vertical accelerations (Esteban, et al., 2000b).

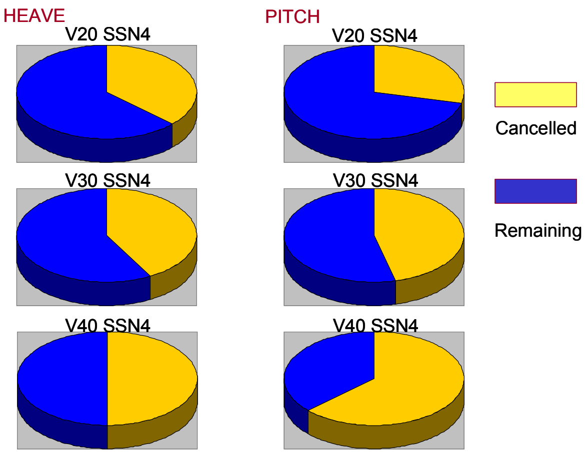

Fig. 5. Vertical accelerations cancelled by actuators

A Simulink model was established, taking into account the motion rate and maximum angle limits and the dynamic response of hydraulic cylinders (Esteban, et al., 2000a).

Recently, part of the research studied the implications of other dimensions and locations of the actuators (Esteban, et al., 2004a). It is possible to increase the actuators efficiency.

7. CONTROL DESIGN

Taking advantage of the model structure, controller and actuators blocks can be easily included. In this way, a simulation environment for control design studies has been built, using Simulink (Esteban, et al., 2000c; 2001a, 2001b).

Since seasickness is caused by vertical accelerations, it is natural to consider the use of accelerometers. With head seas, the worst place for the passenger, where vertical accelerations are larger, is near the bow. An accelerometer is placed there, to measure the WVA (the Worst Vertical Acceleration). The target for the control of actuators is to minimize the WVA.

For practical reasons, the first controller to be studied is the PID. This controller has been put into the simulation environment, and the tuning of the PID has been systematically explored. Integral action has negative effects, so only the PD is useful. Figure 6 shows in 3D the effect of different PD parameters on WVA, for the flaps and for the T-foil (De la Cruz, et al., 2004).

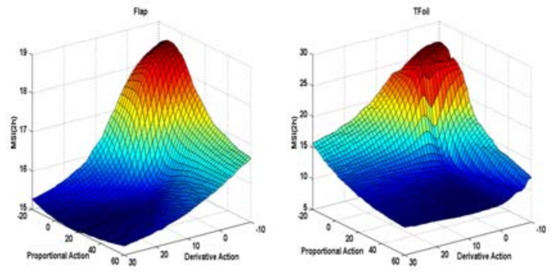

Fig. 6. Best tuning of the PD (T-foil and flaps)

A multivariable PD, based on heave and pitch measurement, has been considered in (Aranda, et al., 2001).

The research on control design continues exploring several alternatives. One is the application of QFT (Aranda, et al. 2004; Velasco, et al., 2004). Another proceeds with multiobjective optimisation (Esteban, et al., 2002). Predictive features have been investigated in (Esteban, et al., 2001c). And the alternative of non-linear control is considered in (Esteban, et al., 2003), with recent results in (Esteban, et al., 2004a).

An automatic code generation tool has been developed, for fast and easy experimental study of any control strategy (Polo, et al, 2001). Using this tool on the field, at CEHIPAR, several experiments have been done to verify the good result of the controlled moving actuators (Giron-Sierra, et al., 2001). Figure 7 shows the results for 40 knots and SSN5.

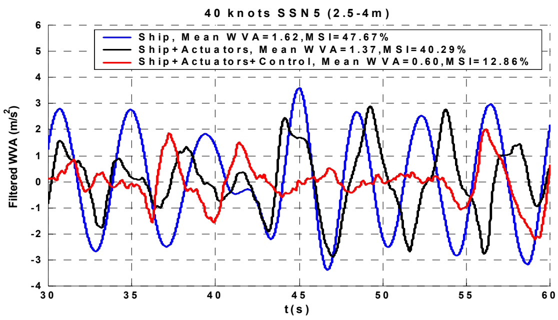

Fig. 7. Effect of the controlled actuators

8. MORE GENERAL HEADING CONDITIONS

The more general case of any heading with respect to waves is now under study. There are headings not possible to handle in the experimental facility, so open air experiments should be done. A new, smaller (1/40 scaled) replica is being developed (Giron-Sierra, et al., 2003c; Recas, et al., 2004b). Since this replica will not be towed, a set of new sensors must be included on-board, together with scaled down waterjets and a distributed control system. In other words, this is an autonomous small ship.

Starting form the data furnished by the simulation program, a 6DOF model of the ship motions is under development (Giron-Sierra, et al., 2003b, 2004). Guidelines for decoupled control design, in the frequency domain, are obtained.

The experiments with the new replica have already started. The first series of experiments is devoted to check the autonomous features of the replica. First control designs will be experimentally verified in the immediate future.

9. CONCLUSIONS

This paper presents an overview of a research on the improvement of seakeeping in fast ferries, using moving actuators such flaps and T-foil. Main results have been presented, with references for more details.

The research has an experimental basis, confirming good expectations from the use of flaps and T-foil.

At present, the research deals with more general 6DOF problems, with a lot of coupling. Experiments require a new system, with an autonomous replica.

Other aspects for the future are to study structural effects of the actuators. New actuators such interceptors and thrusters must also be considered.

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