Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

# Frequency Domain Study of Longitudinal Motion Attenuation of a Fast Ferry Using a T-Foil

**J.M. Giron-Sierra*, S. Esteban*,**

**Dep. ACYA, F. Fisicas, UniversidadComplutense de Madrid, 28040 Madrid, Spain (e-mail: gironsi@dacya.ucm.es)*

**Abstract:** Longitudinal, heave and pitch, motion of ships in response to encountered waves can be smoothed using moving submerged wings, like transom flaps or a T-foil under the bow. Recently a 3 DOF detailed model of the surge, pitch and heave motions of a fast ferry has been developed, in terms of a structure of twelve transfer functions. On the basis of this model the most effective control for motion attenuation using a T-foil has been determined in the frequency domain, both for unlimited or saturated action. The results have been obtained by point to point exploration and depict amplitude and phase profiles of the controller. This result is useful to orientate linear control design. A first preliminary linear controller is presented.

## 1. INTRODUCTION

There are several control issues concerning ships (Fossen, 2002). Decades ago, the only control actuator was the rudder, and so the control studies were centred on trajectories and ship heading. Contrary to sail ships, steam ships suffer from roll motion and an important topic is to attenuate this motion. It can be done with the rudder, with some stabilizing devices inside the ship, or using submerged lateral fins (Perez, 2005). The control of moving lateral fins is a consolidated research topic. Lateral fins can exert a control authority in excess. Other motions of the ship, in response to encountered waves, are heave and pitch motions. For the attenuation of heave and pitch motions, submerged wings can also be used; for instance in the form of transom flaps or a T-foil under the bow (De la Cruz, et al., 2004). In this case, the wings can exert low control authority. Most time the control of moving flaps or T-foil stumbles upon saturation limits. While there are many papers about roll attenuation, only a few consider heave and pitch attenuation (Abkowitz, 1959; Stefun, 1959; Vugts, 1967; Wu-Qiang and Zhu-Shun, 2002; Sclavonous and Borgen, 2004) . This paper focuses on the use of a T-foil for heave and pitch motion attenuation of a fast ferry.

As it will be briefly described below, there is a classical way to model the six motions of a ship in response to encountered waves (Lloyd, 1998). It consists in two decoupled models, considering an horizontal plane (lateral motions) and a vertical plane across bow and stern (longitudinal motion). Consequently, one of the models corresponds to lateral motions: sway, roll and yaw; and the other model to longitudinal motion: surge, heave and pitch. Each of the models is a set of three differential equations. By means of a CFD program, the coefficients of these equations, for several ship speeds and heading angle with respect to waves can be obtained. Starting from these equations and data, a 3 DOF detailed model of the longitudinal motion of a fast ferry has been obtained, in terms of twelve transfer functions. Having this background, the paper studies along a set of frequencies of encounter with waves, what is the control amplitude and phase in each frequency that gets the largest motion attenuation.

In general, the issue of ship motion attenuation is gaining interest. It is not only to ensure passengers comfort, in this time of travelling increase (Haywood, et al. 1995; Ryle, 1998). There are also reasons of safety, operational crew efficiency, and ship stabilization: for instance to get better conditions for helicopter landing on the ship.

Let us mention that this paper is a new step of a research on fast ferry stabilization that started years ago, as it is reported in the review (Giron-Sierra, et al. 2005). The previous control studies were based on some initial models as first approximations. In this paper a new improved model is used (Giron-Sierra, et al. 2003, 2004). A general impression of the fist control studies was that something was missing: that is, a clear reference of what best attenuation can be obtained.

The main idea in this paper is to determine by direct systematic exploration what is the best attenuation that can be obtained for a pertinent set of frequencies of encounter with waves. This has been done with intensive computational efforts. Two cases were studied, one considers no actuation limits, and the other takes into account actuator saturation.

Once the amplitude and phase of the control for best attenuation is determined, there is room for approximations with analytical of heuristic controllers. A preliminary linear control approximation is given at the end of the paper, together with some design considerations.

The paper starts with a description of the problem and the model, then it makes some previous analysis of the control problem, then it focuses on the systematic control profile determination, and ends with a preliminary linear control approximation.

## 2. STATEMENT OF THE CONTROL PROBLEM

The six motions of a slip in response to encountered waves can be modelled with the following set of equations (Lloyd,1998):

$$
\begin{aligned}
&(m+a_{11})\ddot{x}_1 + b_{11}\dot{x}_1 = F_1 \\
&(m+a_{22})\ddot{x}_2 + b_{22}\dot{x}_2 + \\
&\quad + a_{24}\ddot{x}_4 + b_{24}\dot{x}_4 + a_{26}\ddot{x}_6 + b_{26}\dot{x}_6 + c_{26}x_6 = F_2 \\
&(m+a_{33})\ddot{x}_3 + b_{33}\dot{x}_3 + c_{33}x_3 + \\
&\quad + a_{35}\ddot{x}_5 + b_{35}\dot{x}_5 + c_{35}x_5 = F_3 \\
&a_{42}\ddot{x}_2 + b_{42}\dot{x}_2 + (I_{44}+a_{44})\ddot{x}_4 + b_{44}\dot{x}_4 + c_{44}x_4 + \\
&\quad + a_{46}\ddot{x}_6 + b_{46}\dot{x}_6 + c_{46}x_6 = F_4 \\
&a_{53}\ddot{x}_3 + b_{53}\dot{x}_3 + c_{53}x_3 + (I_{55}+a_{55})\ddot{x}_5 + \\
&\quad + b_{55}\dot{x}_5 + c_{55}x_5 = F_5 \\
&a_{62}\ddot{x}_2 + b_{62}\dot{x}_2 + a_{64}\ddot{x}_4 + b_{64}\dot{x}_4 + \\
&\quad + (I_{66}+a_{66})\ddot{x}_6 + b_{66}\dot{x}_6 + c_{66}x_{66} = F_6
\end{aligned}
\tag{1}
$$

Variables $x_1$, surge, $x_3$, heave, and $x_5$, pitch, are longitudinal motions. Variables $x_2$, sway, $x_4$, roll, and $x_6$, yaw, are lateral motions. $F_1$ is surge force, $F_3$ is heave force, $F_5$ is pitch torque. $F_2$ is sway force, $F_4$ is roll torque, and $F_6$ is yaw torque. The $a_{ij}$ coefficients are added masses; the $b_{ij}$ coefficients are damping terms; and the $c_{ij}$ are restoring force coefficients.

Let us focus on the equations with $F_1$, $F_3$ and $F_5$ at the right hand side. These three equations constitute the longitudinal motion model.

The ship selected for our study is an aluminium made monohull fast ferry for 1250 passengers. It is a 110m. long ship, with 40 Knots nominal speed (Anonymous, 1996).

A CFD program has been used to compute forces and coefficients of equations (1) for several study conditions. Head seas have been selected for the study of longitudinal motions.

Using Laplace transform, equations (1) can be put in the following form:

$$
\begin{pmatrix} P_{11} & P_{13} & P_{15} \\ P_{31} & P_{33} & P_{35} \\ P_{51} & P_{53} & P_{55} \end{pmatrix}
\begin{pmatrix} X_1 \\ X_3 \\ X_5 \end{pmatrix} =
\begin{pmatrix} F_1 \\ F_3 \\ F_5 \end{pmatrix}
\tag{2}
$$

or in a more concise way:

$$\mathbf{P_L} X_L = F_L \tag{3}$$

where $\mathbf{P_L}$ is a matrix of polynomials, $X_L$ and $F_L$ are vectors.

Using Cramer's rule, the motions can be put in function of forces:

$$
\begin{aligned}
X_1 &= (G_{11}F_1 + G_{13}F_3 + G_{15}F_5) \\
X_3 &= (G_{31}F_1 + G_{33}F_3 + G_{35}F_5) \\
X_5 &= (G_{51}F_1 + G_{53}F_3 + G_{55}F_5)
\end{aligned}
\tag{4}
$$

In a more concise form:

$$X_L = \mathbf{G_L} F_L \tag{5}$$

where $\mathbf{G_L}$ is a matrix of 9 transfer functions.

The CFD program gives amplitudes and phases of forces for a set of frequency of encounter with waves. The data can be fitted with transfer functions, obtaining three Wave-to-Forces transfer functions ($WF_1$, $WF_3$ and $WF_5$).

Figure 1 shows the structure of the complete longitudinal motion model, from Waves to Motions, including 12 transfer functions.

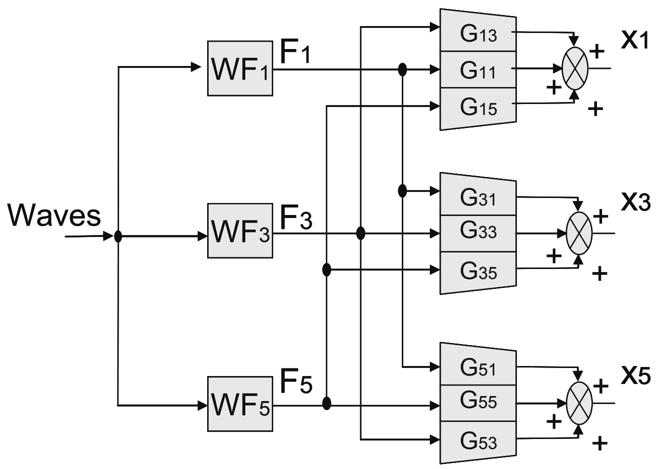


Fig. 1. Structure of the 3 DOF ship motion model.

Mathematical models of seasickness (O'Hanlon and MacCauley, 1974; BS6841, 1987)) have been established, showing that vertical acceleration oscillations with a frequency around 1 rad/s are the most dangerous. Therefore the control study focuses on vertical acceleration oscillations. A point, denoted as PMP, near the bow has been selected to measure there the pitch motions, and take this signal for the control of the T-foil motions.

Figure 2 shows the control loop. The T-foil exerts lift force, which means heave force and pitch torque.

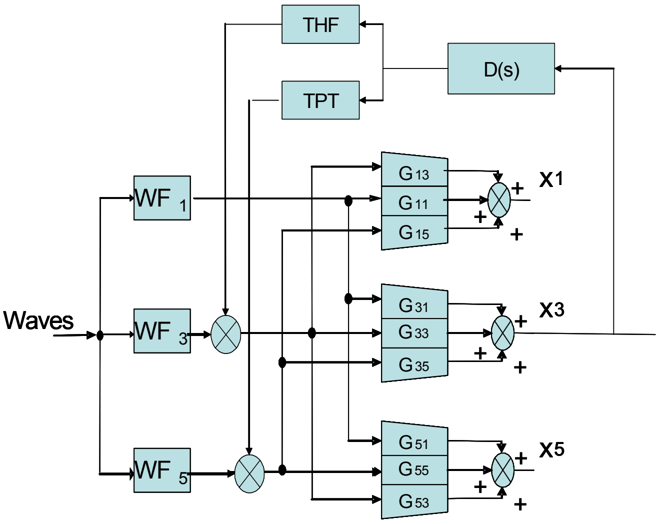


Fig. 2. Control loop

The motion of the T-foil has been modelled as a first order transfer function: both blocks THF and TPT contain the same pole.

Let us assume that waves with a 1m/60m slope are selected. These waves correspond to a moderate sea. The wavelength $\lambda$ and the frequency $\omega_o$ of the waves are related with the following expression:

$$\lambda = \frac{2\pi g}{\omega_o^2} \tag{6}$$

Equation (7) gives the frequency of encounter with waves ωe. It depends on U, the ship's speed in m $s^{-1}$, and the heading angle µ. Naval architects take head seas as 180º heading.

$$\omega_e = \omega_o - \frac{\omega_o^2 U}{g}\cos(\mu) \tag{7}$$

Figure 3 shows the amplitude of waves vs. the frequency of encounter at 40 Knots for the selected 1/60 slope waves.

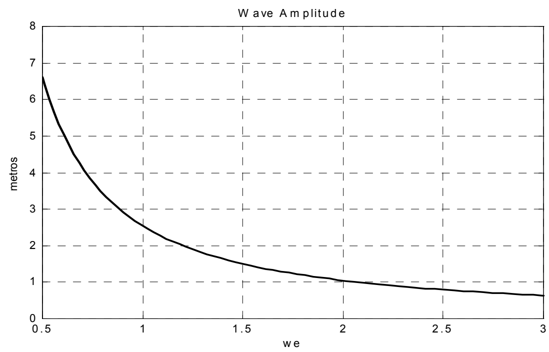


Fig. 3. Wave height

Using the Wave-to-Forces transfer functions, and combining the contribution of heave and pitch motions to the vertical acceleration in the point PMP, the vertical acceleration oscillations ACV to be attenuated by the T-foil are determined. Figure 4 shows ACV in function of the frequency of encounter with waves, at 40 Knots with head seas.

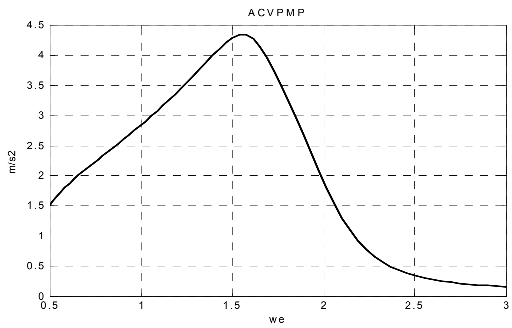


Fig. 4. ACV at the point PMP

The target of the control is to attenuate ACVPMP as much as possible. In particular it is important to attenuate ACVPMP in the nearby of 1 rad/s.

Figure 5 shows a comparison of experimental results and our transfer functions model. The experiments corresponding to 40 Knots and head seas have been done in a large towing tank with wavemaker, using a 1/25 scaled ship. The agreement between model and experiments is fairly good.

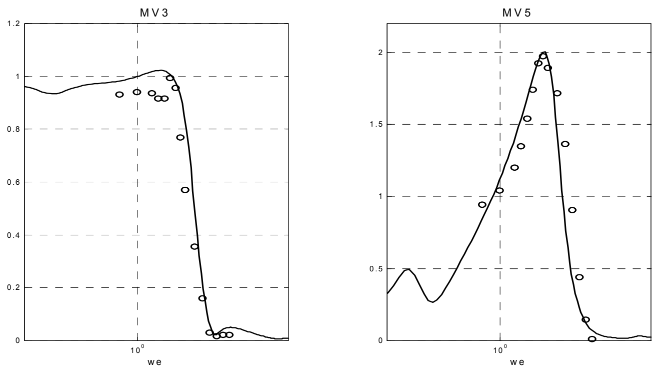


Fig. 5. Comparison of model (curve) and experimental data (points) for 40 Knots speed and heading seas; left plot is heave motion, right plot is pitch motion

## 3. THE EFFECT OF PROPORTIONAL CONTROL

Important initial details can be revealed by trying a proportional control K.

Figure 6 shows the root locus. The closed loop system is unstable for K>18.25.

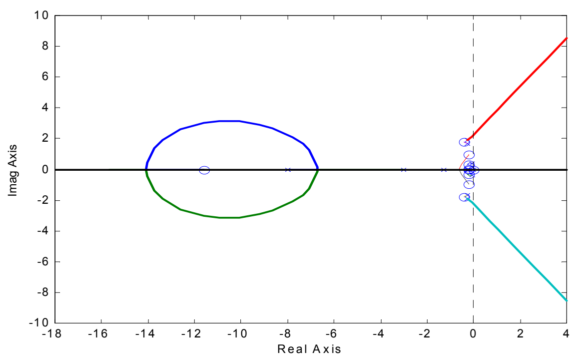


Fig 6. Root locus of the system loop.

The root locus has 14 branches, most of them confined near the origin so it cannot be observed in figure 5, some zooming in is further required for that.

With K=6 the T-foil reaches the saturation angles, so no more motion attenuation efficiency could be achieved. Figure 6 shows at the left hand side ACVPMP for K=6 compared with ACVPMP with no T-foil (the reference ACVPMP). Also, at the right hand side, Figure 7 shows the amplitude on the pitch torque due to the T-foil compared to its maximum value (the horizontal line).

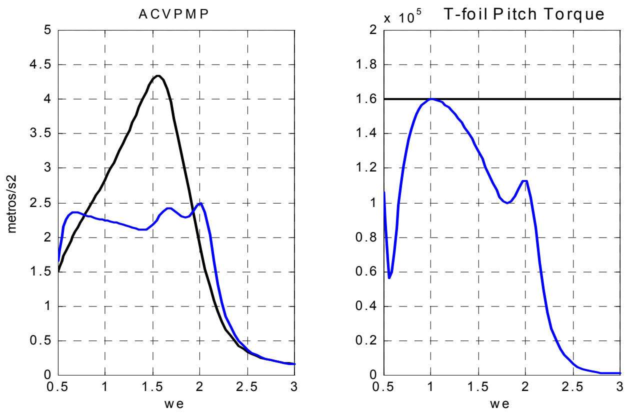


Fig.7. Effects of proportional control

Although the proportional control obtains some attenuation at 1 rad/s (so ACVPMP=2,25), it increases ACVPMP at low frequencies under 1 rad/s and at frequencies over 2 rad/s.

## 4. OPTIMAL SMOOTHING CONTROL

Take a set of frequencies of encounter with waves:

$$\Omega = \{\omega_1, \omega_2, \ldots, \omega_n\} \quad (8)$$

For every frequency $\omega_i$ belonging to $\Omega$ a numerical exploration has been done to determine the best combination of controller amplitude and phase in order to make decrease as much as possible ACVPMP at $\omega_i$. The simple idea for the exploration is to multiply gains of the controller and the rest of the loop, evaluated at $\omega_i$, and to add phases of the controller and the rest of the loop, evaluated at $\omega_i$. The exploration begins with coarse grain, determining ranges of interest, and then continues with fine grain in these ranges. The procedure has been applied for a loop with non-saturating ideal actuator, and then repeated for a loop with T-foil saturation limits.

Figure 8 shows the phase of the best smoothing controller for no saturation limits, and the phase of the best smoothing controller with actuator saturation limits (marked as 'Sat').

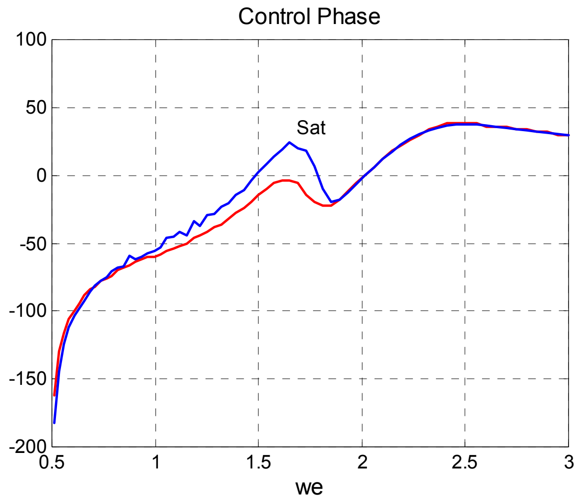


Fig.8. Phase of best smoothing controller for unlimited of for saturated action.

Notice in figure 8 that both curves differ not much. The actual controller should not go too apart from the optimal phase, to not enter into bad action as the proportional controller does in low and high frequencies.

Let us give more details of the best smoothing controller for non-saturating ideal actuator. Figure 9 shows four plots: top left the new ACVPMP compared to the reference ACVPMP, top right the controller gain, bottom left the attenuation of ACVPMP (subtract the new ACVPMP to the reference ACVPMP), bottom right the T-foil pitch torque and its saturation limit.

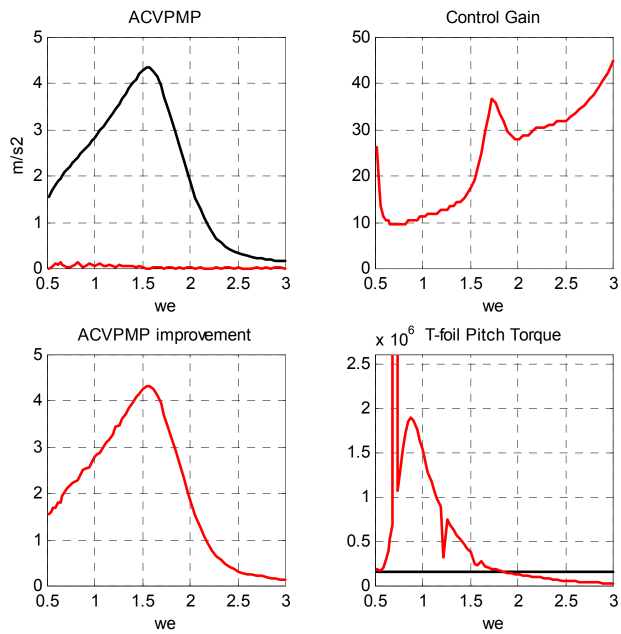


Fig.9. Gain and effect of the unlimited best smoothing controller

The top left plot in figure 9 shows that ACVPMP could be totally eliminated, so the ACVPMP improvement show at bottom left coincides with the reference ACVPMP. What happens is that the actuator torque should be very high, well over the present saturation limit (marked with the horizontal line below the 0.5 level in the right bottom plot).

Figure 10 shows the gain and effect of the best smoothing controller that does not surpass T-foil saturation limits.

The top left plot in figure 10 shows two curves, the reference ACVPMP and under it the new ACVPMP. With T-foil saturation it is not possible to completely eliminate ACVPMP. In particular it happens at 1 rad/s. The bottom left curve, which is the ACVPMP improvement, is under the level 3.1. As shown in the bottom right plot, the T-foil reaches saturation in low and medium frequencies.

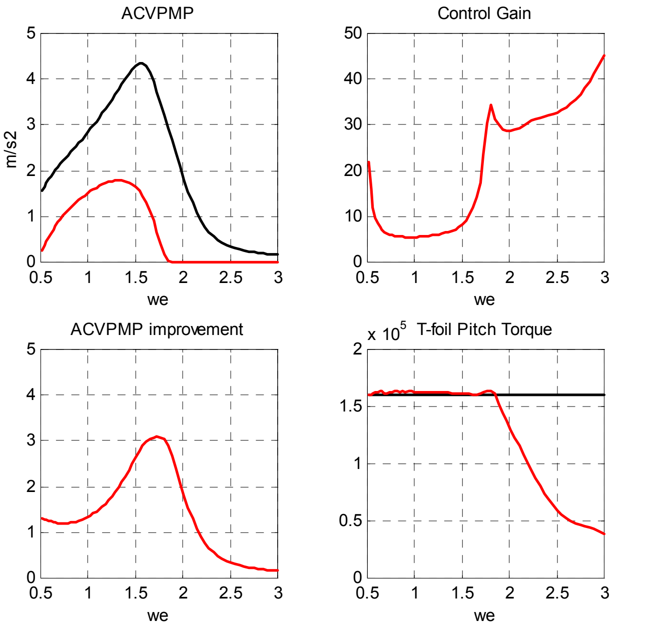


Fig.10. Gain and effect of the under-saturating best smoothing controller

## 5 APPROXIMATION BY LINEAR CONTROL

Linear approximations of a desired gain-phase controller behaviour along a certain frequency range can be obtained by using the *invfreqs* Matlab routine. The user must specify the order of the transfer function numerator and denominator. Unstable controllers can be also tried.

In the case of the non-saturating best smoothing controller, the best approximation after many trials has been an unstable controller with 7 zeros and 9 poles. Figure 11 shows this approximation.

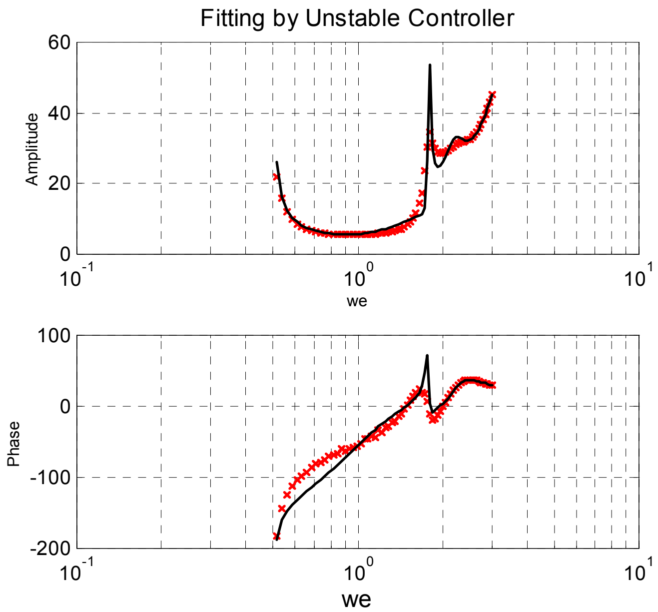


Fig.11. Gain and phase unstable approximation to the non-saturating best smoothing controller

After several attempts with *invfreqs*, a preliminary stable linear controller has been obtained, relaxing the approximation accuracy at low and high frequencies. The controller has 10 zeros and 10 poles. Figure 12 shows the phase of the controller (marked as 'LC') compared to the phase of the best smoothing under-saturating controller.

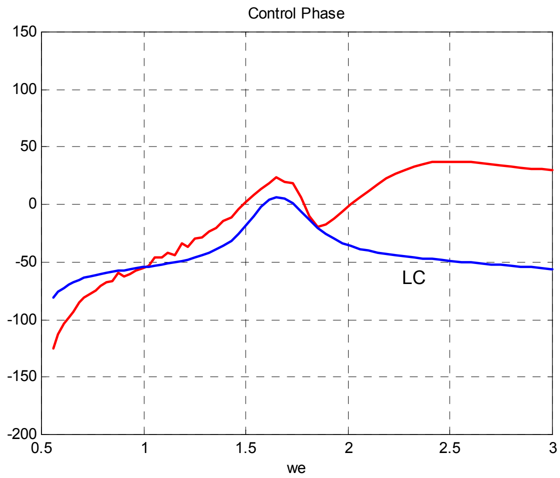


Fig.12. Linear controller phase approximation of the non-saturating best smoothing controller

Figure 13 shows the gain and effect of the preliminary linear controller approximation.

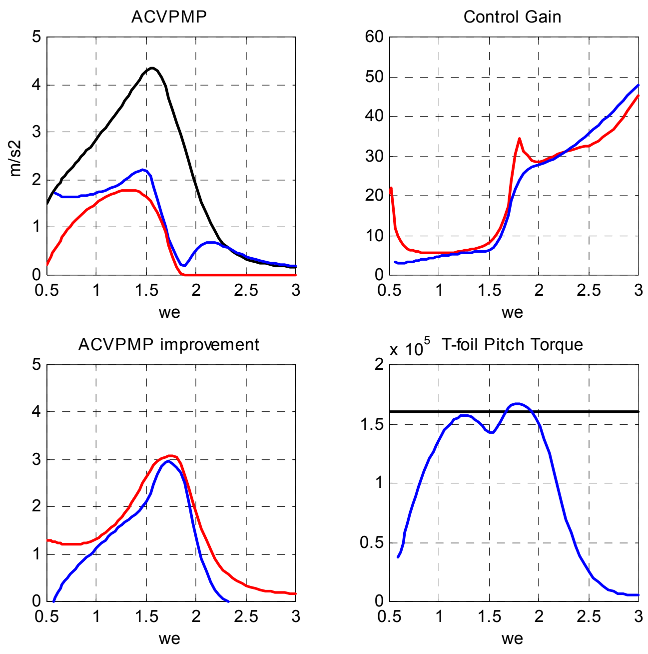


Fig.13. Gain and effect of the linear controller approximation to the under-saturating best smoothing controller

The top left plot in figure 13 shows three curves: the reference ACVPMP, the limit ACVPMP also shown in figure 10, and the new ACVPMP obtained with the linear control. It can be observed that the new ACVPMP is near the limit. The bottom left plot also compares the maximum improvement with the linear controller effect.

## 6. CONCLUSIONS

A study of the attenuation of vertical acceleration oscillations of a ship, using a T-foil, has been presented. The study is based on a detailed 3 DOF frequency domain model. A systematic exploration method has been introduced, determining the amplitude and phase of the best motion smoothing controller for a set of frequencies of encounter with waves. The method can be applied for nonlinear behaviour, such the saturation of the T-foil. On the basis of the optimal smoothing phase and amplitude profiles of the controller, analytical or heuristic approximations can be studied. Indeed this is an interesting target for nonlinear control approaches.

This is an initial step for further studies. Stability and robustness issues must be included, perhaps at the time of systematic exploration, taking into account multi-objective optimization criteria. Other important aspects refer to what measurements are better for the control, using accelerometers or inertial units, which means changing the control loop (an accelerometer will capture a combination of heave and pitch). Likewise, it is also interesting to study variations of the T-foil characteristics.

Following the tradition in our research, confirmed results are candidates for testing in a scaled autonomous ship, using a towing tank facility.

## ACKNOWLEDGMENTS

The authors want to thank the support of the CICYT Spanish Committee (project DPI2003-09745-C04-02).

## REFERENCES

Abkowitz, M.A. (1959). The effect of antipitching fins on ship motion, *SNAME Trans*., vol 67, 210-252.

Anonymous (1996). 126m long Spanish fast ferry launched, Fast Ferries, September, 19-20.

BS 6841 (1987). *British Standard Guide to Measurement and Evaluation of Human Exposure to While-Body Mechanical Vibration and Repeated Shock*. BSI.

De la Cruz, J.M., J. Aranda, J.M. Giron-Sierra, F. Velasco, S. Esteban, J.M. Diaz, B. De Andres (2004). Improving the comfort of a fast ferry with the control of flaps and T-foil, *IEEE Control Systems Magazine*, vol. 24, n. 2, April, 47-60.

Fossen, T.J. (2002). *Marine Control Systems,* Marine Cybernetics AS, Trondheim.

Giron-Sierra, J.M., B. Andres-Toro, S. Esteban, J. Recas, E. Besada, J.M. De la Cruz and A. Maron (2003). First principles modelling study for the development of a 6DOF motions model of a fast ferry, In *Proceedings IFAC MCMC 2003,* Girona, Spain.

Giron-Sierra, J.M., B. Andres-Toro, S. Esteban, J. Recas,, J.M. De la Cruz and J.M. Riola (2004). Advances in the 6DOF motions model of a fase ferry, In *Proceedings IFAC CAMS 2004,* Ancona, Italy.

Giron-Sierra, J.M., S. Esteban, J. Recas, B. De Andres, J.M. De la Cruz, J.M. Riola, J. Aranda and F. Velasco (2005). Overview of a research on actuators control for better seakeeping in fast ships. In *Proceedings IFAC World Congress 2005, Prague.*

Haywood, A.J., A.J. Duncan, K.P. Klaka and J. Bennet (1995). The development of a ride control system for fast ferries, *Control Engineering Practice*, 695-703.

Lloyd, A.R.J.M. (1998). *Seakeeping: Ship Behaviour in Rough Weather*, A.R.M.J. Lloyd, Gosport, Hampshire, U.K.

O'Hanlon, J.F. and M.E. MacCauley (1974). Motion sickness incidence as a function of frequency and acceleration of vertical sinusoidal motion, *Aerospace Medicine*.

Perez, T. (2005). *Ship Motion Control*, Springer-Verlag.

Ryle, M. (1998). Smoothing out the ride, *The Motor Ship*, January, 23-26.

Sclavounos, P.D. and H. Borgen (2004). Seakeeping analysis of a high-speed monohull with a motion-control hydrofoil, *J. Ship Research*, vol.48, n.2, 77-117.

Stefun, G.P. (1959). Model experiments with fixed bow antipitching fins, *J. Ship Research*, vol.3, n.2, 15-23.

Vugts, J.H. (1967). Pitch and heave with fixed and controlled bow fins, *Intl. Shipbuilding Progress*, vol. 15, n.3, 191-215.

Wu-Qiang, L. and D. Zhu-Shun (2002). Reducing the vertical motion in waves of round-bildge boat with controllable transom flaps. *Intl. Shipbuilding Progress*, vol.49, n.1, 37-51.