ROBUST CONTROL FOR THE COUPLING OF LATERAL AND LONGITUDINAL DYNAMICS IN HIGH-SPEED CRAFTS

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Abstract: In this work, the QFT technique was used to control a system with three degrees of freedom of coupled movement. The example is the coupling between the vertical and the horizontal dynamics of a high-speed craft. Since the angle between the heading and the seaway is different from 180 degrees, the action of the actuators for controlling each dynamic produces a coupling in the other dynamic. Firstly, controllers for the two dynamics were designed separately. Then, the actuator coupling was considered, and finally, it was shown how the controllers reduce the three coupled modes in the whole system.

Keywords: actuators, stability, robust control, closed-loop, open-loop, controllers, dynamic behavior models, Nichols chart.

1. INTRODUCTION

Over the past ten years interest in fast ships for cargo and passenger transportation has grown. Different designs have been considered, and significant attention has focused on fast monohull displacement ships (Allison, *et al.*, 2004).

The main objectives in the design and construction of high-speed crafts are passenger comfort and vehicle safety. The vertical accelerations associated with roll, pitch and heave motions are the principal cause of motion sickness.

Previous research by the work group studied longitudinal and transversal dynamics separately. Firstly, heaving and pitching motion for head seas (μ=180deg) (Aranda, *et al.*, 2004a, de la Cruz et al. 2004), modeled actuators and different designed controllers (Aranda, *et al.*, 2002a, Aranda, *et al.*, 2002b) were studied in order to achieve heave and pitch damping with successful results. Secondly, the rolling response was analyzed for lateral waves (μ=90deg) (Aranda, *et al.*, 2004b) and actuator modeling and controller design were also carried out. In this work the study was extended to different incidence angles between 180 and 90 degrees.

One problem observed in these systems is the fact that the actuator action to control the longitudinal modes and the control action itself produce a coupling with the roll mode, and therefore an increase in the vertical roll component. Likewise, the roll control surfaces generate a component in the pitch mode.

It is of particular interest to know whether the use of robust methodologies, like the QFT technique, will allow engineers to build designs for decoupled dynamics when actuators are added that can produce couplings in the dynamics.

Thus, the aim of this paper is the analysis and design of controllers for the system with three degrees of coupled freedom in order to reduce longitudinal and transversal motions. The control technique employed is the QFT (Horowitz (2001), Borghesani (1995), Yaniv (1999)). The SISO multiple-loop feedback (Horowitz, 2003) was used as the solution to a MIMO problem.

Since a first approximation of the system in heading seaway is the lack of coupling between the vertical and horizontal modes, the controller of the two dynamics was designed independently. Next, the actuator coupling was considered, and finally, it was shown whether the designed controllers reduced responses in the coupled system.

2. SYSTEMS DESCRIPTION

Three modes of the system were analyzed in this work: the heave and pitch motions (vertical dynamics) and the roll motion (horizontal dynamics).

2.1 Coupled system

Figure 1 shows the block system diagram with the three degrees of freedom where the coupling of the modes are considered as a consequence of the control surface action in different incidence angles of the seaway.

2.2 Vertical dynamic model

The actuators that were employed for the vertical dynamic control consisted of active stabilized surfaces, one T-Foil on the bow and two flaps on the stern. Figure 1 shows the vertical dynamic subsystem where:

- $G_{TF\text{-}flaps}$ is the transfer function matrix with the angles of attack α_P (deg) and α_H (deg) as the inputs, and the heave force F_{heave} (KN) and the pitch moment M_{pitch}.(KNm) as the outputs.
- G_{1P}, and G_{1H} are the transfer functions with the wave height (m) as the input and the pitch moment (kNm) and the heave force (N) as the outputs.
- G_{2P}, and G_{2H} are the transfer functions with the pitch moment (kNm) and heave force (N) as the inputs, and the pitch (deg) and heave (m) motions as the outputs.
- D_{fins} is the transfer function representing the coupling between the roll and pitch mode. Since the waves do not fall against the ship at an angle of 90 degrees, the action of the lateral fins controlling the rolling mode causes a slight motion in the pitch mode. It will therefore be considered as a disturbance.

2.3 Horizontal dynamic model

The control surfaces employed for the roll control were two fins. They were fitted on the sides of the hull. Figure 1 shows the horizontal dynamic subsystem where:

- G_{fins} is the transfer function with the angle of attack α_R (deg) as the input and with the roll moment M_{roll}(kNm) as the output.
- G_{1R} is the transfer function with the wave height (m) as the input and the roll moment (kNm) as the output.
- G_{2R} is the transfer function with the roll moment (kNm) as the input and the roll motion (deg) as the output.
- D_{TFoil} is the transfer function representing the coupling between the pitch and roll modes. The action of the T-Foil where the incidence angle is different from 180 degrees provides a component in the roll mode.

3. MODELS

Prior to the control design, mathematical models of the ship and actuators were obtained.

3.1 Ship model

The program simulation PRECAL was used for the ship modeling. This program reproduces specified conditions and uses a geometrical model of the craft to predict its dynamic behavior. The measurements obtained from the simulations are given in the frequency domain.

In this work the model was obtained from system identification methods (Aranda, *et al.*, 2004a).

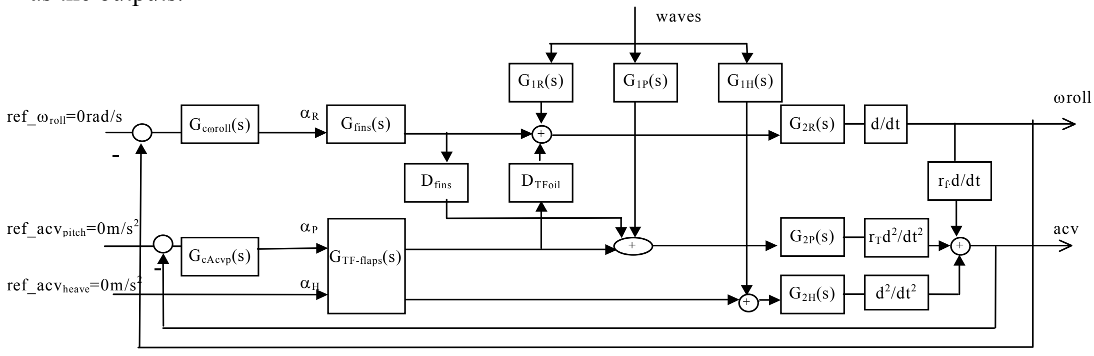

Fig. 1. Block diagram of horizontal and vertical dynamics

This research tried to identify a continuous linear model of heaving, pitching and rolling motion. Specifically, models of G_{1P}, G_{2P}, G_{1H}, G_{2H}, G_{1R}, G_{2R} were identified for incidence waves between 105 and 180 degrees. Each plant model set had the same number of poles and zeros. The problem was considered by focusing on the models identified for each incidence angle as a set of plant uncertainties, where the nominal case chosen is the 135 degrees angle. Equations (1) to (6) show the transfer function models in the nominal case.

$$G^0_{1H}(s) = 9333\frac{26.02s^3 - 22.13s^2 + 160.9s^1 + 0.9}{s^4 + 125.4s^3 + 149.1s^2 + 181.3s^1 + 0.9} \quad (1)$$

$$G^0_{2H}(s) = 1.06^{-4}\,\frac{0.44s^2 - 1.08s^1 + 3.015}{s^2 + 0.63s + 3.015} \quad (2)$$

$$G^0_{1P}(s) = 18{\cdot}10^4\frac{-1.42s^3 + 0.82s^2 - 12.6s}{s^4 + 5.25s^3 + 10.99s^2 + 15.5s^1 + 5.9} \quad (3)$$

$$G^0_{2P}(s) = 4.22^{-6}\,\frac{-0.50s + 2.82}{s^2 + 0.49s2.71} \quad (4)$$

$$G^0_{1R}(s) = 2794\frac{-34.73s^3 + 79.6s^2 - 109s}{s^4 + 67.04s^3 + 125.8s^2 + 247.3s + 135.6} \quad (5)$$

$$G^0_{2R}(s) = 1.2{\cdot}10^{-3}\frac{-1.9{\cdot}10^{-3}s^3 + 0.28s^2 + 0.29s + 3.5}{s^3 + 4.36s^2 + 1.41s^1 + 4.84} \quad (6)$$

3.2 Actuator modeling

Continuous linear models were identified (Aranda, *et al.*, 2004b). Equations (7)-(9) show the transfer functions $G_{TFoil40}(s)$, $G_{flaps40}(s)$ and $G_{fins40}(s)$.

$$G_{flaps40} = \frac{78.6}{s + 1.8} \quad (7)$$

$$G_{TFoil40} = \frac{4406}{s + 1.8} \quad (8)$$

$$G_{fins40} = \frac{5834}{s + 13.5} \quad (9)$$

4. FORMULATION OF THE QFT DESIGN PROBLEM

QFT is a frequency domain design methodology that was introduced by Horowitz (Horowitz, 2001). The foundation of QFT is the fact that feedback is primarily needed when the plant is uncertain and/or there are disturbances acting on the plant. The feedback control of the ship is a good example for using the QFT technique, because the ship model presents uncertainties in the plant and output disturbances (the seaway).
Figures 2 and 3 show the basic configuration of the feedback control for vertical and horizontal dynamics, where

$$G_{pRoll}(s) = G_{fins40}(s)\cdot G_{2R}(s) \quad (10)$$
$$G_{pPitch}(s) = G_{TFoil40}(s)\cdot G_{2P}(s) \quad (11)$$

Each controller must be set up in such a way as to ensure that the actuators develop moments which oppose the moments provided by the waves. In each QFT control design case, couplings with another dynamic are considered a disturbance.

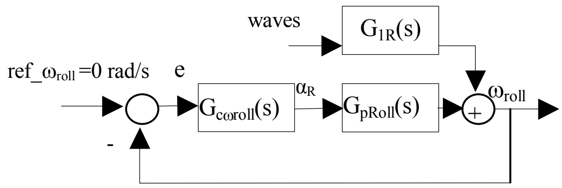

Fig. 2. Block diagram of the closed-loop system for the horizontal plant

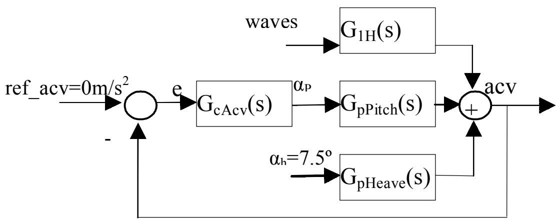

Fig. 3. Block diagram of the closed-loop system for the vertical plant

The QFT design procedure involves four basic steps:

- generation of plant templates
- computation of QFT bounds
- design of the controller (loop shaping)
- analysis of the design

A template is the plant frequency response set at a fixed frequency. Given the plant templates, QFT converts close-loop magnitude specifications into magnitude constraints on a nominal open-loop function (QFT bounds). A nominal open-loop function is then designed to satisfy simultaneously the plant template constraints as well as to achieve nominal closed-loop stability. The open-loop function $L(j\omega)$ is defined as the product of the controller transfer function and the plant transfer function. Thus

$$L_{\omega roll}(j\omega) = G_{c\omega roll}(j\omega)\, G_{pRoll}(j\omega) \quad (12)$$
$$L_{acv}(j\omega) = G_{cacv}(j\omega)\, G_{pPitch}(j\omega) \quad (13)$$

In any QFT design, it is necessary to select a frequency array for computing templates and bounds. In the ship plant system, the range of frequencies is chosen that belongs to the seaway spectrum, with natural frequency $\omega_o \in [0.39, 3]$ rad/s. When the QFT design is complete, an analysis of the closed-loop response is necessary at frequencies other than those used for computing bounds.

4.1 Formulating frequency domain specifications

The transfer function model obtained is an uncertain set. A robust performance problem is thus presented, because the performance specifications must be satisfied for all the possible systems admitted by the specific uncertainty model. In the ship system, it means that the specifications are satisfied for all the incidence angles.

To begin with, the formulation of what is the required behavior of the closed-loop system is necessary. The specifications must be given in terms of frequency response. QFT converts the closed-loop specifications into magnitude constraints on a nominal open-loop function (called QFT bounds).

For the particular ship system, the following conditions are required: *i*) system stability, *ii*) heave, pitch, roll reduction, *iii)* no saturation on T-Foil, flaps and fins.

These temporal domain constraints must be transferred into frequency domain specifications. The QFT specifications used are the gain and phase margin stability (14), the output disturbance rejection or sensitivity reduction (15) and the control effort (16).

- gain and phase margin stability

$$\left| \frac{G_{plant} G_{control}}{1 + G_{plant} G_{control}} \right| \le W_{s1} \qquad (14)$$

- sensitivity reduction

$$\left| \frac{1}{1 + G_{plant} G_{control}} \right| \le Ws_2 \qquad (15)$$

- control effort

$$\left| \frac{G_{control}}{1 + G_{plant} G_{control}} \right| \le Ws_3 \qquad (16)$$

In the Nichols chart, the stability type problem results in bounds about the critical point where the loop response must remain outside the bounds. Sensitivity reduction type problems result in bounds about the origin, where the loop response must remain outside the bounds. Control effort type problems result in bounds about the origin where the loop response must remain inside the bounds.

4.2 Loop shaping

After the stability and performance bounds have been computed, the next step in a QFT design involves the design (loop shaping) of a nominal function that meets the design bounds. The nominal loop *L* has to satisfy the worst case (intersection) of all bounds. The MATLAB toolbox includes an interactive design environment.

5. RESULTS

5.1 System Simulation

Once the controller parameters had been designed using the QFT technique, the closed-loop system was simulated in SIMULINK.

First the system that controls roll angular velocity ω_{roll} (Fig 2) was simulated and then the system that controls vertical acceleration *acv* (Fig 3). Finally, the coupled system with the three degrees of freedom (Fig.1) was simulated. In each system the controllers were examined to discover whether they accomplished the specifications and therefore achieved the damping. In order to evaluate and compare the reduction, two cost functions $J_{\omega roll}$ and J_{acv} (17) were defined. They were based on the mean value of the ω_{roll} and *acv* measured with a simulation test. Percentage reductions were also calculated.

$$J_{\mathrm{var}} = \overline{\mathrm{var}} = \frac{1}{N} \sum_{i=1}^{N} \left| \mathrm{var}(t_i) \right|; \mathrm{var} = \omega_{roll}, acv \qquad (17)$$

Simulations using 40 knots ship speed, regular waves with 0.8 meters of amplitude and a natural frequency in the interval [0.39,3] rad/s were done. In addition irregular waves with SSN= 4, 5, 6 were employed. The angles between the heading and wave direction in the tests were μ = 90, 105, 120, 135, 150, 165, 180 degrees. Results and graphics given in this paper are for the irregular wave SSN=5 and μ = 150 degrees.

5.2 QFT control of the vertical dynamic system

Robust Stability and Performance Bounds. The specifications fixed for QFT design are given in relation (18). S_2 is equal to S_{21} *U* S_{22}. S_{21} is the magnitude value of (15) for low frequencies (ω ≤1.5rad/s) and $G_{control}$=4. Likewise, S_{22} is the magnitude value of (15) for high frequencies (ω >1.5rad/s) where $G_{control}$=-167·(s+1.3)/(s+133). Each controller guarantees adequate sensitivity reduction in its respective frequency rank.

- gain and phase margins W_{s1}= 0.8
- sensitivity reduction W_{s2}=S_2 (18)
- control effort W_{s3} = 15

Control Design. The designed controller (19) is a fourth order filter. Figure 4 depicts the loop shaping in the Nichols chart. It is seen that the nominal open-loop function (13) L_{acv}(jω) lies outside the margin bounds at the corresponding frequencies. It is therefore shown that the controller meets the specifications (18).

$$G_{C_{acv}}(s) = -10 \frac{\left(\frac{1}{1.7^2} s^2 + \frac{1.26}{1.7} s + 1 \right) \left(\frac{1}{2.79} s + 1 \right) \left(\frac{1}{6.05} s + 1 \right)}{\left(\frac{1}{0.48^2} s^2 + \frac{0.4}{0.48} s + 1 \right) \left(\frac{1}{8.2^2} s^2 + \frac{0.32}{8.2} s + 1 \right)} \qquad (19)$$

Analysis in temporal domain. Table 1 shows the values of J_{acv} and the vertical acceleration reduction percentage for irregular waves SSN=5 and μ = 120, 135, 150 degrees with the controller $G_{cacv}(s)$. Figure 5 shows the movement of the fins, where it can be observed that there is no saturation.

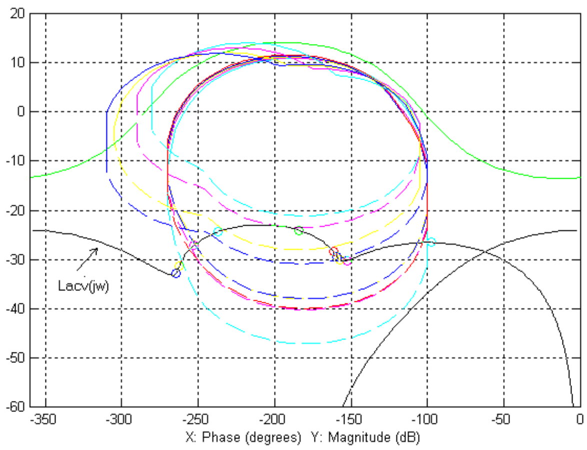

Fig. 4. Loop shaping. Nominal open-loop function $L_{acv}(j\omega)$ and intersection of all bounds.

Table 1. Value of J_{acv} and reduction for G_{cacv} controller V = 40 knots. SSN=5

Incidence angle μ	J_{acv}	acv reduction (%)
120 deg	2.11	8.93 %
135 deg	2.01	9.90 %
150 deg	1.71	10.74 %

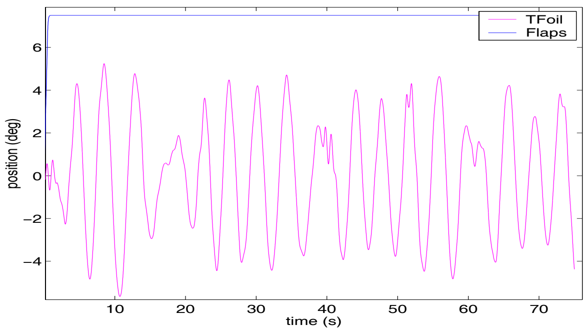

Fig. 5. T-Foil and Flaps movement. SSN=5. μ =150º.

5.3 QFT control of horizontal dynamic system

Robust Stability and Performance Bounds. The specifications fixed for the QFT design (20) guarantee adequate gain margins, sensitivity and control effort.

- gain and phase margins W_{s1}= 1.8
- sensitivity reduction W_{s2}=1.6 (20)
- control effort W_{s3} = 15

Control Design. The designed controller is a first order filter (21). Figure 6 shows the Nichols chart of the open-loop function $L_{\omega roll}(j\omega)$ (12) with the specifications (20). It is seen that $L_{acv}(j\omega)$ remains outside the margin bounds at the respective frequencies, so the controller meets the specifications.

$$G_{c\omega_{roll}} = 1.23 \cdot \frac{\left(\frac{1}{0.64}s+1\right)}{\left(\frac{1}{0.41}s+1\right)} \qquad (21)$$

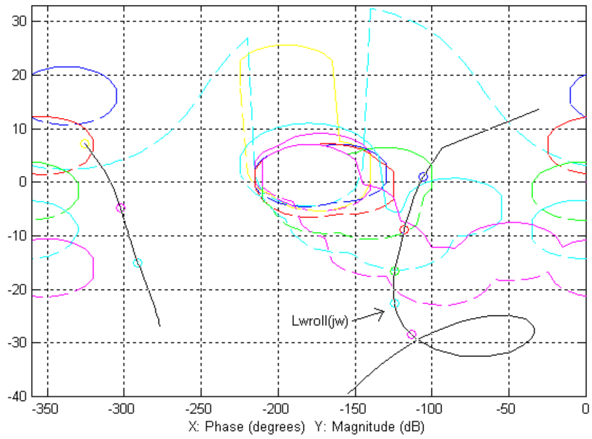

Fig. 6. Loop shaping. Nominal open-loop function $L_{\omega roll}(j\omega)$ and the intersection of all bounds.

Analysis in temporal domain. Table 2 shows the values of $J_{\omega roll}$ and the roll angular velocity reduction percentage for irregular wave SSN=5 and μ = 120, 135 and 150 degrees with the controller $G_{c\omega roll}(s)$. Figure 7 shows that there is no saturation in the fins.

Table 2. Value of $J_{\omega roll}$ and reduction for $G_{c\omega roll}$ controller V = 40 knots. SSN=5

Incidence angle μ	$J_{\omega roll}$	ω_{roll} reduction (%)
120 deg	2.03	14.57 %
135 deg	1.49	23.93 %
150 deg	1.30	15.27 %

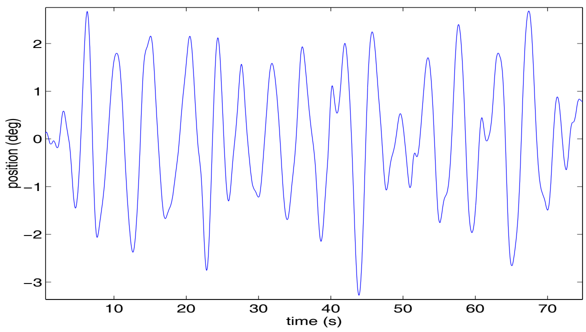

Fig. 7. Fin port movement. SSN=5. μ =150º. Fin starboard movement is symmetrical.

5.4 Coupled system

Table 3 shows the values of the vertical acceleration reduction, the roll angular velocity reduction, J_{acv} and $J_{\omega roll}$ for irregular wave SSN=5 and μ = 120, 135 and 150 degrees. It is shown that the controllers $G_{cacv}(s)$ and $G_{c\omega roll}(s)$ reduce both the vertical and horizontal movement. The temporal response of the coupled system is also observed. Figure 8 shows the comparison between the vertical acceleration output with and without control, and Figure 9 compares the roll angular velocity with and without control.

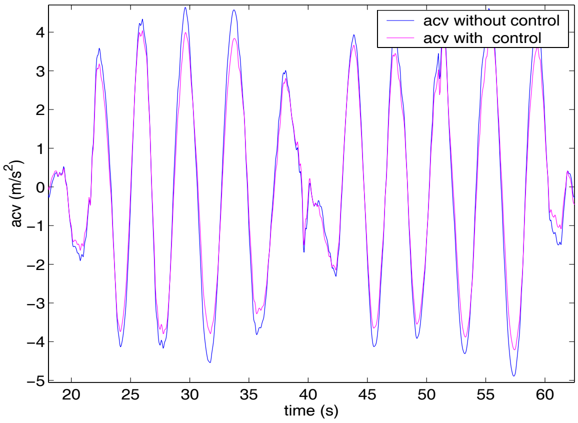

Fig. 8. Comparison of total acv with and without control in the coupled system. SSN=5. μ =150º.

Table 3. Value of J_{acv}, $J_{\omega roll}$, and reduction for G_{cacv} $G_{c\omega roll}$ controllers. V = 40 knots. SSN=5

Incidence angle μ	J_{acv}	$J_{\omega roll}$	acv reduction	ω_{roll} reduction
120 deg	2.22	1.93	9.93 %	19.34 %
135 deg	2.11	1.40	12.09 %	29.04 %
150 deg	2.26	1.24	11.05 %	19.14 %

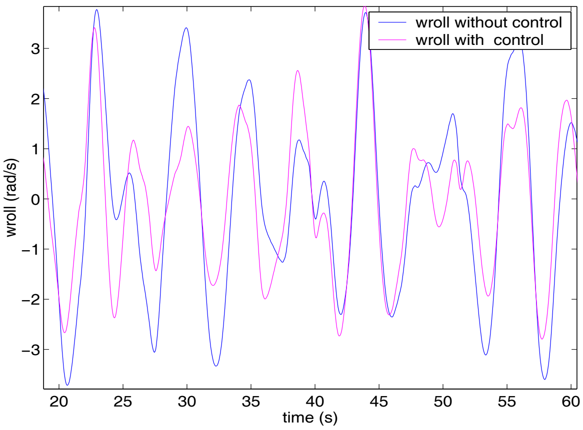

Fig. 9. Comparison of ω_{roll} with and without control in coupled system. SSN=5. μ =150º.

6. CONCLUSIONS

This research has used the QFT technique to control a coupled system on a fast ferry. In cases where the angle μ between the heading and the seaway was different from 180 (head seas), it was observed that the actuator action for controlling the heave and pitch modes (T-Foil and flaps) increased the roll vertical component. Likewise, the lateral fins generated a component in the pitch mode. A controller was designed for each dynamic separately. These systems are very appropriate for QFT control, they present plant uncertainties (the system's response to different incidence angles of the waves), and disturbance output (the waves). In QFT design, temporal domain specifications (system stability, no actuator saturation, motion reduction) are transferred into frequency domain specifications. It was shown that the designed controllers damped both the vertical and horizontal systems.

Moreover, it was shown that these controllers were capable of reducing the three coupled modes in the whole system. Compared with other approaches applied in earlier works and the results obtained, the use of the QFT technique is justified because the problem can be applied to any incidence angle and only one controller is required for any speed or sea state.

7. ACKNOWLEDGMENTS

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