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Robust Dynamic Positioning of Offshore Vessels using Mixed-μ Synthesis Part II: Simulation and Experimental Results ⋆

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Abstract: This paper is a follow-up of a companion paper by Hassani et al. (2012b) on a control design methodology for Dynamic Positioning (DP) of marine vessels and offshore rigs subjected to the influence of sea waves, currents, and wind loads using mixed-μ synthesis. The present paper describes the results of a design exercise in which robust controllers were designed for a representative vessel. Its main focus is on the discussion of the results of numerical simulations and experimental model-testing of a set of robust DP controllers operating under different sea conditions: calm, moderate, high, and extreme seas. The robust DP controllers were first evaluated in a high fidelity nonlinear DP simulator, illustrating the efficiency of the design. To bridge the gap between theory and practice, the results were experimentally verified by model testing of a DP operated ship, the Cybership III, under different simulated sea conditions in a towing tank equipped with a hydraulic wave maker.

Keywords: Robust Control, Dynamic Positioning, Wave Filtering.

1. INTRODUCTION

This is the second in a series of two papers on the design of robust DP controllers using the mixed-μ synthesis. In the first paper by Hassani et al. (2012b), using a low speed of operation assumption, a linear model of a vessel with parametric uncertainty was developed. The model proved to be instrumental in the design of robust DP controllers for vessels under different sea conditions (calm, moderate, high, and extreme seas). In the design process, the choice of appropriate weighting functions in $\mathcal{H}_\infty$ related performance criteria was also of paramount importance.

The present paper describes the results of a design exercise in which robust controllers were designed for a representative vessel. Its main focus is on the discussion of the results of numerical simulations and experimental model-testing of a set of robust Dynamic Positioning (DP) controllers operating under different sea conditions: calm, moderate, high, and extreme seas. The robust DP controllers were first evaluated in a high fidelity nonlinear DP simulator, illustrating the efficiency of the design. To bridge the gap between theory and practice, the results were experimentally verified by model testing of a DP operated ship, the Cybership III, under different sea conditions in a model test tank with a hydraulic wave maker at the Marine Cybernetics Laboratory (MCLab) of CeSOS, Department of Marine Technology, the Norwegian University of Science and Technology.

The structure of the paper is as follows. Section 2 introduces the frequency weighting functions for different sea conditions; it also describes and compares the robust controllers designed for different sea conditions following the methodology proposed in Hassani et al. (2012b). In section 3 a brief description of the Marine Cybernetics Simulator (MCSim) and the results of numerical Monte-Carlo simulations are presented. In section 4, a short description of the model-test vessel, CybershipIII, and experimental results of model-tests are presented. Conclusions and suggestions for future research are summarized in Section 5.

2. CONTROLLER DESIGN SUMMARY

The notation used and the mathematical set-up adopted for robust control system design are those detailed in the companion paper by Hassani et al. (2012b), to which the reader is referred for details. For operating conditions from calm to high seas, the transfer function of the performance weight upon the output η_L^p is selected as

$$W_p(s) = A_p \frac{\alpha_1 s^3 + \alpha_2 s^2 + \alpha_3 s + \alpha_4}{\beta_1 s^3 + \beta_2 s^2 + \beta_3 s + \beta_4} \tag{1}$$

where the coefficients of $\alpha = [\alpha_1\ \alpha_2\ \alpha_3\ \alpha_4]$ and $\beta = [\beta_1\ \beta_2\ \beta_3\ \beta_4]$, obtained after several iterations, are condensed in Table 1. The selection of the $W_p(s)$ for different sea conditions is done by cascading a low-pass and a notch filter together. The low-pass part is responsible for good low frequency disturbance rejection and the band pass filter (in mid range frequency) is tuned to have a bandwidth similar to the range of the frequencies that

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waves have their most (first order) effect on the motion (WF components of motion); see Fossen (2011); Sørensen (2011) for more details on DP wave filtering using cascaded low-pass and notch filtering. Fig. 1 depicts the magnitude of the frequency response of the computed performance weighting transfer functions for $A_p = 1$. In extreme sea conditions we suggest a new frequency weighting function $W_p(s)$ as

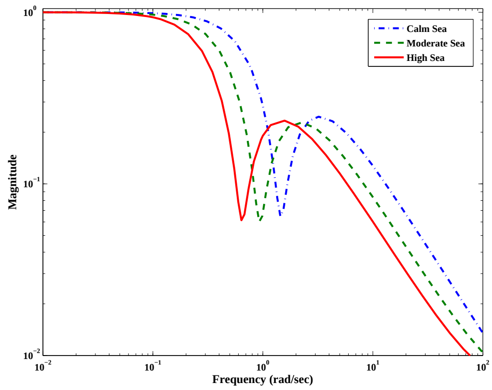

Fig. 1. Choice of Weighting Functions $W_p(s)$ for $Ap = 1$.

$$W_p(s) = A_p \frac{0.5}{s + 0.5} \tag{2}$$

which is applied to the total motion of the vessel, i.e. the controller should compensate for both LF and WF motions.

Table 1. Weighting Functions' Coefficients

Calm	α	[0.0008 1.3498 0.3955 2.8633]
	β	[1.000 4.4722 6.2482 2.8633]
Moderate	α	[0.0059 0.8612 0.1689 0.7543]
	β	[1.0000 3.0957 2.6665 0.7543]
High	α	[0.0060 0.6080 0.0823 0.2521]
	β	[1.0000 2.1406 1.2811 0.2521]

In this paper the control action is penalized with the frequency domain weight

$$W_u(s) = \frac{s^2 + 0.3652s + 0.0333}{s^2 + 36.52s + 333.43}.$$

Fig. 2 depicts the magnitude of the frequency response of the computed control action weighting transfer function. This selection allows for larger control action at lower frequencies and penalizes large control activity at higher frequencies. Throughout this paper the same weight is applied to all control channels.

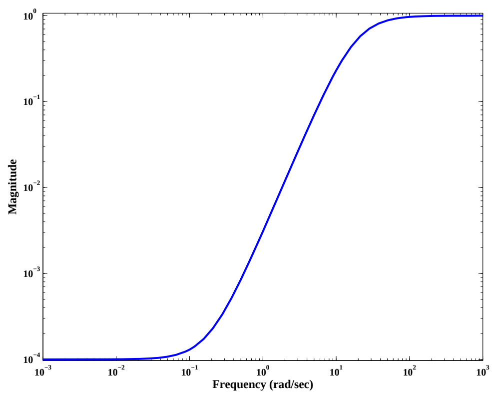

Fig. 2. Choice of Weighting Functions $W_u(s)$ to Penalize the Control Action.

We assume that input forces and torque applied to the vessel are provided through a first-order low pass actuator whose bandwidth is unknown but lies in the interval [2.46 4.10] rad/sec; its DC gain has 2 percent uncertainty; this actuator can be described in the form of a nominal model $G_0(s)$ and multiplicative uncertainty $W_{\text{unc}}(s)$ as follows:

$$G_0(s) = \frac{1}{3.2859s + 1},$$
$$W_{\text{unc}}(s) = \frac{2.9153s^2 + 0.9529S + 0.0200}{8.0978s^2 + 5.7503s + 1.0000}.$$

The computed frequency-domain upper-bound for the unstructured uncertainty, which serves in this example as a surrogate for unmodelled dynamics, $W_{\text{unc}}(s)$, captures some important practical features. This implies that the designed controller $K(s)$ provides robust-stability and-performance for the nominal vessel model with 9% - 33% model perturbation (in each control channel, independently) over the frequency range from 0.1 to 1 rad/sec, and almost 35% model perturbation, for frequencies over 1 rad/sec. Recalling the frequency content of the disturbances in the DP applications, one can verify how a particular selection of $W_{\text{unc}}(s)$ can capture the effect of different disturbances over the dynamics of the vessel.

Table 2 summarizes the results of the design of robust DP controllers for different sea conditions. As expected, the best performance index, i.e. A_p, is achieved for calm sea condition and the worst is for extreme sea.

Table 2. Summary of Controller Performance Index

Controller	A_p	μ
Calm Sea	3	$.99 \leq \mu < 1$
Moderate Sea	2.5	$.99 \leq \mu < 1$
High Sea	1.9	$.99 \leq \mu < 1$
Extreme Sea	1	$.99 \leq \mu < 1$

Note that all controllers are three-input three-output LTI systems since the controllers produce surge and sway forces as well as a yaw moment, and measurements are available for three states: surge, sway and heading. Fig. 3 compares the four local controllers by examining their singular value plots; it is clear that at low frequencies the local controllers generate a larger gain and in mid-range frequencies (where WF motion has its maximum effect) the local controllers generate a (significantly) lower gain; naturally, this leads to good disturbance-rejection in low frequencies and wave filtering in mid-range frequencies. We emphasize that each individual local controller has guaranteed performance- and stability-robustness over its associated parameter subintervals of Table 2 in Hassani et al. (2012b). Due to the fact that the mixed-μ upper-bound inequality of $\mu \leq 1$ is only a sufficient condition for both robust-stability and robust-performance, each local controller will actually have a wider stability region, see Vasconcelos et al. (2009).

Fig. 4 illustrates the potential wave filtering effect of the robust DP controllers in calm to high sea conditions by using plots of the maximum singular value of the closed loop system from control channel (where the effect of the waves enters as forces in surge and sway and torques in yaw) to the output position of the vessel. For calm to high sea conditions, it is shown that a band-pass kind of effect exists such that the mid-range frequency components of the vessel's motion are not counterbalanced by controller. However, we will see later that robust DP controllers can not carry out the wave filtering task entirely. In extreme

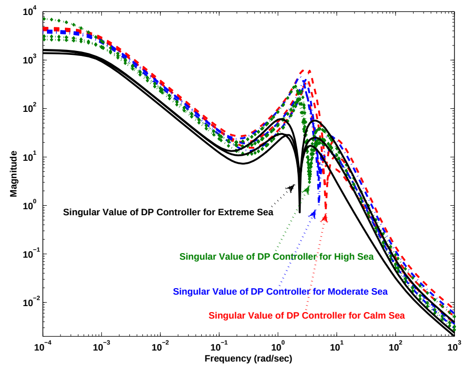

Fig. 3. Singular Values of the Local $\mathcal{H}_\infty$ DP Controllers for Calm to Extreme Seas.

sea, the WF components of motion are also regulated by the robust controller.

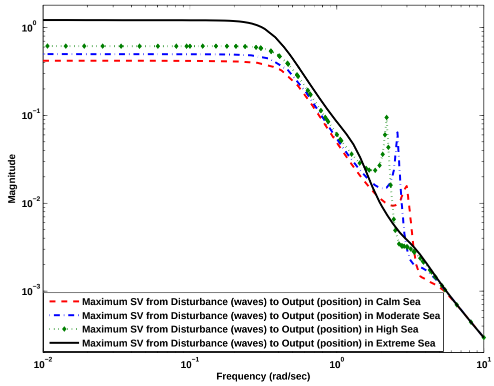

Fig. 4. Maximum Singular Value of the Closed-Loop system for Calm to Extreme Seas.

3. NUMERICAL SIMULATIONS

3.1 Overview of the Simulator

In what follows we test the performance of our controllers using the Marine Cybernetics Simulator (MCSim), later on upgraded to Marine System Simulator (MSS). The MCSim is a modular multi-disciplinary simulator based on Matlab/Simulink. It was developed at the CeSOS of the Norwegian University of Science and Technology (NTNU). The MCSim incorporates high fidelity models, denoted as process plant model or simulation model in Sørensen (2011), at all levels (plants and actuators). It captures hydrodynamic effects, generalized coriolis and centripetal forces, nonlinear damping and current forces, and generalized restoring forces. It is composed of different modules that include the following:
1) **Environmental module**, containing different wave models, surface current models, and wind models.
2) **Vessel dynamics module**, consisting of a LF and a WF model. The LF model is based on the standard 6DOF vessel dynamics, whose inputs are the environmental loads and the interaction forces from thrusters and the external connected systems.
3) **Thruster and shaft module**, containing thrust allocation routine for non-rotating thrusters, thruster dynamics and local thruster control. It may also include advanced thrust loss models for extreme seas, in which case detailed information about waves, current and vessel motion is required. The shaft is modeled as a rotational mass, with propeller speed given from motor torque and propeller load torque.
4) **Vessel control module**, consisting of of different controllers, namely, nonlinear multivariable PID controller, for DP.
For more details on the MCSim see Sørensen et al. (2003); Perez et al. (2005, 2006), and Fossen and Perez (2009).

Fig. 5. CybershipIII.

3.2 Numerical Simulations

This section described the results of simulations with the MCSim using the controllers designed in the previous sections. [1]

Figs. 6-7 shows the results of Monte-Carlo simulations of the robust DP system in different sea conditions. [2] From Figs. 7 it is seen also that even with using wave filtering frequency weighting functions (in the design process of the controllers), some of the 1st-order wave frequency components are seen in the LF components of motion. [3] Here we should highlight that in Fig. 7 we present only the LF components of the motion. However, the controllers are fed with the total position (LF+WF).

In these simulations, the different environment conditions from calm to high seas are simulated using the spectrum of the Joint North Sea Wave Project (JONSWAP), see Hasselmann et al. (1973). The calm, moderate, high and Extreme seas are simulated with Dominant Wave Frequency (DWF) of 1.20 (rad/sec), 0.91(rad/sec), 0.65 (rad/sec) and 0.4 (rad/sec), respectively.

4. EXPERIMENTAL MODEL TEST RESULTS

The designed controllers were tested using the model vessel, CybershipIII, at the Marine Cybernetic Laboratory (MCLab) of the Department of Marine Technology, Norwegian University of Science and Technology (NTNU). This section presents the experimental results of model tests for robust DP systems in different sea conditions produced by a hydraulic wave maker.

[1] The performance of the robust DP controllers designed for different sea conditions is compared with that obtained with LQG and PID controllers in Hassani et al. (2012a), both through numerical simulations using MCSim, and experimentally, using model test experiments. The results in Hassani et al. (2012a) show satisfactory performance of robust DP controllers in different sea conditions; in particular, superior performance of robust DP controllers in extreme sea condition is shown in Hassani et al. (2012a).
[2] All the results are presented in full scale.
[3] At this point, we should emphasize that the controllers are designed according to the simple model of (24)-(29) in Hassani et al. (2012b), while they are tested in the MCSim with a high fidelity model that captures hydrodynamic effects, generalized Coriolis and centripetal forces, nonlinear damping and current forces, and generalized restoring forces. Moreover, in the MCSim the JONSWAP wave spectrum is used to simulate the waves while the linear model captures the wave effects with second order approximation of the waves' spectral density.

4.1 Overview of the CybershipIII

CyberShip III is a 1:30 scaled model of an offshore vessel operating in the North Sea. Fig. 5 shows the vessel at the basin in the MCLab and table 3 presents the main parameters of both the model and the full scale vessel.

Table 3. Model main parameters

	Model	Full Scale
Overall Length	2.275 m	68.28 m
Length between perpendiculars	1.971 m	59.13 m
Breadth	0.437 m	13.11 m
Breadth at water line	0.437 m	13.11 m
Draught	0.153 m	4.59 m
Draught front perpendicular	0.153 m	4.59 m
Draught aft. perpendicular	0.153 m	4.59 m
Depth to main deck	0.203 m	6.10 m
Weight (hull)	17.5 kg	Unknown
Weight (normal load)	74,2 kg	22.62 tons
Longitudal center of gravity	100 cm	30 m
Vertical center of gravity	19.56 cm	5.87 m
Propulsion motors max shaft power (6% gear loss)	81 W	3200 HP
Tunnel thruster max shaft power (6% gear loss)	27 W	550 HP
Maximum Speed	Unknown	11 knots

CybershipIII is equipped with two pods located at the aft. A tunnel thruster and an azimuth thruster are installed in the bow.[4] It has a mass of m = 75 kg, length of L = 2.27 m and breadth of B = 0.4 m. The internal hardware architecture is controlled by an onboard computer that communicates with the onshore PC through a WLAN. The PC onboard the ship uses QNX real-time operating system (target PC). The control system is developed on a PC in the control room (host PC) under Simulink/Opal and downloaded to the target PC using automatic C-code generation and wireless Ethernet. The motion capture unit (MCU), installed in the MCLab, provides Earth-fixed position and heading of the vessel. The MCU consists of onshore 3-cameras mounted on the towing carriage and a marker mounted on the vessel. The cameras emit infrared light and receive the light reflected from the marker.

To simulate the different sea conditions a wave maker system, produced by the Danish Hydraulic Institute (DHI), is used. It consists of a single flap covering the whole Breadth of the basin, and a computer controlled motor, moving the flap. It is able to produce regular and irregular waves with different spectrums. We have used JONSWAP spectral for simulating the different sea conditions for our experiment.

4.2 Experimental Results

Figs 8 shows the vessel position and heading in different sea conditions. The results of the model test are in agreement with with the ones obtain in the numerical simulation study, showing satisfactory performance of the robust DP controllers in different sea conditions.

The results of the experimental test are consistent with those obtained using the MCSim in the simulation study. At this point we should also stress that the robust DP controllers designed using mixed-μ are usually of very high order. In this study the designed robust controllers were of order 120. We used model reduction and checked if the reduced order controllers satisfied the closed-loop robust stability and performance requirements. The reduced order controllers have orders of (approximately) 30 in all cases, and through the experiment they were discretized with a sampling time $T_s = 0.3$ (s).

[4] For technical reasons in this experiment the tunnel thruster was deactivated.

5. CONCLUSIONS

This paper offered a comprehensive evaluation of the performance obtained with a set of robust DP controllers designed for different sea conditions, for a representative vessel model. The evaluation included Monte-Carlo simulations, as well as model-test experiments with a vessel in a water tank equipped with a wave maker. The results obtained confirmed the efficacy of the methodology adopted for robust controller design. Future work will include the application of the methodology developed to the design of DP controllers for a real vessel.

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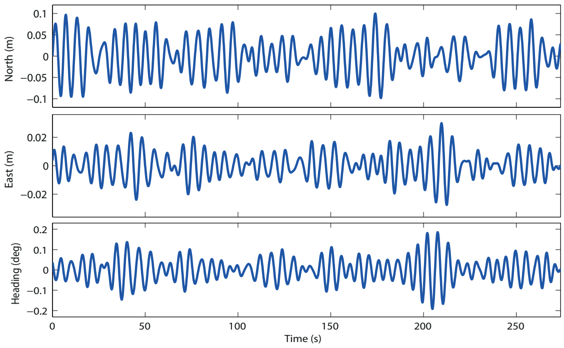
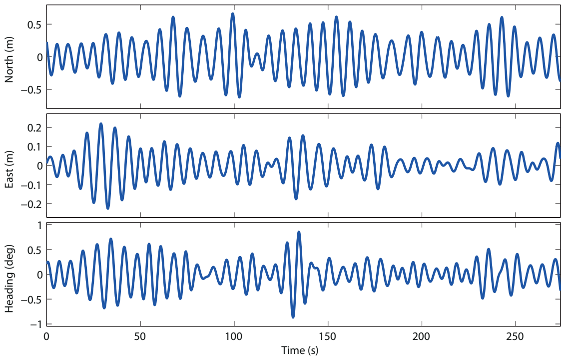
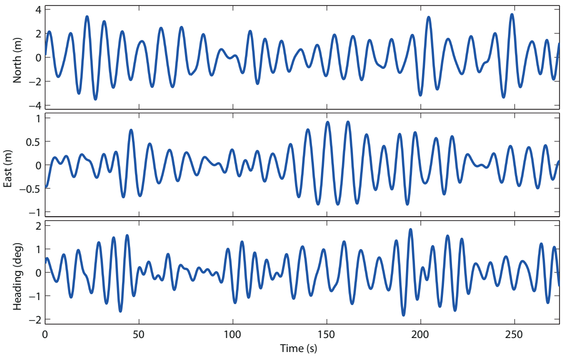


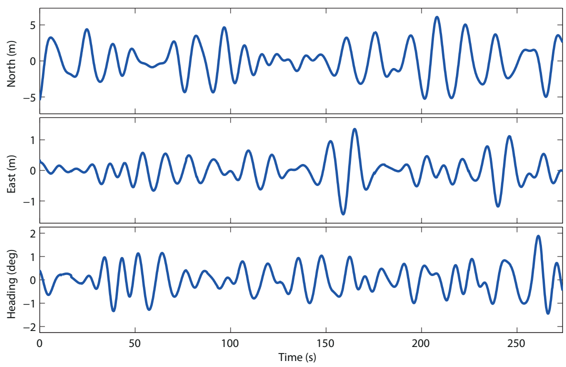
(a) Calm Sea



(b) Moderate Sea

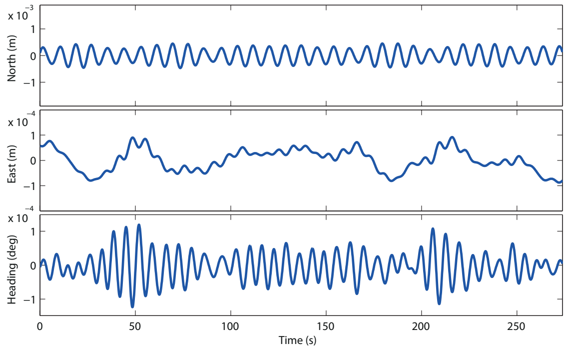


(c) High Sea

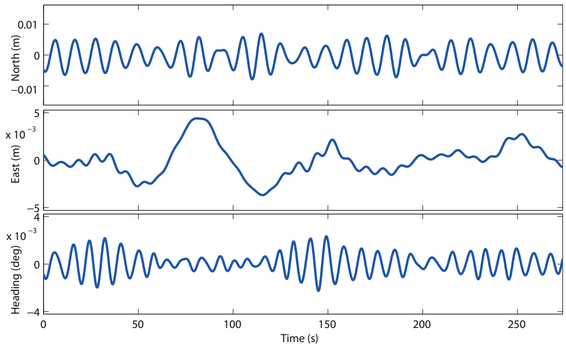


(d) Extreme Sea

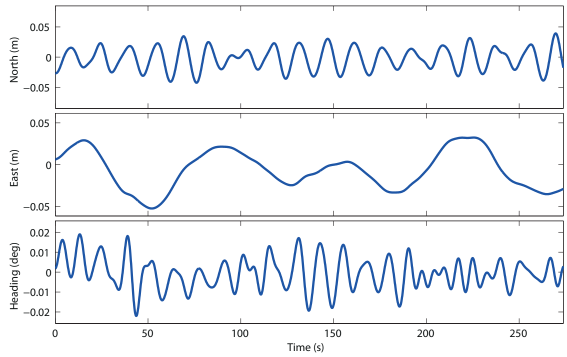
Fig. 6. Simulation Results: Total Position and Heading of the DP system using robust DP controller in Different Sea conditions.



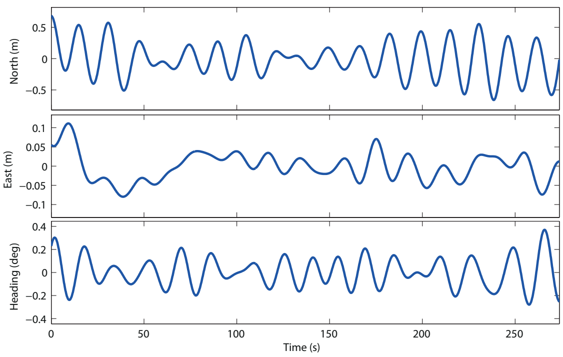
(a) Calm Sea



(b) Moderate Sea

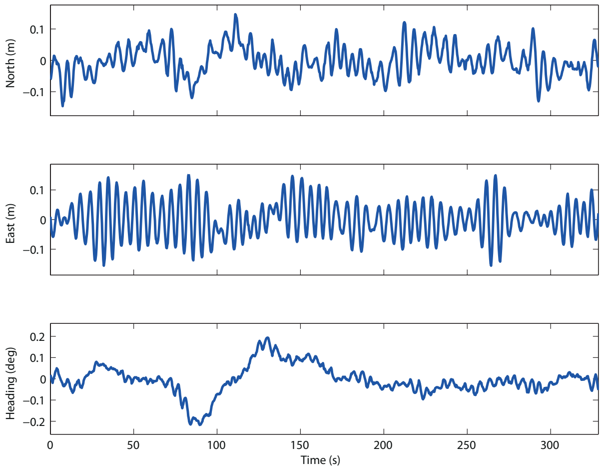


(c) High Sea

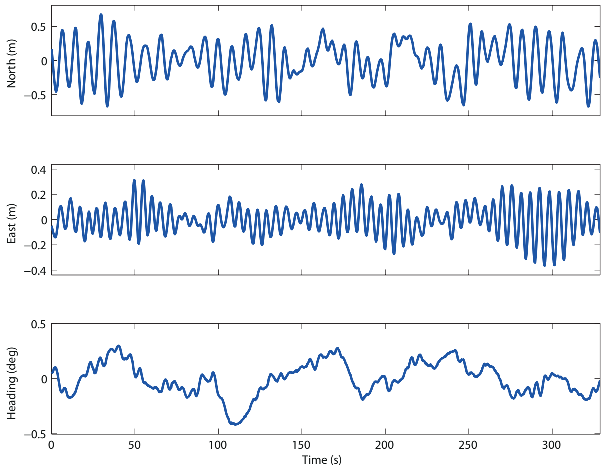


(d) Extreme Sea

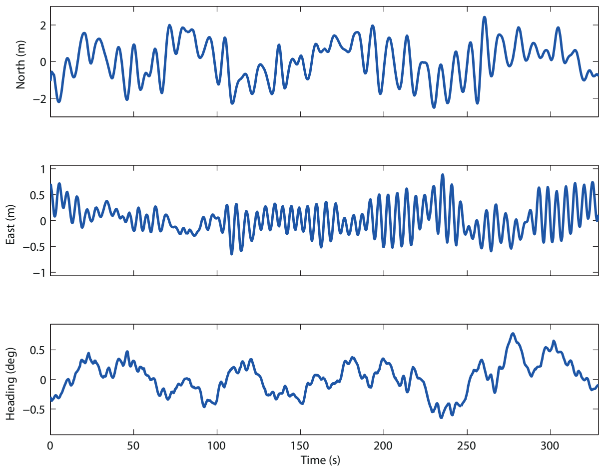
Fig. 7. Simulation Results: LF Position and Heading of the DP System using Robust DP Controller in Different Sea conditions.



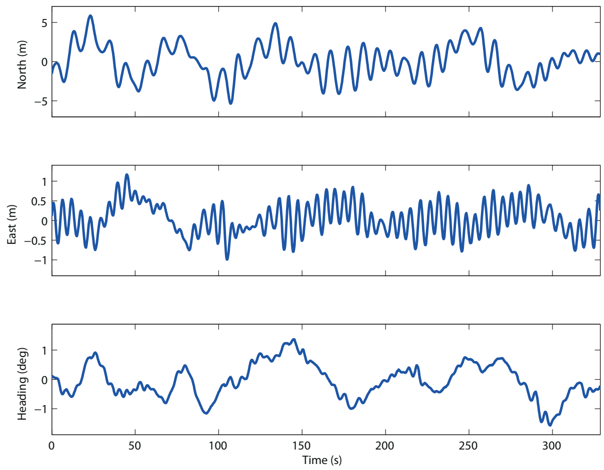
(a) Calm Sea



(b) Moderate Sea



(c) High Sea



(d) Extreme Sea

Fig. 8. Experimental Results: Total Position and Heading of the CybershipIII in DP Operation using robust DP controller in Different Sea conditions.