CONTROL DESIGN FOR SLOW SPEED POSITIONING

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ABSTRACT

The problem under study is a synthesis of position and heading control system for low frequency model of surface vessel described by 3 DOF mathematical model. The recursive vectorial backstepping control design was used to keep fixed position and heading in presence of wave disturbances. The controller has been simulated on computer model of scaled supply vessel. It has been assumed that the actuators produce generalized forces in all 3 degrees of freedom. The backstepping controller proposed in this paper in configuration with passive observer and wave filtering make a good quality to keep fixed position and heading at low forward speed in comparison with PD controller.

INTRODUCTION

For many years, scientists have been conducting research which aim to study integrated systems of the vessel's motion management. Despite the increase in the level of automation, steering the ship is still in the area of intensive research, especially at the entrances to ports and narrow waterways corridors. In view of the manoeuvre difficulties caused by the weight of ships, it is not as easy task to improve the quality of navigation, especially for ships moving at slow speeds - (e.q. slow speed positioning - called dynamic positioning).

Dynamic positioning system for marine vehicles is a challenging practical problem. It includes station keeping, position mooring and slow speed references tracking. Of that three, the main purpose of the DP system is to maintain a certain accurate position and course, regardless of the interference such as waves and wind. This task should only be achieved under its own propulsion and using navigation systems. Application of the appropriate method of adjustment for DP vessel is directly related to the adopted model, its purpose, structure and number of the installed actuators. A significant number of vessels have a single propeller and rudder. In such device configuration large ships must be put into port by auxiliary ships. Currently, most of ships have installed an additional tunnel thruster at the bow of the vessel. It gives the possibility to fully actuate the ship for maneuvering at low speeds with mild entering the ports and narrow waterways corridors. Unfortunately, such system loses its properties at high speeds. Today a future of DP systems are azipod propulsion systems, which produces full nominal torque, available in either direction over the entire speed range.
The Diesel - Electric drivers are currently used on polyvalent ships of AHTS and PSV type. They have an aim to transport large cargo for drilling platform and anchor. Equipped with DP2 positioning system, are designed for use in all sea areas, regardless of weather conditions.
The station keeping for DP system can be achieved using only three control inputs when it is considered a fully actuated ship operating in the horizontal plane. Hence, the dynamic positioning system can be designed by using feedback from position and heading angle (Fossen 2002). These state variables are in some cases available through satellite navigation systems as GPS / DGPS, supported by the gyros and accelerometers. But in general more signals like for example velocities accelerations and stationary varying disturbances due to wind, ocean current and nonlinear wave effects, are necessary in the control law. In the process of steering the ship, direct measurement of longitudinal and transverse velocity is not available when they attain low speed values. However, it is possible to calculate the estimated value of velocity on the basis of the measurements of the position and direction by the state observer. In most cases, an accurate measurement of the position and direction is disturbed by the wind, waves and sea currents, as well as by the interference of the measuring sensors. Therefore the estimates should be filtered by using so-called wave filtering (WF) techniques. Oscillatory disruptions of a WF motion component are filtered before feedback is applied. However, the remaining LF motion components which are associated with the deviation from the given position and direction are compensated by the steering system

The examples of several solutions mentioned above to solve these problems have been recently obtained. Most of them base on signal filtering, state estimation and appropriate selection of the steering method. The first DP systems were designed using conventional PID controllers in cascade with low-pass and notch filters. There, the wave disturbances are filtered before feedback is applied in order to avoid unnecessary control action. Model-based controls for positioning of ships includes also LQG, sliding mode control (Tomera

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2010), robust H∞ control (Grimble et al. 1993; Messer, and Grimble 1993), non-linear backstepping (Krstic et al. 1995; Fossen and Strand 1999) method and another state - space techniques (Fossen 2002). A number of works were carried out within the scope of application of the dynamic positioning of artificial intelligence (Xu et al. 2011), fuzzy logic (Cao et al. 2001) and neural nets (Cao et al. 2000). In the DP systems, filtering the wave and state estimation are resolved using an extended Kalman filter (EKF) (Grimble and Fung. 1983) or Luenberger observer. Unavailable, meaning immeasurable size measurement, is estimated on the basis of the mathematical model which binds both estimated and measured size. In contradiction to linear systems, no general theoretical guarantee can be given for nonlinear systems for a stable observer-controller combination, as for nonlinear systems no general separation principle exist. Another method is the linearization of nonlinear systems and multi-controller synthesis (Banka et al. 2010). There is no guarantee for global stability of the total system. In addition, controlling the total system by a set of linearized systems will decrease the performance of the total system.

Unfortunately, if the extended Kalman filter and Luenberger observer are combined with a state feedback controller, using the estimates of the states global expotential stability cannot be quaranteed. This is the most important drawback of EKF. Alternative solution for the state feedback controllers is observer backstepping (Fossen and Grovlen 1998), passive observer and wave filtering (Fossen and Strand 1999). This methods were used by Lyapunov stability theorem and Kalman Yakubovich - Popov theorem during designing GES observer. Passive observer in comparison to the backstepping observer has less tuning parameters so it is easier to apply.

In the DP systems, specific steering algorithms calculate required forces and moments which compensate for the deviation, on the basis of the estimated size of the input including the measurement of the location and direction compared with setpoints. Modern methods of steering use nonlinear control methods which let to take into account the complex dynamics of the vessel, its purpose, structure and number of the installed devices, in the process of designing the control law. One of them is a Backstepping method (Krstic et al. 1995, Witkowska and Smierzchalski 2012). The backstepping controller proposed in this paper in configuration with passive wave filtering make possibility to keep fixed position and heading at low forward speed. The observer-controller system has been simulated on computer model of scaled supply vessel. It has been assumed that the actuators produce generalized forces in all 3 degrees of freedom.

LOW SPEED MODEL FOR DYNAMICALLY POSITIONED SHIP

During dynamically positioning (DP) it is a common assumption to consider the low speed, low frequency model omitting the centrifugal/coriolis forces, moments and nonlinear damping effects. Consequently for DP, the 6 DOF is reduced to a simpler 3 DOF model that is linear in kinetic part. Since we only consider the 3 horizontal DOF's, the kinematical equations for surface ships which describe the relationship between the earth-centred and the geographical reference frames are given by:

$$\eta' = R(\psi)\nu. \tag{1}$$

The state vector $\eta=[x,y,\psi]^T$ where (x,y) is the position of ship in an earth-centred inertial frame and $0<\psi<2\pi$ is the heading angle of the ship relative to geographic North. The vector $\nu=[u,v,r]^T$ contains linear body fixed velocities in surge, sway and angular in yaw. Rotation matrix R with the property $R^T= R^{-1}$ is defined by

$$R(\psi) = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

For DP (station keeping), the linear dynamical models for surface ship denote the control forces in surge, sway and moment in yaw by τ.

$$M\nu' + D\nu = \tau + \tau_w \tag{3}$$

where $M\in\mathbf{R}^{3x3}$ is the matrix of inertia, $D\in\mathbf{R}^{3x3}$ is the damping matrix, $\tau_w = R(\psi)^T b$ is a vector of slowly varying forces and moments that act on the hull due to environmental disturbances such as wind, currents and waves or unmodelled dynamics. The vector $\tau\in\mathbf{R}^3$, $\tau=[\tau_x, \tau_y ,\tau_n]^T$ of forces and moments acting on the ship's hull refers to the forces generated by the propellers and rudders, can be written as.

$$\tau = Bu. \tag{4}$$

The matrix B is the control matrix described the thruster configuration and u is the control input.

DP CONTROLLERS

Vectorial backstepping

When designing the control law with backstepping method, we assumed that we have precise information about an object, i.e. we considered the model parameters as known in the ship model. Then the DP controller could be derived using the classical vectorial backstepping method, as it was discussed in detail (Krstic et al. 1995).

The dynamic positioning problem, considered in this paper is to find a feedback control law, which provides asymptotic convergence $\eta \to \eta_d$, at $\nu \approx 0$. The reference

signals needed for control are the desired state vector $\eta_d=[x_d,y_d,\psi_d]^T$ and its first and second order derivatives. All reference signals the heading angle ψ_d and the desired position (x_d,y_d) are assumed to be bounded. The vectorial backstepping design for ship mathematical model (1)- (4) was performed in two steps.
The first step of backstepping is to define new error variables $z_1\in\mathbf{R}^3$ and $z_2\in\mathbf{R}^3$ as:

$$z_1=[z_{11}, z_{12}, z_{13}]=\eta-\eta_d, \quad (5)$$
$$z_2=\eta'-\alpha, \quad (6)$$

The vector of functions $\alpha=[\alpha_1,\alpha_2,\alpha_3]^T$ stabilizes the system with respect to control Lyapunov functions (clf) candidate. The following DP controller is proposed

$$\tau=D\nu-MR^T(C_2z_2+z_1+R'\nu+C_1z_1'-\eta_d'')-R(\psi)^Tb,$$

using the error definitions (5)-(6); control Lyapunov functions candidate $V_1=0.5z_1^Tz_1$ and $V_2=V_1+0.5z_2^Tz_2$ and the vector of stabilizing functions $\alpha=-C_1z_1+\eta_d'$.
Now, the error dynamics can be written as:

$$z_1'=-C_1z_1+z_2,$$
$$z_2'=-z_1-C_2z_2.$$

While all reference signals η_d are constant and assuming that the state variables are available measurably, the equilibrium point $(z_1, z_2)=(0,0)$ is GAS. Stability is established by using LaSalle's theorem, since $V_2>0$ and $V_2'\leq 0$. Among other things it is satisfied where designed parameter matrices $C_1=C_1^T>0$ and $C_2=C_2^T>0$ are chosen in a diagonal form.

PD

Nowadays, autopilots which are part of equipment on vessels, use the algorithm of PD controller to adjust the position and heading angle of a ship. The operation of a classic, conventional PD controller for DP is defined by the following formula:

$$\tau=K_p(\eta-\eta_d)+T_d(\eta'-\eta_d')$$

where K_p, T_d - are vectors of coefficients illustrating the influence of individual components of a proportional and differentiation in three degrees of freedom.
When the state variables are not available measurably, then it is necessary to estimate them. Next, on the basis of the estimated values, derivatives of state variables required in the controller are calculated. It is assumed that only position and heading measurements are availble. The observer was used to produce the velocity estimates for feedback control. The position and heading should not containing a WF part of the motion.

DP MODEL-BASED OBSERVER

The model-based observer described in detailed in (Fossen and Strand 1999) was used to reconstruct the system's non-measured states. The chosen observer was designed on the basis of the Lyapunov Stability Theory. The idea of the state observer is to reproduce in the mathematical model (virtually) a state that accurately reflects the reality. There are some differences between the real output and the model output. This error is fed back into the mathematical model to correct the difference and bring the mathematical model closer to the reality. The technique of the state observer consists in developing a model for the system under analysis and comparing the estimated outputs with the measured ones. It is assumed that only position and heading measurements are availble. The following ship model (1)-(4) was considered. The measured position and heading, y_m can be seen as a superposition of the LF motions and WF motions.

$$y_m=\eta+\eta_w$$

The zero mean Gaussian measurement noise is assumed to be negligible with respect to the first-order-wave disturbance η_w. The idea of passive observer is to reconstruct η, η_w from y based on output y and vector forces τ.
The following WF model approximation was used for simplified DP model of the ship dynamics.

$$h_i(s)=\frac{2\zeta_i\varpi_{0i}\sigma_i}{s^2+2\zeta_i\varpi_{0i}s+\varpi_{0i}^2}, \quad (7)$$

where: ζ_i - relative damping ratio, ω_{0i} - dominating wave frequency, σ_i-wave intensity parameter
Wave model is generated for each degree of freedom (i=1,2,3). The wave forces were added to the positions and heading measurements. A state space realization of wave frequency (WF) model (7) can be expressed as

$$\chi'=\Omega\chi, \quad (8)$$
$$\eta_w=\Gamma\chi, \quad (9)$$

Here $\chi\in R^6$ is a state vector, $\Omega\in R^{6x6}$ is a constant matrix results directly from transformation of the transmittance (7) to the state space model, $\Gamma\in R^{3x6}$ is a constant matrix converts the vector χ to space R^3 as the vector dimension η_w.
The bias state b can be used to represent slowly-varying environmental forces and moments due to second-order wave drift, ocean currents, wind and unmodelled dynamics. The bias state is modelled by a first-order Markov process

$$b'=-T^{-1}b \quad (10)$$

where $T\in R^{3x3}$ is a diagonal matrix representing positive bias time constants.

On the basis of a complete model of the system ship-environment which consists of a ship model (1) - (4), bias model (10) and WF model (8) - (9), proposed in (Fossen and Strand 1999) resulting observer is composed of the following equations described
state estimators:

$$\dot{\hat{\eta}} = \mathrm{J}(\mathrm{y_m})\hat{\upsilon} + K_2\tilde{y}$$
$$\dot{\hat{\upsilon}} = -\mathrm{M}^{-1}\mathrm{D}\hat{\upsilon} + \mathrm{M}^{-1}\mathrm{J}(\mathrm{y_m})^{\mathrm{T}}\hat{b} + \mathrm{M}^{-1}\tau + \mathrm{J}(\mathrm{y})^{\mathrm{T}}K_4\tilde{y}$$

measurements estimator:

$$\hat{y} = \hat{\eta} + \Gamma\hat{\chi}$$

If a state observer is applied estimates of the bias and WF motion components can also be computed.
bias estimator:

$$\dot{\hat{b}} = -\mathrm{T}^{-1}\hat{b} + K_3\tilde{y}$$

wave estimator:

$$\dot{\hat{\chi}} = \Omega\hat{\chi} + K_1\tilde{y}$$

Here $\tilde{y} = y_m - \hat{y}$ is the estimation error and $K_1 \in R^{6x3}$, $K_2 \in R^{3x3}$, $K_3 \in R^{3x3}$ and $K_4 \in R^{3x3}$ are observer gain matrices. More details can be found in the literature (Fossen and Strand, 1999) and (Fossen, 2002). Both the GES and passivity for the observer were proven.

CONTROL SYSTEM STRUCTURE

Simulation studies were carried out in the system shown in Figure 1. Ship control structure consists of a block "Set point" which sets selected turn point position and direction with which they should be achieved. According to the assumption of DP steering, control takes place at low speeds of the ship. Therefore, turn points and parameters do not have to be determined automatically. They are usually defined by the operator. Wave interference influence on the state variables. Waves were modeled on the basis of the transmittance (7). In the considered system occurs block "DP controller", in which the set points of the position and course are compared with estimated values. In the "Observer" block, status variables are estimated based on the measured input and output signals of the model. In the simulation studies, a linear mathematical model of the ship CyberShip 2 was used as the object.

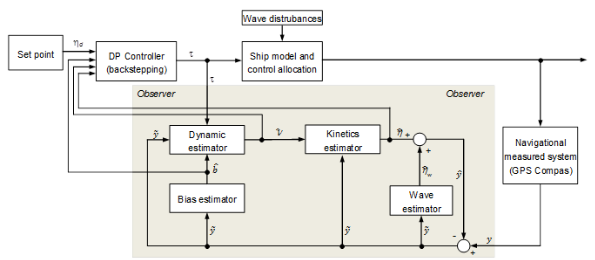

Figure 1: Simplified diagram of the DP system with an observer

The tested control systems were modeled in the computing environment called Matlab/Simulink. Simulations were carried out in the time domain. Numerical integration was done using Runge-Kutta method in fourth-order integration with a period equal to 0.1s.

SIMULATION RESULTS

Simulation model

The mathematical model of Cybership 2 was used during simulation. The model is 1:70 scaled of supply ship. The length is 1.255m. and the weight is 23.8kg. The CG is located about 4.25cm. of midship. Cybership 2 is modeled by the linear dynamic positioning model (1) - (4) with following mass and damping matrix coefficients:

$$M = \begin{bmatrix} 25.8 & 0 & 0 \\ 0 & 33.8 & 1.0115 \\ 0 & 1.0115 & 2.76 \end{bmatrix}$$

$$D = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 7 & 0.1 \\ 0 & 0.1 & 0.5 \end{bmatrix}$$

The maximum surge force is 2N, the maximum sway force is 1.5N and the maximum yaw moment is about 1.5N.

The ship model selected for designing and testing the control system with the backstepping method, was developed at the Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. The physical model of this ship sails in the Marine Cybernetics Laboratory (MCLab), NTNU.
Five actuators actuate the ship. In the bow, there is a small two-bladed rpm controlled tunnel thruster which produces a sway force. At the stern, there are two rpm controlled main propellers with rudders which produce a surge and sway force.

Reference (Skjetne 2005, Tomera 2010) give more information about model structure and his dimensional hydrodynamic coefficients, also thrust allocation.

Case study

Consider the Cybership 2 DP model in combination with observer and backstepping controller, the results of the simulations are shown in Figures 2-3.

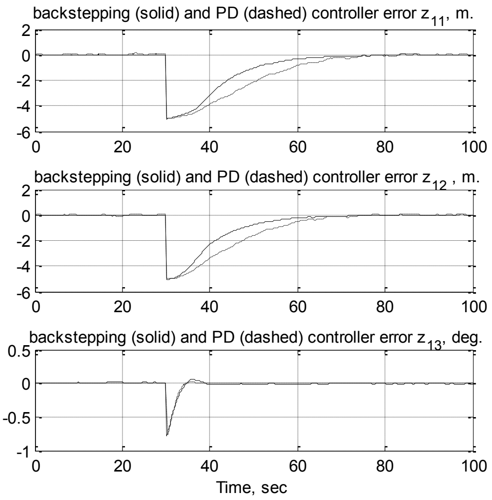

Figure 2:Position and heading observer-controller errors of the DP model.

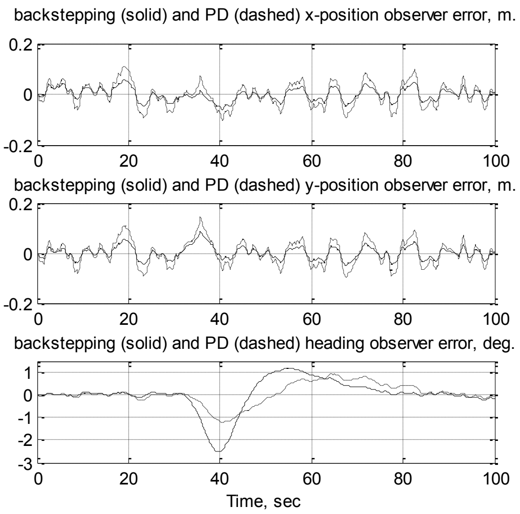

Figure 3:Position and heading observer errors of the DP model

The vessel starts with u_0=0.01m/s., v_0=0m., $\psi'_0=0^0$, x_0=0m. y_0=0m., $\psi_0=0^0$ while the initial values of the estimates are set as zero. After 30s. the designed states was generated by x_d=5m., y_d=5m. and $\psi_d=45^0$.

The simulation studies of the vectorial backstepping controller with observer were carried in the presence of the wave disturbances (7). The set parameters of the first order wave induced motion model were set as ζ_i =0.1, ω_{0i}= 0.8rad/s, σ_i=0.5m. The amplitudes of the wave - induced motion were limited to 1.0m., 1.0m., 2^0 respectively for surge, sway and yaw.

The observer - wave gains were chosen for the same order as the gains used in (Fossen and Strand 1999):

$$\Omega = \begin{bmatrix} 0 & I \\ \Omega_{21} & \Omega_{22} \end{bmatrix},$$

$$\Omega_{21} = -\mathrm{diag}(\varpi_{01}^2, \varpi_{02}^2, \varpi_{03}^2),$$

$$\Omega_{21} = -\mathrm{diag}(2\zeta_1\varpi_{01}, 2\zeta_2\varpi_{02}, 2\zeta_3\varpi_{03}),$$

$$\Gamma = [0 \quad I],$$

Filter gains are set as K_1=[diag(1.1,1.1,1.1), diag (0.8,0.8,0.8)]^T and K_2=1.1*diag(0.8, 0.8, 0.8), bias gains: K_3=diag(0.1, 0.1, 0.01), velocity observer gains: K_4=diag(0.1, 0.1, 0.01), bias time constants T=diag (100,100,100). For the PD controller, two vector parameters were to be selected as K_p=[0.3, 0.18, 2]^T, T_d=[3, 3, 3]^T. At the same time for the backstepping control law, designed parameter matrices are chosen in a diagonal form: C_1=diag (0.01,0.01,0.01) and C_2=diag (10,10,10).

The simulation tests aim at checking the operation correctness of the vectorial backstepping controller with passive observer and wave filtering for DP model. First the computer simulation is performed to show the convergence of the position and heading to their desired value. The time-histories shown in Fig. 2 confirm the good ability of the backstepping and PD control system to keep fixed position and heading in presence of wave disturbances. In comparison with PD, the backstepping method gives better time quality coefficients such as rise time, maximum overshoot, time control. The new state vector components $z_1 = [z_{11}, z_{12}, z_{13}]$ tend to zero after about 30s. for both position and after about 10s. for heading. The surge, sway velocity and yaw angle were estaimated from observer. To compare the simulation results shown in Figs. 3 - 6 it is seen that all the observer errors tend to zero for velocity, position and heading. Velocity estimation errors does not exceed 2% of the steady-state. The time-histories in Figs. 5 and 6 show additionaly measured and estimated LF position and heading of the DP model with backstepping and PD controller.

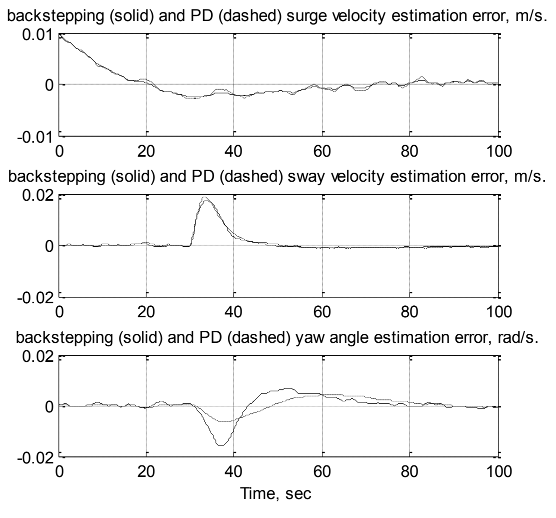

Figure 4:Estimation error of surge, sway velocity and yaw angle of the DP model.

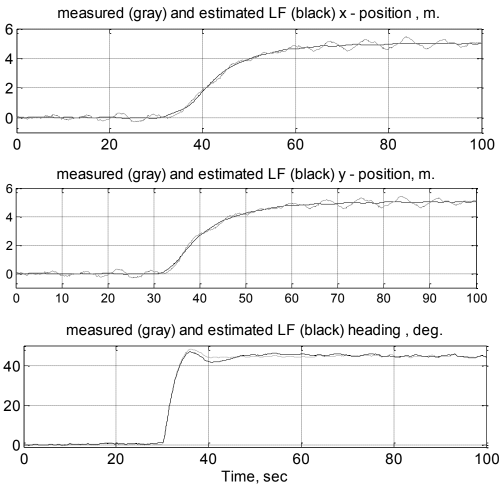

Figure 5: Measured and estimated LF position and heading of the DP model with backstepping controller.

CONCLUSIONS

Ships with DP system are used to perform operations on the sea, especially in the output of crude oil. Functions, that these vessels implement, are able to eliminate the tugs work and are able to quickly respond to changes in weather or operating parameters. This gives the versatility of using this type of vessels. In this paper the station keeping for DP system was achieved using only three control inputs when it is considered a fully actuated ship operating in the horizontal plane.

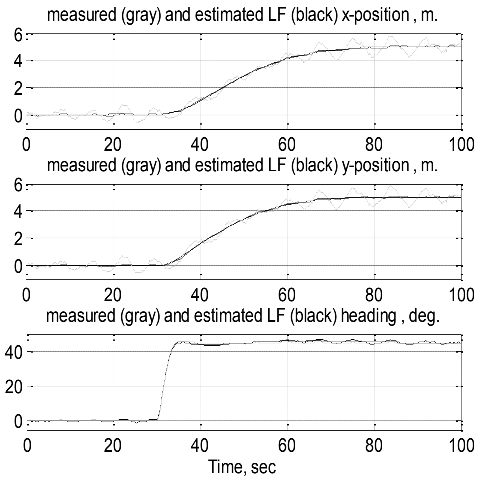

Figure 6:Measured and estimated LF position and heading of the DP model with PD controller.

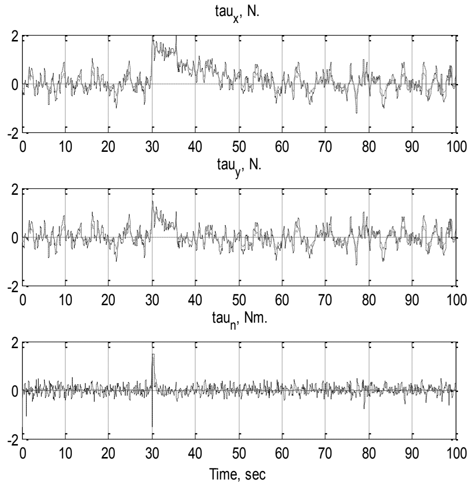

Figure 7: Control inputs in surge, sway and yaw (PD - gray line, backstepping - black line).

In this paper output feedback controller for DP was derived using vectorial backstepping method. The backstepping requires that state variables position, headings and velocities are available measurably for feedback control. For velocity estimates and wave filtering the controller was developed with observer. This combination of controller-observer confirm the good ability of the control system to keep fixed position and heading in presence of wave disturbances. It is known (Fossen and Strand) that in the case where disturbances were neglected the system was GAS. Basis on simulation results in presence of wave disturbances only the input-to state stability property is maintained. The system can be an alternative to using the method of control systems with PID or switching systems.

In simulation results was assumed precise knowledge of ship model parameters. But in practical solution the model has an parametric uncertainties. So the adaptive backstepping DP control law is necessary to consider. It will be disscused in the next part of research.

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