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Model Predictive Control of the ship's motion in presence of wind disturbances

Anna Miller

Gdynia Maritime University, Department of Vessel Automation
81-225 Gdynia, ul. Morska 81–87, e-mail: anwas@am.gdynia.pl

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Abstract
Model Predictive Control is a control strategy which can be used for ships guidance and trajectory tracking problems. Linear multidimensional MPC controller is used to control the transversal, longitudinal and rotational velocities of a ship. Control system based on the MPC algorithms is robust to wind disturbances and thus can be used in real sailing conditions. It is proved by the computer simulations results and described in detail in this publication. Whole control system was designed and simulation studies were carried out on the basis of the real floating training ship model. A Model Predictive Controller synthesis steps, including linearization of the nonlinear ship model in the vicinity of operating point, are shown.

Introduction

Fully automatic ship control requires precise determination of the control signal values, what allow for reference tracking. In conventional autopilot systems installed on board of commercial vessels, only the ship heading is controlled. In case of the manned sailing units exploited in the merchant navy, officer on watch is responsible for speed control and setting ship's appropriate course. Nevertheless, more and more frequently fully automated ship motion control systems are used. These systems are deployed to ensure a possibility of free movement in the desired direction. This direction is not completely arbitrary, what is related to the fact that ship is a nonholomic object. It means that speed constraints are imposed on her motion and according to the maneuvering characteristics – vessel has limited circulation radius. In the full automation ship control systems it is necessary to control longitudinal (u [m/s]), transversal (v [m/s]) and rotational (r [rad/s]) speed. In real applications, the above described control is used, in special purpose ships, during underway replenishment [1], or when controlling Unmanned Surface Vehicle (USV) motion.

Vessels are moving on the border of two media – water and air. The individual propellers and steering gear generate thrust force, which can be pointed in any direction, providing ship movement in transversal (y) or longitudinal (x) plane and torque (ψ). Their values are connected with the individual speeds. In real conditions both the water and the air can generate disturbances acting directly on ship. Wind acting on superstructures and ship's sides will also cause generation of the individual speeds – longitudinal (u_w), transversal (v_w) and rotational (r_w). These additional components are added to the velocities resulting from the objects dynamics and kinematics. A similar effect on the ship's movement have waves. The both types of disturbances are additive ones which in real conditions cannot be completely eliminated. It is the reason why there is a need to design the control system which will take into account the presence of noise originating from wind and waves and despite their occurrence allow for automatic regulation of the individual velocity values.

Model predictive control is not a particular control strategy, but is a set of rules using the predicted output signal values, based on the object's mathematical model, to count the command signals. Controllers working on the basis of the predictive control theory are mainly used in chemical and petrochemical industry, where processes are generally slowly alternating [2]. Nevertheless, due to the easy way of taking into account the restrictions for both the input and the control variables, they are applied in many other areas. In particular, where the real object is controlled and control signals are limited by physical properties of actuators and too high signal value provision could destroy the system.

In marine applications Model Predictive Control also has found its place. As in the case of controllers used in petrochemical industry, in this field their prototypes were optimal controllers, which required to solve the similar problems as in MPC. Ship trajectory tracking has been automated for the first time with the use of predictive control algorithms in 1999 by Wahl and Gilles [3]. They used ship model with one degree of freedom (1DOF) linearized around the operating point. Oh and Sun in [4] introduced the concept of linear MPC controller with constraints imposed on control signals arising from the acceptable ranges of actuators working conditions. Trajectory tracking concept was evolved in [5], where the influence of rudder blade motion on course and roll dynamics was included. In [6] the concept is taking into account ship motion in presence of disturbances. Close to naval issues are brought up in publications concerning motion control of the airplanes or Unmanned Flying Vehicles (UFVs).

The aim of this work is to solve the problem of the ship's longitudinal, transversal and rotational velocity control in presence of wind disturbances. For this purpose there was designed a linear predictive controller which is based on linearized model of the real floating training ship (LNG Carier Dorchester Lady) built in 1:24 scale. This ship is owned by the Foundation for Safety of Navigation and Environment Protection. Model Predictive control requires continuous estimation of the output signal values. This is done on the basis of the present and predicted control signal values. They have to be determined in real time when controlling a floating training ship. Therefore it is necessary to use as simple model of the object as possible and to avoid a long prediction horizon.

Ship's model

In process of Model Predictive Controller synthesis the real floating ship's model Dorchester Lady (Fig. 1) was used. This floating model was built on the basis of real ship. The training vessel's length overall is 11.55 m, breath equals to 1.8 m and displacement is 8.21 T.

Thrusters

Dorchester Lady has two azipods placed astern, bow thruster and rotational bow thruster, which are shown in figure 1. Thrust can be generated in any direction when all thrusters located on board are used. Bow thrusters are used only when controlling ships motion at small speeds. Their performance is satisfactory when a longitudinal speed does not exceed 4 kn for a real ship which in the case of training ship model gives a speed about 0.4 m/s. The designed ship's speed controller is designed to work in normal operation conditions, it means that ship is moving "half ahead". This corresponds to a longitudinal speed of 1.1 m/s for the LNG Carrier Dorchester Lady. Bow thruster is useless and there is only an opportunity to control ship's motion using the azipods. Their maximal rotation angle amounts to 360° and a set point range limit is: 0–10, where 0 corresponds to the stopped thruster and 10 – corresponds to the maximal rotational speed of the propeller.

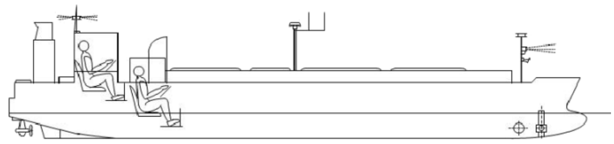

Fig. 1. LNG Carrier Dorchester Lady silhouette [7]

Proper operation of the individual thrusters, when the conventional automatic control systems (such as PID) are applied, requires cooperation with the thrust allocation system. It allows for an optimal power distribution between all thrusters and in case of the rotational thrusters also for a rotation angle determination, depending on the values of the forces and moments worked out by the control system.

When using a linear MPC controller, it is possible to completely eliminate the thrust allocation system. It is associated with the ability of direct control signal values calculation in form of thrusters set points as well as with the possibility of taking into account actuators physical constraints. They are minimal (u_{min}) and maximal (u_{max}) set points and acceptable angles for the rotational thrusters and their rate of change (Δu). These constant values are described by the equation (1) and treated as constraints in the predictive control algorithm.

$$u = [n \quad \delta]^T, u_{min} \leq u \leq u_{max}, \Delta u_{min} \leq \Delta u \leq \Delta u_{max} \quad (1)$$

where: n – azipod pitch set point, δ – azipod rotation angle.

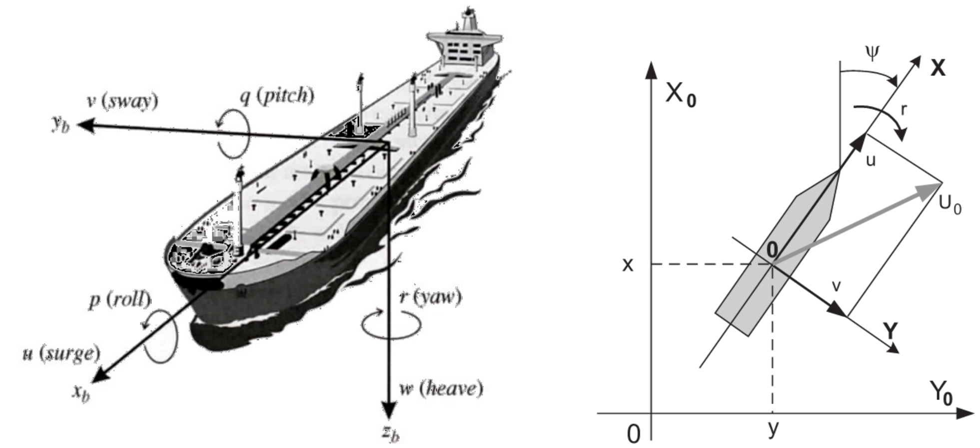

Fig. 2. 6DOF ships model (left) [8]; Two-dimensional coordinate systems to describe the ship dynamics (3DOF) (right) [9]

Ship's dynamics

Ship is an object threated as a rigid body with six degrees of freedom (6DOF). They are movement along the longitudinal axes (x_b), transversal axis (y_b), vertical axis (z_b) and rotations about these axis, which is shown in figure 2. This (6DOF) model is used when the dynamics of the underwater vehicle is described. In case of the surface vessel. It is assumed that ship moves on the surface which is flat, so model may be simplified to the three degrees of freedom rigid body (3DOF). This simplification significantly reduces the complexity of description. When taking into account the above mentioned training ship Dorchester Lady, this simplification does not have meaningful influence on the quality of designed model, because when sailing on lake there are no roll, pitch and heave [9]. In this case it is assumed that $w = p = q = 0$, which is shown in figure 2. The simplified (3DOF) ship dynamics can be described by (2).

$$\begin{aligned} m(\dot{u} - rv) &= X_{\mathrm{TOT}} \text{ [N]} \\ m(\dot{v} + ru) &= Y_{\mathrm{TOT}} \text{ [N]} \\ I_z \dot{r} &= N_{TOT} \text{ [Nm]} \end{aligned} \tag{2}$$

where: m – ships mass, X_{TOT}, Y_{TOT} – total forces acting along the axes x and y, N_{TOT} – total torque about z axis, I_z – moment of inertia about z axis.

The above described nonlinear model of the training ship – LNG Carrier Dorchester Lady, was used in process of model linearization, as well is treated as a reference dynamics when conducting simulation experiments. The linear model was used during the Model Predictive Controller synthesis.

Model linearization around the operating point

A precise modeling of an object or process which is controlled, plays a key role in the Model Predictive Control. This model is used for prediction of the output signals future values $\hat{y}(t+k \mid k)$ in discrete time moments $t+k$. They are determined on the basis of data available in the concrete time moment k. On the basis inter alia above mentioned values, control signals are calculated in particular moments of time. So the mathematical model is a part of system ensuring proper operation of MPC controller and shall comply with the following assumptions:

- model of the object (process) is described with sufficient precision to represent its dynamics;
- model is as simple as possible, to provide the ability to compute predicted values;
- model should allow for theoretical analysis;
- complete model can be divided into the separate process and disturbance models.

In general, real control systems cooperate with the nonlinear objects. Special attention should be payed to the fact, that in the Model Predictive Control we deal with object and its model, which is located inside the controller block.

The most popular configuration, in which MPC controller works when controlling ship's motion is nonlinear object and its lonearized model. This approach ensures an ease of prediction, sufficient computing speed and optimal solution finding, while minimizing control performance index. Therefore, during the identification procedure nonlinear model was linearized around the operating point and Dorchester Lady training ship's linear model was obtained. When selecting an operating point it was assumed that both azimuth thrusters are working with the same speed and angle of inclination. The propeller set point n and thrusters angle δ are respectively 7 and 0°. This corresponds to the movement of ship with longitudinal velocity equal to 1.1 m/s and transversal and rotational speeds equal respectively to 0 m/s and 0 rad/s. When conducting the identification experiments, it was assumed that the azipod propellers set point will oscillate in range: $5 \le N \le 9$, and its angle of rotation in range of: $-20° \le \delta \le 20°$. Pseudo-random waveforms of control signals having different amplitudes and periods in the above described oscillating limits were applied to the inputs of nonlinear 3DOF mathematical model of the LNG Carrier in Matlab / Simulink. Output signals, which are longitudinal u, transversal v and rotational r speeds, were recorded.

Model Predictive Controller is a discrete one and requires internal linear discrete model. It was decided to linearize dynamics on the basis of the ARIMA (Auto-Regresive Integrated Moving Average) model which is most commonly used during the MPC controller synthesis [10, 11]. This model describes the relation between input and output as a discrete transfer function. When creating multidimensional linear model of the LNG Carrier Dorchester Lady a variation of ARIMA model, called Box-Jenkins was used. This model is described by the relationship (3).

$$y(t) = \frac{B(z^{-1})}{F(z^{-1})}u(t-1) + \frac{C(z^{-1})}{D(z^{-1})}e(t) \qquad (3)$$

where: B, C, D, F are polynominal matrices and z^{-1} is unit delay operator, $e(k)$ is a vector of white noise with zero mean value.

As an input signal vector containing propeller set point n and azipods angle of rotation δ was adopted. Output signal – velocities vector consists of u, v and r. In figure 3 comparison of the longitudinal, transversal and rotational velocities is shown. The velocities u_{DL}, v_{DL} and r_{DL} are the results of signal vectors u provision on inputs of the nonlinear model of LNG Carrier. In turn values u_{m1}, v_{m1} and r_{m1} are velocities obtained on the basis of the linear model.

While analyzing the results shown above, it can be concluded that the dynamics of the object described by the nonlinear and linearized models are very close to each other. The differences in particular velocities do not exceed 6%. So a sufficient accuracy of the process modeling was provided and this model can be used during the MPC controller synthesis.

Model predictive controller synthesis

Predictive control uses an idea of the optimal control problem recursive solving. A sequence of control signals is obtained during the objective function optimization. Only the first one from computed signals is applied to the object. These controls are determined in such a way to allow for possible the fastest coverage of output signal with predetermined reference signal. In case of the synthesized controller based on a linear object's model, reference signal vector is described as: $y_{ref} = [u_{ref}, v_{ref}, r_{ref}]$, where values u_{ref}, v_{ref} and r_{ref} are reference velocities values. Designed controller is based on the receding horizon concept. In order to determine the expected output signal, there are counted predicted control signal values which form a vector: $u(k) = u(k|k), u(k+1|k),...,u(k+N_u-1|k)$, where N_u – is control horizon. Outside this range the control signals satisfy relationship: $u(k+p|k) = u(k+N_u-1|k)$ for $p \ge N_u$. All signals are changing at every time moment in the control horizon, due to their values optimization which takes place continuously [2]. The shown above transcription "$k+p|k$" means the signal value is predicted for the $k+p$ moment of time determined in the k time moment. When synthesizing controller it is necessary to establish length of the control and prediction horizons. The shorter prediction horizon

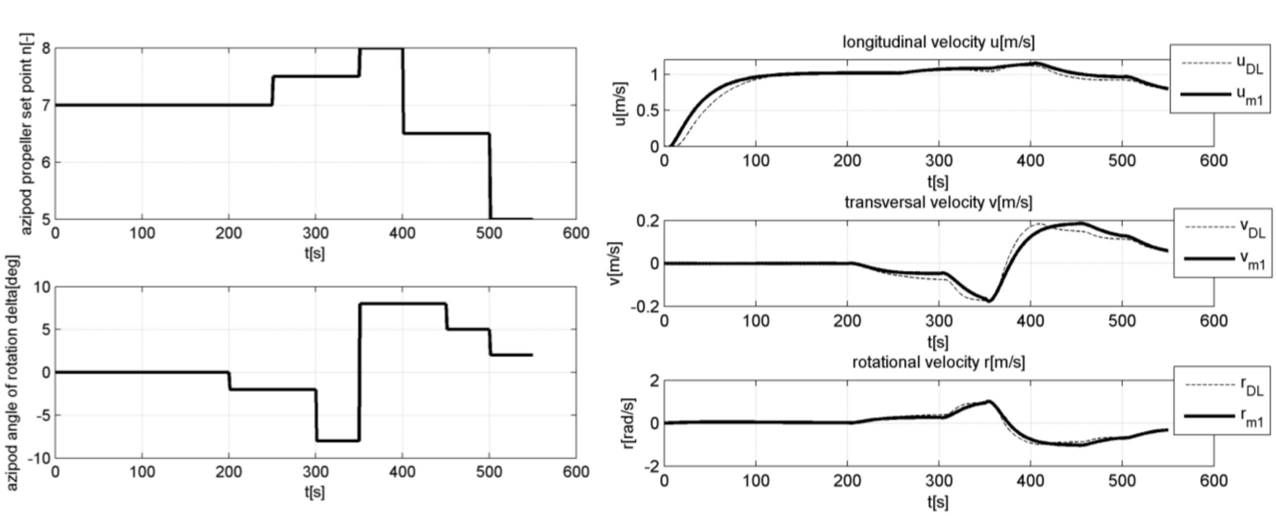

Fig. 3. Longitudinal, transversal and rotational velocities (right) for a step change in input signals (on the left)

is, the faster is operation of the control system. However it is directly connected with the system robustness. Reduction of prediction horizon causes decrease in the system resistance to disturbances. Their occurrence can lead open loop control system to the stability boarder.

Goal of the predictive control algorithm is minimization of error $e(k) = s(k) - y(k)$, which is a difference between set point and output signal values in the k moment of time. In the synthesized control system, which is MIMO configuration, cost function, which is minimized at each time step is described by (4) according to [12].

$$J = \sum_{p=N_1}^{N} \left\| Mx(k+p\,|\,k) - y(k+p) \right\|_{Q(p)}^2 + \sum_{p=0}^{N_{u-1}} \left\| \Delta u(k+p) \right\|_{R(p)}^2 \tag{4}$$

where: M – output matrix C (when objects model is described in state space), $y(k + p)$ – output signal in the $k+p$ moment of time, $\Delta u(k+p)$ – control signal change in the $k+p$ moment of time.

Norm $\|.\|_Q^2$ is defined based on the cost function α as follows: $\|\alpha\|_Q^2 = \alpha^T Q \alpha$. Similarly Norm $\|.\|_R^2$ is defined based on the cost function α as follows: $\|\alpha\|_R^2 = \alpha^T R \alpha$. Matrix Q – is a matrix of weights for the output signals increments and R – is a matrix of weights for the control signals increments.

Designed MPC controller is applied to the training ship Dorchester Lady. In the described model a pair of conjugated azipods is used to change three velocities. This approach entails limitations that are associated with the objects nonholomity. The propellers' set point n change at zero inclination angle δ of the azipod gives ability to control the longitudinal speed. Whereas a change of inclination angle δ of the thruster in the range of small angles (±20°) influences simultaneously the change in both the transversal v and the rotational r speed. Analyses of the relation between these speed values pointed out that in the steady state at a speed oscillating in range from 0.9 m/s to 1.2 m/s the ratio $v / r \approx -0.18$. This dependency between the channels $\delta \rightarrow v$ and $\delta \rightarrow r$ there was taken into account during MPC controller synthesis. MPC task is to control longitudinal speed u and the pair of transversal v and rotational r velocities. Wherein further considerations treat, that the change of rotational speed is directly related to the change of transversal speed. This assumption in normal working conditions is not a limitation, because the ships course is adjusted for a small values and a rapid changes in the angular velocity are realized only in close proximity of the waypoints.

Quick change in the transverse velocity with a small change of transversal and rotational velocity at the same time requires azipods working at angles of rotation about ±90°. So there will be the need of switching between a pair of predictive controllers operating on the basis of two independent linear models.

The results of computer simulations

Predictive controller working on the basis of linearized model of the training ship (LNG Carier – Dorchester Lady) after tuning is characterized by following parameters. Prediction and control horizons amount respectively to $H_p = 20$ samples and $H_u = 4$ samples. Determination of the matrices R and Q is based on the approximate methods. During MPC controller synthesis they were computed based on the empirical method to the large extent. Values of the individual elements of matrices are defined by (5).

$$R = \begin{bmatrix} 2 & 0 \\ 0 & 1.7 \end{bmatrix}, \quad Q = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 0.7 & 0 \\ 0 & 0 & 3.7 \end{bmatrix} \tag{5}$$

It was assumed that the control signal cannot exceed permissible values. In case of the azipod propellers revolutions constraints are actual physical set points limitations of the ship actuators. There is a possibility to change set points in range from 0 to 10. Declaring limits for thruster deflection angles, it was assumed that they cannot exceed ±10°, so as not to go beyond linear range, which is located nearby the operating point. The constraints vector is given by the equation (6). Output signals are not constrained.

$$\begin{bmatrix} 0 \\ -10 \end{bmatrix} \le \begin{bmatrix} n \\ \delta \end{bmatrix} \le \begin{bmatrix} 10 \\ 10 \end{bmatrix} \tag{6}$$

Manipulated speed values and control signals computed without taking into account the effect of wind disturbances occurrence on the ship movement are presented in figure 4. The smallest error occurs in longitudinal speed response (Fig. 4). Transversal and rotational speeds are regulated much slower. It is associated with the selected weights defined by (5). Nevertheless, the steady state error is absent which indicates a good quality of the regulation and opportunity of its application to a real object.

Control signals defined as azipods' set points *n* and angles of rotation δ (Fig. 4) are continuous and are in the range given by the equation (6). The absence of step changes in control signal is a desirable feature when controlling real objects and it has a significant influence on the occurrence of actuators failures.

In figure 5 are presented regulated values – individual speeds and control signals in presence of wind disturbance. Time runs of the wind disturb-

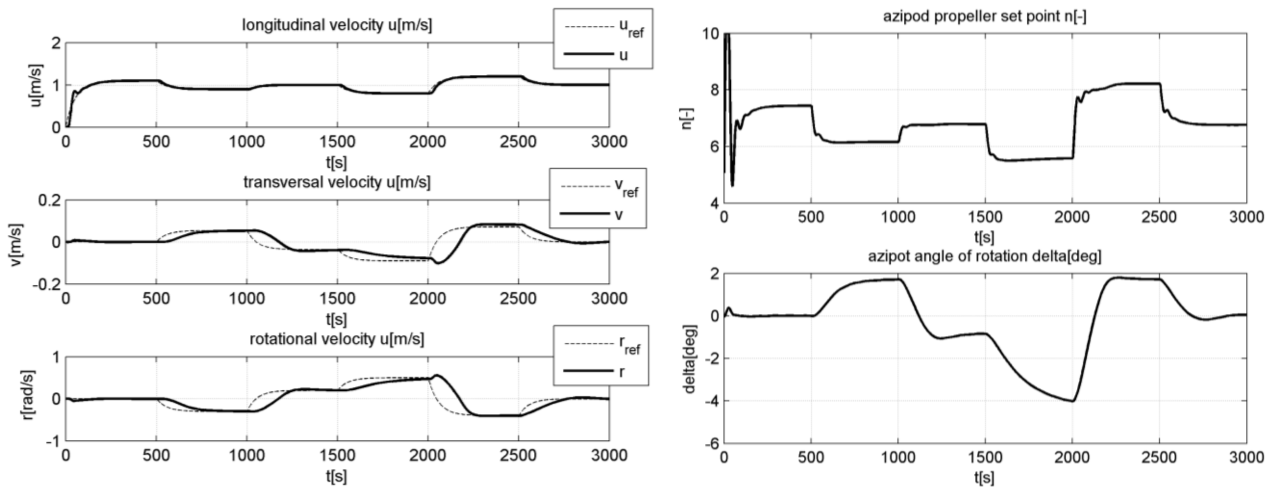

Fig. 4. MPC performance (left); control signals values – azipod set points (*n*) and rotation angles (δ) (right)

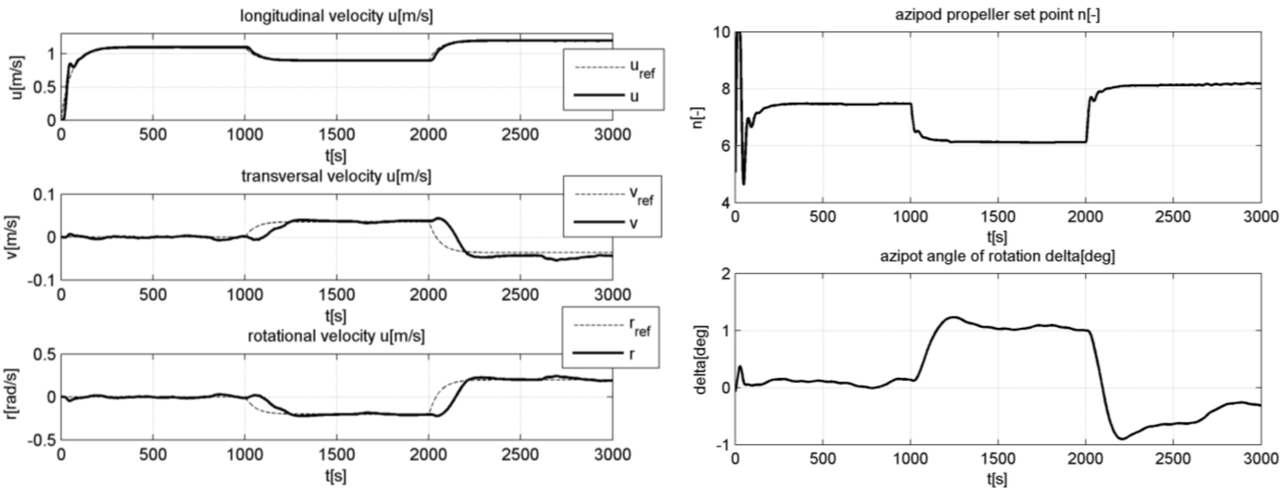

Fig. 5. MPC performance (left); control signals values – azipod set points (*n*) and rotation angles (δ) (right) in the presence of wind disturbances

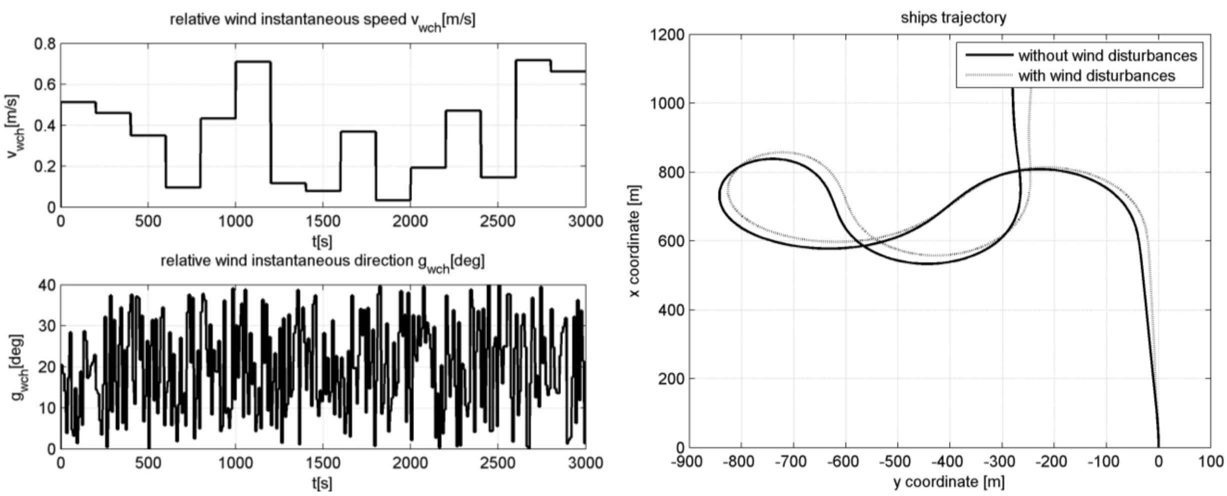

Fig. 6. Apparent wind velocity and direction runs (left); Comparison of the ship trajectory with and without wind disturbances (right)

ances are shown in figure 6. This additive disturbance was simulated as a relative wind whose speed oscillated between 0 and 1 m/s and direction was within the range of 0° and 40°. It means that during simulations wind was blowing from the starboard side bow of the ship. It is clearly seen, that the occurrence of the disturbance in case of frequent changes of reference set point has insignificant influence on the control quality.

While analyzing situation where reference set point changes every 1000 seconds (Fig. 5) in the presence of wind disturbances, there can be observed a lack of deviation in case of the longitudinal velocity and appearance of small oscillations of the transversal and rotational velocities. These oscillations do not exceed a few percent of the set point value. Their appearance is related to the ships dynamics. Changes in lateral and angular speed of the vessel under influence of the wind disturbances are much larger than the longitudinal velocity changes. Therefore, the propeller revolutions defined by a set point values n are similar when wind disturbances are present and without them. However, there is seen change in the angle of the thrusters' rotation δ (Fig. 5) which is slightly oscillating to allow reference value tracking. There are hesitations in the signal values in steady state. It is associated with not full compensation of impact of disturbances on the output values – accurately r and v velocities.

A comparison of vessels' trajectories, in the presence of additive disturbances and their absence (Fig. 6), implies the following conclusion. Ships are moving in a similar manner and wind performance is seen as a displacement in position along the vessel's transversal axis. This offset does not exceed a distance equal to the length of ship.

Simulation studies were also performed with the alternating sinusoidal reference signal for the longitudinal velocity. Based on these simulations results, it was found that it is possible to design such a predictive control system which will provide offset-free reference signal tracking. There is one disadvantage of this system. Namely in presence of

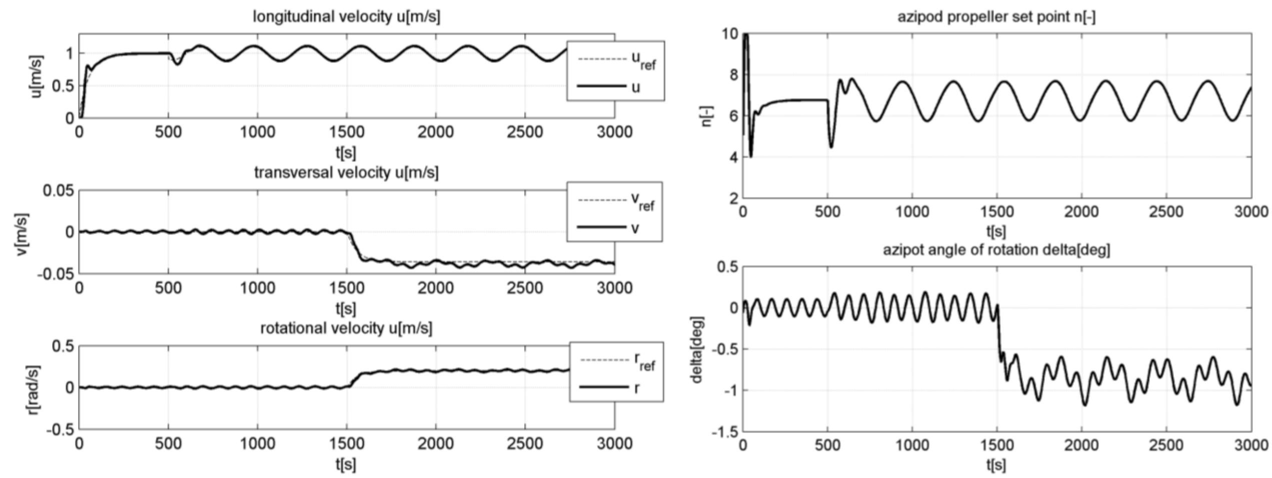

Fig. 7. MPC performance (left); control signals values – azipod set points (n) and rotation angles (δ) (right)

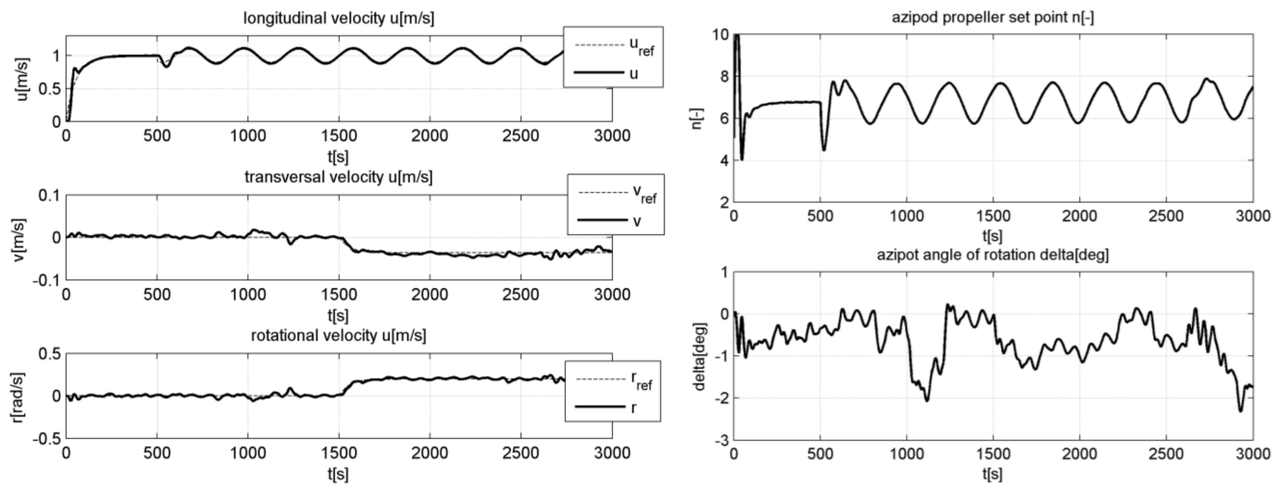

Fig. 8. MPC performance (left); control signals values – azipod set points (n) and rotation angles (δ) (right) in the presence of wind disturbances

external disturbances there occur fluctuations in the thrusters rotation angle control signal δ (Fig. 7). They translate into the presence of the oscillations in the transverse and rotational velocities (Fig. 7). This is a result of compensation of transverse force and torque generated by the change in thrusters revolutions.

The other one simulation carried out for the same sinusoidal reference signal for the longitudinal speed and constant values of transverse and rotational velocities, but in the presence of wind disturbances. In the above mentioned experiment, it was assumed that the relative wind speed fluctuates between 0 and 2 m/s and its direction oscillates between 220° and 260°. So, the control system deals with the wind blowing from the port side stern quarter. There is no steady state error in the longitudinal velocity. Whereas there are noticeable oscillations in the outputs of the lateral and angular velocities (Fig. 8). There are no significant differences in control signal of the propellers set points shown in figures 7 and 8. There is shown that increase of wind speed caused the occurrence of rapid changes in thrusters' rotation angles. The presence of the "jerks" in control signal indicates that the whole control system is not able to minimize errors in output signals v and r. This is related to the object dynamics and therefore there is no possibility to compensate for the rapidly varying wind disturbances with a wide span of amplitude and direction (Fig. 9).

Ship's trajectory in presence of wind disturbances and without them, indicates that ship in both the cases moves in similar way. Ship in presence of wind disturbances starts to alter the course earlier. It is directly connected with the angular velocity change which is the most subjected to the wind disturbances, when taking into account all mentioned velocities.

Summary

Predictive control systems can be successfully used not only in the petrochemical industry, but also to control the speed of ships in multidimensional systems. Presented in the literature concepts are mostly connected with the trajectory tracking problems. The conception of the three vessel's velocities maintaining has not been discussed yet.

Simulation results show that it is possible to use a linearized mathematical model of the ship, with its all limitations during the MPC controller synthesis. This approach guarantees a big simplification of the controller structure which allows for the computations fastening in relationship to the nonlinear multidimensional controllers proposed in the literature. Carried out analyzes show that the designed control system can be used in real-time and predicted output and control signals values can be determined on-line.

Big advantage of the synthesized Model Predictive Controller is lack of necessity to use a thrust allocation system when working with a real ship. The computed control signals are the set points of the ship's actuator, not the thrust values, as in conventional PID autopilot systems. This approach simplifies whole automatic control system, but a little complicates the controller structure.

Results of the carried out research show, that ship's motion Model Predictive Controller is working correctly even in the presence of the most common, in real sailing conditions, disturbances. System is resistant to the wind interference and there is no need to use feed forward controller which is necessary for the conventional PID ship's

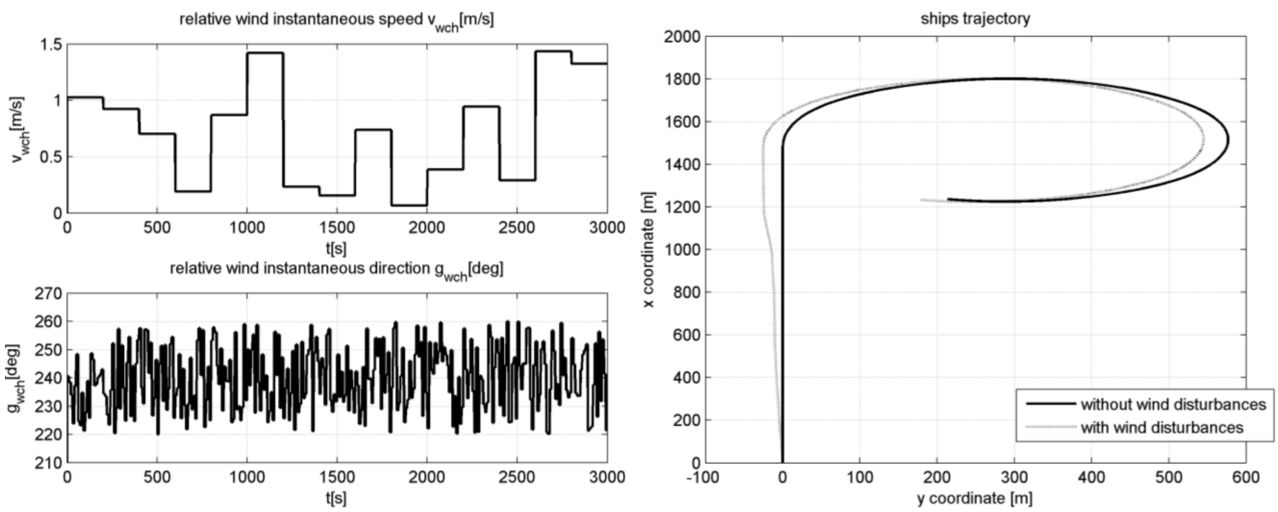

Fig. 9. Apparent wind velocity and direction runs (left); Comparison of the ship trajectory with and without wind disturbances (right)

motion controller, when dealing with wind disturbances.

The conducted simulation studies confirm the possibility of using the synthesized MPC system to the floating training ship model Dorchester Lady. The system allows for a very good tracking of the longitudinal speed reference set point and for a sufficient control of the pair of transversal and rotational velocities.

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