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Input data selection for identification of the incremental ship's model

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Key words: model identification, mathematical linear model, model for Model Predictive Control (MPC), selection procedure, data, parameters

Abstract

The procedure of Linear Incremental Model (LIM) identification requires input and output signal deviations as opposed to their actual values. When considering a vessel as a plant, the sequence of input signals determines the traceability of the estimated LIM. The manual input signals selection procedure is a demanding and time consuming empirical procedure. In order to increase the speed of object identification and to eliminate input-output signal sequences which give unreliable data, an incremental linear model identification algorithm was developed and is presented. Moreover, the method of parameter selection for input signal pseudo-random sequences is described in this paper. Emphasis is placed on the practical aspect of astatic objects – ship's LIM creation and input-output signal deviations selection method.

Introduction

Model Predictive Control (MPC) is a control strategy, which requires an adequate mathematical model for proper operation. This means that control signal values are computed on the basis of the previously designed model, whose structure should be adequate with respect to the controller's operational goal. This model should be as simple as possible (Camacho & Bordons, 1999, pp. 11–13) to guarantee fast computations, and therefore modelling is intimately associated with the MPC. Generally, linear state-space or transfer function models are incorporated into the controller's structure.

This paper focuses on linear incremental model (LIM) identification for future model predictive controller design. Data preparation for incremental model identification is more complicated than for an ordinary linear model. It is connected with the need to use signal deviations with respect to the operating points instead of signal values in the operating points during the identification procedure, so the incremental mathematical models are not very popular. Procedures for the linear system's LIM identification and usage are described in (Jayawardhana et al., 2007; Rajasekar & Sundaram, 2012). A model identification procedure often is based on the data sets, which were obtained during real experiments or simulations (Gelu & Toma-Leonida, 2013; Theisen et al., 2015). Moving objects like ships (Gierusz, 2016), aircraft (Armanini et al., 2016) and cars are modelled and identified on the basis of big data sets obtained during real experiments, and linearized for future control systems. The collection of data sets, containing high quality input-output signals which will give favorable results in the object's identification procedure, is a time consuming iterative process. When taking into account LIM, where output signal deviations are dependent on the input signal deviations and past input signal values, the procedure of data set composition becomes more complicated. In this work, input data selection and output data verification for the ship's incremental linear model is presented. This procedure can be adapted for other astatic objects such as planes, cars and wheeled robots.

In this paper are described the conditions under which identification of the LIM is possible, operating point selection, input signal period selection and its influence on the quality of the identification process. The influence of the input signal's deviation on the quality of obtained data was also taken into account. The research undertaken shows that it is possible to find rules for input signal for identification process selection, which give better results in a shorter time than empirical data selection. The identification process was performed with the use of the Matlab System Identification Toolbox. Simulation results were obtained using Matlab Simulink software.

Incremental Mathematical Model of Ship Dynamics

Developing a model of a system must be related to the application it is going to be used for (Ljung, 2016). The incremental linear ship's model is designed for the future Model Predictive Control (MPC) for a service ship (SS) during replenishment while underway. The identified model is the LIM of the real floating Liquid Natural Gas (LNG) Carrier 'Dorchester Lady', built to 1:24 scale. It is owned by the Foundation for Safety of Navigation and Environment Protection. It is equipped with two rotatable azipods on the stern, bow tunnel and rotatable thrusters. A ship is a highly nonlinear object, which may be linearized around the chosen operating point. A linear model does not require such large computing power as nonlinear one during MPC control signals computation, and it also maps input-output dependences in a relevant way. Therefore, the MPC controller incremental, state-space model (1), (2) was chosen.

$$\dot{x}(t) = A \cdot x(t) + B \cdot \Delta u(t) \tag{1}$$

$$\Delta y(t) = C \cdot x(t) \tag{2}$$

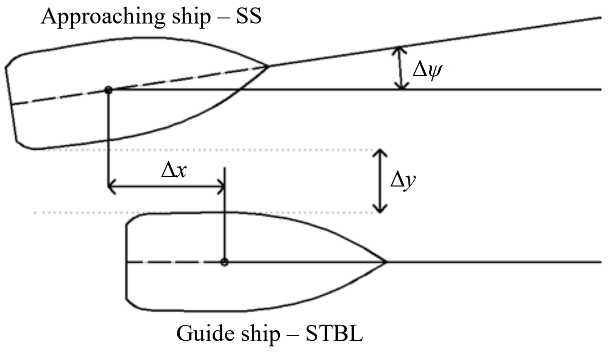

Figure 1. Ships' configuration during replenishment while underway (Gierusz & Miller, 2016)

where:

$x(t)$ – state space vector;

A, B, C – estimated dynamics, input, output (sensor) matrices;

$\Delta u(t)$ – input signal deviations vector (which consists of azipods revolution deviation, Δn, and angle of rotation deviation, $\Delta\delta$);

$\Delta y(t)$ – output signal deviations vector (which consists of longitudinal shift, Δx_p, transversal shift, Δy_p, and course deviation, $\Delta\psi_p$), as presented in Figure 1.

Linear IM Identification Procedure

Dorchester Lady is a real floating training ship, which is a highly nonlinear Multiple Input, Multiple Output (MIMO) plant. Its input and output signals are shown in Figure 2. The input signals vector $[n\ \delta]$ consists of thruster revolutions (n) and thruster angle of rotation (δ). The thrust allocation system computes forces and moments derived by the ship propelling and steering plants ($[X_i\ Y_i\ N_i]$). Output signals are: position (x, y), heading (ψ), longitudinal speed (u), transversal speed (v) and rotational speed (r).

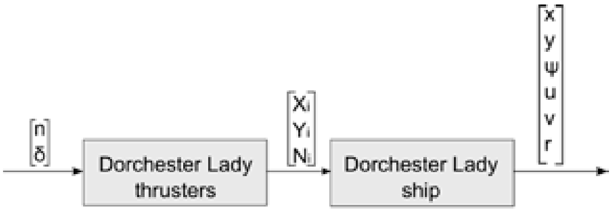

Figure 2. Input and output signals of the LNG carrier model

The linear incremental state-space model is designed to predict plant outputs and designate optimal values of the MPC control signals. Its identification requires estimation of the particular elements of the matrices A, B and C. The identification procedure was carried out with the use of Matlab System Identification Toolbox. This software enables space-state, transfer function and polynomial black-box model parameters estimation. In order to obtain the best possible model in the shortest time, the identification algorithm presented in Figure 3 was developed.

The LIM identification procedure using Matlab System Identification Toolbox is an incremental procedure. It was carried out 'experimentally' according to (Gierusz, 2004). First of all there is a need to choose which type of model is required. For the future MPC control system, the black-box state space model was chosen. This will be the simplest model and will allow for the fast computation of output signals. The LNG Carrier 'Dorchester Lady' is a MIMO plant, so its LIM also has to be a MIMO one. Matlab System Identification Toolbox allows for MIMO black-box model identification (Ljung, 2016); there are two possible ways to do this:

- directly identify the MIMO object on the basis of all measured outputs and inputs;
- merge SIMO (Single Input Multiple Output) models obtained for each input signal.

Modelling multiple outputs as a combination of single-input models gives better control of the identified channel behavior. It also enables faster proper input signals sequence finding, because the user has to control only one input when analyzing if the shift (Δx, Δy) and heading ($\Delta\psi$) deviations have accepted values. During the LIM identification procedure, which needs very precise and careful selection of input signals and output signals verification, the second described method was chosen.

According to Figure 2, the 'Dorchester Lady' linear model incorporates thruster and ship dynamics. It has two input signals, namely azipods set point (n) and azipods angle of rotation (δ), and six output signals. The identified LIM will be used for the future Underway Replenishment (UNREP) control system, so its structure needs adjustment for this purpose. It needs azipod set point (Δn) and angle of rotation ($\Delta\delta$) deviations as input signals, and output signal deviations of position (Δx, Δy) and heading ($\Delta\psi$) deviations. Input signal deviations are counted as a difference between set point $n = 7$ and angle of rotation $\delta = 0°$, allowing for the straight motion at half ahead speed ($u = 1.1$ m/s for the model ship) and current set point. Output signal deviations are the differences between the reference position, where the ship would be at the specific time point if it proceeded with the half ahead speed from its current position. Course deviation is counted in the same way as position deviation.

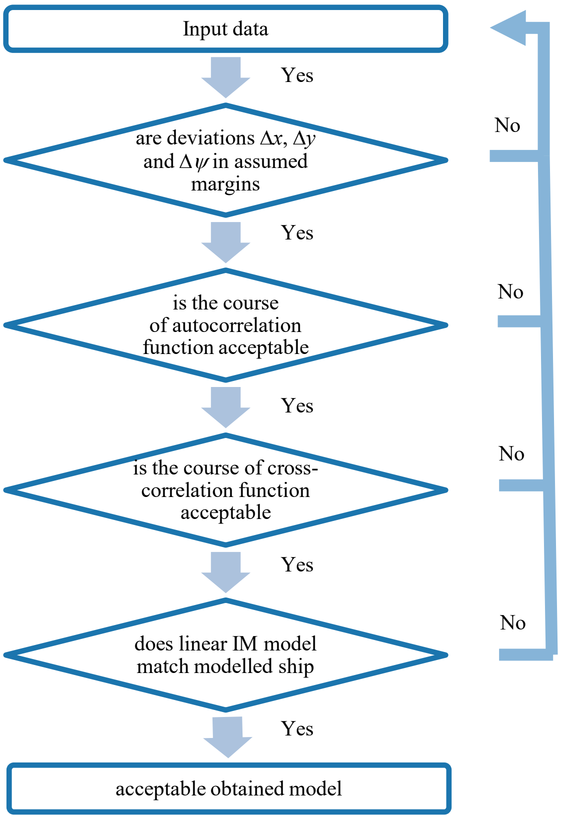

Figure 3. Incremental linear model identification algorithm

The LIM model was estimated based on the simulations of the nonlinear model. This method is more complicated than data acquisition on the real floating ship during sea trials, because it requires the creation of a nonlinear model, but it allows the analysis of wide range of input data sequences and the selection of the best quality ones for model identification. This is very important when estimating the LIM model, where input data period and sequence have a big influence on the quality of the output data. Figure 4 shows the Simulink scheme which was used during input-output data acquisition. The 'Dorchester Lady' block is the non-linear multidimensional ship's

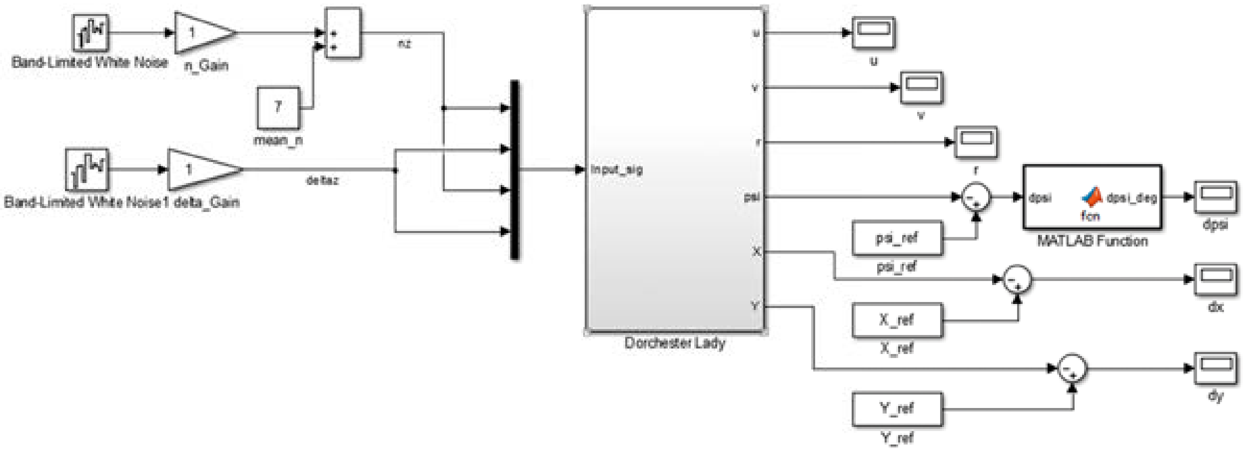

Figure 4. Matlab Simulink scheme for input-output data acquisition

model (Gierusz, 2016). Input signals were simulated by the 'Band-Limited White Noise' blocks that are normally distributed random numbers. The starting seed of the random number generator and the sample time are parameters defined by the user. The label 'nz' refers to the azipod set points and 'deltaz' are azipod angles of rotation. Their values are the same for both thrusters, because it was assumed that they will work in a coupled mode in the future control system. The blocks called 'psi_ref', 'X_ref' and 'Y_ref' are reference data used for the output signal deviations count. All output signals are shown on the scopes. During input-output data sets simulations, only those which fulfilled the first algorithm condition (Figure 3) were taken into account during the identification procedure.

The Linear IM of the LNG Carrier 'Dorchester Lady' was estimated in two separate channels, which are presented in Figure 5. In the first part of the data acquisition process, the azipods were in the straight position ($\Delta\delta = 0°$), and their set-point deviations were variable (red line in Figure 5). The second part of the data acquisition process involved constant azipod set-points ($\Delta n = 7$) and variable angle of rotation deviations (blue line in Figure 5).

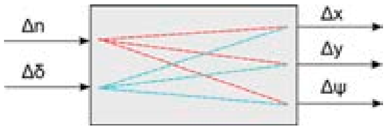

Figure 5. Linear IM identification channels

This input signals separation allowed for better output signals monitoring and disqualification of the input-output data which did not fulfil the conditions described in the next section.

Input Data Preparation

The input data sequence has a big influence on the quality of the identification process. There is a need to find signals which will allow for system dynamics mapping while preserving input/output couplings between identified channels. Therefore, special attention should be paid to the input sequence and its sampling time. This means that the period of the random signal should match plant dynamics and not be shorter than the plant's delay or much longer than its time constant.

Analysis of the Acceptable Input Signal Parameters for the LIM Identification Process

Assumptions for channel $\Delta n \rightarrow [\Delta x, \Delta y, \Delta\psi]$ identification:

- simulated and reference trajectories should not differ significantly, and Δx had to oscillate around a mean value 0 with a magnitude not bigger than 7 m or smaller than 0.5 m;
- Δy and $\Delta\psi$ also had to oscillate around 0, and their magnitude had to not to exceed 0.1 m and 0.1°, respectively;
- output signal deviations in acceptable trials were not allowed to change monotonically; their character had to be oscillatory.

At first, the LNG Carrier 'Dorchester Lady' dynamics and output signal deviations were analyzed as the response. In order to check how fast the ship reacts on the azipod set-point change, longitudinal shift deviation derivative was counted (Figure 6), because speed change has the greatest impact on this value. This changes fast during the 100 s after azipod set-points change and becomes constant after 200 s. The time delay for the 'Dorchester Lady' is about 10 s.

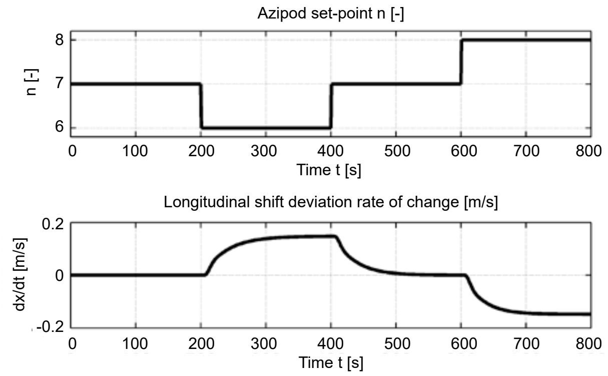

Figure 6. Longitudinal shift deviation rate of change with respect to azipod set-point

Figure 7 shows that long periods of the azipod set-points lead to large values of the longitudinal deviation (Δx), which exceed design criteria. Even in these conditions, transversal shift (Δy) and heading ($\Delta\psi$) deviations are smaller than the values declared in the assumptions. Azipod set-points should oscillate between 6 and 8, which gives speeds between 'slow ahead' and 'full ahead'. Simulations have proved that preserving the value of Δx in the predefined limits requires a change of azipod set-points from $n = 6$ to $n = 8$ after 68 seconds of motion, and after the next 92 seconds of motion the observed value crosses the limit, as shown in Figure 8.

Analysis of the simulation results showed that the azipod set-points change period should be not smaller than 10 seconds due to the plant delay, and should not exceed 68 seconds because of the Δx signal's

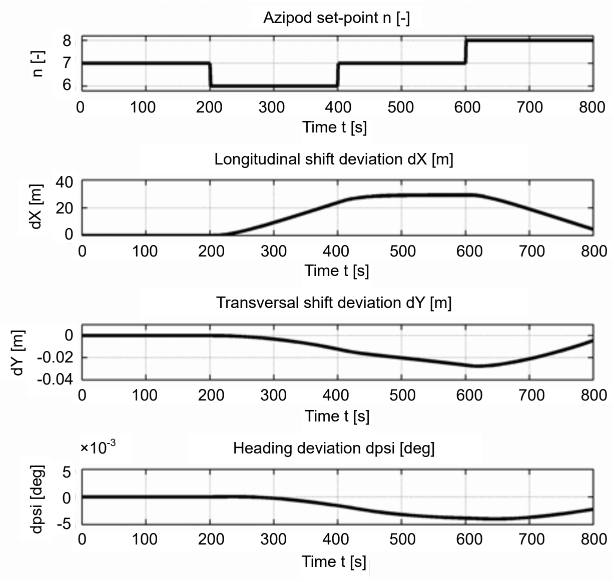

Figure 7. Longitudinal, transversal and heading deviations according to azipod set-points change

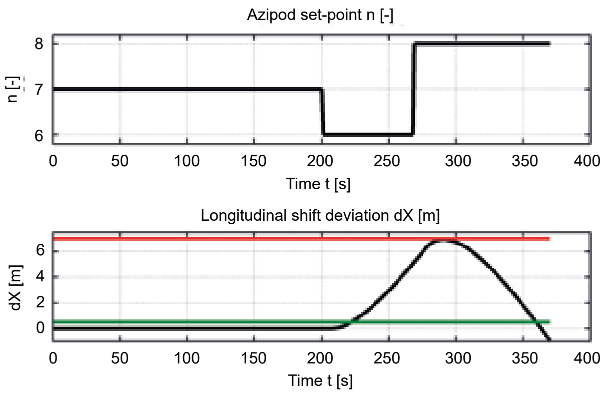

Figure 8. Longitudinal shift deviation according to azipod set-points change

value limitation, when taking into account an input signal standard deviation equal to 1.

Assumptions for channel $\Delta\delta \rightarrow [\Delta x, \Delta y, \Delta\psi]$ identification:

- simulated trajectory should oscillate around reference trajectory and training ship was not allowed to circulate during trial;
- Δx was able to change monotonically, but its magnitude was not allowed to exceed 1.5 m;
- Δy and $\Delta\delta$ also had to oscillate around 0 and their magnitude was not to exceed 9 m and 7°, or be smaller than 0.5 m and 0.5°, respectively.

As in the case of the first channel, the 'Dorchester Lady' dynamics and output signal deviations were analyzed as the response to the change in the azipod angles of rotation. In order to check how fast the ship reacts to the change of the azipod angle of rotation, a heading deviation derivative was measured (Figure 9), because this changes in the fastest way when taking into account all described above output signals.

The heading deviation derivative changes fast during the first 50 seconds after the angle of rotation change, then it becomes almost constant. The time delay does not exceed a second.

Figure 10 shows that such long periods of constant values of azipod angle of rotation lead to constantly increasing values of the longitudinal (Δx) and transversal (Δy) shift deviation. So this output signal does not fulfil the input signal selection criteria. Also the heading deviation does not oscillate around 0°. In Figure 11, it is shown that acceleration of the changes in the angle of rotation leads to minimization of the heading deviation magnitude. When taking into account the standard deviation of the angle of rotation equal to 5°, the input signal should change from 5° to –5° after 118 seconds and should not last more than 67 seconds.

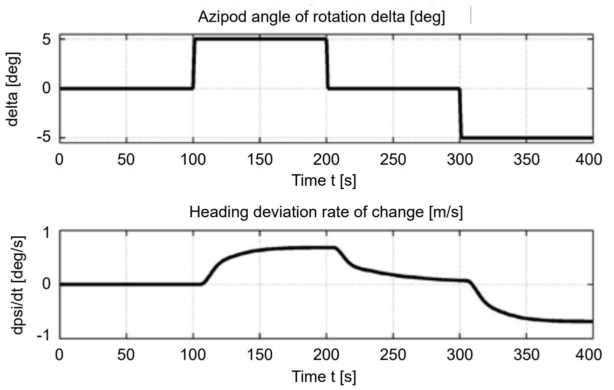

Figure 9. Heading deviation rate of change with respect to azipod angle of rotation

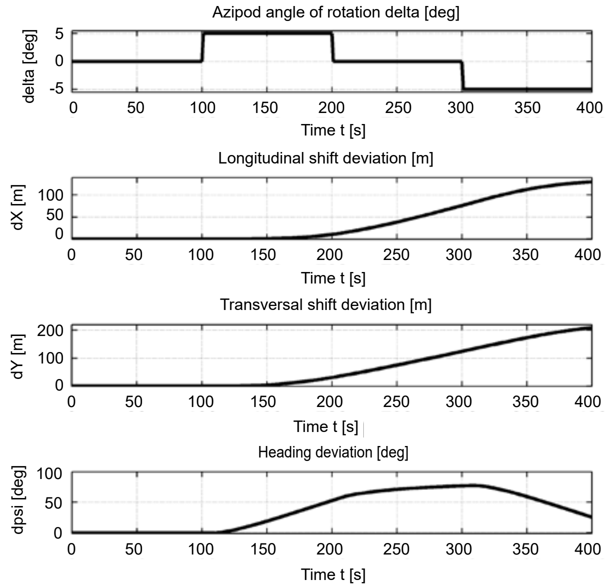

Figure 10. Longitudinal, transversal and heading deviations according to azipod angle of rotation change

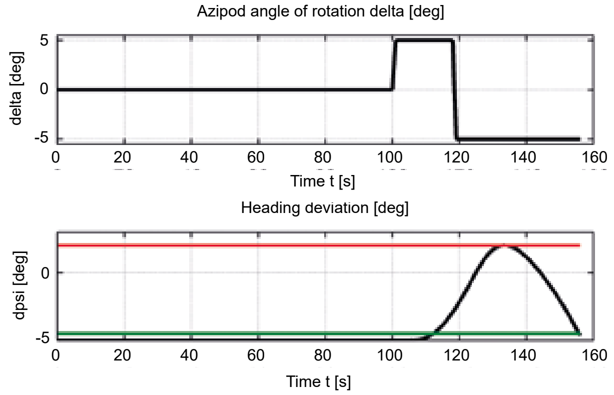

Figure 11. Heading deviation with respect to azipod angle of rotation

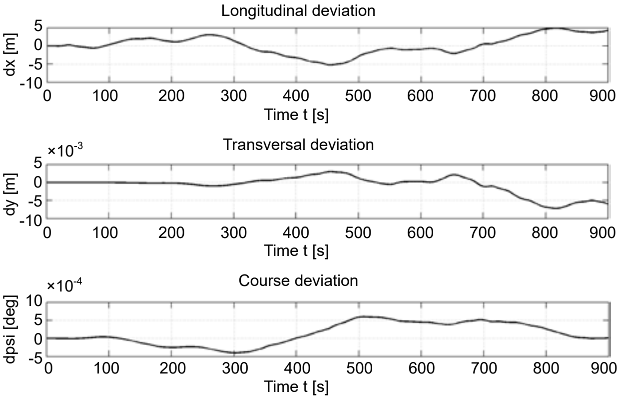

Figure 14. Exemplary acceptable output signal deviations for variable Δ*n* and constant Δ*δ* = 0

Examples of the Acceptable and Unacceptable Input-Output Signal Sets for the LIM Identification

Exemplary input signals, acceptable ship's trajectory and output signal deviations for variable Δ*n* and constant Δ*δ* = 0 are presented in Figures 12, 13 and 14, respectively. In all figures, *δ* is described as 'delta' and Δ as 'd'.

In Figure 13, the trajectory and reference trajectory coincide, so they are presented as a single line. When exemplary input signals (Figure 12) are applied to the LIM, it does not change heading, but it influences only the longitudinal speed. So the model moves with a different speed, but on the same trajectory as the ship when $n_{\mathrm{ref}} = 7$ and $\delta_{\mathrm{ref}} = 0$.

Exemplary acceptable ship's trajectory and output signal deviations for variable Δ*δ* and constant Δ*n* = 0 are presented in Figures 15, 16 and 17.

Furthermore, an exemplary unacceptable input signals sequence, ship's trajectory and output signal deviations for variable Δ*δ* and constant Δ*n* = 0 are presented in Figures 18, 19 and 20. In these figures it is shown that the training ship's simulated trajectory

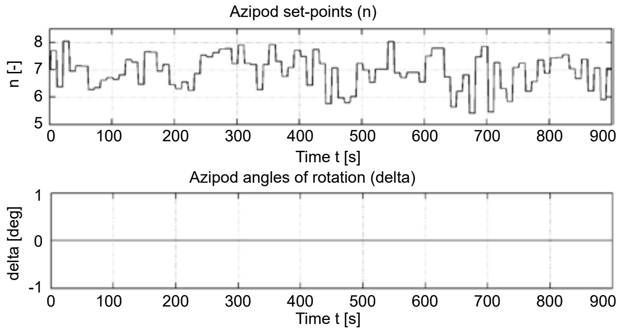

Figure 12. Exemplary acceptable input signals for model identification

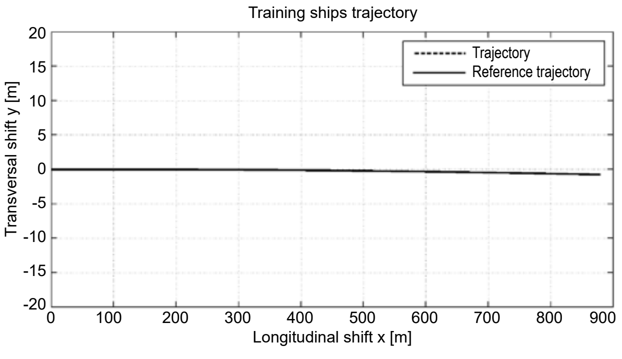

Figure 13. Exemplary acceptable ship's trajectory for variable Δ*n* and constant Δ*δ* = 0

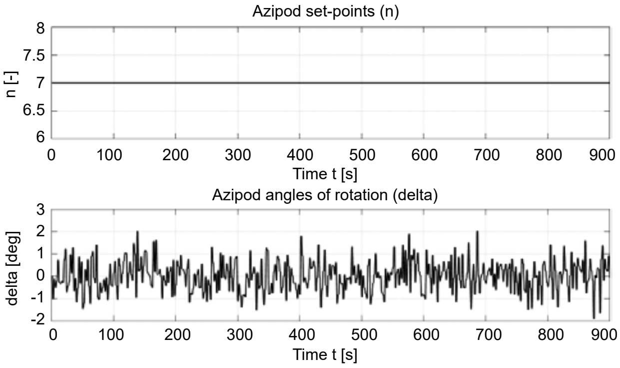

Figure 15. Exemplary acceptable input signals for model identification

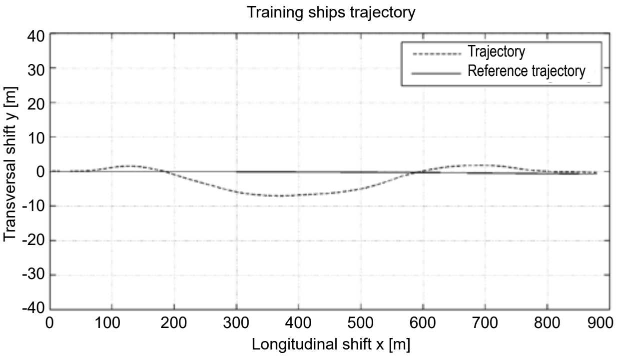

Figure 16. Exemplary acceptable ship's trajectory for variable Δ*δ* and constant Δ*n* = 0

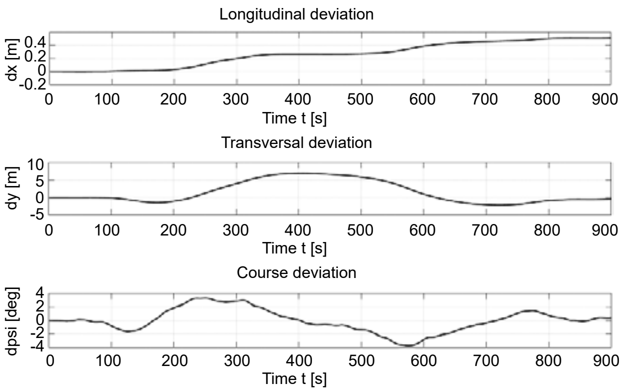

Figure 17. Exemplary acceptable output signal deviations for variable $\Delta\delta$ and constant $\Delta n = 0$

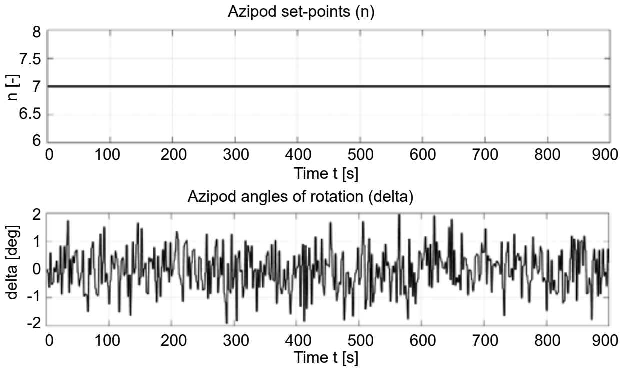

Figure 18. Exemplary unacceptable input signals for model identification

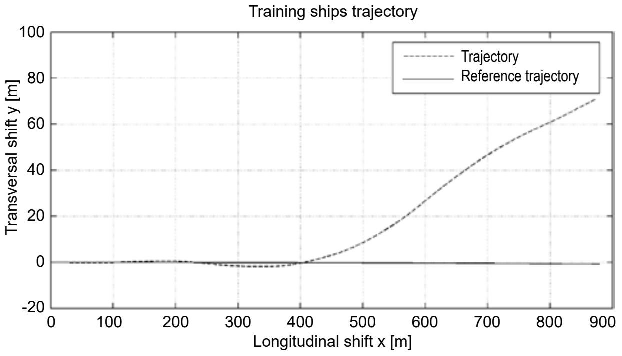

Figure 19. Exemplary unacceptable ship's trajectory for variable $\Delta\delta$ and constant $\Delta n = 0$

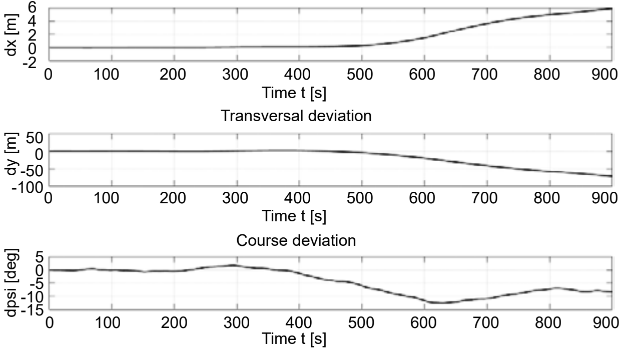

Figure 20. Exemplary unacceptable output signal deviations for variable $\Delta\delta$ and constant $\Delta n = 0$

recedes in a constant fashion. Neither longitudinal nor transversal deviations fulfill assumptions and they monotonically increase to 6 m and decrease to –60 m, respectively. Trials such as these presented in Figures 19 and 20 were rejected, and did not take part in the incremental linear model identification procedure.

The finally chosen identification signal values are presented in Table 1. Due to the expected future use of the identified model, the input signals had to change with different periods. The azipod angles of rotation $\Delta\delta$ had to change about 10 times faster than the azipod set-points to avoid ship circulation.

Table 1. Acceptable values of signal standard deviation and signal change period

Input signal	Reference value	Unit	Standard deviation	Signal change period [s]
Δn	7	[–]	0.6; 0.8; 1	10; 15; 20; 30
$\Delta\delta$	0	[deg]	1.5; 2; 5	1; 2; 5

An identified channel has to fulfill certain conditions. In order to obtain the LIM model, which in simulations will give results approximate to the plant output signals near the set point, input signal deviations should be chosen carefully. Their range of values should be chosen on the basis of the particular plant. The only way to check if the input signal sequence is suitable is to look at the object outputs after simulation. Therefore, the output signal deviations and ship's trajectory were analyzed after every trial. For each channel certain criteria had to be fulfilled, according to the algorithm presented in Figure 3.

Conclusions

This paper has proposed an incremental linear model identification algorithm, which was developed on the basis of a real floating training ship – the LNG Carrier 'Dorchester Lady'. This procedure was created based on the simulations carried out with the use of Matlab Simulink and Matlab System Identification Toolbox by Mathworks. The proposed algorithm can also be customized for the modelling of other plants.

The presented method is proven for MIMO plants and it requires model division into SIMO channels. These are identified in the separate simulations (experiments) and after successful completion of the algorithm, a MIMO linear incremental model is produced by merging two or more SIMO models.

Moreover, in this paper is described a procedure which allows for a fast input signal change period and its standard deviation selection. It involves plant dynamics analysis based on its response to the input signal deviations for each channel. Knowledge of the plant dynamics and change in set-point allows for faster input signal deviation change periods and determination of standard deviations.

The proposed input-output data selection procedure is based on empirical rules and analysis of simulation results, and requires earlier recognition of the future model destination. Therefore this method is based on the expert's knowledge.

There are several limitations of the LIM identification process. The proposed method gives a linear model, which may be used only in special applications such as model predictive control. It is not suitable for simulation of objects, because the input/output signals are chosen deviations. This method is easy to use when someone has a nonlinear mathematical plant's model at their command. Conformity of this method to the modelling on the basis of a real object (ex. floating ship) and data acquisition according to the presented scheme will require a huge amount of experimentation. This is because the presented method is iterative and its results may be proved only after a particular step of the algorithm is finished.

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