Determining the Hydrodynamic Derivatives of a Basic Model of the REMUS AUV

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Introduction

With the term manoeuvring we mean: to conduct a planned and controlled motion of the ship i.e. a horizontal translation and change of heading of the ship. In physical terms manoeuvring is a planned and controlled translation and rotation of the ship as a result of all forces and moments acting on the vessel. For a free moving body, three translations and three rotations are possible. They have to satisfy, and can be calculated from, Newton's second law of motion. A manoeuvring model is thus a system of equations of motion and the manoeuvring behaviour of a ship can be simulated by (numerically) solving this system of equations. Applicability of the model and its degree of correspondence with reality are important considerations in model building and is reflected in the number of equations and the number of terms in an equation. Any term or combination of terms represents a certain physical force or moment that affects the motion of the ship. Each term also contains a coefficient (or proportion constant). The essential step in producing a manoeuvring model is estimating these coefficients. In principle there are three options (i) model tests, (ii) empirical formulas based on model tests, (iii) full-scale sea trials.

Initially, simple models were used, such as that of Nomoto. In 1971 the Royal Netherlands Naval College (RNLNC) started the development of a night vision simulator. This simulator has been in operation since about 1974 and remained in use until the early nineties. The applied manoeuvring model describes three degrees of freedom and for one of them the Nomoto equation was used. A more elaborate model is that of Inoue [1]. Also three degrees of freedom are described, the model contains approximately 23 terms including at least 23 coefficients to be determined. The terms used in the model are directed to their physical origins. This is certainly not the case with the Abkowitz model [2], a large number of coefficients have to be determined by the presence of a large number of terms resulting from a Taylor series expansion. Each term contributes to the forces or the moments acting on a ship but the physical meaning of an individual term is not always clear.

In the nineties the Delft University of Technology (TU Delft), faculty Maritime Technology (MT), department of hydromechanics, and the RNLNC, nautical sciences department, led by professor J.A Spaans, explored the possibility of determining the coefficients from full-scale sea trials [3]. As a starting point the model by Inoue was used. But, this model has some drawbacks if the values of the coefficients have to be calculated from full-scale sea trials [4].

Research question

The drawbacks have led to two research questions namely:

1. Is there a basic model that can simulate basic manoeuvres of 'normal' ships with 'sufficient accuracy' and which is valid and useful for a 'wide range' of speeds and rudder angles?

2. What is the optimal method to calculate the values of the coefficients of such a model, based on data derived from full-scale sea trials?

For surface ships both these research questions can be answered more or less in the affirmative.

Some time ago the navigation department of the NLDA was facing the question whether a mini-submarine, in this case of the type Autonomous Underwater Vehicle Remote Environmental Measurement Units (AUV REMUS), the same basic model can be used and whether in the same way the coefficients of the model can be estimated. The answer to these questions is given in this article.

Outline

This article does not discuss the mathematical and physical backgrounds that form the basis for composing a manoeuvring model. This can be found in literature [1-8]. In section two the basic manoeuvring model is described. Section three deals with the process to calculate the values of the coefficients of the model with data based on full-scale sea trials. Section four describes the AUV REMUS, and the process of identification and validation of the coefficients for the mathematical model of the REMUS. Section five ends with some conclusions.

The Manoeuvring Model

Conditions and restrictions of the model

The design of a basic manoeuvring model by which the coefficients are determined with the aid of full-scale trials is based on the following conditions:

- As few coefficients as possible, because on the sea the directions of motion can not be uncoupled from each other.
- No additional modification of the model for different types of prime movers, type of propeller etc.
- The model is suited only for basic manoeuvres, for some velocities and rudder angles, such as when the vessel is in transit mode.
- Wind forces and moments can be covered but are primarily considered as disturbances and ignored.

The model

After investigation, the following model is created:

$$\begin{aligned} \dot{u} &= c_{u1}rv + (c_{u2} + c_{u3}\,|u| + c_{u4}speed)(u - speed) \\ &\quad + c_{u5}(\delta^2 + \delta_d^2)(u \cdot speed)^{c_{u6}} \\ v &= c_{v1}r \\ \dot{r} &= c_{r1}(r^2)^{c_{r2}}\frac{1}{V_t^{c_{r3}}} + c_{r4}\delta(u \cdot speed)^{c_{r5}}, \end{aligned} \tag{1}$$

where:

u	longitudinal velocity [m/s]
v	lateral velocity [m/s]
r	rate of turn [rad/s]
V_t	total velocity $(u^2 + v^2)^{0.5}$ [m/s]
δ	rudder angle [rad]
δ_d	diving rudder angle [rad], towards the REMUS
speed	velocity of the vessel which corresponds to a certain telegraph position [m/s]

This model contains twelve coefficients to be determined. The input parameters are the rudder angle δ and speed. The variable *speed* is the final velocity of the ship that belongs to a position of the telegraph. To determine the coefficient with the aid of full-scale trials the variables u, $\dot{u}$, v, $\dot{v}$, r, $\dot{r}$, δ, δ_d and *speed* must be known.

The considerations which have led to this model, given the conditions, are the following:

X-equation

The first term represents the centrifugal force; this term also follows from the Euler equation. The resistance has the form of: $c_{u2}u + c_{u3}u\,|u|$. The propulsion is described as the difference between the set speed and actual longitudinal velocity u, adjusted by a coefficient C_{u4}. The advantage of the term (u-speed) is that in the end always a stationary speed is created equal to the set speed if v or r equals zero and δ and δ_d equal zero. The rudder term depends on the rudder position to the square and is supplemented by the current velocity u and the set speed.

Y-equation

According to Keizer, the transverse velocity v of the vessel can be described as a constant multiplied by the rate of turn of the ship. Extensions of the equation with terms in which appear the variables r and v are mostly ineffective, because the corresponding coefficients are not readily identifiable from full-scale trials. Furthermore, the transverse velocity is generally quite small.

N-equation

With c_{r2} equal to a half and c_{r3} and c_{r5} equal to zero, the equation of Nomoto remains. In the equation of Nomoto the coefficients are in fact not constant because the values of the coefficients remain dependent on the set speed and rudder angle. With the extra variables and coefficients this must be overcome.

In principle the model can be extended with other forces.

Calculating the values of the coefficients based on full-scale sea trials

With the vessel the next trials must be sailed: natural stop trials, gradual acceleration trials, turning circle trials and zigzag trials. During the trials the values of the exact time, position, heading, position of the telegraph and rudder angle have to be collected and saved on a computer. Then the data has to be edited.

First of all the velocities, accelerations, both body-bound, rate of turn and angular accelerations should be calculated. By twice differentiating the measured earth-bound positions and rotating them to the body-bound coordinate system these variables can be calculated. A data file is created with the following variables: Time [s], x [m], y [m], u [m/s], v [m/s], $\dot{u}$ [m/s^2], $\dot{v}$ [m/s^2], ψ [rad], r [rad/s], $\dot{r}$ [rad/s^2], δ [rad], δ_d [rad].

The coefficients now can be calculated with the aid of two mathematical methods. First with the least square method (LSM) and secondly by solving the system of differential equations (SDE) of Formula 1 in a certain way.

The least square method

If we look at a natural stopping manoeuvre, the trial is as follows: first of all the vessel is ordered to sail on a straight line with a steady speed and the rudder angle, transverse speed and acceleration, rate of turn and angular acceleration all equal zero. Secondly the vessel is ordered to reduce the number of revolutions of the propeller to zero with all the above named variables try to stay at zero. Finally the trial is finished if the velocity of the vessel is very low or the vessel is stopped. From the system of differential equations (Formula 1) only the following equation remains:

$$\dot{u} = c_{u2} + c_{u3}\,|u|$$

In matrix notation for time step i from 1 to k:

$$\begin{pmatrix} \dot{u}_1 \\ . \\ \dot{u}_i \\ . \\ \dot{u}_k \end{pmatrix} = \begin{pmatrix} u_1 & u_1 \cdot |u_1| \\ . & . \\ u_i & u_i \cdot |u_i| \\ . & . \\ u_k & u_k \cdot |u_k| \end{pmatrix} \cdot \begin{pmatrix} c_{u2} \\ c_{u3} \end{pmatrix} \Leftrightarrow B = A \cdot C$$

Values of c_{u2} and c_{u3} are found by $C = (A^T A)^{-1} A^T B$.

Solving the system of differential equations

The computer program MATLAB features a subroutine called *fminsearch*. Fminsearch is a multidimensional unconstrained nonlinear minimization routine. Given the coefficients in the system of differential equations an initial value, the system can be solved. The values of the solved variables can be compared with the same measured values of these variables from the full-scale trials. An error ϵ can be defined as a difference between measured values and solved values so fminsearch can minimize this error by varying the coefficients in the system of differential equations. If the error is minimised a set of coefficients is determined.

The initial values can be calculated with the least square method or by estimation of the value of the relevant coefficient in another way. To get reasonable results, the total error is built up out of an error in position, two errors in the velocities, an error in the rate of turn and an error in the heading of the vessel.

Determining the coefficients or the identification process

As stated, three kinds of manoeuvres are conducted, namely: natural stopping manoeuvres, to determine c_{u2} en c_{u3}; acceleration manoeuvres, to determine c_{u4} and turning circles manoeuvres, to determine the rest of the coefficients.

Four files are compiled. File A contains all the data belonging to the natural stopping manoeuvre, file B contains all the data of the acceleration manoeuvre, file C includes all the data of the turning circle manoeuvre and finally file D contains all the data of all the trials.

The process by which the coefficients are determined is a kind of iteration. In Table 1 the solution scheme can be seen.

Table 1: Solving scheme. To solve the coefficients 12 steps must be calculated. Bold face typed coefficients are endresults.

Step	Solving method, variable	File type	Initial values of coefficients	Final values of coefficients	Error based on
1	LSM, u	A		c_{u2}, c_{u3}	
2	SDE, u	A	step 1	$\mathbf{c_{u2}}$, $\mathbf{c_{u3}}$	$\epsilon_{pos} \cdot \epsilon_u$
3	SDE, u	B	0.0	c_{u4}	$\epsilon_{pos} \cdot \epsilon_u$
4	LSM	C		c_{u5}	
5	SDE, u	C	step 4 and 1.0	c_{u5}, c_{u6}	$\epsilon_{pos} \cdot \epsilon_u$
6	SDE, u	B	step 3	$\mathbf{c_{u4}}$	$\epsilon_{pos} \cdot \epsilon_u$
7	SDE, u	C	step 5	c_{u5}, c_{u6}	$\epsilon_{pos} \cdot \epsilon_u$
8	LSM, v	C		c_{v1}	
9	SDE, v	C	step 8	c_{v1}	$\epsilon_{pos} \cdot \epsilon_v$
10	LSM, r	C		c_{r1}, c_{r4}	
11	SDE, r	C	step 10, 0.5, 0.0, 0.0	c_{r1} t/m c_{r5}	$\epsilon_{pos} \cdot \epsilon_\psi \cdot \epsilon_r$
12	SDE, u, v, r	D	step 7, 9 and 11	$\mathbf{c_{u1}}$, $\mathbf{c_{u5}}$, $\mathbf{c_{u6}}$, $\mathbf{c_{v1}}$, $\mathbf{c_{r1}}$ **t/m** $\mathbf{c_{r5}}$	$\epsilon_{pos} \cdot \epsilon_u \cdot \epsilon_v$ $\epsilon_\psi \cdot \epsilon_r$

This process is more or less applied to a number of Royal Netherlands Navy ships (see Table 2).

Table 2: Ships of the Royal Netherlands Navy of which coefficients have been determined in the past.

Name	Period of measurement	Reference
Vlaardingen	June 1993	
Amsterdam	August 1996	
Zeefakkel	1990	[3]
	August 1997	
van Kinsbergen	August 2001	
Tydeman	July 2002	[9]
REMUS	2007, 2009	[10]

Some notes to the identification process

The calculation of the coefficients in steps is for a number of reasons. In the original approach to estimate the values of the coefficients [3], only the least squares method was used, this has three drawbacks.

First of all, the equations contain velocities and accelerations. They are calculated by applying a numerical differentiation formula to the measured positions and the headings of the vessel. This differentiation process creates inaccuracies which adversely affect the values of coefficients to be determined. Secondly the least squares method can result in the character and or the value of a coefficient in a term being physically incorrect. Finally the model contains coefficients which are included as a power. They are difficult to calculate with a LSM.

By systematically varying the coefficients and solving the system of differential equations the above disadvantages do not arise, because the error which is to be minimized is based on positions, heading etc, and these variables are hardly affected by mathematical operations. Secondly by solving the system the coefficients must have a value. This value can be manipulated in character and in the size of the value during the process. For instance c_{u2}, c_{u3}, c_{u4}, c_{u5}, c_{v1}, c_{r1} and c_{r4} are necessarily negative or c_{u1} has to lie between pre-calculated values. Finally coefficients included as a power are automatically optimized.

Yet this process of solving the system of differential equations also has some drawbacks. The fmin search routine in MATLAB is based on the so called Nelder-Meade simplex method for function minimization:

- As more coefficients are to be estimated and the initial values lie far away from the final values, the necessary computer time becomes more than proportionately longer. Hence the recommendation to start with the estimated initial values as a result of the LSM.
- It is unclear whether this minimization routine is able to find the absolute minimum, experience shows that there are reasons to believe that it can also lead to a local minimum. This can be concluded from the fact that different initial values cause different final values.

The AUV REMUS

The AUV REMUS is torpedo-shaped, and can be equipped with different sensors to conduct measurements of its surroundings. Modelling is a very useful tool to either simulate the behaviour of the vehicle, or to improve the performance of the steering algorithms. For instance, when based on an accurate model, the usages of the vehicle fins become much more efficient. The simulated behaviour of the vehicle can also be used to predict the vehicles attitude and position, either to check the positioning data for major errors, or to be used as a backup on the primary positioning system. In this latter case, a system could be developed, that calculates a future position estimate, based on the last known position and velocity, and on fin and thruster data. In a military context, this type of positioning system is very useful as a secondary system, because it does not depend on information from sources outside of the platform, such as satellites or beacons.

This study only looked at the manoeuvring behaviour of the REMUS in the **horizontal plane**. The behaviour in the vertical plane is treated in [11] and [12].

The REMUS vehicle

The Royal Netherlands Navy acquired the REMUS AUV for mine detection purposes. Autonomous means, in this context, that the vehicle is not connected to any object, or computer operator. It will carry out a preprogrammed mission, and then return to a rendezvous point. However, the REMUS is designed as an environmental sensing unit. This poses no problems however, because the REMUS can carry a variety of sensors. Its fuselage is made up from different compartments, each having its own functions. However, a couple of parts are essential for normal operation, and can not be altered. For instance, the battery compartment, and the tail are not to be altered. The tail contains, apart from the fins and the propeller, the computer hardware. The nose cone contains some navigational hardware. The other sensors can be altered to the user's preference. In the case of the Royal Netherlands Navy, an object detecting sonar can be installed. The added weight of the sensor modules are however limited. This is because the buoyancy must be positive. This will drive the vehicle to the surface when it is not propelled, for instance, in the case of a flat battery or when it is out of order for whatever reason. So, generally it can be said that the REMUS vehicle can serve many purposes as long as the sensors needed for the measurements fits the fuselage. For this research, no additional sensor will be used as the REMUS vehicle itself stores manoeuvring and position data.

To manoeuvre, the REMUS uses two sets of two fins and a single propeller. However, the command issued to these fins cannot be directly altered. Hydroid, the manufacturing company of the REMUS vehicle, equipped the REMUS with its own decision making program. The fin angles are determined based on vehicle attitude, altitude, depth and mission. The propeller RPM can be directly altered, and is set in a mission file. Basically, the only control possibilities of the REMUS vehicle are to write a mission file. In this mission file a propeller RPM can be set. The vehicle can keep a given depth, or a given altitude above the sea bed. The mission is described using waypoints. The vehicle will determine its position, either based on the given positions of one or more beacons (with a pre-defined position and frequency), or by taking a GPS position. In this latter case, the vehicle will have to come to the surface. Based on this position information, its goal position (the waypoint in the mission file), and its current heading, the vehicle will calculate the required course alteration. In other words, this results in one error in the attitude that is calculated. The other errors are determined in a similar way. For instance, pitch and depth are calculated by the difference between the actual depth and the set depth. The roll should be zero, as the vehicle should be upright. This results in a given error in attitude. From this, the setpoint for the fins is calculated.

It should be noted, that a set of fin angle is needed to neutralise the roll, induced by the reaction force resulting from the revolutions of the propeller.

Dimensions

For the description of the vehicle specifications, three sources have been used. First of all, the website of the manufacturing company, which gives some basic specifications on the vehicle. Although a citation, some of the data has been deleted (shipping details for instance). Secondly, previous research is used by Prestero [11], and finally, some missing specifications are measured, estimated or calculated based on the vehicle owned by the RNLN.

Full-scale sea trials

As stated, to determine the coefficients of the model, some trials have to be conducted. The experiments took place somewhere on the Amstelmeer, which is a lake in the North-West of the Netherlands, near a village called De Haukes. During the trials a major difficulty is posed by the fact that the rudder can not directly be altered. Basically, the vehicle will sail either from waypoint to waypoint, or on a given course. The rudder settings will be automatically adapted to follow either the given course or the course to the next waypoint. This fact made it very hard to conduct ‘zigzag trials’, because the turning points should be entered in advance as waypoints. They can not be based on turning speed, time or any other property. It has been chosen to omit this trial. This results in the fact, that turning the properties have to be fully derived from the turning circles.

The identification process

On the Amstelmeer some tracks are sailed and data is logged to a computer. For this study, fifteen pieces (experiments) are cut from these data. Four of them are natural stopping manoeuvres, five of them are acceleration manoeuvres and six of them are turning circle manoeuvres. The four files A to D are compiled.

Table 3 shows the whole identification process in a schematic way. Column one shows the number of successive steps. Column two gives the method used to determine the coefficients, LSM represents the least square method and SDE stands for solving differential equation. It also indicated which variables are solved. Column three is the type of file used to determine the coefficients. Column four shows the initial value of the coefficients and column five gives the final value of the coefficients. The last final values of the coefficients are shown in bold face letter type.

Results and analysis of the validation process

With the coefficients found, the fifteen trials can be simulated. Of three simulations, the results are shown. Figures 1 and 2 show the results of a natural stopping manoeuvre. In Figures 3 and 4 the results of an acceleration manoeuvre and in the Figures 5 and 6 the results of a turning circle manoeuvre can be seen.

The dotted green line represents the measured value of the trials; the solid blue line is the result of the simulation.

The X-equation

The natural stopping manoeuvre is used to determine the resistance of the vessel. Experience shows that in almost all cases good to excellent results are achieved. This is well illustrated in Figure 2, longitudinal velocity u

Table 3: The identification process.

Step	Process, variable	File type	Initial value	Final value
1	LSM 1, u	A		c_{u2} = -0.0517 c_{u3} = -0.0896
2	SDE 1, u	A	c_{u2} = -0.0517 c_{u3} = -0.0896	**c_{u2} = -0.0162** **c_{u3} = -0.1362**
3	SDE 2, u	B	c_{u4} = 0.0	c_{u4} = -0.0421
4	LSM 2, u	C		c_{u5} = 0.5399 c_{u6} = 1.0
5	SDE 3, u	C	c_{u5} = 0.5399 c_{u6} = 1.0	c_{u5} = -0.3620 c_{u6} = 1.1541
6	SDE 2, u	B	c_{u4} = -0.0421	**c_{u4} = -0.0391**
7	SDE 3, u	C	c_{u5} = -0.3620 c_{u6} = 1.1541	c_{u5} = -0.3619 c_{u6} = 1.1541
8	LSM 3, v	C		c_{v1} = -0.8766
9	SDE 4, v	C	c_{v1} = -0.8766	c_{v1} = -0.0759
10	LSM 4, r	C		c_{r1} = -0.5429 c_{r2} = 0.5 c_{r3} = 0.0 c_{r4} = -0.3094 c_{r5} = 0.0
11	SDE 5, r	C	c_{r1} = -0.5429 c_{r2} = 0.5 c_{r3} = 0.0 c_{r4} = -0.3094 c_{r5} = 0.0	c_{r1} = -176.8837 c_{r2} = 2.8177 c_{r3} = -2.8616 c_{r4} = -0.2983 c_{r5} = 2.0092
12	SDE 6, u, v, r	D	c_{u1} = 1.14 c_{u5} = -0.3619 c_{u6} = 1.1541 c_{v1} = -0.0759 c_{r1} = -176.8837 c_{r2} = 2.8177 c_{r3} = -2.8616 c_{r4} = -0.2983 c_{r5} = 2.0092	**c_{u1} = 0.7980** **c_{u5} = -0.6639** **c_{u6} = 0.8277** **c_{v1} = -0.0459** **c_{r1} = -7.3560** **c_{r2} = 0.7812** **c_{r3} = 0.8896** **c_{r4} = -2.1965** **c_{r5} = 0.5016**

against time. Because the propeller is not modelled separately, the effect of the propeller on the resistance is ‘embedded´ into the coefficients c_{u2} and c_{u3}.

The position accuracy is in general less. This has to do with the fact that with an ever lowering velocity, the disturbances have a greater influence on the path the vessel sails. These disturbances are corrected during the trial

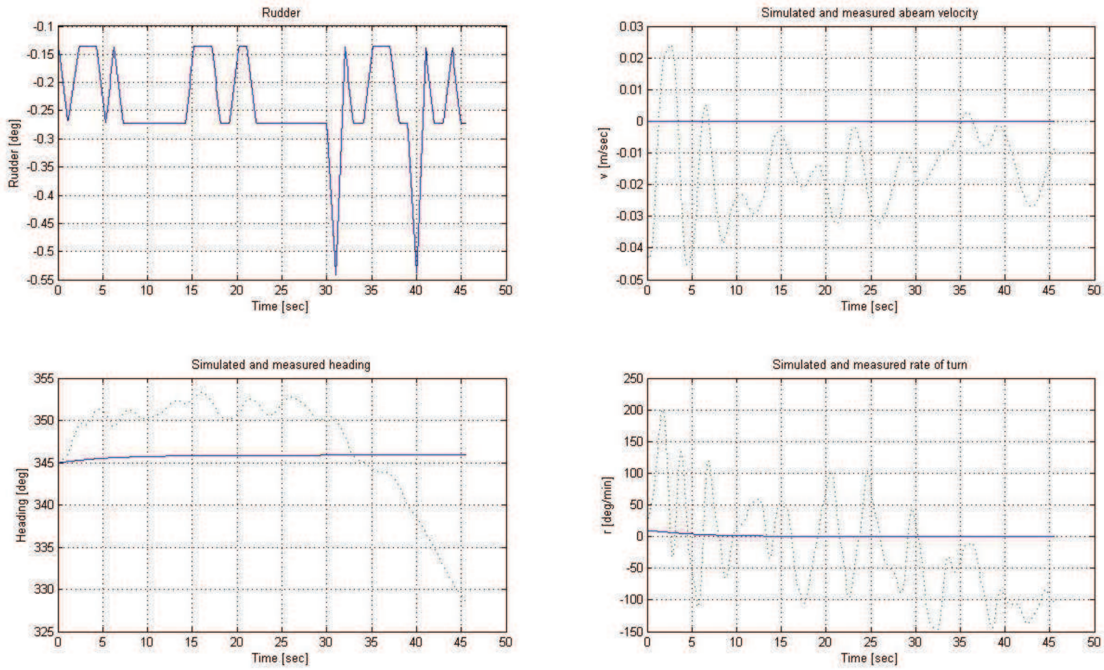

Figure 1: Results of natural stopping manoeuvre.

with the rudder, but these distortions are not included in the simulation model, while during the simulations the rudder signal of the trial is used as an input.

The acceleration manoeuvre is used to determine the thrust of the propeller. Usually a run is sailed in which a gradual acceleration is applied. For the REMUS this is not possible. The results of the acceleration trial are reasonable, see Figure 4. Again longitudinal velocity u against time is shown.

The position accuracy is very moderate. The reason is that it is extremely difficult to accelerate a vessel from zero speed without inducing a rate of turn. This has been difficult on a surface ship, let alone the REMUS. Secondary propeller effects for instance are not modelled. In addition, if the velocities of the REMUS equals zero the vessel comes up to the surface due to positive buoyancy.

Simulating a turning circle manoeuvre the accuracy of the positions will be especially important. We see in Figure 6 that the positions are well simulated. Due to added resistance from the fins the longitudinal velocity decreases during a turning circle manoeuvre. This is nicely simulated,

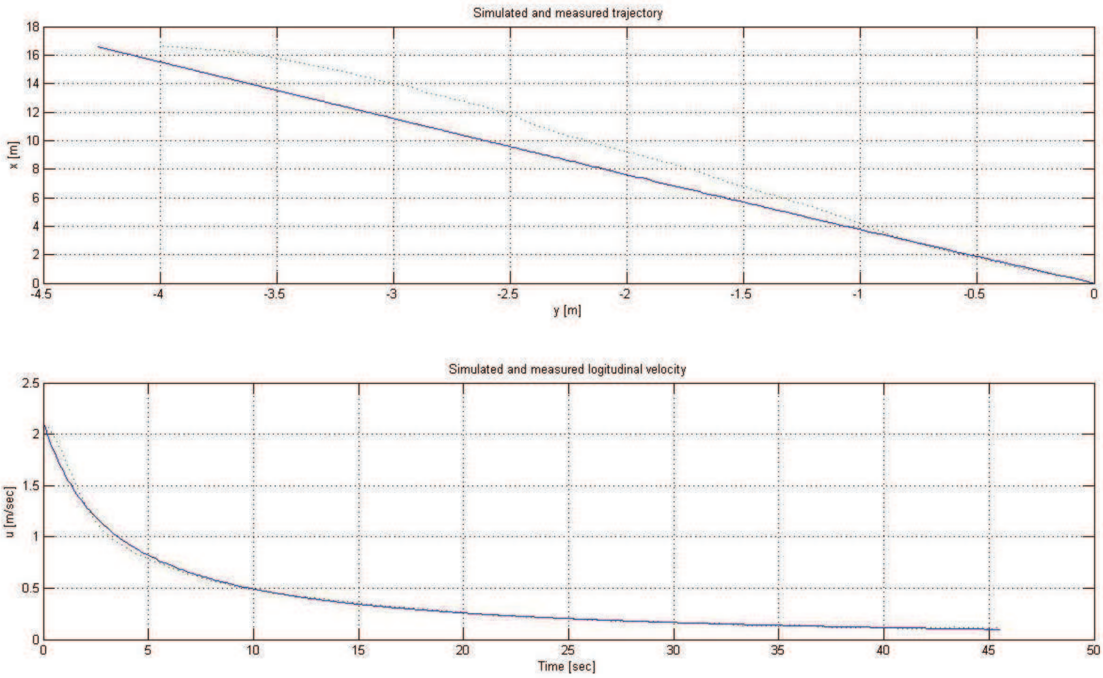

Figure 2: Results of natural stopping manoeuvre.

shown in the plot of the longitudinal velocity u against time.

The Y-equation

About the abeam velocity v we can be brief. In literature it can be found that the lateral velocity v can be written as a coefficient multiplied by the rate of turn of the ship. To describe this variable otherwise, a Nomoto expression can be used, but the Nomoto equation gives a number of additional coefficients to be determined.

The measured values of the abeam velocity v during the trials shows no correlation between a single parameter. For instance sailing a turning circle to starboard, an abeam velocity v to port is expected, none of the trials however shows this behaviour. This means that either the measurements of this variable during the trials is imprecise, or that the vessel did not get a clear transverse drift velocity v by sailing a turning circle. The latter seems unlikely. Because no correlation is found, c_{v1} is very small and as a consequence the values of the lateral velocity v lie around zero meters per second. See Figures 1, 3 and 5, v against time.

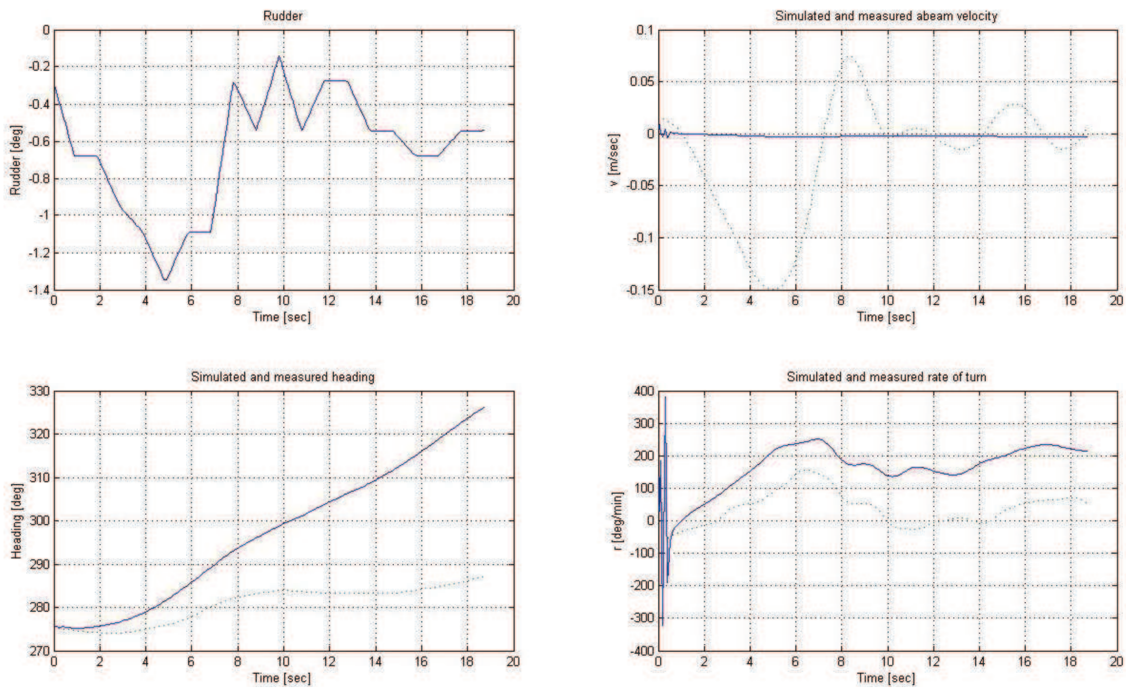

Figure 3: Results of acceleration manoeuvre.

The N-equation

Both during the natural stop manoeuvre and the acceleration manoeuvre little stirs are given. The tracks are almost straight. The rate of turn, heading and position in the turning circle trial is well simulated. The results of the simulation of the other turning circle trials are well comparable. An important criterion is the simulated behaviour of the rate of turn when the rudder is placed amidships, to see in Figure 6 the rate of turn r against time.

Some additional notes to the identification process

On a theoretical basis the value of coefficient c_{u1} is easy to calculate. The start value of 1.14 is the calculated value. In solving the system of differential equations a deviation of thirty percent is allowed. This percentage is arbitrary.

From the solution scheme in Table 1 it can be concluded that to calculate the final values of the coefficients of the model, only one last step, from eleven to twelve is needed. In practice this is somewhat optimistic, sometimes extra steps are needed to get the final set coefficients. This requires expertise and experience and often some additional research.

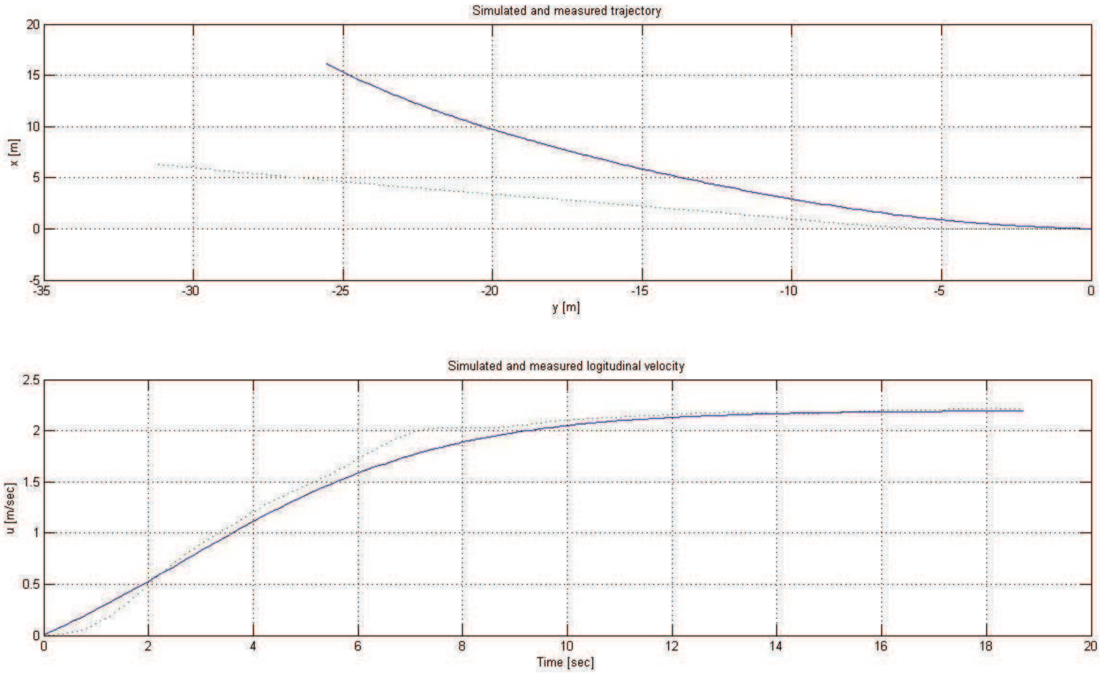

Figure 4: Results of acceleration manoeuvre.

To determine the coefficients involved in the turning of the ship it is not strictly necessary to take into account data from the natural stopping trials or acceleration trials. After all with that type of trial no rudder is given and so the rate of turn of the ship is very low. Yet there are two reasons to take into account the data of these types of trials. First of all, by conducting these trials often some rudder is given to hold the vessel on a straight heading. So the data file contains additional rudder information by which the values of the coefficients are 'better' calculated. This means the set of coefficient determined 'better' simulate the manoeuvring characteristics of the ship. The second reason is of more importance. When simulating the manoeuvring characteristics of the ship as stated you have to deal with a model and a set of coefficients. To simulate, the system of differential equations has to be solved. Depending on the initial condition of the variables and the values of the coefficients it may occur that the solution did not converge so the simulation delivered no solution. This occurs most frequently when in step 12 only the data of the turning circle trials and or zigzag trials are taken into account. Then, there is a change; neither the natural stop trial nor the acceleration trials can be well simulated.

In the case of the REMUS the error, which is minimized and which is

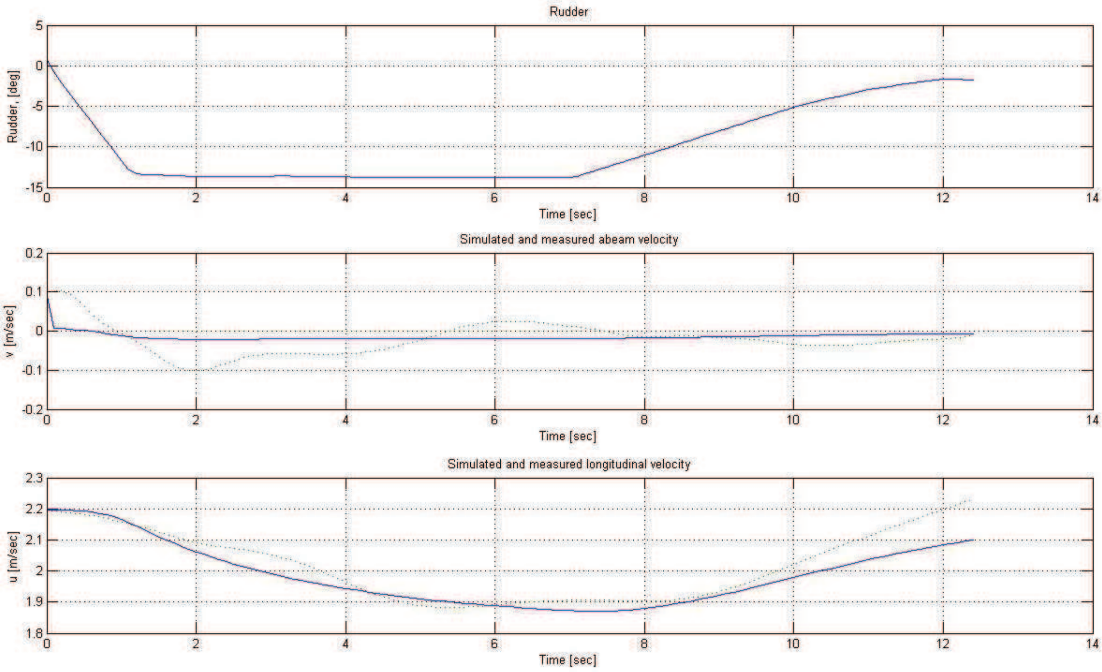

Figure 5: Results of turning circle manoeuvre.

important to find the final value of the coefficients, is split up into two errors. The first is based on the natural stopping trials and acceleration trials (error_a) and the second is based on the turning circle trials (error_b). Initially to optimize the coefficients involved by the turning of the ship only the error based on the turning circle trials (error_b) has to be minimized, so the error which will be minimized is defined as follows:

$$Error = \frac{error_b}{error_a} \cdot error_a + error_b$$

This seems absurd, but if error_a becomes *not a number*, because during the integrating process the values of the variables do not converge, the total error also becomes *not a number* and the process to find the values of the coefficients will continue until the error is found with the lowest real value. Please note, by this choice of the error, only the error from the turning circle trials is used to optimize the determined coefficients. Then step 12 is performed again, but error_a is divided by a factor. This factor is the last value of error_b divided by error_a from the previous step. Please note, by this choice error_a is of the same order of magnitude as error_b, but

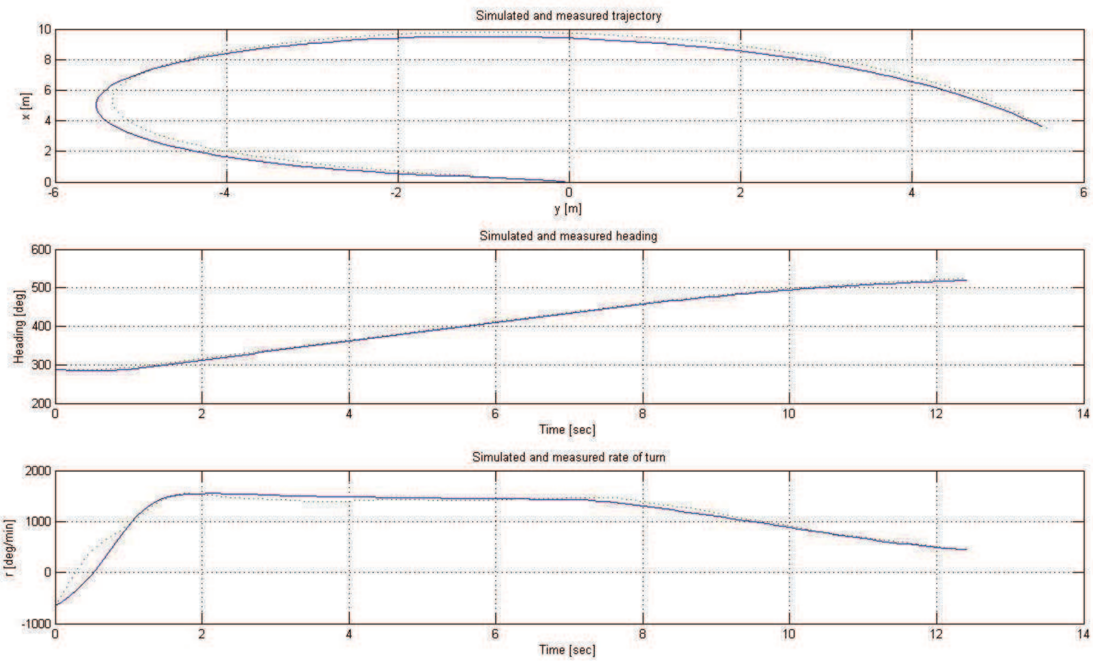

Figure 6: Results of turning circle manoeuvre.

the found values of the coefficients are based and optimized on the data of all the trials.

In the case of the REMUS, theoretically the propeller thrust can be modelled very simply in another way. The propeller of the REMUS has a fixed pitch so the velocity of the vessel is governed by the amount of revolutions per second n. The amount of revolutions can be measured during the trials. The x-equation becomes:

$$\dot{u} \;=\; c_{u1}rv + c_{u2}u + c_{u3}\left|u\right|u + c_{u4}un + c_{u5}n^2 + c_{u6}(\delta^2 + \delta_d^2)(uspeed)^{c_{u7}}$$

The propulsion section now has the form: $c_{u4}un + c_{u5}n^2$. By measuring the revolutions, c_{u5} and c_{u6} can be determined by using a LSM and SDE method in the same way as the other coefficients. It is expected that acceleration behaviour of the vessel will be better simulated.

The minimization routine is a standard call in the program MATLAB. In the past, to find a reasonable set of coefficients steps seven to twelve have to be conducted to find the final set. If in step twelve, the chosen initial values of the coefficients equals zero and only cu1 gets an estimated or calculated value, no realistic set of coefficients was found. For the REMUS, as an additional research, this is tried again, see Table 4. The values of the final set so found (column five) shows little differences with the values found according the process from Table 3. This can be a matter of luck or the software version of MATLAB used. It seems that the minimization routine in this case is able to find the absolute minimum. This makes step seven until eleven redundant. This can lead to considerable time saving.

Table 4: Differences between the final values of the coefficients by different initial values, step 12.

Coefficient	Initial values steps 7-12	Final values Table 3	Initial values	Final values
c_{u1}	1.14	**0.7980**	1.14	0.7980
c_{u5}	-0.3619	**-0.6639**	0.0	-0.6563
c_{u6}	1.1541	**0.8277**	0.0	0.8386
c_{v1}	-0.0759	**-0.0459**	0.0	-0.0447
c_{r1}	-176.8837	**-7.3560**	0.0	-7.5152
c_{r2}	2.8177	**0.7812**	0.0	0.7917
c_{r3}	-2.8616	**0.8896**	0.0	0.9035
c_{r4}	-0.2983	**-2.1965**	0.0	-2.1538
c_{r5}	2.0092	**0.5016**	0.0	0.5116

As a last step, a large number of simulations should be performed to test whether in all (realistic) situations the model converges. This is not done as part of this brief research.

Interesting in this context is Figure 3. The figure of the rate of turn r and the lateral velocity v presents a small form of instability. The reason for that can be: the start values of the variables, the found values of the set coefficients or the used solution method of the differential equations. Also this issue is not further investigated.

Conclusions

The research question, whether for the REMUS the same type of simulation model can be used as for surface ships and whether a set of coefficients can be found based on full-scale trials, can be fairly positively answered. The fifteen trials as a basis for determining the coefficients can be reasonably well simulated with the set of coefficients found and the applied model. Please note, the modelling is only valid in the horizontal plane.

Some concern exists about the conducted full-scale trials. The REMUS navigates using a mission file. It should be investigated whether the vessel can be controlled by hand instead of the mission file, resulting in all relevant standard manoeuvring trials being performed.

The frequency of writing the data is too low. A rule of thumb states:

$$f = \frac{10u_{max}}{L_{ll}}$$

For the REMUS, this represents 16 [Hz]. During the full-scale trials, data is logged with a frequency of one hertz. By interpolation this is increased to ten hertz.

The discussed method to find a set of coefficients by solving the system of differential equations and to define an error as the difference between measured values and simulated values can also be applied if the values of the coefficients are determined otherwise. Then the method can be used to fine tune the set of coefficients of the manoeuvring model. The initial values of the coefficients are then the values based on an empirical formula or on towing tank trials. During the integration process the coefficients are allowed to differ from the initial value by an arbitrary margin.

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