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DATA SMOOTHING APPLICATION TO THE SHIP MOTION MATHEMATICAL MODEL IDENTIFICATION

ABSTRACT A smoothing algorithm is applied to differentiation-gathered velocities from full-scale turning test results. It produces with enough accuracy a clear picture of resultant forces acting during the turning maneuver and thus enables a direct and proper parameters identification in ship motion equations. Obtained results necessitate making a better focus in the future upon a rudder force model.

INTRODUCTION

In the previous report [Artyszuk, 1999] a concept of dynamics (differentiation) based identification method (DBI) for ship motion mathematical model was introduced. The primary cause for such approach is a lack of adequacy of most existing ship motion mathematical model (SMMM) modular structure i.e. developed with H-P-R technology. The latter technology makes use of an independent treatment of hull, propeller, rudder general forces (referred to as forces and moments) and their mutual interactions. What places mathematical model structures in contrast to each other is generally a complexity of used mathematical expressions and assignment of some factors in those expressions as parameters for an identification. a proper settlement of essential relationships and parameters to be identified plays a key role in a validation of SMMM. The proposed DBI method seems to fulfill this task to some extent. Through its use, it is also possible to assess the quality of maneuvering full-scale trials results as the main data sources for the development, identification and validation of SMMM. This thing is of major importance when high accuracy of motion prediction is required as in the case of integrated navigational systems.

The most disadvantage of the previous procedure [Artyszuk, 1999] is that the resultant velocities and accelerations gathered from differentiation analysis of an original turning test diagrams have too much oscillations. They make an image of final forces just unclear and thus of little usefulness. The oscillations are more pronounced in case of accelerations as those are derivatives of corresponding velocities. a drawback of using differentiation is always amplifying the errors imposed upon discrete input data.

Digitization errors of converting shipyard's graphical maneuvering charts into numerical data seem to contribute mostly in our case (though DGPS measurements were used).

SMOOTHING BASICS

Let's recall some essential points about DBI method. Symbols used in previous work will be maintained in general.

We are concerned with three kinematic variables in fixed-ship system (midship as origin) ensuring a complete description of ship motion. These are:

v_x - surge velocity,

β_A - drift angle,

ω_z - angular velocity.

We can call them in a simplest way as developed respectively:

- from differentiation of midship trajectory (its time history considered) for v_{xy} and φ:

$$v_x = v_{xy} \cdot \cos \beta_A , \quad (1)$$

$$\beta_A = \psi - \varphi , \quad (2)$$

where: v_{xy} - instant velocity over track,

ψ - ship's course,

φ - instant track direction,

- from differentiation of ship's course ψ - we receive directly ω_z.

A best solution for the above problem is to have all input data smoothed just before differentiation could be applied. It is well appreciated when we could find a differentiable function fitting very well to the input data [Ralston, 1983]. All further operations would be carried out upon that function. But this could be hardly done for both trajectory and course curves of turning test due to their complexity. a more convenient approach is suggested which allows a direct differentiation of trajectory and course but makes resultant values of v_x, β_A and ω_z smooth before entering the second stage of differentiation - for calculation of accelerations. An explanation is due in this place. Drift angle β_A was chosen to represent the motion status instead of transverse velocity v_y because by giving a simple mathematical shape it is more suitable for smoothing.

Fig.1 shows error-fouled first stage differentiation output according to [Artyszuk, 1999]. The most important appears an exact fitting of angular velocity ω_z as this highly contributes to the inverse operation (integration) while good final trajectory prediction is wanted. See fig. 2, which demonstrates for an imaginary ship how a 10% change in all three above motion components affect the position accuracy. Of relatively low impact is here a fairing of drift angle β_A.

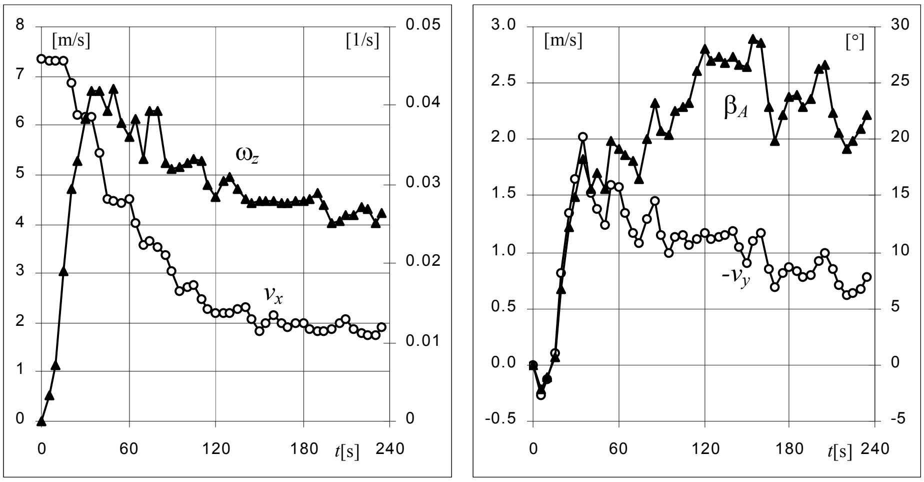

Fig.1. Differentiation gathered velocities during chemical tanker FAH35[0] turning test.

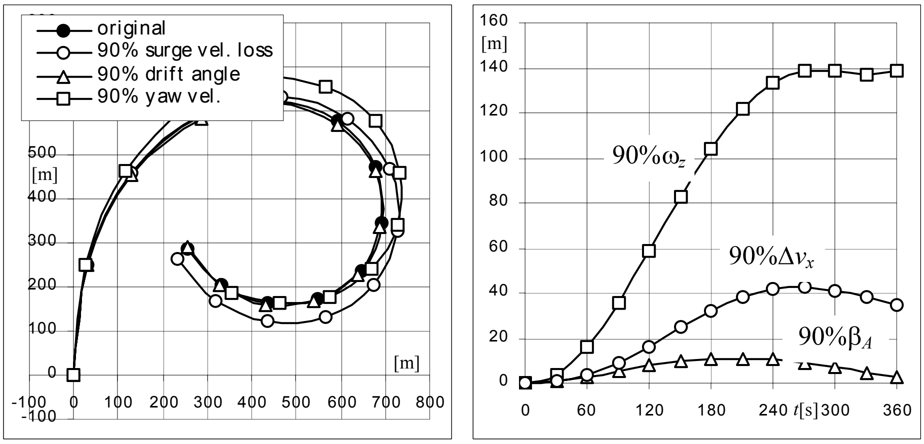

Fig.2. Trajectory sensitivity upon particular velocities - image (left) and accuracy (right).

The analysis of an output of inherently nonlinear SMMMs and many full-scale trials results revealed that during a turning test the surge velocity loss and the drift angle change could be approximated by inertia element of second order.

Let's define a main function as:

$$f_{in2}(t,T_1,T_2)=1+\frac{T_1}{T_2-T_1}\exp\left(-\frac{t}{T_1}\right)-\frac{T_2}{T_2-T_1}\exp\left(-\frac{t}{T_2}\right) \qquad (3)$$

where: t - time (independent variable)

T_1, T_2 - time constants (parameters).

Function (3) has its derivative at t=0 equal to zero and is symmetrical in relation to T_1, T_2 constants i.e.:

$$f_{in2}(t,a,b) = f_{in2}(t,b,a) \tag{4}$$

where a, b are arbitrary values. Thus for a simplification of the fairing procedure we could assume further $T_1 > T_2$.

Using expression (3), surge velocity v_x and drift angle β_A during the turning test could be written as follows:

$$v_x = (v_{x0} - v_{x1}) \cdot [1 - f_{in2}(t, T_{v1}, T_{v2})] + v_{x1}, \tag{5}$$

$$\beta_A = \beta_{A1} \cdot f_{in2}(t, T_{b1}, T_{b2}), \tag{6}$$

where: v_{x0} - initial surge velocity at t=0,

v_{x1}, β_{A1} - steady state values of v_x and β_A in turning test (to be identified),

$T_{v1}, T_{v2}, T_{b1}, T_{b2}$ - time constants (to be identified).

A chart of angular velocity ω_z during a turning test is usually similar to that of transverse velocity v_y - Fig. 1 could serve also for an example. Taking into account a well known relationship:

$$v_y = -v_x \ \mathrm{tg}(\beta_A) \approx -v_x \beta_A, \tag{7}$$

we can finally compose the change of ω_z as follows:

$$\omega_z = a_1 \cdot [1 - f_{in2}(t, T_{w1}, T_{w2})] \cdot f_{in2}(t, T_{c1}, T_{c2}) + \omega_{z1} \cdot f_{in2}(t, T_{c1}, T_{c2}), \tag{8}$$

where: ω_{z1} - steady state value of ω_z in a turning test (to be identified),

a_1 - local maximum parameter (to be identified),

$T_{w1}, T_{w2}, T_{c1}, T_{c2}$ - time constants (to be identified).

On the basis of expressions (5), (6), (8), derivatives of v_x, β_A and ω_z could be easily drawn. It enables with the help of ship motion differential equations an identification of resultant forces and moments [Artyszuk, 1999]. a derivative of v_y, acting explicitly in motion equations, is to be gained from:

$$\frac{dv_y}{dt} = -\left(\frac{dv_x}{dt} \cdot \mathrm{tg}\,\beta_A + v_x \cdot \frac{1}{\cos^2 \beta_A} \cdot \frac{d\beta_A}{dt} \right) \tag{9}$$

Our smoothing algorithm will focus upon minimizing of the following discrete expression:

$$\Delta_{avg} = \frac{1}{n} \sum_{i=1}^{n} \left| Y_i^{org} - Y_i^{sm} \right| \tag{10}$$

where: Δ_{avg} - average smoothing error for Y variable (Y stands for v_x, β_A, ω_z),

n - total number of data points (Fig. 1),

Y_i^{org} - unsmoothed data (Fig. 1),

Y_i^{sm} - smoothed data according to equations (5), (6), (8).

This process will apply an iterative variance of all identifiable parameters in the equations (5), (6) and (8). In this case a range of their values and a step size should be supplied for those parameters. This could be originally rough estimations, aimed only at an initial guess and thus enabling more refined data.

SMOOTHING RESULTS AND CONCLUSIONS

Numerical details concerning inputs and outputs of the smoothing algorithm for the turning test of the ship investigated (Fig.1) are presented in Tab.1. Smoothed curves of all motion components are shown in Fig. 3.

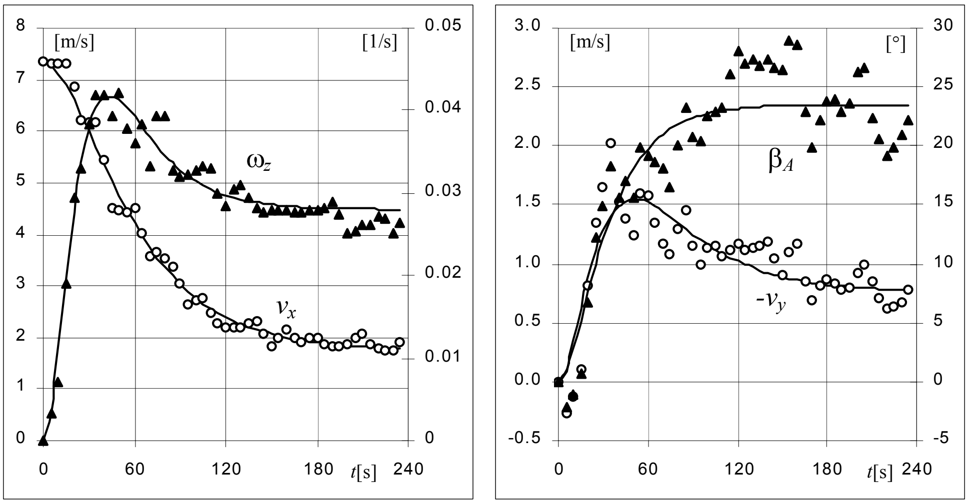

Fig.3. Smoothed velocities during chemical tanker FAH35 (turning test).

Fig. 4 shows how essential in our case is a smoothing of specific motion variables for the overall trajectory simulation. Errors of about 10[m] seem to be not negligible. They comprise both inadequacy of used approximating expressions and under- or overestimation of parameters thereof. In the future a look into a digitization process accuracy and first stage differentiation (Fig.1) accuracy should also be made.

Fig. 5 illustrates all three motion accelerations i.e. of surge, sway and yaw according to exact derivatives of expressions (5), (6) and (8).

Tab. 1. Numerical details of smoothing algorithm.

v_x			β_A			ω_z		
	1st attempt	2nd attempt		1st attempt	2nd attempt		1st attempt	2nd attempt
Δ_{avg}	0.1365 [m/s]	0.1313	Δ_{avg}	2.4261 [°]	2.3149	Δ_{avg}	0.002039 [1/s]	0.001371
v_{x1}	1.8 [m/s]	1.76	β_{A1}	22.5 [°]	23.5	ω_{z1}	0.025 [1/s]	0.028
T_{v1}	35[s]	34	T_{b1}	20[s]	25	a_1	0.1 [1/s]	0.1
T_{v2}	30[s]	30	T_{b2}	15[s]	11	T_{w1}	25[s]	26
						T_{w2}	20[s]	15
						T_{c1}	25[s]	25
						T_{c2}	15[s]	15
step v_{x1}	0.1	0.02	step β_{A1}	2.5	0.5	step ω_{z1}	0.005	0.002
step T_{v1}	5	2	step T_{b1}	5	1	step a_1	0.02	0.01
step T_{v2}	5	2	step T_{b2}	5	1	step T_{w1}	5	1
v_{x0} [m/s]	7.3418	7.3418				step T_{w2}	5	1
						step T_{c1}	5	5
						step T_{c2}	5	5

An identification of total forces acting during the investigated turning test is demonstrated in Fig. 6. It is based on sway added mass m_{22} of 100% of ship's displacement [Artyszuk, 1999]. The latter value serves only as a rough estimation due to a lack of a more accurate data.

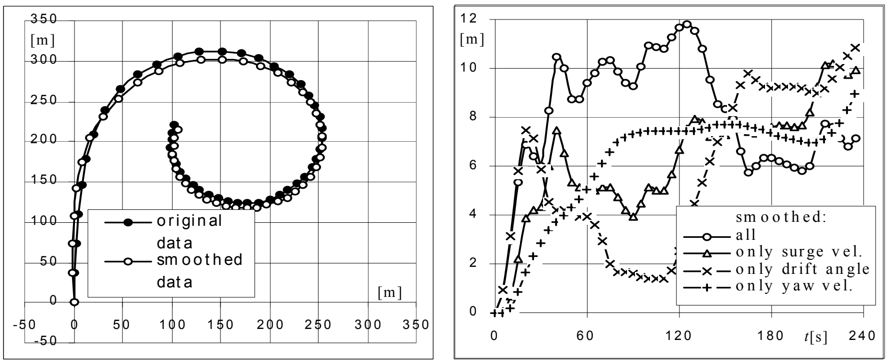

Fig. 4. Calculated trajectory from original and smoothed data (left) and its accuracy for individual smoothing (right)

Because of the great impact of m_{22} upon the appearance of surge force F_x and yaw moment M_z (sway force F_y very hardly affected), Fig. 6 comprises also a possible variation of m_{22}.

In the next Fig. 7, a decomposition of total surge force F_x into main components i.e. of hull (F_{xH}), propeller (F_{xP}) and rudder (F_{xR}) is carried out. Rudder surge force F_{xR}, as the most difficult for calculation, is given a closer look in Fig. 8. One valuable conclusion is to be drawn here that after the first 30[s] the water inflow into the rudder is most likely from the opposite side than at the beginning of the maneuver - the rudder surge force starts to act forwards. Its magnitude obviously depends upon unknown sway added mass, but even 50% of the assumed original value turns this force into zero i.e. null rudder incidence angle is reached. In such situation, the weighing factors of sway v_y and yaw ω_z velocities while computing a transverse inflow velocity at the rudder position (local rudder drift angle) amounts to 2.0 each at least (null rudder incidence). Comparatively, [Kose, 1982] reports values of order 0.5 each.

Fig. 9 shows some details necessary to complete rudder force calculation (lift and drag components): velocity in the propeller slipstream v_{PS} (ideal propeller momentum theory), velocity in the wake v_A, ratio of the rudder area in the propeller slipstream (slipstream contraction applied) A_{PS} / A_R and the propeller thrust load coefficient c_{Th}.

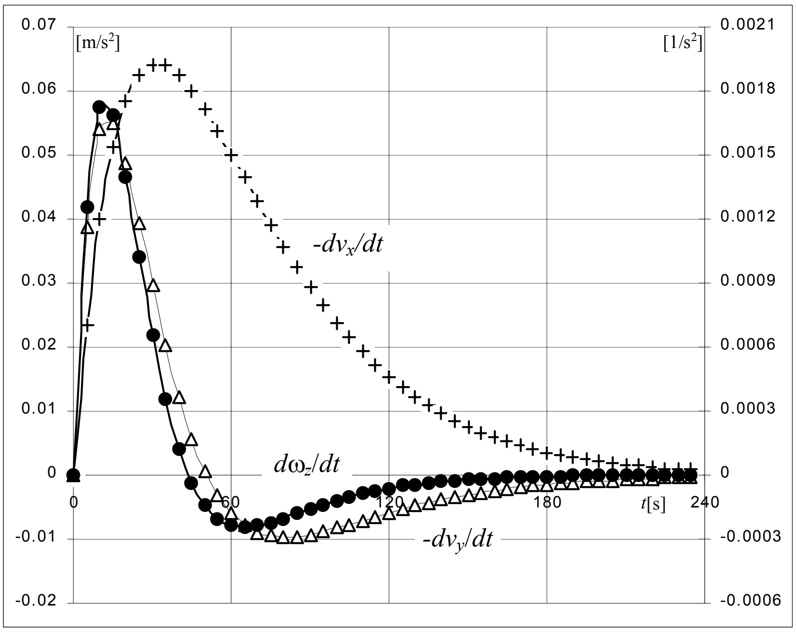

Fig.5. Accelerations during chemical tanker FAH35° turning test

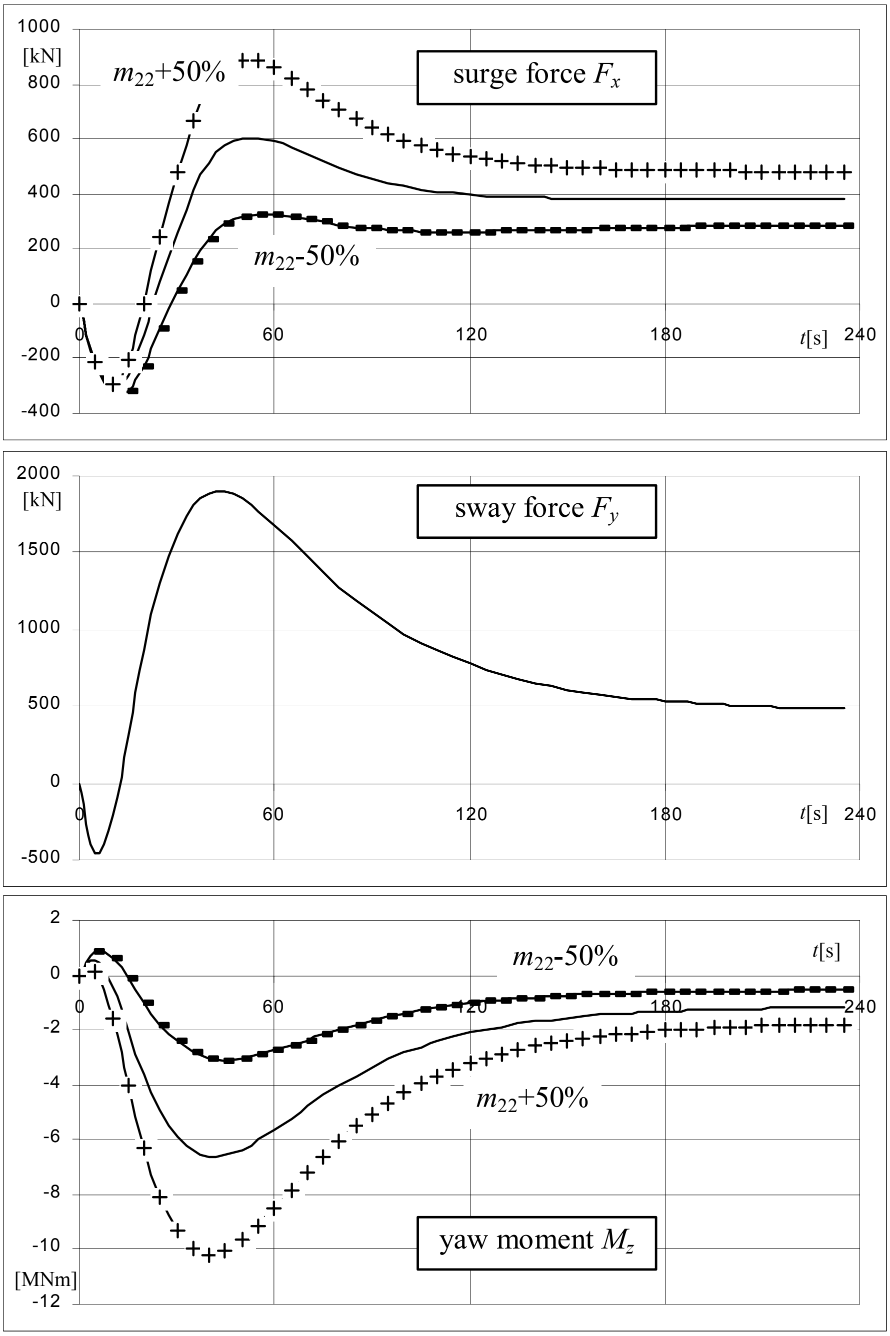

Fig.6. Total forces during chemical tanker FAH35^0 turning test

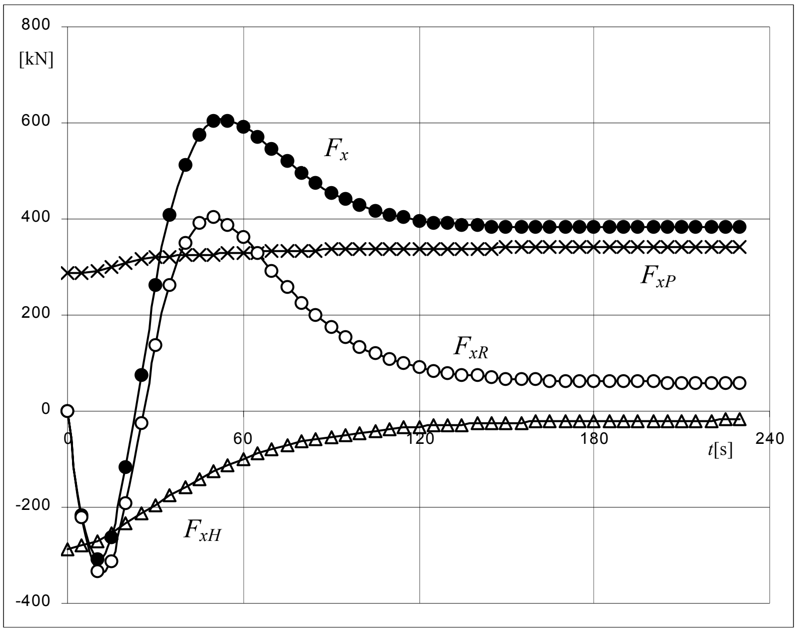

Fig.7. Surge force decomposition.

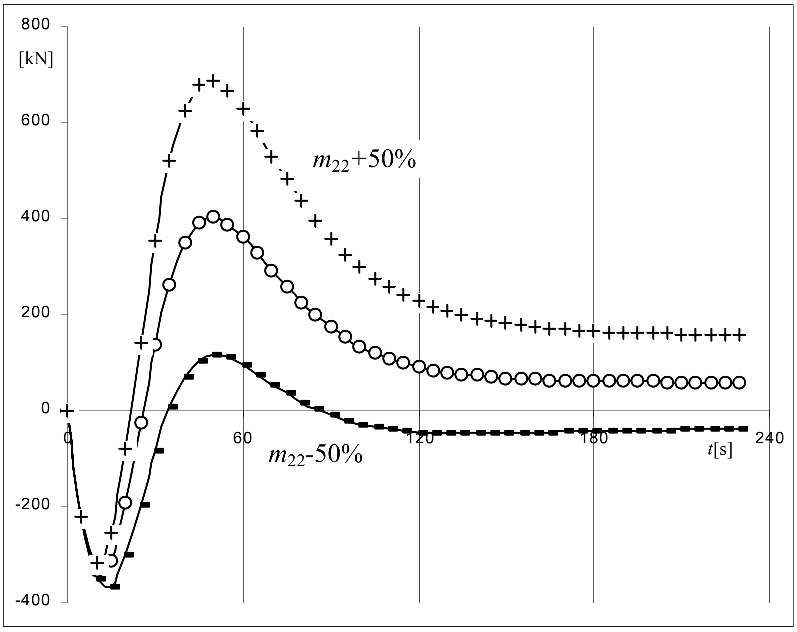

Fig.8. Rudder surge force as function of sway added mass.

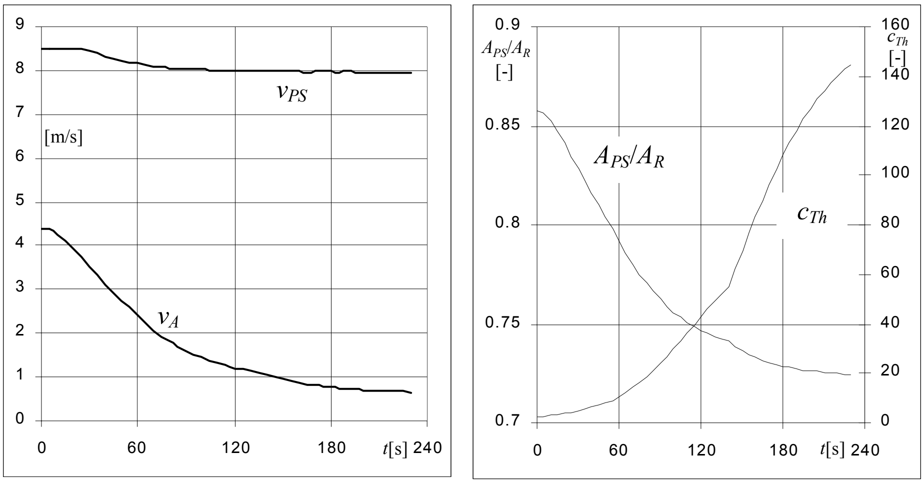

Fig.9. Rudder flow analysis: component velocities (left), active rudder area ratio and propeller thrust loading coefficient (right).

Propeller-rudder interaction is a bit complicated phenomenon, see e.g. [Müller and Landgraf, 1975], [Baumgarten and Müller, 1979], [English et al., 1971-72], [Gofman, 1988], [Kulczyk and Tabaczek, 1996], [Molland and Turnock, 1996], till now not sufficiently generalized to encompass any kind of hull-propeller-rudder configuration. Because of that fact and also taking into account a curiosity of identification results in the present study of the rudder surge force, it seems more reasonably to treat an analysis of the total rudder force structure as the last step during SMMM identification. This is in some way against the suggestions given in [Artyszuk, 1999].

It is also advisable to concentrate research efforts (analytical and experimental) more and more upon a transverse rudder inflow velocity. As opposed to propeller-rudder interaction, this problem experiences a relatively low interest in the open literature.

REFERENCES

1. Artyszuk J.: *Dynamics-Based Identification of Ship Motion Mathematical Model from Full-Scale Trials Results*. Annual of Navigation 1/99 s.77-89, Polish Academy of Sciences/Polish Navigation Forum, Gdynia, 1999.
2. Baumgarten B., Müller E.: *Pressure and Force Measurements on Rudders with and without a Propeller Slipstream*. (in German) STG Jahrbuch, 1979.
3. English J. W., Rowe S. J., Bain D. C.: *Some Manoeuvring Devices for Use at Zero and Low Ship Speed*. Trans. NECIES, vol. 88, 1971-1972.
4. Gofman A.D.: *Propeller-Rudder Complex and Ship Manoeuvring (Handbook)*. (in Russian) Sudostroenie, Leningrad, 1988.

5. Kose K.: *On a New Mathematical Model of Maneuvering Motions of a Ship and Its Applications*. ISP No.336, 1982.
6. Kulczyk J., Tabaczek T.: *Calculation of Influence of Propeller Slipstream on Marine Rudder Performance*. Polish Maritime Research, No. 2, 1996.
7. Molland A. F., Turnock S. R.: a *Compact Computational Method for Predicting Forces on a Rudder in a Propeller Slipstream.* Trans. RINA, 1996.
8. Müller E., Landgraf J.: *Rudder in a Propeller Slipstream*. (in German) STG Jahrbuch, 1975.
9. Ralston A.: a *First Course in Numerical Analysis*. (in Polish) PWN, Warsaw, 1983.

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