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On the improvement of ship manoeuvring simulation in restricted waters by means of captive model test results

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Abstract

Possibilities for improving the mathematical model of a ship manoeuvring simulator, based on results of captive motion tests with ship models, are discussed. Most topics concern simulation of manoeuvres in rather extreme conditions, such as very shallow water, harbour manoeuvres, and effects due to lateral restrictions of the navigational area. For validation of mathematical models, a technique based on captive model tests is proposed as well.

1 Introduction

Real-time ship manoeuvring simulation has proved to be a very useful tool for several purposes, e.g. design of new navigation areas, evaluation of the access of new shipping traffics to existing ports, training of pilots and crew.

When discussing simulation techniques, distinction should be made between the *internal* part of the simulator, i.e. the mathematical manoeuvring model, calculating the ship's path as a result of hydrodynamic, control and external forces, and the *external* part, consisting of bridge mock-up, outside view, radar screen, etc. Over the years, the evolution of computer facilities has led to spectacular progress of *external* simulation techniques: artificial bridges have become more realistic, quality of visual display has increased. Stronger computers also offer more possibilities for simulating special effects, e.g. target ships. Improvements of the *internal* part of the simulator, on the other hand, do not primarily depend on hardware evolutions, but on the availability of reliable data concerning manoeuvring behaviour. Therefore, fundamental ship hydrodynamics research, numerical calculation algorithms, experimental data and validation techniques are required.

Especially for simulators used for waterways design, the quality of the internal simulator performance is of particular interest. If a ship's behaviour is not modelled in an accurate way, simulation results may lead to under- or overestimation of dimensions of waterways and harbour areas and may therefore affect either safety or economics.

Computational techniques and empirical data do not yet allow determination of a mathematical manoeuvring model for a specific ship, in particular in shallow or restricted areas. Therefore, it is expected that experimental techniques will keep fulfilling an important task during the next decennia.

A number of possibilities for improvement of the mathematical model of a ship manoeuvring simulator, based on results of captive manoeuvring tests with ship models, are discussed. Most topics concern the simulation of ship manoeuvres in rather extreme conditions:

- manoeuvring in very shallow water, characterized by an under keel clearance (UKC) less than 20 % of draught;
- harbour manoeuvres at low and reversed speed, low and reversed propeller rpm, large drift angles;
- effects due to lateral restrictions (e.g. quay walls, banks).

A validation technique for mathematical models, based on captive model tests, will be discussed as well.

2 Captive model test techniques

Captive model test techniques are commonly applied for the experimental determination of coefficients occurring in mathematical manoeuvring simulation models formulating the forces and moments acting on the ship as functions of a set of parameters. During such tests, a ship model is forced by an external mechanism to undergo a prescribed trajectory in the horizontal plane, while the forces and moments acting on the model are measured.

Trajectories are selected in such a way that one (or more) parameters mentioned above is variable during a test (or test series), while the other parameters are kept constant. In this way, the influence of one parameter can be isolated, or the interaction between two parameters can be assessed. The nature and number of parameters depend on the mathematical manoeuvring model, but in general a distinction can be made between:

- kinematical parameters (forward and lateral velocity components u and v, rate of turn r, corresponding accelerations);
- control parameters (e.g. rudder angle δ, propeller rpm n);
- geometry parameters (e.g. ship-bank distance).

According to the trajectory shape, distinction can be made between:

- stationary rectilinear tests (e.g. resistance, propulsion, oblique towing, rudder angle tests), carried out by means of a classical towing carriage;
- stationary circular tests, requiring a rotating arm facility or a computer controlled planar motion mechanism (PMM);
- harmonic oscillation tests (sway, yaw), by means of a towing carriage equipped with a mechanical or computer controlled PMM.

The tests referred to in following sections were carried out in the *Towing tank for manoeuvres in shallow water, cooperation Flanders Hydraulics - University of Ghent* in Antwerp, installed for providing experimental data for development of mathematical models for the ship manoeuvring simulator at Flanders Hydraulics, [1]. The mechanism consists of a main carriage, a sway carriage and a yawing table, which are independently controlled by a personal computer. Sampling and storage of analog signals are performed by a second PC. The control system allows unmanned, continuous operation.

3 Shallow water effects

Introduction

The depth in the area in which a ship sails is of particular importance, as a ship's behaviour is modified as a function of the depth-to-draught ratio h/T. In [2], following ranges are defined:

$3.0 < h/T$ . . . . deep

$1.5 < h/T < 3.0$ . . medium deep
$1.2 < h/T < 1.5$ . . . . . . shallow
$1.0 < h/T < 1.2$ . . very shallow
If the bottom is covered with fluid mud, even negative UKC values (referred to the mud-water interface) occur, see [3].

Although in many approach channels and harbours a UKC of less than 20% of draught is common practice, experimental data on ship manoeuvrability in very shallow water do practically not occur in literature. This lack of data can probably be explained taking account of the practical difficulties occurring when model tests are carried out in such conditions:

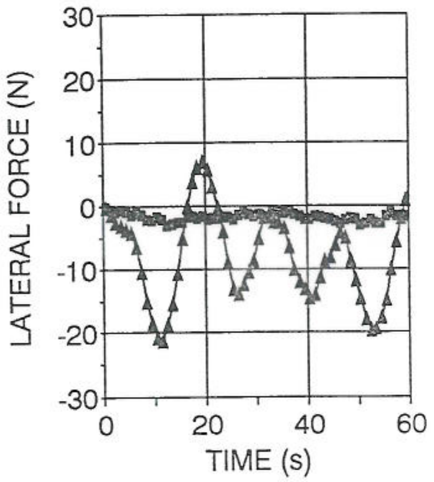


Figure 1: Captive tests with 1/75 model of 150000 tdw bulkcarrier: $u=0.3$ m/s;$v=r=\delta=0$;$n=-100\%$. Lateral force: effect of h/T (■ : 2.5 ; ▲ : 1.1).

- the horizontal accuracy of the tank bottom has to meet high standards;
- waiting times between two tests increase substantially (e.g. from 15 minutes at $h/T = 2.5$ to 40 minutes at $h/T = 1.1$);
- due to transient phenomena, a longer measuring interval is required for steady-state tests, so that the number of conditions per run decreases;
- interpretation of test results may be difficult due to secundary hydrodynamic effects. For example, figure 1 shows low frequency oscillations occurring at reversed propeller rate (also reported by Ch'ng [4]). The effect of negative rpm is usually simulated by means of a steady lateral force acting to port; in (very) shallow water, however, this appears to be insufficient, as the amplitude of oscillations may exceed the steady term.

On the other hand, the hydrodynamic coefficients of a mathematical manoeuvring model are very sensitive to water depth modifications in the very shallow water range, so that extrapolation from larger h/T is unlikely to yield reliable results. This will be illustrated in figures 2 and 3.

Example: forces due to drift
Figure 2 shows results of oblique towing tests carried out with a 1/75 scale model of a partially laden 150000 tdw bulkcarrier (L_{PP}=259 m; B=43 m; T=14.6 m), carried out at three UKC values. Non-dimensional presentations for the lateral force Y and the yawing moment N are used in order to eliminate the influence of the total ship speed $V = (u^2 + v^2)^{1/2}$. The drift angle is defined as $\beta = \arctan(-v/u)$.

It can be concluded that due to a decrease of h/T from 2.5 to 1.2, lateral force and yawing moment are amplified with factors 4-5 and 2-3, respectively. A decrease of the UKC from 20 to 10% of draught causes a further increase of Y, while N remains approximately constant. This implies that the application point of the lateral force shifts in longitudinal direction, which is of particular importance for directional stability.

Example: rudder action
Results of stationary rudder angle tests at maximum rpm are presented in figure 3. Lateral force and yawing moment induced by rudder action increase with forward speed u. This can be explained as follows: at u=0, forces due to rudder action are concentrated on the rudder, which is situated in the propeller slipstream. At nonzero forward speed, the relative motion of the hull through the water is influenced by the asymmetry due to the rudder

deflection, so that an additional lateral force applies on the hull. The rudder module proposed by Group-MMG is based on this analysis, [5]:

$$\begin{aligned} Y &= (1+a_H)Y_R \\ N &= Y_R x_R + a_H Y_R x_H \end{aligned} \qquad (1)$$

Y_R being the force acting on the rudder, a_H the ratio between lateral forces on rudder and hull and x_H (x_R) the longitudinal position of the application point of the force acting on the hull (rudder).

The effect of water depth is negligible in bollard pull conditions, but is very important for nonzero speed. The lateral force Y increases significantly with decreasing UKC, which implies that the component $a_H Y_R$ acting on the hull becomes more important. Actually, the factor a_H, typically between 0 and 0.5 in deep water, can take values up to about 3 in very shallow water. The effect on the yawing moment N is less important, which indicates that the application point of the hull force moves towards midships with decreasing h/T. It can be concluded that particular attention should be paid to the formulation of a_H and x_H if equations (1) are used for modelling forces due to rudder action in (very) shallow water.

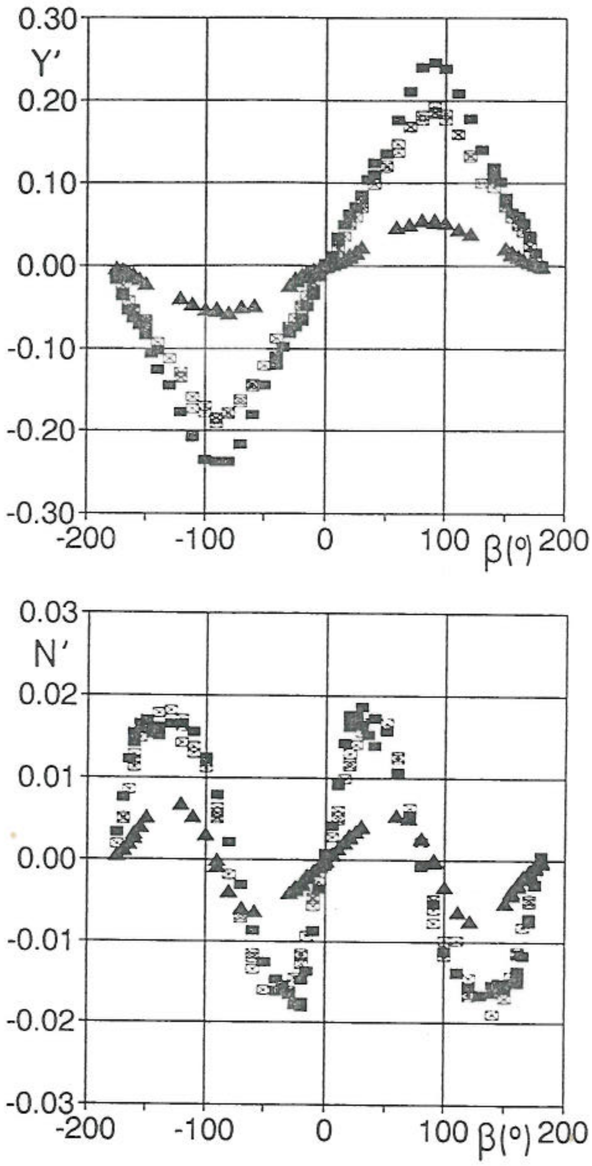


Figure 2: Tests with 1/75 model of 150000 tdw bulkcarrier. Lateral force $Y' = Y \div (\frac{1}{2}\rho V^2 L^2)$ and yawing moment $N' = N \div (\frac{1}{2}\rho V^2 L^3)$ as functions of drift angle. Effect of h/T: 2.5 (▲), 1.2(⊠), 1.1(■).

Figure 3 also illustrates the effect of UKC on controllability at $u<0$. In medium deep water, forces and moments induced by rudder action combined with propeller action full ahead are decreased due to reversed speed, but are still effective. At 20% UKC this is only the case at very low speed; at 10% effective rudder action cannot be taken if $u<0$.

4 Restricted water

A formulation of longitudinal force X, sway force Y and yaw moment N due to ship-bank interaction, suited for implementation into the mathematical model of a manoeuvring simulator, requires a large number of captive model tests, as many parameters are involved: ship-bank distance, forward speed, UKC, propeller thrust, drift angle, rudder angle.

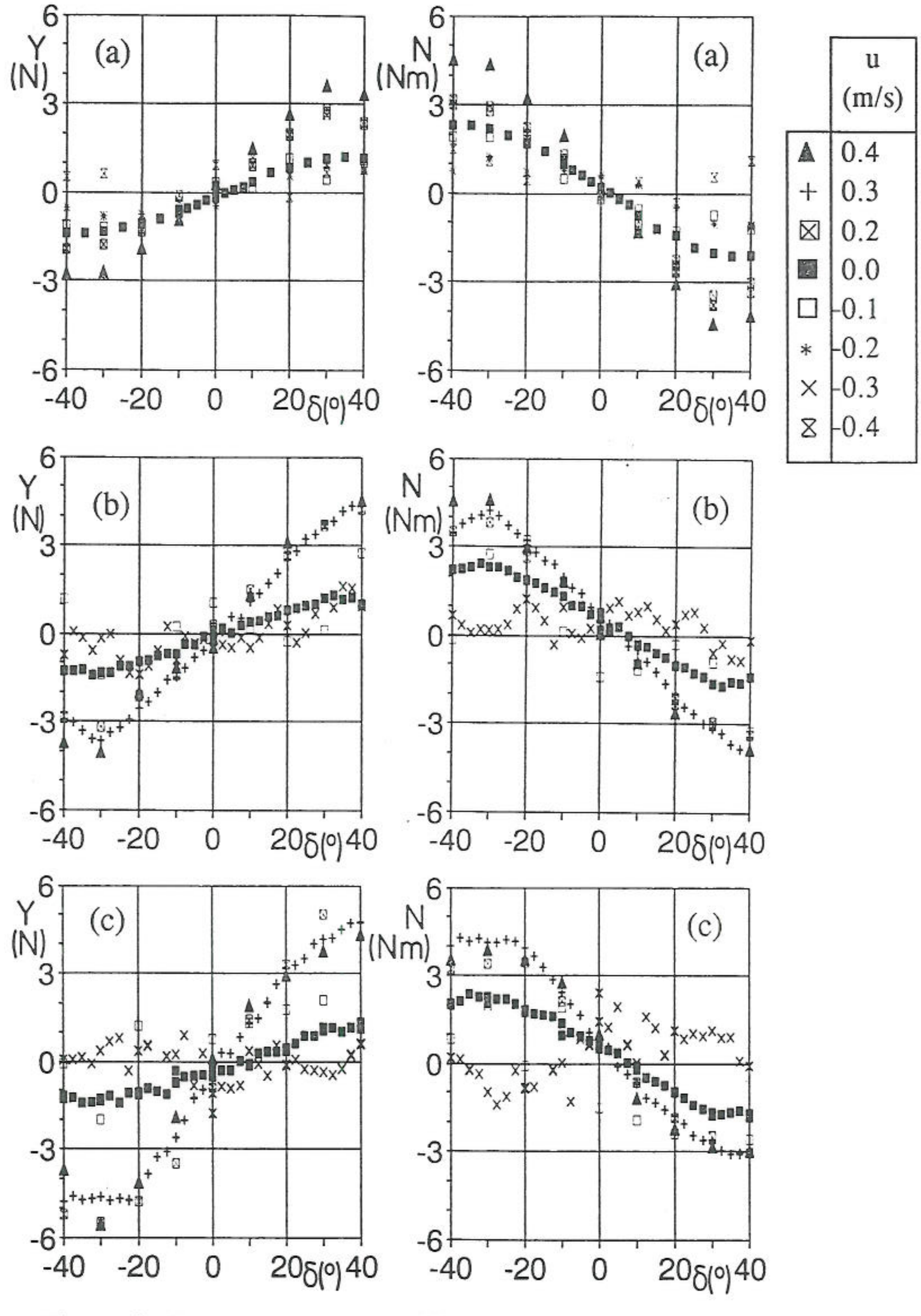


Figure 3: Rudder tests with 1/75 model of 150000 tdw bulkcarrier: v=r=0, n=100%. Lateral force Y and yawing moment N vs rudder angle δ for several forward speeds u. h/T = (a) 2.5; (b) 1.2; (c) 1.1.

Especially in very shallow water, interaction effects are very sensitive to depth variations. If h/T exceeds a critical value, a ship moving in parallel course with a bank at zero rpm is attracted to the bank, while at lower h/T, repulsion from the bank takes place. The critical depth-to-draught ratio varies between 1.1 and 1.3, according to data in [6] and [7]. Applying a positive propeller rpm results in an attraction between the stern and the bank; at very low h/T, bank repulsion at zero rpm can be changed into bank attraction due to this effect.

Experimental investigations can be avoided if a reliable calculation method is available. In [7], it was concluded that an empirical method proposed by Ch'ng et al [6], resulting into a formulation for Y and N as functions of forward speed, ship-bank distance, h/T and propeller thrust, provides an excellent base for medium deep water. However, extensions for (very) shallow water are required, a formulation for the longitudinal force X should be proposed, and the effect of drift should be taken into account. It can be concluded that, especially in (very) shallow water, a reliable simulation of bank effects requires an extensive captive model test program.

5 Validation of manoeuvring simulation models

Motivation

Simulator studies carried out for design purposes only yield reliable conclusions if the mathematical simulation model represents the forces acting on the ship during the manoeuvres in a sufficiently accurate way. Therefore, special attention should be paid to the validation of simulation models.

Especially in shallow and/or restricted waters, validation of manoeuvring models is very difficult. If available, results of full-scale tests usually concern trial manoeuvres carried out in deep water, which are often executed at an unusual loading condition. Moreover, full-scale trials result into a time history of the ship's kinematics as a function of control variables, while a simulation model yields force and moment components. As a consequence, trial results only provide an indirect means for validation.

Multimodal harmonic tests

For the reasons mentioned, an experimental technique for evaluating the validity of a mathematical manoeuvring model was developed. The method is based on comparison of the forces and moments predicted by the simulation model with those measured on a captive ship model performing a series of tests which have not been used for the development of the mathematical model or the determination of hydrodynamic coefficients.

For this purpose, software has been developed for generating trajectories for 'multimodal harmonic tests'. Two or more of the parameters f (= u, v, r, δ, n) occurring in the mathematical simulation model are simultaneously varied as harmonic functions of time:

$$f = f_m + f_A \sin(\omega_f t + \phi_f) \qquad (2)$$

Amplitude f_A, pulsation ω_f (= $2\pi/T_f$, T_f being the period) and phase angle ϕ_f can be chosen independently for each parameter f.

Advantages and disadvantages

This technique has several advantages:

- A large number of combinations of values for the input parameters of the mathematical model is obtained during the same run.
- The influence of dynamic effects is not neglected, which is important for the validation of mathematical models which are partially based on results of stationary captive model tests.
- The method yields a numerical value for the difference between measured forces and the simulation model output, so that the importance of discrepancies can be compared with the magnitude of other forces (e.g. tugs, wind, bank suction, rudder action).

- The parameter ranges or parameter combinations for which the mathematical model is unsatisfactory can be identified. If these ranges are expected to occur during simulation studies to be performed with the mathematical model, the latter should be adapted.
- Only a few supplementary captive model tests have to be carried out.

Following disadvantages could be mentioned.

- The simulation model is evaluated for the scale model, not for the full scale ship. Deviations due to scale effects are not taken into account.
- For most multimodal harmonic tests a computer controlled PMM is required. However, most other test facilities allow execution of similar tests, although not all motion parameters can be selected independently.

Example: rudder module

A rudder force module was developed for a panamax type bulk carrier (L_{PP}= 220 m; B=32.2 m; T=12.25 m; C_B=0.81) at h/T=1.1, based on stationary captive model tests carried out with a 1/64 scale model. For the formulation of Y and N due to rudder action, two mathematical models were selected:

- a twelve-term regression model 1 (similar expression for N):

$$Y = \sum_{j=0}^{3} \left(Y_{\delta^j uu} \delta^j u^2 + Y_{\delta^j un} \delta^j u n + Y_{\delta^j nn} \delta^j n^2 \right) \tag{3}$$

- model 2, based on the Group-MMG rudder model (1), with addition of asymmetry terms. The factor a_H is found to depend on u/n and δ, while x_H appears to be a function of u. Y_R is formulated as follows:

$$Y_R = (b_1 u^2 + b_2 u n + b_3 n^2)(c_1 \delta + c_2 \delta^2 + c_3 \delta^3) \tag{4}$$

During the multimodal tests executed for evaluating these mathematical rudder models, lateral velocity v and rate of turn r were zero. Figure 4 shows the results of a test performed at constant propeller rpm (100%), harmonically varying rudder angle (T_δ=40 s; δ_A=40°; δ_m=0°) and harmonically varying forward speed (T_u=200 s; u_A=u_m=0.25 m/s). Model 1 overestimates the lateral force at low speed; the agreement between measured values and results of model 2 is quite good. The yawing moment N is underestimated by model 2 in all conditions; the agreement is better for the regression model. At maximum speed, both models underestimate N.

6 Conclusion

Reliable manoeuvring simulation studies require the availability of a mathematical model matching reality with a sufficient accuracy. Indications have been given that captive model test techniques fulfil an important function in the development and validation of mathematical manoeuvring models, especially in confined waterways.

References

1. Vantorre, M. Concept and operation of a computer controlled towing tank for manoeuvres in shallow water, in CADMO'94 (ed T.K.S. Murthy, P.A. Wilson & P. Wadhams), pp. 123-132, *Proceedings of the Fifth International Conference on Computer Aided Design, Manufacture and Operation in the Marine and Offshore Industries, incorporating the Fourth Ice Technology Workshop*, Southampton, U.K., 1994, Computational Mechanics Publications, Southampton/Boston, 1994.
2. *Capability of ship manoeuvring simulation models for approach channels and fairways in harbours*. Report of Working Group 20 of Permanent Technical Committee II. Suppl. to PIANC Bulletin, 1992, 77, 49 pp.

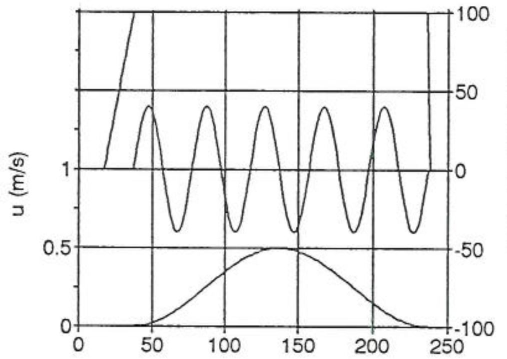
3. Vantorre, M. Ship behaviour and control in muddy areas: State of the art, in MCMC '94 (ed G.N. Roberts & M.M.A. Pourzanjani), pp. 59-74, *Proceedings of the 3rd International Conference on Manoeuvring and Control of Marine Craft*, Southampton, UK, 1994, Maritime Research Centre, Southampton Institute, Southampton, 1994.

4. Ch'ng, P. & Renilson, M.R. The effect of astern revolutions on manoeuvring behaviour, *The Naval Architect*, 1993, E35-36.

5. Ogawa, A. & Kasai, H. On the mathematical model of manoeuvring motions of ships, *International Shipbuilding Progress*, 1978,**25**,306-319.

6. Vantorre,M. Experimental study of bank effects on full form ship models in: Mini Symposium on Ship Manoeuvrability (ed K.Kijima), pp. 85-101, Fukuoka, 1995, The West-Japan Society of Naval Architects, 1995.

7. Ch'ng, P., Doctors, L.J. & Renilson, M.R. A method of calculating the ship-bank interaction forces and moments in restricted waters, *International Shipbuilding Progress*, 1993, **40**, 7-23.



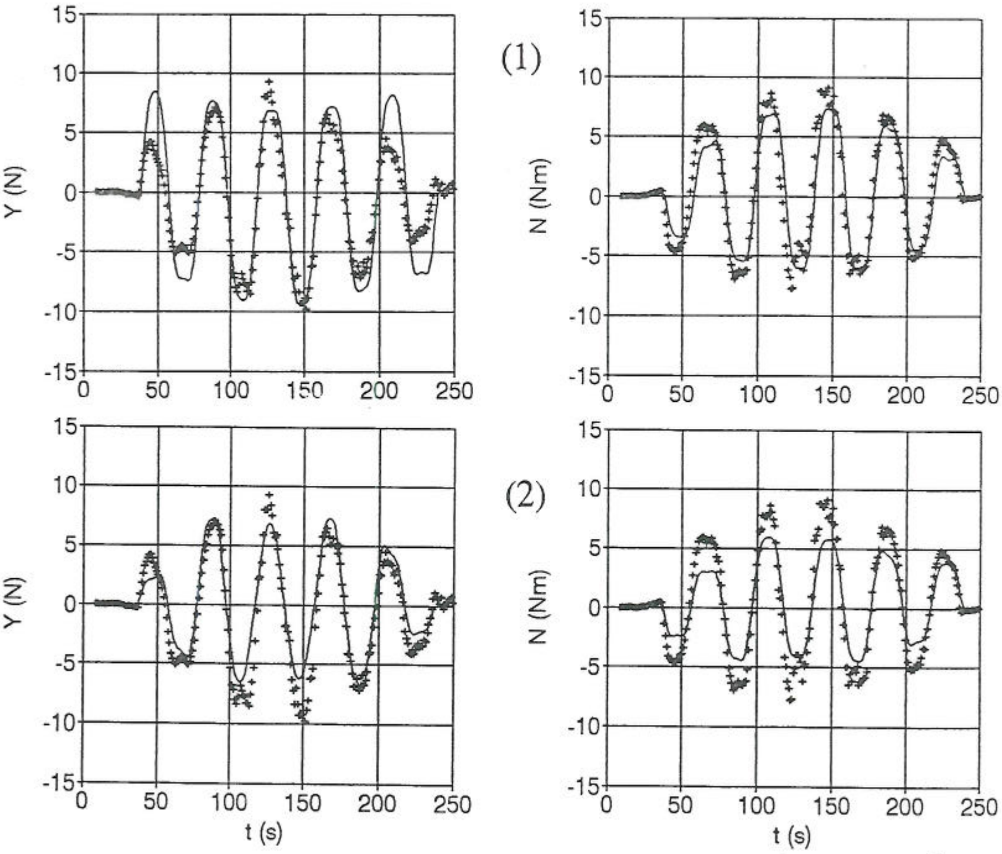


Figure 4: Multimodal harmonic tests with 1/64 model of panamax size bulkcarrier, h/T=1.1. Comparison of measurements (+) with rudder modules (--). (1) 12-term regression model; (2) model based on MMG.