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Dynamic Modelling, Investigation of Manoeuvring Capability and Navigation Control of a Cargo Ship by using Matlab Simulation

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Abstract: In this paper a simplified dynamic analysis of a cargo ship using simulation and modelling are presented. Provided with mathematical equations dynamics of ship motion characteristics with several maneuvering capabilities are demonstrated with MATLAB & SIMULINK as simulation tool. The equations extended with acting thrust, resistance, steering and ruder forces are demonstrated for several maneuvers like on straight track coasting from full ahead to stop, turning actions A numerical application of fast time simulations on a freighter ship is given with graphical representations. Furthermore a simplified model for rolling motion of ship is introduced and some examples are simulated to explain the general effects of stability and wave parameters. The relation of these results to the more practical use for decision making to avoid resonance effects of ship in waves by loading operations or speed/course changes is demonstrated by means of simulation tool.

Keywords: Navigation, Cascade Control, Ship, Modeling, Steering, Route

1.INTRODUCTION

Ship motion dynamic and ship manoeuvring is an important topic in ship Handling and Automatic navigation Control. Dynamic motion and analysis of a ship is associated with the knowledge of the couplings between surge, roll, yaw, and sway and this is an important task to improve the manoeuvring ability and modelling.

Generally for description of ship motion four degrees of freedom models are well known, as given by Abkowitz and Chislett and Stom-Tejsen, but models describing the interaction between surge, roll sway and yaw have only been scarcely studied.

Son and Nomoto presented a model obtained by combining planar motion mechanism (PMM) test data for lateral motion, using different values of static heel for the model under test, with independent roll motion tests. Källström and Otterson [10] obtained a model by combining a lateral PMM model with theoretical estimates of roll coefficients, using free sailing model tests to calibrate the roll parameters. Perez - Blanke presented models based on experimental results in the unique 4-DOF roll planar motion mechanism (RPMM) facility at the Danish Maritime Institute that allow model testing with full dynamic interaction between motions in roll, sway, yaw and surge.

Although different model publications are presented in the literature it is still difficult to find a fully-parameterized models. The main contribution of this paper is to provide a simplified approach for the equations of ships motion and manoeuvring.

Fully-parameterized non-linear and linear models can be utilized as a basis for analysis and design of ship motion control strategies. The results of a Matlab – Simulink model for cascaded navigation simulation are shown for different actions

In addition, to demonstrate the results of the obtained linearized model, a built up real like ship navigation model with cascade control is implemented successfully.

2.MOTION MODEL WITH ACTING FORCES AND MOMENTS

The equations describing ship dynamics are well known. They are obtained from Newton's laws expressing conservation of linear and angular momentum.The main difficulty when deriving the equations is to describe the hydrodynamic forces acting on the hull. The forces are in general complicated functions of the ship's motion, i.e. the time history of the velocity, angular velocity and the rudder motion. They also depend on trim and draught. In shallow water and close to shore the forces will also depend on the topography.

If a ship is considered as a rigid body it has 6 degrees of freedom corresponding to translations in 3 directions and rotation around 3 axes. The equations of motion are conveniently expressed using a co-ordinate system fixed to the ship. The hydrodynamic forces are easy to describe in such a co-ordinate system because the symmetry of the hull can be exploited. Neglecting sensor and actuator dynamics, the ship can thus be modelled as a 12-order system. Additional dynamics are also introduced by the rudder servo. In many cases it has, however, been shown that the model can be simplified. It is customary at least for tankers and similar ships to neglect the coupling between the yaw motion and the

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pitch and roll motions.Since the yaw motion is often sufficient to discuss steering and autopilot design, the following treatment will be limited to this motion only.

There are significant factors that couple the speed of a ship and its path. For example, path changing (turning) and even path keeping (course-keeping) cause involuntary speed reductions. These effects arise from the fact that any misalignment between the x-axis of the ship as shows in Figure 3 and its velocity vector, V, increases the drag force acting on the ship.

Motion model of a ship or vessel with acting forces and moments is shown in Figure 1.

A seagoing vessel is subjected to forces from wind, waves and current as well as from forces generated by the propulsion system.

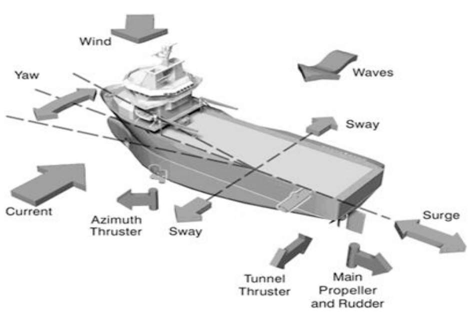

Fig. 1: Motion model of a see going ship with acting forces and moments

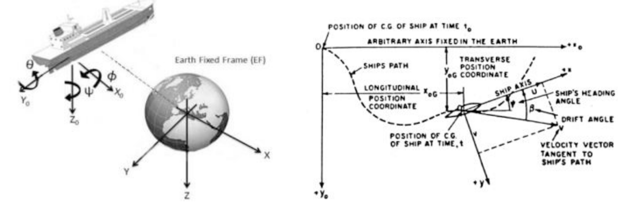

Fig. 2: Orientation of fixed and moving axes

The vessel's response to these forces, i.e. its changes in position, heading and speed, is measured by the position-reference systems, the gyrocompass and the vertical reference sensors. Reference systems readings are corrected for roll and pitch using readings from the vertical reference sensors. Wind speed and direction are measured by the wind sensors.

The dynamic positioning control system calculates the forces that the thrusters must produce in order to control the vessel's motion in three degrees of freedom - surge, sway and yaw - in the horizontal plane.The system is designed to keep the vessel within specified position and heading limits, and to minimise fuel consumption on the propulsion equipment.

Dynamic motion and analysis of a ship is associated with the knowledge of the couplings between roll, yaw, and sway and this is an important task to improve the manoeuvring ability and modelling.

3.EQUATIONS OF MOTION

The basic dynamics of manoeuvring and course-keeping can be described and analysed using Newton's equations of motion. Basic equations in the horizontal plane can be considered first with reference to onset of axes fixed relative to the earth and a second set fixed relative to the ship.

Figure 2 shows typical fixed and moving axed for a surface ship. The path is usually defined as the trajectory of the ship's centre of gravity. Heading refers to the direction (ψ angle of yaw) of the ship's longitudinal axis with respect to one of the fixed axes. The difference between the heading and the actual course (or direction of the velocity vector at the centre of gravity) is the drift or leeway angle β.When the ship is moving along a curved path, the drift angle is thus the difference in direction between the heading and the tangent to the path of the centre of gravity.

The motion of a ship in six degrees of freedom is considered as a translation motion (position) in three directions: surge, sway, and heave; and as a rotation motion (orientation) about three axes: roll, pitch and yaw. To determine the equations of motion, two reference frames are considered: the inertial or fixed to earth frame O that may be taken to coincide with the ship-fixed coordinates in some initial condition and the body-fixed frame O0— see Figure 1. For surface ships, the most commonly adopted position for the body-fixed frame is such it gives hull symmetry about the x0z0-plane and approximate symmetry about the y0z0-plane, while the origin of the z0 axis is defined by the calm water surface The magnitudes describing the position and orientation of the ship are usually expressed in the inertial frame and the coordinates are noted: [x y z]t and [φ θ ψ]t respectively, whilst the forces [X Y Z]t, moments [K M N]t, linear velocities [u v w]t, and angular velocities [p q r]t are usually expressed in the body-fixed

$$J(\phi,\theta,\psi) = \begin{bmatrix} c(\psi)c(\theta) & -s(\psi)c(\phi)+c(\psi)s(\theta)s(\phi) & s(\psi)s(\phi)+c(\psi)c(\phi)s(\theta) \\ s(\psi)c(\emptyset) & c(\psi)c(\phi)+s(\phi)s(\theta)s(\phi) & -c(\psi)s(\phi)+s(\psi)c(\phi)s(\theta) \\ -s(\theta) & c(\theta)s(\phi) & c(\theta)c(\phi) \end{bmatrix}$$

$$\mathrm{M_{RB}}\dot{\nu} = \tau(\dot{\nu},\nu,\eta) - \mathrm{C_{RB}}(\nu)\nu \tag{5}$$

Where MRB is the matrix mass and inertia due to rigid body dynamics, the term CRB(ν)ν arise from the coriolis and centripetal forces and moments also due to rigid body dynamics, and J(η) is given in (3). The forces and moments vector τ is defined as

$$\tau = [\mathrm{X} \quad \mathrm{Y} \quad \mathrm{Z} \quad \mathrm{K} \quad \mathrm{M} \quad \mathrm{N}]^{\mathrm{T}} \tag{6}$$

And these magnitudes are generated by different phenomena and can be separated into components according to their originating effects:

τ = τhyd + τcs + τprop + τext where

• hyd: These forces and moments arise from the movement of the hull in the water.

prop: These forces and moments come from the propulsion system, e.g., propellers and thrusters.
• cs: These forces and moments arise due to the control surfaces (CS) like rudder, fins, etc. movement.
• ext: These are the forces and moments acting on the hull due to the environmental disturbances, e.g., wind, currents and waves.
Motions in pitch and heave can generally be neglected in comparison with the other motions for conventional surface ships; thus, ship motion modelling can be considered only 4-DOF: surge, sway, yaw and roll. Therefore, from (6) the following approximations can be made:

$\dot{\phi} = p \quad \dot{\psi} = r\cos(\dot{\phi}) \qquad (7)$

In the sequel we treat only the motion in four degrees of freedom (4-DOF.) For this case, the equations of motion (8) are

$$\begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & -mz_G & -mx_G \\ 0 & -mz_G & I_{xx} & 0 \\ 0 & mx_G & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ K \\ N \end{bmatrix} + \begin{bmatrix} m(vr + x_G r^2 - z_g pr) \\ -mur \\ mz_G ur \\ -mx_G ur \end{bmatrix} (8)$$

where m is mass of the ship, Ixx and Izz are the inertias about the x0 and z0 axes, and xG and zG are the coordinates of the centre of gravity CG with respect to the body-fixed frame, i.e., CG = [xG, 0, zG].

4.SIMPLIFIED EQUATIONS OF MOTION FOR DIFFERENT MANOEUVRİNG ACTİONS

4.1. Surge Equation

The basic dynamics of manoeuvring and course-keeping can be described and analysed using Newton's equations of motion

As introduction into ships dynamic a simplified approach for the equations of ships motion and samples for manoeuvres on straight track in one degree of freedom (1 DOF) like coasting from full ahead to stop can be given with (1)

$$m\frac{dV}{dt} = \Sigma F \qquad (1)$$

For this basic ship motion on straight track this equation represents the equilibrium of forces on the ship: the forces of inertia on the left side due to the acceleration of the ship (consisting of ships mass and added mass, multiplied by acceleration from changing ships speed per time) are balanced by the forces on the right side due to constant motion (consisting of the thrust T of the propeller and the ships resistance R).

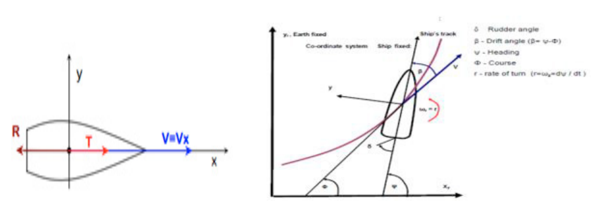

Fig.3 General ship motions

For modelling of the forces resistance and thrust several of motion which has the character of an Ordinary Differential Equation (ODE) of first order, normally non-linear due to the character of the forces T and R.

In the following the effect of these forces in a simplified way for two specific manoeuvres will be described.

4.2. Coasting Stop Manoeuvre

During the coasting stop manoeuvre the engine will be brought to STOP when the ship has a certain initial speed Vo. Due to the resistance the ship will slow down, the propeller is assumed to generate no thrust anymore, T=0.
For the resistance the following formula will be taken into account
R= CR* (ρ/2)* V2* A
This leads to a simple equation of motion:
(m)(dV/dt)= CR* (ρ/2)* V2* A
If the resistance coefficient CR and the ships lateral area A are taken as constants we can put them together into the constant C and get:
dV/dt= C.V2/(m)
and the exact solution as :

$$V = \frac{m+m_x}{C.t+\frac{m+m_x}{V_0}}$$

4.3. Acceleration and Crash stop manoeuvre

For the complete speed behaviour the thrust T has to be added to the equation of motion:

$$(m\frac{dV}{dt} = T - R) \qquad (2)$$

for a Thrust force using the equation

$T= K_T.\ \rho.D^4\ .n^2 \qquad (3)$

where D is the propeller diameter, n revolutions, ρ water density;

Kτ – Thrust coefficient ,The thrust coefficient Kτ (J) can taken from experiments as open water propeller diagram which is suitable to represent manoeuvring conditions for constant speed and small accelerations/decelerations between speed ranges from zero to service speed.

Both the motions and the forces are defined in the ship reference frame, with the origin located at the ship’s centre of mass. Therefore, in the solid body motion model the ship’s translational motion is expressed by:

$$m_{ship}\frac{d_{v_s}}{d_t} + D_{trans}v_s = F_{ship} + F_{rudder} + F_1 z + F_{coriolis}$$
(4)

where F_{ship} includes the restoring forces and the pressure forces on the ship hull, Flzs is the lift force of the bare hull, and $F_{Coriolis}$(3) is the Coriolis force due to the movement of the ship coordinates with the yaw motion

The solid body rotation is governed by the Liouville equation defined in the ship reference frame:

$$I.\frac{d\Omega}{dt} + \Omega \times (I.\Omega) + D_{rotat}\Omega = \Gamma_{Ship} + \Gamma_{rudder} + \Gamma_{c(I)} + \Gamma_{Coriolis(3)} \qquad (5)$$

The forces and moments generated by the deflected rudder are described by the following expressions

$$Fx = 0.5 * \rho * V^2 * A * \mathrm{Sin}^2\delta * \quad (6)$$

$$Fy = 0.0.5 * \rho * V\hat{}2 * A * \mathrm{Sin}\,\delta * \cos\delta \quad (7)$$

and Ruder moment M can be written as

$$M = 0.25 * \rho * V\hat{}2 * A * \mathrm{Sin}2\delta * R \quad (8)$$

The equations of motion:

Longitudinal forces in x-direction $m * \frac{dVx}{dt} - m * Vy * wz = Fx$

Longitudinal forces in y-direction $m * \frac{dVy}{dt} + m * Vx * wz = Fy$

Yawing moment around –z axis $I * \frac{dWz}{dt} = Mz$

Linear Speed Translation Vector:

$$V = \begin{bmatrix} Vx = \text{surge} \\ Vy = \text{sway} \\ Vz = \text{heave} \end{bmatrix} = \begin{bmatrix} V.\mathrm{Cos}\beta \\ -V.\mathrm{Sin}\ \beta \\ 0 \end{bmatrix} \quad (9)$$

Angular Speed Vector:

$$\omega = \begin{bmatrix} \omega x = \text{roll} \\ \omega y = \text{pitch} \\ \omega z = \text{yaw} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \omega z \end{bmatrix} (10)$$

5.MATLAB SIMULATION AND NUMERICAL VALUES FOR SIMULATION EVALUTION

According to the motor speed and ruder angle as Inputs a general block diagram model of ship motion and dynamics is shown in Fig.4 The details of this simulation scheme is demonstrated in Fig.5

To describe the different manoeuvring actions of the non-linear system with simplified equations for surge, sway and yaw motions a detailed Matlab-Simulink block diagram representation in Fig.5.is used. Simulation results of outputs with different motor speeds and ruder angles as input variables are evaluated and shown with relevant graphics.

For the numerical evaluation following datas of a model vessel ship are used:

M=4000 ton (mass of ship)
Normal velocity. V=20 Knot
D=1500 cm (Diameter of Propeller)
n= 225 rev/min (motor speed)
ρ=0.001025 Kg/cm3 (density of water)
L=12000 cm (Length of the ship)
B=1400 cm (width of the ship)
A=460000 cm2 (Ships lateral area

KT=0.14 (Thrust coefficient)

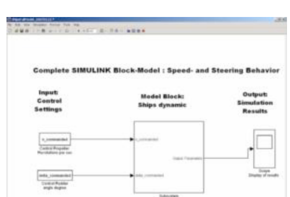

Fig.4 General Simulation Block presentation of ship dynamics

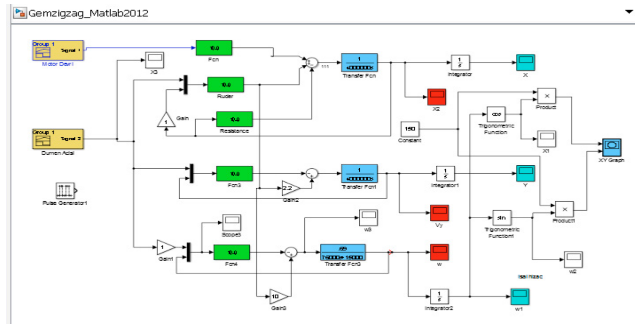

Fig.5 General Simulink simulation model of the ship motion and steering

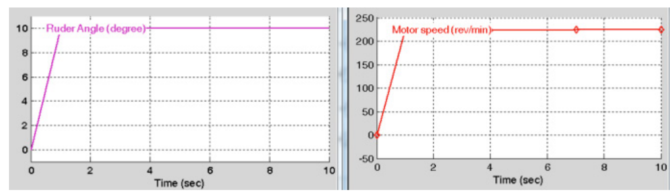

Fig.6.a.Ruder angle and Motor speed changes as Input variables

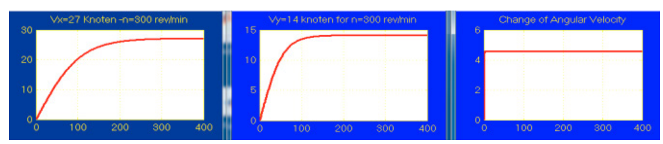

Fig.6.b Simulation test results of thrust-sway and angular velocities according to above input changes in Fig.6a

5.1. Turning tests

The results like surge – sway and yaw speed changes according to the motor speed and various ruder angle changes are presented in Fig.6.a and 6.b. For different ruder angles from 10 to 20 and 30 degrees the change of turning manoeuvres of ship are demonstrated with different graphics of turning circles as given in Fig.7 From test results demonstrated in Table 1 it can be seen clearly the reducing diameter of turning circle with increasing ruder angle.

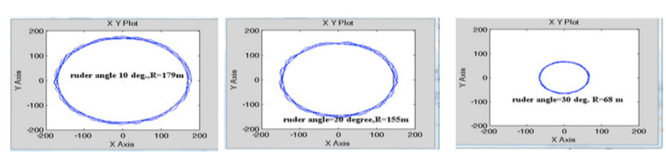

Fig.7 Turning circle manoeuvre with different ruder angles

Table 1. Change of Turning Angle according to motor Speed and Ruder Angle

Motor Speed(rev/min)	Ruder Angle(degree)	Turning Circle Diameter(cm)
225	10	17900
225	20	15500
225	30	6800
300	10	18200

On the other hand the effect of changing motor speed from 225 to 300 rpm/min on surge-sway and angular velocities with relevant change on turning radius are demonstrated in Table.1 and Fig 7

With increasing rate of motor speed increase also the surge speed from 20 to 27 Knot and sway speed from 10 to 14 Knot. The effect of ruder angle by using simulation diagram in Fig 5 is also demonstrated in Fig.8. From given graphics it can clearly be seen the rein forward motion without sway and yaw motions when there is no ruder deflection. In this case the ship moves only under the influences of thrust and resistance forces. With increasing motor speed also the surge velocity can be increased

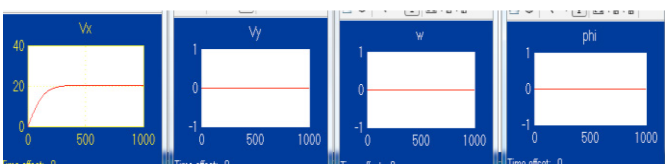

Fig.8 Thrust motion without ruder deflection

5.2. Zig-Zag manoeuvring test

Lastly Zig-Zag ability according to changes of ruder angle is also demonstrate in Fig.9 Here changes of sway velocity, heading and angular velocity of turning are demonstrated for a periodical change of ruder angle between 0-10 degrees, with a periodical change of 100 and with a pulse width of 30 seconds. As seen from these Graphics ship shows a very good zig - zag tracking ability to follow periodical changes of ruder..

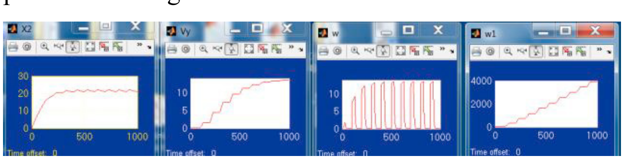

Fig.9.Responses of sway and angular velocities and heading according to periodical change of ruder

6.SHIPS ROLLING MOTION

6.1. Roll Equations and Simulation Model

Using a simplified Roll motion model with following linearized equation is also investigated with Matlab-Simulink .Block diagrams given in Figure 10

The equation of motion for the ships rolling represented by the balance of moments around the longitudinal x-axis of the ship as;

$$I.*\varphi'' + d.\varphi' + D*g*GZ(\varphi) = MR'' \quad (11)$$

where:

I_x, is the moment of inertia around x-axis of ships mass

d – damping coefficient

D – displacement mass of ship

G – gravity constant

GZ – upright lever of restoring moments

MR – external moment

Division by Ix produces a result in the more suitable form:

$\varphi'' + \delta*\varphi' + g*GZ(\varphi)/k2 = MR$ (12)

with k - radius of inertia ≈ 0,37 to 0,5 • B, normally represented by k=Cr • B, where Cr is the inertia coefficient for rolling motion and B is the ships beam.

The result of this differential equation specifically for the steady state motion with small Rolling angles Φ is well known to ships officers: For small rolling angles we can replace GZ by using the metacentric height GM=GZ (Φ)=GM• sin(Φ), which can be further simplified by sin(Φ) ≈ Φ. The natural roll time period can be calculated then as in following formula

$T = (\pi.Cr.B)/\sqrt{(g.GM)}$ (13)

6.2. Simulation Results of Roll Experiments

Results for ships rolling motion are investigated with relevant Simulink diagram given in Fig.10

For demonstrating the dynamic characteristics of the ships rolling motion the behaviour after certain initial disturbances are calculated. The ship starts from an initial heeling and then it is released

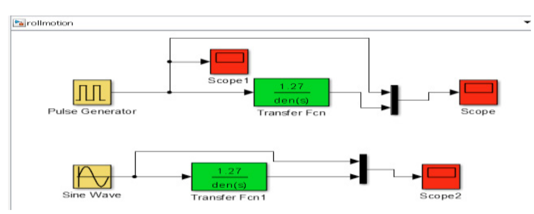

Fig.10 Simulation diagram of roll motion

Two different Input functions are used to investigate the rolling behaviour; as first a pulse function with a period of 30 seconds and amplitude of 10 degree is applied. To demonstrate the frequency response a harmonic function of frequency f=0.5 Hz with an amplitude of 10 degree is applied. Both responses are then shown with graphics in Fig.11.The roll time periods Tr =12 s is measured during the oscillations.

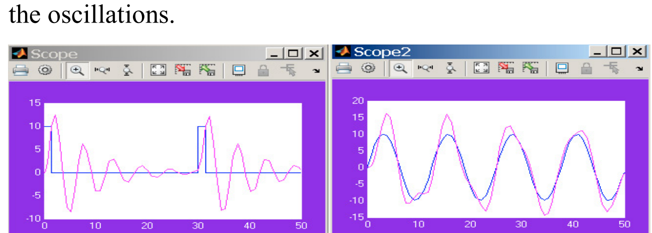

Fig. 11: Results for ships rolling motion without waves

Following results are obtained from simulation tests: :

- Due to the damping effect the amplitudes of the oscillations decreases.

- For the GZ (Φ) curves with rising characteristic the roll time period Tr is getting smaller because of the larger restoring moments for higher roll angles

- For the GZ (Φ) curves with falling characteristic the roll time period Tr is getting higher.

7.CONCLUSIONS

In this paper the motion dynamics of a ship with simplified but non-linear modelling using Matlab-Simulink is investigated and with various graphics demonstrated.

After a brief introduction to basics of ship dynamics (manoeuvring and course-keeping) general equations of motion in the horizontal plane are derived by using Newton's laws.

In the modelling as mentioned before, motions in pitch and heave are neglected in comparison with the other motions and only the impact of rudder (as hydrodynamic) and motor speed with inertial forces and moments are taken in to consideration

The forces and moments (left hand side) of the equations of motion (10) are built up four types of forces that act on a ship during a manoeuvre:

- Hydrodynamic forces acting on the hull and appendages due to ships velocity and acceleration, ruder deflection, and propeller rotation.
- Inertial reaction forces caused by ship acceleration.
- Environmental forces due to wind, waves and currents.
- External forces such as tugs or thrusters.

The first two types of forces generally act in the horizontal plane and involve only surge, sway and yaw responses, although rolling effects (heel) occur in the manoeuvring of high-speed ships. Hydrodynamic forces fall into two basic categories, those arising from hull velocity through the water (damping forces) and those arising from accelerations through the water (added mass forces). The ship accelerations produced by these and any external forces result in balancing inertial reaction (d'Alembert Forces and Moment), especially when turning.

The effect of a rudder on turning is indirect. Moving the rudder produces a moment that causes the ship to change heading so as to assume an angle of attack (leeway angle) to the direction of motion of the centre of gravity. Consequently, hydrodynamic forces on the hull are generated which, after a time, cause a change of lateral movement of the centre of gravity. The lateral movement is opposed by the inertial reactions. If the rudder remains at a fixed position, a steady turning condition will evolve when hydrodynamic and inertial forces and moments come into balance. Fig.[12]

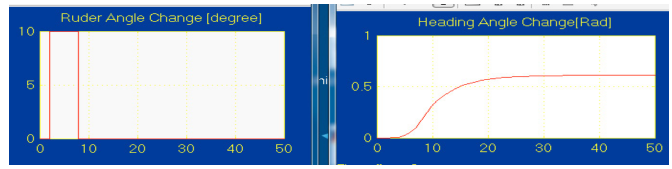

Fig.12 Heading Change with Ruder motion

The ship may also be operating and manoeuvring in an environment where wind, waves, and current are present. The effect of current is usually incorporated with the hydrodynamic forces by considering the relative velocity between the vessel and the water although studies in restricted water require more careful analysis. Wind and wave forces are generally treated as external forces as described in.

Wind velocity is generally unsteady and hence forces and moments due to wind will be time dependent. These forces are generally proportional to the above water area of the ship and the square of the relative velocity between the ship and the wind. Forces and moments also vary with the direction of the wind velocity relative to the ship's axes.

Two distinct types of wave forces act. The steady and slowly varying forces due to second-order wave drift effects are generally more important for ship controllability than the first-order forces, which are of primary importance for sea-keeping. However, the latter can be important for the case of following seas where frequency of encounter is small. Wave drift forces depend primarily on ship length and on the relative magnitudes of wave length and amplitude.

Pitching motion changes the shape of the immersed hull and can therefore have significant effects on the coefficients in the equations of motion, particularly in quartering and following seas.

Finally, tugs and thrusters create effective forces when utilized at relatively slow speeds. The forces they develop are for the most part external to the hydrodynamics of the manoeuvre and are normally treated as independent additions.

The simple case of controllability, assuming a calm open sea without wind, waves, current and external forces can also be considered as described in.

In a previous work the cascade navigation control is further demonstrated with a built up real like model implementation.This is especially thought as a teaching model which emphasizes various control actions and their results. As future work results from fast time simulation of several manoeuvres using obtained with Matlab Simulation will be used to improve a more enhanced visual program version. This can be very helpful for providing knowledge on the dynamics of ship motion in university level and perhaps as a training basis for maritime students.

REFERENCES

Abkowitz, M.A. (1975), "*Lectures on ship hydrodynamics-steering and manoeuvrability*", Technical Report Rep. No. Hy-5 , Hydro og Aerodynamisk Laboratorium Lyngby,Denmark,

Blanke, M. and A. Christensen, "*Rudder roll dumping autopilot robustness to sway-yaw-roll couplings*", pp. 93–119,Proceedings of 10th SCSS, Ottawa, Canada

Blanke, M. and A.G. Jensen, (1997) "*Dynamic properties of container vessel with low metacentric height*", Technical Report doc. No. R-1997-4173, Dept. of Control Engineering, Aalborg University, Denmark,

Blanke, M., P. Haals and K.K. Andreasen, (1989) "*Rudder roll damping experience in Denmark*", Proceedings of IFAC work shop CAMS'89, Lyngby, Denmark,

Blanke, Mogens, (1981), "*Ship propulsion losses related to automatic steering and prime mover control*", PhD thesis, Servo laboratory, Technical University of Denmark, Lyngby Denmark,

Chislett,M.S.,(1990),"*The addition of heel-roll servo mechanism to the dmi horizontal planar motion mechanism*", Proc. of MARSIM and ICSM, Tokio, Japan,

CHISLETT, M. S., ~ND STROM-TEJSEN, g. 1965 Planar Motion Mechanism Tests and Full-Scale Steering and Maneuvering Predictions for Mariher Class Vessel, Technical Report Hy-6, Hydro- and Aerodynamics Laboratory, Copenhagen, Demark.

T.I. Fossen, (1994) "*Guidance and Control of Ocean Marine Vehicles*", John Wiley and Sons Ltd. New York, US,

Goodman, A. and M. Gertler, (1962), *"Planar motion mechanism system*", US patent 3052120,

Källström, C.G. and P. Otterson,(1983) "*The generation and control of roll motion of ships in closed turns*", Proc. 4th-IFAC/IFIP Symposium on Ship Operation Automation, Genova, Italy

S. Arikan, E. Uyar, (2014) "*Built Up Implementation Model for Cascade Ship Navigation*", Dipl. Thesis, Ege University, Electrical & Electronics Engineering Department, İzmir, Turkey,

Son, Kyoung-Ho, and K. Nomoto, (1982) "*5. On the Coupled Motion of Steering and Rolling of a High-speed Container Ship.*", p.73-83, Naval architecture and ocean engineering 20, Dept. of Astronomy, U. of Tokyo 113, Japan

J.van Amerongen, (1982) "*Adaptive steering of ships - A model reference approach to improved manoeuvring and economic course keeping*", PhD thesis. Delft University of Technology, The Netherlands,

P.G.M. van der Klugt, (1987) "*Rudder roll stabilization*", PhD thesis. Delft University of Technology,Netherlands,

T. Perez, M. Blanke, (2002) "*Mathematical Ship Modeling for Control Applications*",Technical Report, Dept. of Electrical and Computer Engineering The University of Newcastle, NSW, 2308, Australia Section of Automation at Ørsted.DTU Technical University of Denmark, Building 326 DK-2800 Kgs. Lyngby, Denmark

Erjen Lefeber, Kristin Ytterstad Pettersen, and Henk Nijmeijer,(2003),"*Tracking Control of an Underactuated Ship*".IEEE transactions on control systems technology, vol. 11, no. 1, Dept. of Mech. Eng., Eindhoven Univ. of Technol., Netherlands

Ray-Qing Lin • Michael Hughes • Tim Smith. (2010) "*Prediction of ship steering capabilities with a fully nonlinear ship motion model. Part 1: Maneuvering in calm water*". pp. 131–142,J Mar Sci Technol 15:131–142.DOI 10.1007/s00773-010-0084-z Marine Science and Technology, Tokyo, Japan,