THEORY, ANALYSIS, AND DESIGN METHODOLOGY FOR SHIP MANEUVERABILITY

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Contents

Summary

Ships are vital in world trade and logistics, and maneuverability is an important ability of ships to perform the navigation and mission of the voyage. Maneuverability is essential for the operation and soundness of any ship from the danger of collisions and stranding. It is directly related to the safety of the ship, and composed of turning, course change, course keeping, speed change and stopping ability etc. The dynamics of ship motion and structures of hydrodynamic forces and moment in a simultaneous equation of motion, the so-called 'hydrodynamic model', are explained first. Simplified differential equations of ship motion to the steering response in a different viewpoint and approach are also shown. It is called 'response model'. These dynamic theories and models are principle of maneuverability, and they are applied to auto-pilot system design and other advanced navigation systems.

In the latter part, navigation and ship control are discussed in the relationship between ship maneuverability and ship safety. A large time constant of steering response and the directional instability of very large crude oil carriers (VLCC) require the seamen to work under extreme pressure. The Maneuvering Standard of International Maritime Organization (IMO) had been established after tragic maritime accidents and environmental pollution by heavy oil spills. A land based marine traffic control and information support is also necessary for the safe navigation in congested waters. Ships are designed primary in economical point of view, but maneuverability as capability of ship performance for safe navigation is also quite important in practice. Improvement of ship maneuverability in various approaches including onboard navigation equipments and bridge design etc. are introduced.

1. Preface

Maneuverability is defined as performance ability of ships related to ship motion due to steering. It is an important ability of ships to perform the navigation and mission of the voyage. Because maneuverability is essential for the operation and soundness of ship in averting the danger of collisions and stranding, it is directly related to the safety of ship. It is composed of turning, course change, course keeping, speed change, stopping ability etc. The dynamics of ship motion and structures of hydrodynamic forces and moment are explained first. A different explanation of ship response to the steering is also shown.

Auto-Pilot systems were developed and applied in practice in 1920's as automation of steering devices for keeping heading angle of ships. At present the system is not be considered as a steering device but a total navigation system inevitable at ocean and congested water ways.

Ships are vital in world trade and logistics, and shipping business and shipbuilding industries both have world market, and ships are designed primary in economical point of view. After tragic maritime accidents, especially heavy oil spills from huge tanker disasters and their environmental pollution, IMO (International Maritime Organization) had established the Maneuvering Standard in order to shut out so-called Sub-Standard Ships. Because a large time constant of steering response and the directional instability of very large crude oil carriers (VLCC) required seamen to work under severe pressures, sometimes beyond human ability. Maneuverability of ships as capability of ship to perform the safe navigation which is quite important in practice is also discussed. Improvement of ship maneuverability, onboard navigation equipments and bridge design are achieved as well as skill up training by ship handling simulators with real time computer graphics contribute to maritime safety and environmental protection. A land based marine traffic control and information support by the Maritime Authority is also necessary to keep the safety level of navigation in congested waters, is introduced.

2. Principle of Steering

When a ship is running in a straight course with a constant propeller rotation and midship rudder position, a rudder movement induces the ship to turn and the heading angle changes. Keeping the rudder angle constant, the ship reaches a steady turning condition with constant radius within a few minutes. The plots of the inverse of radius of circular trace of the ship against the rudder angle give $r \sim \delta$ curve which represents turning ability of the ship. A ship in a steady turning condition is shown in Figure 1, where R, r, V, β represents radius of turning, angular velocity of turning, ship speed and drifting angle respectively.

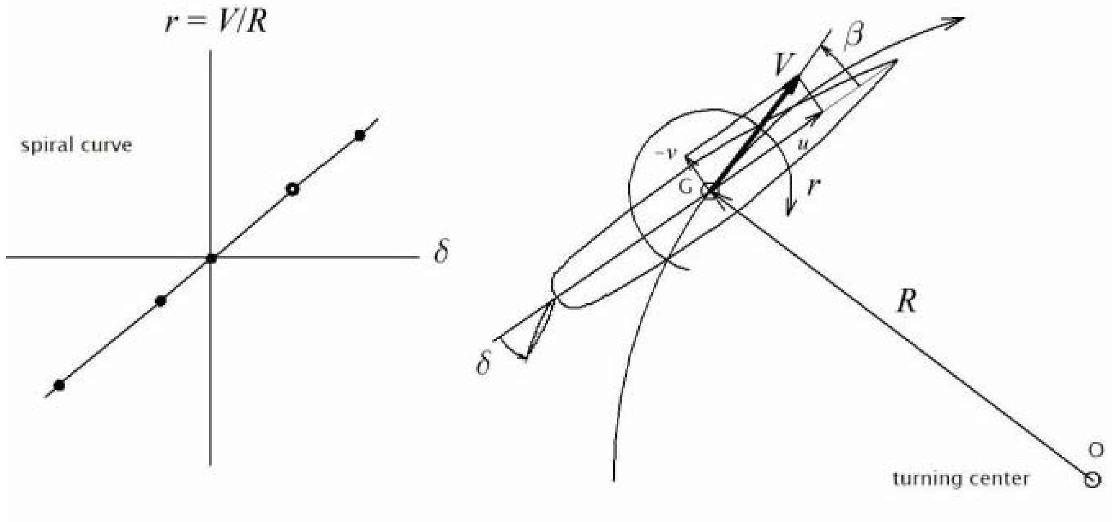

Figure 1. Steady turning state and spiral curve

A transition from straight forward running condition to a steady turning by a rudder movement is easily understood. Let’s see the principle and dynamic mechanism of the steering (see Figure 2). For a ship running straight forward with a constant speed, its resistance balances with propeller thrust in longitudinal direction. Hydrodynamic force in lateral direction acting on the ship in the condition is zero, because flow field is symmetrical in the lateral direction and hydrodynamic pressures on the hull surface in port and starboard balance each other.

Flow field near ship stern and rudder changes by the movement of rudder.

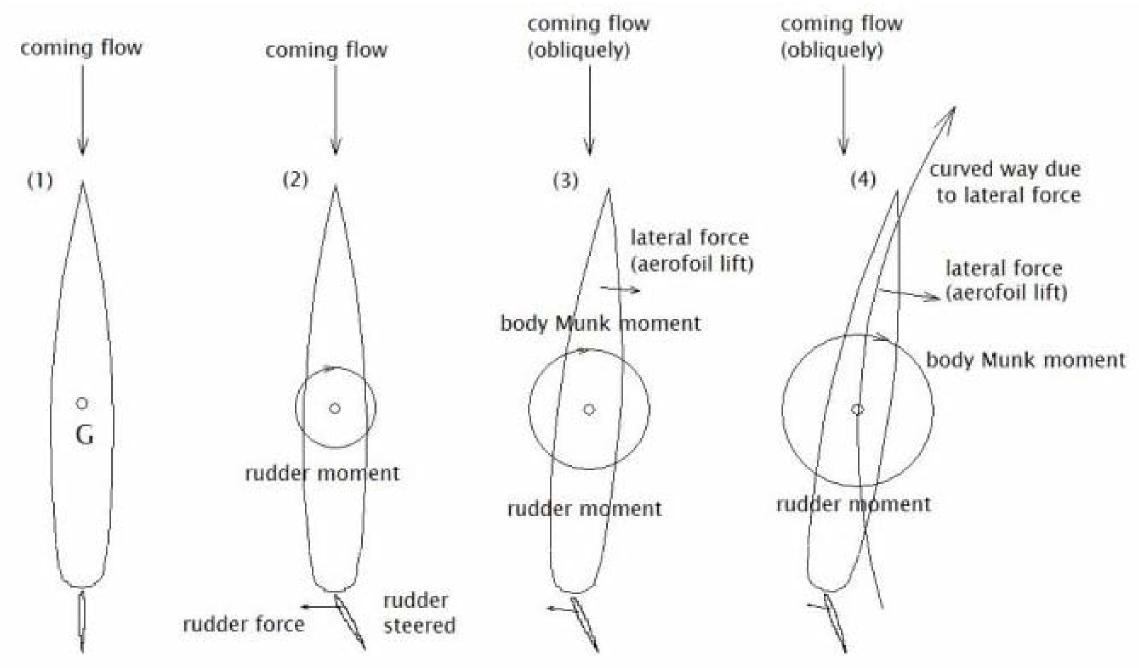

Figure 2. Schematic explanation of transition from straight running to turning

By means of aerofoil effect of the rudder, lift force acting on the rudder induces rotational moment to turn the ship hull slightly. Then the hull has drift angle to the main flow and induces lateral force and rotational moment. The lateral force on the hull is lift force when the hull is considered as a wing. Even the lift coefficient is a poor characteristic because the wing has small aspect ratio and big thickness, a large area makes comparable force as rudder lift. Moreover unstable hydrodynamic moment on the hull, called as Munk moment (Ashley 1965, Newman 1977), plays an important role in the turning motion.

When these hydrodynamic forces and moments and inertial force and moment balance, the ship reaches steady turning condition. Hydrodynamic force acting on the rudder is similar to the lift of wing of birds or airplane.

In order to understand or study more precise mechanism of ship steering, equations of ship motion should be introduced. The equation of motion is based mainly upon Newton's Law.

3. Basic Equation of Ship Steering Motion

Consider a ship running with constant speed in still water and calm air. The maneuvering motion of the ship due to rudder steering is described by the yaw angle ψ (heading direction angle), forward speed u, transverse speed v of the center of gravity of a ship and the rudder steering angle δ (drift angle $\beta = -v/u$). See the coordinate system and positive direction of those quantities in Figure 3, where the positive direction of each quantity is shown by the arrow head. The positive rudder angle is defined as it generates the positive yawing. The dynamic behavior of these quantities is governed also by the Newton's laws of rigid body dynamics. It can be written by the following equations with respect to the axes fixed on a ship shown in Figure 3, introduced as the Euler's equations.(Crane 1989, Motora 1982, Hirano 201)

$$\left.\begin{aligned} m\dot{u} - mvr &= X(u,v,r,\delta,\dot{u},\dot{v},\dot{r}) \\ m\dot{v} + mur &= Y(u,v,r,\delta,\dot{u},\dot{v},\dot{r}) \\ I\dot{r} &= N(u,v,r,\delta,\dot{u},\dot{v},\dot{r}) \end{aligned}\right\} \quad (1)$$

where, the dot denotes differentiation with respect to time and
m ; Mass of the ship
I ; The moment of inertia respect to the vertical axis at the center of gravity of the ship
X, Y ; Longitudinal and transverse hydrodynamic forces acting on the ship
N ; Hydrodynamic moment respect to ship's center of gravity
r ; Angular velocity of turn, which has the relation, $r = \dot{\psi}$; it is also called yawing rate.

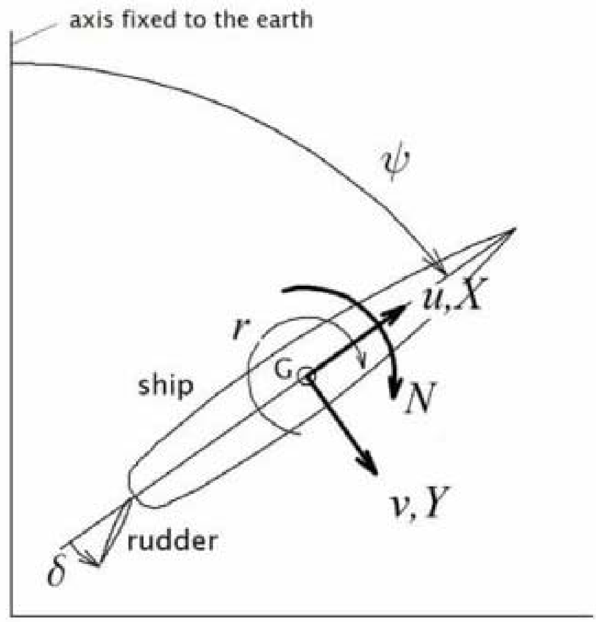

Figure 3. Coordinate system of maneuvering motion

3.1. Virtual Masses and Virtual Moment of Inertial

The hydrodynamic forces have the components proportional to the acceleration of the body. The proportional factors are called added masses and added moments of inertia. They come from the mass of water around the ship in steering motion. Denote the longitudinal and transverse added masses m_x, m_y and added moment of inertia J_z, the equation of motion is described as (Lamb 1932, Inoue 1964)

$$\left.\begin{aligned} &(m+m_x)\dot{u} - (m+m_y)vr = \overline{X}(u,v,r,\delta) \\ &(m+m_y)\dot{v} + (m+m_x)ur = \overline{Y}(u,v,r,\delta) \\ &(I_z+J_z)\dot{r} = \overline{N}(u,v,r,\delta) \end{aligned}\right\} \quad (2)$$

Here the rest of those hydrodynamic forces are represented as $\overline{X}, \overline{Y}, \overline{N}$. The terms, $(m+m_x)$, $(m+m_y)$ and (I_z+J_z) are called virtual masses and virtual moment of inertia which are typical terms seen in ship motions compared with those of airplane. The added mass is proportional to the fluid density ρ around the body; therefore it is not negligible in ship motion and is negligible in air plane, because the values are comparable to the mass of the ship, according to the hydrodynamic theoretical calculation and experimental results. (Newman 1977, Saunders 1965, Motora 1959, Motora 1960a, Motora 1960b)

The added mass and added moment of inertia are derived from the analysis of inviscid fluid while the rest of the terms of the hydrodynamic forces are derived from viscous effect of the water. It is remarkable that the second terms of the top two equations have added masses. Those terms indicate the centrifugal forces of the ship in turning motion and they are also affected by added masses (Lamb 1932).

3.2. The Characteristics of Hydrodynamic Damping Forces and Propeller, Rudder Exciting Forces

$\overline{X}, \overline{Y}, \overline{N}$ in the right hand side of Eqs. (2) are called hydrodynamic damping forces and moment because of the dependence upon the velocities of the ship, u, v and r. They consist of the forces or moment acting on the hull, propeller and rudder. They are dependent on the shapes and configurations of the hull, propeller and rudder, affected by the flow field conditions as well as the working condition such as propeller revolution and rudder angle.

$$\left.\begin{aligned} \overline{X} &= X_{\mathrm{M}} + X_{\mathrm{P}} + X_{\mathrm{R}} \\ \overline{Y} &= Y_{\mathrm{M}} + Y_{\mathrm{P}} + Y_{\mathrm{R}} \\ \overline{N} &= N_{\mathrm{M}} + N_{\mathrm{P}} + N_{\mathrm{R}} \end{aligned}\right\} \qquad (3)$$

In this expression each subscript means as follows.

M; force or moment due to ship motion
P; force or moment due to propeller action
R; force or moment due to rudder action

The representation of $\overline{X}, \overline{Y}, \overline{N}$ as functions of those velocities is much complicated. The flow field around hull is very difficult to analyze theoretically because of the viscous effect and the sophisticated geometry of the hull surface. It is also affected by the propeller slip stream and rudder working very closely with each other. By these terms hydrodynamic interactions of the ship hull, the propeller and rudder and their movement are represented. Then there can be considered several models of those effects, but a perfect representation has not been established yet. It is hard to show it reasonably in the detail. So let's see the characteristics of those effects by referring mainly the mathematical model proposed by the MMG in Japan as an example (Ogawa 1981, Kose 1981).

3.2.1. Forces and Moment due to the Ship Motion

The hydrodynamic forces and moment are represented as following series expansions in case of transversely symmetric hull.

$$\left.\begin{aligned} X_{\mathrm{M}} &= -R(u) + X_{vv}v^2 + X_{vr}vr + X_{rr}r^2 \\ Y_{\mathrm{M}} &= Y_v v + Y_r r + Y_{vvv}v^3 + Y_{vvr}v^2 r + Y_{vrr}vr^2 + Y_{rrr}r^3 \\ N_{\mathrm{M}} &= N_v v + N_r r + N_{vvv}v^3 + N_{vvr}v^2 r + N_{vrr}vr^2 + N_{rrr}r^3 \end{aligned}\right\} \quad (4)$$

Here R is the ship resistance merely depending on u. The terms $Y_v v, N_v v$ resemble the lift and moment of wing. The linear terms respect to the variables v and r play important role in the response of steered ship which will be mentioned later. Those linear coefficients are called maneuvering derivatives of the ship hull.

3.2.2. Forces and Moment due to the Propeller Action

In running ahead condition with constant propeller revolution in ordinary direction, forces acting on the ship due to the propeller action are simple. The longitudinal components only exist and it consists of the hydrodynamic force on the hull and the thrust T at the propeller shaft. The resultant longitudinal force is $X_{\mathrm{P}} = (1-t)T$ with small amount of thrust reduction ratio t. T is described by the product of the propeller revolution rate n, propeller diameter D and thrust coefficient K_{T} give by the propeller performance; $T = \rho D^4 n^2 K_{\mathrm{T}}$

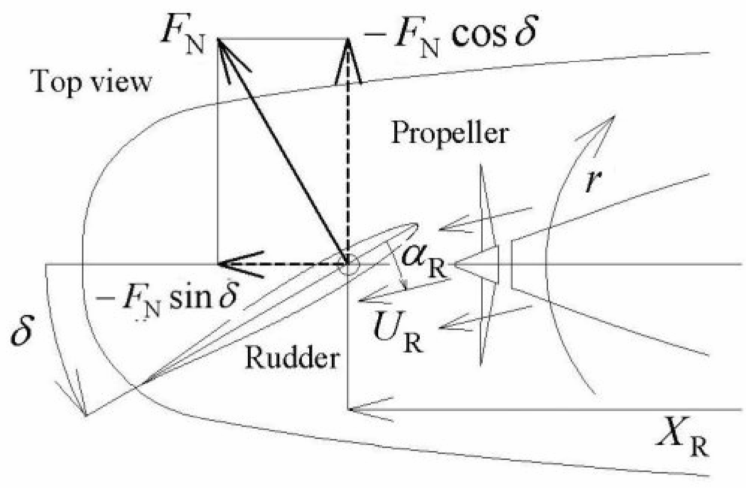

Figure 4. Rudder normal force

3.2.3. Force and Moment due to the Rudder Action

The horizontal sectional shape of the rudder is symmetric and just same as wing sections of airplane. The rudder generates lift force by the steered angle. The force is usually defined as the normal force F_{N} on the rudder’s symmetrical plane (see Figure

4), and presented by

$$F_N = (1/2)\rho \cdot A_R \cdot U_R^2 \cdot f_R \cdot \sin\alpha_R \tag{5}$$

Here α_R is the incident angle of inflow to the rudder that is made by rudder steered angle and the resultant flow of propeller slip stream and ship turning motion. Here f_R is the performance coefficient of the rudder section as a wing. This expression explains the effect of rudder area A_R and incident flow speed to the rudder U_R.

The resultant force and moment acting on the ship is described as follows.

$$\left.\begin{aligned} X_R &= -F_N \cdot \sin\delta \cdot (1 + a_X) \\ Y_R &= -F_N \cdot \cos\delta \cdot (1 + a_Y) \\ N_R &= -F_N \cdot \cos\delta \cdot (x_R - x_G)(1 + a_N) \end{aligned}\right\} \tag{6}$$

The rudder normal force F_N is the source of the forces induced by rudder. The force is projected to forward and transverse components by $\sin\delta$ or $\cos\delta$. The turning moment is the product of the transverse force and the distance $(x_R - x_G)$ from the rudder axis to the center of gravity of the ship. (Remark; the x coordinate is negative in the aft-body then $(x_R - x_G)$ has negative value.) Those forces are augmented by a_X, a_Y, a_N on the ship hull. Considering the hydrodynamic interactions and their correction by the similar concept as thrust reduction ratio *t*, factors a_X, a_Y, a_N are introduced there. (Remark;– N_R is expressed in slightly different form from MMG's formula.)

3.3. The Estimation and Utilization of the Equations

All the coefficients mentioned above are obtainable by the estimation based on some theoretical calculations or force measurement in some kinds of experimental tank with special equipment by using scale model of ship. Those estimations are works of much effort as shown in appendix. Those results are utilized in several simulations with above equations in the wide region from ship designing to the training simulator for professional operators of ships. To get the solutions of u, v, r and ψ as functions of time in above equations, numerical integration technique such as Runge-Kutta method is employed.

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Biographical Sketches

Dr. Takeshi Fuwa has been engaged in various research activities related to ship hydrodynamics, ship performance, ship motion and control, system engineering etc. He carried out active research studies for many years as a researcher and also as an executive director at the National Maritime Research Institute, Japan. Maneuverability has been his original major subject since graduated student age. He carried out many frontier studies such as Advanced Automatic Navigation System and High Speed Marine Vehicles including Wing-in-ground-effects. He is currently at the Japan Ship Technology Research Association.

Dr. Tatsuo Kashiwadani has been engaged in various studies related to ship hydrodynamics, maneuverability and marine propulsors. He carried out research studies and designs of naval ship at the Technical Research and Development Institute of Ministry of Defense, Japan. He carried out studies including water-jet inlet and biomechanical marine propulsor. He is currently at the Defense Technology Foundation.