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THE APPLICATION OF MATHEMATICAL MODELS AND BRIDGE SIMULATIONS IN THE FEASIBILITY STUDY OF SHIP MANOEUVRING

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Abstract: It is obvious that the development of modern bridge simulators nowadays provides an advanced tool for maritime training. Apart from the educational function, advanced simulators can, with the proper knowledge and tools, be exploited for the feasibility study of ship manoeuvring for existing ports, ships under operation as well as ships, ports and locks in the design phase. Thus, it is necessary to set up proper ship mathematical models and establish a scientific process for assessment of ship manoeuvring in simulators. This paper aims to systematically introduce mathematical modelling and proposes a method to assess the ship manoeuvring in six degrees of freedom and in real-time mode influenced by all possible forces on the vessel. The mathematical model and assessment method were used in applied research projects which have been conducted by the study group during the research period.

1 INTRODUCTION

The mathematical model of ship motions is considered as an artificial brain deciding the processing capability of a bridge simulation system and ensuring the reality of ship manoeuvring. It can be described as a set of differential equations based on Newton's equation. The factors of the equations are defined based on hydrostatic, hydrodynamic, aerodynamic theories and empirical data. Davidson and Schiff (1946) [1] set up a mathematical model for yawing and drifting in 2DOF. Nomoto (1957) [2] described a simple equation posted in Zosen Kiokai Journal. Norrbin (1971) [3], Inoue (1981) [4] and other researchers developed 3DOF model including surging, swaying, yawing. Eda (1980) [5], Hirano (1980) [6] and Oltmann (1993) [7] described 4 DOF model by adding the rolling motion. By adding heaving and pitching motions Ankudinov (1983) [8] and Hooft & Pieffers (1988) [9] established 6DOF model. A generalized mathematical model in 6 degrees of freedom in the form of a matrix can be referred in Fossen (2011) [10]. Based on the mathematical model, a simulation algorithm is set up to stimulate the ship motion in the bridge simulators. In the past, it was mostly developed for 3DOF limited to surging, swaying, yawing. Nowadays, more degrees of freedom are integrated into the model, but in frequently applied methods some components are simplified, ignored or added separately from the main equation for making the additional effects to experience rolling, heaving and pitching. To develop a ship mathematical model, a modeller must manually calculate all necessary hydrodynamic and hydrostatic coefficients or design it based on the mathematical model tools created by the simulator manufactures. More advanced mathematical model tool for 6DOF can be referred to the Kongsberg's publication [11].

The idea is how to use a suitable mathematical model to simulate the ship motion in six degrees of freedom and in real-time mode with satisfying behaviour for the feasibility study of ship manoeuvrability. This paper aims to systemize a detailed mathematical model and propose a method for assessment of the ship manoeuvrability in simulators taking into account all possible internal and external forces.

2 MATHEMATICAL MODELLING

Fundamentally, a general equation describing the ship motions can be described in six degrees of freedom in the form of the matrix:

$$M_S\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\\ \dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} + C_S(v)\begin{bmatrix}u\\ v\\ w\\ p\\ q\\ r\end{bmatrix} + M_A\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\\ \dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} + C_A(v)\begin{bmatrix}u\\ v\\ w\\ p\\ q\\ r\end{bmatrix} + D(v)\begin{bmatrix}u\\ v\\ w\\ p\\ q\\ r\end{bmatrix} + g(\eta) = \begin{bmatrix}X\\ Y\\ Z\\ K\\ M\\ N\end{bmatrix} \tag{1}$$

Where, M_S and M_A are a generalized mass matrix of the ship and added masses; $C_S(v)$, $C_A(v)$ are Coriolis and centripetal matrixes of the ship and added masses; D(v) is a damping matrix; $\dot{x} = v = [u,\ v,\ w,\ p,\ q,\ r]^T$ is velocity matrix, $\ddot{x} = \dot{v} = [\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}]^T$ is acceleration matrix; g (η) is generalized gravitational/buoyancy forces and moments. $f = [X, Y, Z, K, M, N]^T$ is matrix of propulsion and external forces and moments affecting to the ship. To solve the equation (1), all the factors including M_S, M_A, $C_S(v)$, $C_A(v)$, $D(v)$, $g(\eta)$ and f must be defined in detail.

2.1. $\mathbf{M_S}$, $\mathbf{M_A}$, $\mathbf{C_S(v)}$, $\mathbf{C_A(v)}$

M_S is defined based on the ship's design and given loading condition.

$$M_s = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_{xx} & -I_{xy} & -I_{xz} \\ -mz_g & 0 & -mx_g & -I_{yx} & I_{yy} & -I_{yz} \\ -my_g & mx_g & 0 & -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \tag{2}$$

Where: m is the ship mass, $(x_g, y_g, -z_g)$ is the position of the ship's centre of gravity; I_{xx}, I_{yy}, I_{zz} are inertia moments and I_{xy}, I_{yx}, I_{xz}, I_{zx}, I_{zy}, I_{yz} are deviation moments of inertia

$$M_A = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} & m_{16} \\ m_{21} & m_{22} & m_{23} & m_{24} & m_{25} & m_{26} \\ m_{31} & m_{32} & m_{33} & m_{34} & m_{35} & m_{36} \\ m_{41} & m_{42} & m_{43} & m_{44} & m_{45} & m_{46} \\ m_{51} & m_{52} & m_{53} & m_{54} & m_{55} & m_{56} \\ m_{61} & m_{62} & m_{63} & m_{64} & m_{65} & m_{66} \end{bmatrix} \quad (3)$$

M_A can be estimated by combining methods: assuming the ship wet hull as an elongated ellipsoid [12] and applying slender body strip theory with Lewis transformation mapping [13, 14]. Clarke typically applied this method for a flat plate and introduced an equation set for estimation of the added masses [15]. To reach maximum reality the authors suggest to use a combination method for estimating all the component m_{ij} of the M_A in [16]. The Coriolis forces $C_S(v)$ and $C_A(v)$ can be calculated based on the kinematics theory that was systemized in [10].

2.2. D(v)

The damping D(v) consists of linear damping D and non-linear damping $D_n(v)$: $D(v) = D + D_n(v)$: D is formed due to potential damping and possible skin friction. $D_n(v)$ is created by the effect of "viscous fluid". To estimate damping, empirical or semi-empirical formulas or simulation tests are applied. Cross-flow drag can be referred to the equations of Fedyaevsky and Sobolev [17] in sway and yaw. Main empirical methods can be referred to the studies of Wagner Smitt, Norbin, Inoue, Clake [18], Lee [19], Kijima and Nakiri [20]. The authors suggest a method to estimate the damping by calculating the damping forces *d(v):*

$$d(\boldsymbol{v}) = D(v)\begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} = \begin{bmatrix} X_{LD} \\ Y_{LD} \\ Z_{LD} \\ K_{LD} \\ M_{LD} \\ N_{LD} \end{bmatrix} \quad (4)$$

$[X_{LD}\ Y_{LD}\ Z_{LD}\ K_{LD}\ M_{LD}\ N_{LD}]^T$ are damping forces due to drag and lift in 6DOF. Detailed calculation is presented in [21].

2.3. g(η)

g (η) can be ~~easily~~ calculated based on the hydrostatic theory.

$$g(\eta) = \begin{bmatrix} -\rho g \int_0^z A_{wp}(\zeta) d\zeta \sin(\theta) \\ \rho g \int_0^z A_{wp}(\zeta) d\zeta \cos(\theta) \sin(\phi) \\ \rho g \int_0^z A_{wp}(\zeta) d\zeta \cos(\theta) \cos(\phi) \\ \rho g \nabla \overline{GM}_T \sin(\phi) \cos(\theta) \cos(\phi) \\ \rho g \nabla \overline{GM}_T \sin(\theta) \cos(\theta) \cos(\phi) \\ \rho g \nabla (-\overline{GM}_T \cos(\theta) + \overline{GM}_T) \sin(\phi) \sin(\theta) \end{bmatrix} \quad (5)$$

Where ρ is water density. $A_{wp}(\zeta)$ wetted area at waterline; ζ, θ, ϕ, ∇, $\overline{GM}_T$ are the heel angle, pitching angle, displacement and metacentric height.

2.4. Force f

In overview, the forces and moments affecting on the ship hull consist of:

a) Propulsion forces: created by propellers and rudders.

b) External forces: caused by the environmental effects including current, wind, wave, squat, bank suction, ship-to-ship interaction, mooring line, towing, tug support, anchor, collision, grounding.

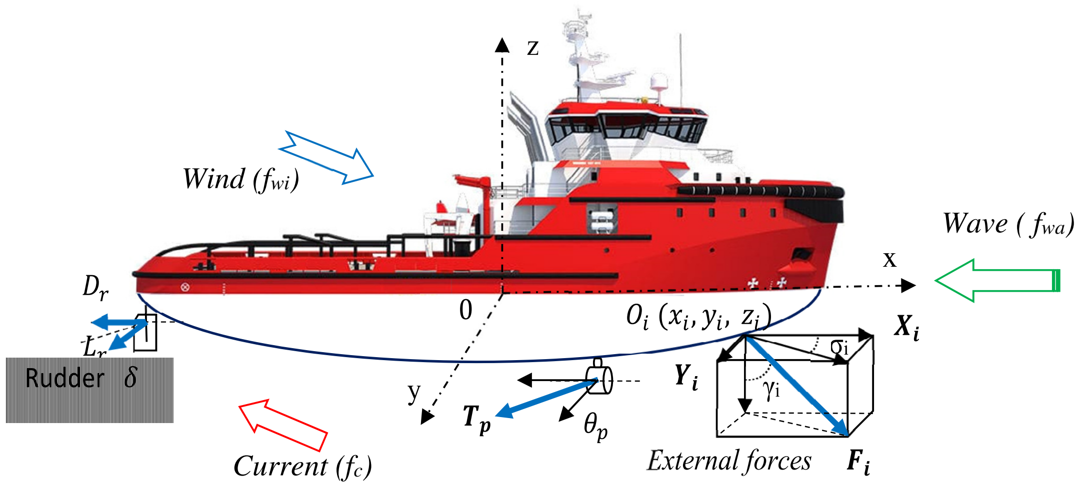

Figure 1: Description of components of a single i[th] force

In practice, the force components are very complex and differ depending on the status of ship propulsion system, loading condition and environmental conditions.

While the ship is moving, all the forces are changing from time to time. Thus, in every real-time condition, a new status needs to be set up according to new parameters of affecting forces. This paper is introducing an aggregate force model applied to all components of force $\sum_{i=1}^{n} F_i$. Considering a single force F_i defined as the i^{th} force, σ_i as azimuth angle and γ_i as declination angle of the forces vector in a xyz frame from position O_i:

$$f_i = [X_i \quad Y_i \quad Z_i \quad K_i \quad M_i \quad N_i]^T;\ F_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2} \tag{6}$$

The matrix of total forces and moments is described :

$$f = \sum_{i=1}^{n} \begin{vmatrix} X_i \\ Y_i \\ Z_i \\ K_i \\ M_i \\ N_i \end{vmatrix} = \sum_{i=1}^{n} F_i \begin{bmatrix} cos(\sigma_i)\, sin(\gamma_i) \\ sin(\sigma_i)\, sin(\gamma_i) \\ cos(\gamma_i) \\ z_i.(sin(\sigma_i)\, \sin(\gamma_i)) \\ z_i\, cos(\gamma_i) \\ y_i.cos(\sigma_i)\, sin(\gamma_i) + x_i.sin(\sigma_i)\, sin(\gamma_i) \end{bmatrix} \tag{7}$$

Where x_i, y_i, z_i are lever arms of the force F_i over axis OX, OY, OZ: $x_i = OX_i$; $y_i = OY_i$; $z_i = OZ_i$. With this calculation, all the forces can be considered as separate components i^{th}, j^{th}, k^{th}.

This enables to calculate and add single forces into the equations (1) in real-time simulation. Detailed calculation of a specific force can be referred to the posted researches.

2.5. Describing the ship's motion status in real-time mode

From the equation (1). The ship's acceleration can be described in 6DOF over the time :

$$\dot{v}(\text{t}) = \frac{1}{M_S+M_A}[f - \text{g}(\eta)\text{-}g_0 - (C_S(v) - C_A(\text{v})\text{-} d_n(\text{v}))v(t)] \quad (8)$$

Thus, the velocity in 6DOF over the time in each degree of freedom can be obtained:

$$v(t) = v(0) + \dot{v}(t) \times dt \quad (9)$$
$$u(t) = u(0) + \dot{u}(t) \times dt \quad (10)$$
$$w(t) = w(0) + \dot{w}(t) \times dt \quad (11)$$
$$p(t) = p(0) + \dot{p}(t) \times dt \quad (12)$$
$$q(t) = q(0) + \dot{q}(t) \times dt \quad (13)$$
$$r(t) = r(0) + \dot{r(t)} \times dt \quad (14)$$

The position of the ship can be presented in the Descartes frame :

$$x(t) = x(0) + v(t) \times cos(\psi - \beta)dt \quad (15)$$
$$y(t) = y(0) + u(t) \times sin(\psi - \beta)dt \quad (16)$$
$$z(t) = z(0) + w(t) \times dt \quad (17)$$

The heel $\phi(t)$, trim $\theta(t)$, heading $\psi(t)$ and drift angle $\beta(t)$ described :

$$\phi(t) = \phi(0) + p(t) \times dt \quad (18)$$
$$\theta(t) = \theta(0) + q(t) \times dt \quad (19)$$
$$\psi(t) = \psi(0) + r(t) \times dt \quad (20)$$
$$\beta(t) = \frac{v(t)}{u(t)} \quad (21)$$

Based on the parameters determined as above, the status of the ship in 6DOF can be described over the time in the simulator in real-time mode.

3 APPLICATION OF MATHEMATICAL MODEL IN THE FEASIBILITY STUDY OF SHIP MANOEUVRING

With a full mathematical model as above given description, the ship can be simulated in a bridge simulator system if it is capable of handling this approach. The objectives can include:

- Feasibility study on manoeuvring of a vessel.
- Feasibility study on the design of ports/jetties.
- Feasibility study on the design of fairways.

Method of application for modelling and simulator assessment can be described by the following steps illustrated in Figure 2.

Step 1 - Ship model development: The ship mathematical and visual model is created. The mathematical modelling guarantees the correct behaviour of a ship including the characteristics of hydrodynamics, hydrostatics, aerodynamics, propulsion system, power management system, water ballast system, mooring, towing system and mechanical system. The visual model includes external visuals, internal visuals, wheelhouse, wet hull area of the vessel, radar geometry, collision geometry, navigation lights and deck light arrangement.

Step 2 - Area visual database development: This work creates the 3D-visual database of the navigation areas including fairway, TSS, depths, terminals, jetties, navigation light/buoy systems, landmarks and landscapes in the area. The reference data are based on WGS84 and in accordance with the last updated navigation charts and port design drawings.

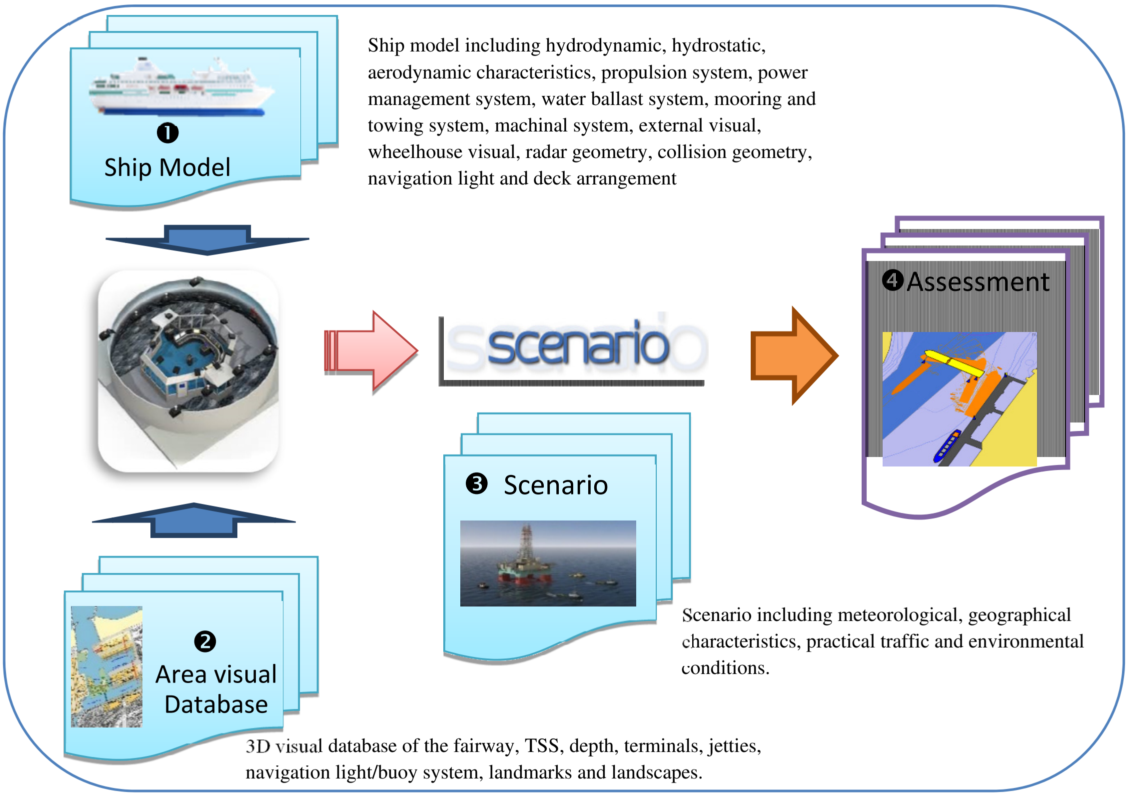

Figure 2: The process of the modelling and manoeuvrability assessment of a ship

Step 3 - Scenario development: This work involves creating scenarios for feasibility assessment on the simulator. In this step, traffic situations are built according to the requirements and objectives of the design. The meteorological, geographical characteristics, as well as practical traffic conditions, are included in the scenarios. If applicable storms, currents, wind, waves, tides, depths and other weather conditions such as rain, snow, ice, day or night are added to the scenarios.

Step 4 – Assessment: Based on the design and simulation development in step 1, 2 and 3, the scenarios will be run in the bridge simulator when applicable, under the observation and required assessment of navigators, pilots, tugboat captains, VTS's operators, assessors and concerned parties. The output of the simulator runs, visual and digital figures recorded by and exported from the simulator system will be used for the final report which describes the detailed results of the feasibility study and can include advices on the ship, port, fairway design and safety measures.

4 PRACTICAL APPLICATIONS

During the duration from 2016 to 2018, the study group conducted several applied research projects with the application of the above-mentioned method and process. Facilities used for the researches included the Full mission bridge (FMB) simulator of the Ho Chi Minh City University of Transport (UT-HCM) and the advanced Kongsberg's K-Sim simulator platform of the Maritime Centres of Excellence (Simwave), the Netherlands. Simwave is the biggest and most advanced maritime simulator centre in the world located in Barendrecht, the Netherlands. The projects involved many experts and authorized personnel of related organizations.

Project 1: Feasibility study for the calling of 14,000 TEU container ship at Tancang-Caimep with FMB simulator (2016). This project was conducted at the request of Tancang Pilot in the simulator location of UT-HCMC. The 3D visual database for Tan Cang Caimep terminal and water area in Vung Tau and a specific 14,000 TEU container ship with several tugboats were modelled. The simulator test was conducted successfully and approved in December 2016.

Figure 3: Manoeuvring test of 14,000 TEU container ship at Tancang-Caimep

Project 2: An overall study of the fairway Vung Tau - Cai Mep – Thi Vai (2016). This project was funded by the Ministry of Transport (MOT) of Vietnam. The feasibility test was carried out in the bridge simulator system of the UT-HCMC. Apart from the visual database for the fairway, more than 20 ships of different real ocean and inland water vessels were modelled.

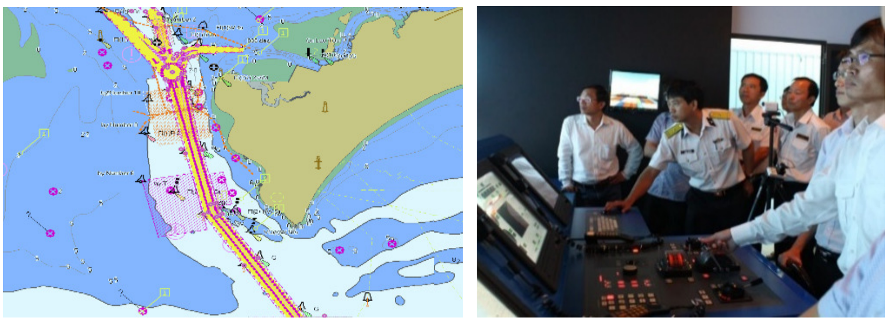

Figure 4: Simulator assessment on the new Vung Tau fairway and TSS

The project included a complex traffic separation scheme (TSS), which is the first introduced in Vietnam, at the main connecting area of the fairways of Vung Tau, Sai Gon, Song Dinh and Thi Vai. The simulator test was conducted successfully and approved by MOT in October 2016.

Project 3: Feasibility study for calling of 18000 TEU container ship at CMIT port with FMB simulator. The Project was conducted at the request of Cai Mep International Terminal company (CMIT) and with the cooperation of Maersk Lines. The goal was to assess the ability for calling the supper large Maersk's Container ship 18,000TEU Triple-E at the CMIT port in Vung Tau, Vietnam. The ship mathematical model, area design and many scenarios with various environmental conditions and traffic situations were simulated according to the recommendations of the local maritime management organizations.

Figure 5: Assessment of the manoeuvring of Triple-E ship

The simulation test was conducted by experienced captains of Maersk Lines, Vungtau pilots, Pilotco 1, Haivan Tugboat company with the supervision of Vietnam Maritime administration, Vungtau port authority, Vungtau VTS, Southern Maritime Safety Corporation. The project was approved by the authorized parties in December 2016.

Project 4: Real-time simulations regarding safe berthing and unberthing of a completely newly designed bulk carrier sailing from and to the Port of Conakry in Guinea, Africa (2018). This is a special project requested by Concordia, the Netherlands to model a ship in the design stage. This is a new design and the port is also under construction. A new ship model and a 3D visual database of the port were developed.

Figure 6: New ship design and Port of Conakry deployed in Kongsberg platform

The final test on February 2018 showed that the mathematical model and visual design were satisfactory. This outcome supports the theory that the method can be applied to ships and areas under design stage.

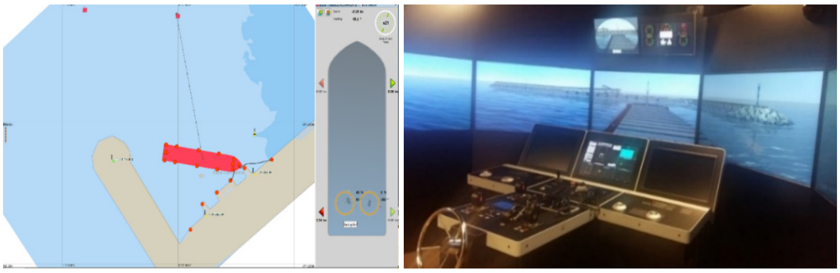

Figure 7: Manoeuvring test of the newly designed ship on Simwave's bridge simulator

5 CONCLUSION

With the application of the mathematical modelling, the assessment of ship manoeuvrability can be done in a high-end bridge simulator. This paper systemizes and introduces a combinative method to establish a complete mathematical model describing the full 6DOF of ship motions in real-time mode with the detailed formulas to calculate hydrostatic, hydrodynamic coefficients and the generalized formula describing all forces and moments of the propulsion systems and the environmental effects including current, wave, wind, shallow water and other external forces. Thus, the method improves the missing or limitation of the mathematical models in existing simulator systems by adding all components of the differential equation in 6DOF. The approach of this study is also based on theoretical formulas which are faster and easier for digitalizing and computing in a simulator system and can be applied for modelling a ship in the design stage. Moreover, the paper also suggests a procedure to set up the necessary work of the testing process for the existing bridge simulators including ship mathematical and visual model, port and fairway visual databases and scenarios.

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