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

ỨNG DỤNG MÔ HÌNH TOÁN VÀ MÔ PHỎNG BUỒNG LÁI TRONG VIỆC NGHIÊN CỨU TÍNH KHẢ THI CỦA CÔNG TÁC DẪN TÀU

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Abstract: *It is obvious that the significant introduction and development of bridge simulators nowadays provides an advanced tool for maritime training. Apart from the educational function, the simulators can be exploited for the feasibility study of ship maneuvering for existing ports, ships under operation as well as in the design phase. Thus, it is necessary to set up proper ship mathematical models and establish a scientific process for assessment of ship maneuvering in simulators. This paper aims to systematically introduce the mathematical modelling and propose a method to assess the ship maneuvering in six degrees of freedom and in real-time mode. The mathematical model and assessment method were used in some applied research projects which have been practically conducted by the study group during the researching duration.*

Keywords*: Ship mathematical modeling, Ship maneuvering, Bridge simulator, Simulator assessment.*

Classification number: *2.5*

Tóm tắt: *Ngày nay, việc ra đời và phát triển của mô phỏng buồng lái đã và đang cung cấp một công cụ tiên tiến cho công tác huấn luyện hàng hải. Ngoài chức năng huấn luyện và đào tạo, hệ thống mô phỏng buồng lái còn có thể khai thác trong việc nghiên cứu tính khả thi của công tác điều động tàu. Ứng dụng này có thể áp dụng đối với các tàu bè, cảng biển hiện hữu cũng như trong giai đoạn thiết kế. Để thực hiện, cần phải thiết lập mô hình toán chuyển động của tàu phù hợp và xây dựng một tiến trình khoa học cho việc điều động tàu trên mô phỏng. Bài viết này mong muốn giới thiệu những nét chính của việc phát triển mô hình toán học cho chuyển động tàu và đề xuất phương pháp để đánh giá khả năng điều động tàu trên mô phỏng sáu bậc tự do và ở chế độ chuyển động thực. Mô hình toán và phương pháp đánh giá đã được áp dụng thực tế trong một số dự án nghiên cứu ứng dụng mà tác giả đã thực hiện trong thời gian nghiên cứu.*

Từ khóa*: Mô hình toán học tàu, điều động tàu, mô phỏng buồng lái, đánh giá bằng mô phỏng.*

Chỉ số phân loại*:2.5*

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 maneuvering. It can be described as a set of status differential equations based on Newton’s equation. The factors of the equations can be defined based on hydrostatic, hydrodynamic, aerodynamic theories and empirical data. A simple mathematical model of one equation was introduced by NOMOTO, K. (1957). Davidson and Schiff (1946) described yawing and drifting in 2DOF. Norrbin (1971), Inoue (1981), Ankudinov (1993) and other researchers developed 3DOF model including surging, swaying, yawing. Eda (1980), Hirano (1980) and Oltmann (1993) described 4 DOF model by adding rolling motion. By adding heaving and pitching motions Ankudinov (1983) and Hooft & Pieffers (1988) did establish 6DOF model [1], [2]. Thor I. Fossen (2011) systemized the mathematical model in 6 degrees of freedom in the form of a matrix [3].

The principal for calculating added mass was based on work of Ursell (1949) [4] and Frank (1967) [5] for an arbitrary symmetric cross section. Then Keil (1974) introduced method for any arbitrary water depth based on a variation of the method of Ursell with Lewis conformal mapping [6]. Frank (1967) described the pulsating source method for deep water [5].

Nils Salvesen, E. O. Tuck and Odd Faltisen (1970) introduced new method to predict heave, pitch, sway, roll and yaw motions as well as wave-induced vertical and horizontal shear forces, bending moments, and torsional moments for a ship advancing at a constant speed with arbitrary heading in regular waves [7].

For calculating damping coefficients, a simple set of equations was presented by Society of Naval Architects and Marine Engineers (SNAME) in 3DOF including surge, sway and yaw [8]. Fedyaevsky and Sobolev introduced equations to calculate cross-flow Drag in sway and yaw [9]. Nils Salvesen, E. O. Tuck and Odd Faltisen suggested a method to calculate damping components in “Ship Motions and Sealoads” [7]. Recent studies on the calculation of ship resistance have trended to improve the accuracy of previous methods or apply computational fluid dynamics (CFD).

K. Zelazny introduced a method to improve the precision of ship resistance at preliminary stages of design [10]. Mucha et al. had a validation study on numerical prediction of resistance in shallow water based on the solution of the Reynolds-averaged Navier-Stokes (RANS) equations, a Rankine Panel method and a method based on slender-body [11]. The application of CFD can be typically referred to the study of Yasser M. Ahmed et al. [12]. For roll damping coefficients, it can be referred to study of Frederick Jaouen et al. [13] and the calculation of Yang Bo et al. by using numerical simulation based on CFD [14]. Burak Yildiz et al. introduced a URANS prediction of roll damping due to the effects of viscosity based on CFD [15] while Min Gu et al. presented a roll damping calculation based on numerical simulation on the RANS model in calm water [16]. In 2017, D. Sathyaseelan et al. introduced an efficient Legendre wavelet spectral method (LWSM) to ship roll motion model for investigating the nonlinear damping coefficients [17]. The idea is how to use a suitable mathematical model to stimulate the ship with satisfied behaviour in a simulator for the feasibility study of ship manoeuvring. Moreover, the study also aims to propose a method to assess ship manoeuvring in simulators in six degrees of freedom and in real-time mode.

2. Mathematical modelling

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

-Hydrodynamic forces: Including Coriolis forces and damping forces;

-Hydrostatic forces: Including buoyancy forces and restoring moments;

-Propulsion forces: Created by propellers and rudders;

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

In practice, the force components are very complex and strictly depending on the status of ship propulsion system, loading condition and environmental condition. While the ship moving, all the forces are changing time to time. Thus, in every real-time condition, a new status needs to be set up according to new parameters of affecting forces.

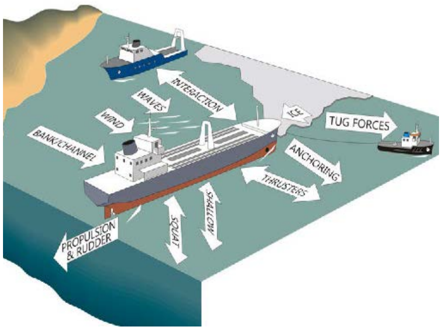

Figure 1. *overall description of forces impacting to the ship in 6DOF.*

Basically, a general status equation describing the ship motions can be represented:

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = f \qquad (1)$$

Where M is generalized mass, and $C(\nu)$ is Coriolis and centripetal forces of the ship and added masses due to the motions or the rotations about the initial frame. $D(\nu)$ is damping force. $g(\eta)$ is generalized gravitational/buoyancy forces and moments and f are the propulsive and external forces and moments affecting to the ship. The variables of the equation are υ and $\dot{\nu}$ which are velocity and acceleration of the ship.

The equation can be described in six degrees of freedom in the form of the matrix.

$$M_S\begin{bmatrix}\dot{u}\\\dot{v}\\\dot{w}\\\dot{p}\\\dot{q}\\\dot{r}\end{bmatrix}+C_S(v)\begin{bmatrix}u\\v\\w\\p\\q\\r\end{bmatrix}+M_A\begin{bmatrix}\dot{u}\\\dot{v}\\\dot{w}\\\dot{p}\\\dot{q}\\\dot{r}\end{bmatrix}+C_A(v)\begin{bmatrix}u\\v\\w\\p\\q\\r\end{bmatrix}$$

$$+D\begin{bmatrix}u\\v\\w\\p\\q\\r\end{bmatrix}+D_n(v)\begin{bmatrix}u\\v\\w\\p\\q\\r\end{bmatrix}+g(\eta)=\begin{bmatrix}X\\Y\\Z\\K\\M\\N\end{bmatrix}q \qquad (2)$$

Table 1. *Parameters defined in the body-fixed reference frame.*

DOF	*Description*	*Velocities*	*Forces*
1	*surge - motion in x direction*	*u*	*X*
2	*sway - motion in y direction*	*v*	*Y*
3	*heave - motion in z direction*	*w*	*Z*
4	*roll – rotation about x axis*	*p*	*K*
5	*pitch - rotation about y axis*	*q*	*M*
6	*yaw - rotation about z axis*	*r*	*N*

$$M = M_S + M_A \qquad (3)$$

$$D(v) = D + D_n(v) \qquad (4)$$

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 and $D_n(v)$ are linear and non-linear damping matrixes. $v = [u, v, w, p, q, r]^T$ is velocity matrix, $\ddot{x} = [\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}]^T$ is acceleration matrix. $f = [X, Y, Z, K, M, N]^T$ is matrix of external forces and moments affecting to the ship. To solve the equation (2), all the factors including M_S, M_A, $C_S(v)$, $C_A(v)$, D, $D_n(v)$ and f must be defined.

2.1. $M_S, M_A, C_S(v)$

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

M_A, $C_A(v)$ were solved and described in the previous study of the author "Determination of Added Mass and Inertia Moment of Marine Ships Moving in 6 Degrees of Freedom" [18].

2.2. $D, D_n(v)$

D and $D_n(v)$ were solved and represented in the previous study of the author "Establishing Mathematical Model to Predict Ship Resistance Forces" [19].

2.3. *g(η)*

The gravitational and buoyancy g (η) was solved and described sufficiently in six degrees of freedom by hydrostatic theory.

2.4. Force *f*

The force f is very complex and consists of the propulsion thrusts created by the ship's propellers and rudders and external forces caused by current, wind, wave, squat, bank suction, ship-to-ship interaction, mooring line, towing, tug support, anchor, collision, grounding. The detailed calculation of each particular component can be referred to available studies. A single force can be calculated simply based on the aggregation of force vectors. This study 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 an oyz frame at a position O_i :

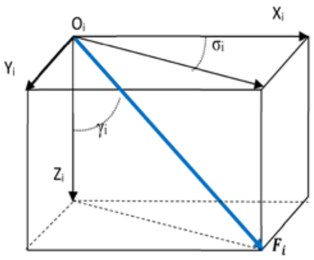

Figure 2. *Description of components of a single i[th] force.*

$$f_i = [X_i \quad Y_i \quad Z_i \quad K_i \quad M_i \quad N_i]^T \qquad (5)$$

$$F_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2} \qquad (6)$$

Based on basic physics and mathematics, the mathematical model of forces and moments of the surfing, swaying and heaving motions at position O on the ship are expressed:

$$X_i = F_i\,cos(\sigma_i)\,sin(\gamma_i) \qquad (7)$$

$$Y_i = F_i\,sin(\sigma_i)\,sin(\gamma_i) \qquad (8)$$

$$Z_i = F_i\,cos(\gamma_i) \qquad (9)$$

Thus, the moments in rolling, pitching and yawing rotations are obtained:

$$K_i = F_i.z_i.(sin(\sigma_i)\sin(\gamma_i)) \qquad (10)$$

$$M_i = F_i.x_i\,cos(\gamma_i) \qquad (11)$$

$$N_i = F_i.y_i[cos(\sigma_i)\,sin(\gamma_i) + x_i.sin(\sigma_i)\,sin(\gamma_i)] \qquad (12)$$

Where x_i, y_i, z_i are lever arm of the force F_i over axis OX, OY, OZ: $x_i = OX_i$; $y_i = OY_i$; $z_i = OZ_i$.

Thus, the matrix of total forces and moments:

$$f = \sum_{i=1}^{n} \begin{vmatrix} X_i \\ Y_i \\ Z_i \\ K_i \\ M_i \\ N_i \end{vmatrix} \quad (13)$$

$$\sum_{i=1}^{n} F_i \begin{bmatrix} cos(\sigma_i)\, sin(\gamma_i) \\ sin(\sigma_i)\, sin(\gamma_i) \\ cos(\gamma_i) \\ z_i.(sin(\sigma_i)\sin(\gamma_i)) \\ z_i\, cos(\gamma_i) \\ y_i.cos(\sigma_i)\, sin(\gamma_i) + x_i.sin(\sigma_i)\, sin(\gamma_i) \end{bmatrix} \quad (14)$$

$$\boldsymbol{f} = \begin{vmatrix} X_\eta \\ Y_\eta \\ Z_\eta \\ K_\eta \\ M_\eta \\ N_\eta \end{vmatrix} + \sum_{i=1}^{m} \begin{vmatrix} X_{ri} \\ Y_{ri} \\ Z_{ri} \\ K_{ri} \\ M_{ri} \\ N_{ri} \end{vmatrix} + \sum_{j=1}^{n} \begin{vmatrix} X_{pj} \\ Y_{pj} \\ Z_{pi} \\ K_{pj} \\ M_{pi} \\ N_{pj} \end{vmatrix} + \sum_{k=1}^{l} \begin{vmatrix} X_{ek} \\ Y_{ek} \\ Z_{ek} \\ K_{ek} \\ M_{ek} \\ N_{ek} \end{vmatrix} \quad (15)$$

Where:

$f_\eta = [X_\eta \quad Y_\eta \quad Z_\eta \quad K_\eta \quad M_\eta \quad N_\eta]^T$ is restoring force matrix;

$f_{ri} = [X_{ri} \quad Y_{ri} \quad Z_{ri} \quad K_{ri} \quad M_{ri} \quad N_{ri}]^T$ is force matrix of the i^{th} rudder;

$f_{pj} = [X_{pj} \quad Y_{pj} \quad Z_{pj} \quad K_{pj} \quad M_{pj} \quad N_{pj}]^T$ is force matrix of the j^{th} propeller;

$f_{ek} = [X_{ek} \quad Y_{ek} \quad Z_{ek} \quad K_{ek} \quad M_{ek} \quad N_{ek}]^T$ is force matrix of the k^{th} external forces.

With such the calculation, all the forces can be considered as separate components i^{th}, j^{th}, k^{th}. This enables to calculate and add single force into the general equations (2) in real-time simulation.

Detailed calculating formulas of each force can be preferred to previous and existing studies of different researchers.

3. Application of mathematical model in the feasibility study of ship manoeuvring

With a full mathematical model as above description, the ship can be simulated in a bridge simulator system for assessing the feasible manoeuvring of the ship. The objectives of study can be including:

Feasibility study on manoeuvring of vessel: The mathematical model of the real ship is created then deployed in the bridge simulators for assessment of her manoeuvring ability.

Feasibility study on the design of ports/jetties: In this case, the ports are modelled. Environmental and traffic conditions are built as accurate as reality for simulation runs to assess the proper design of the port constructions.

Feasibility study on the design of fairway: The details of fairway including light and buoy system, geographic, hydrographic are modelled, not only according to the navigational charts but also reflexing the real 3D-visual condition.

Method of application for modelling and simulator assessment can be described according the following steps illustrated in figure 3:

Step 1 - Ship model development*:* The ship mathematical and visual model are created. This step creates all mathematical characteristics of the ship including hydrodynamic, hydrostatic, aerodynamic, propulsion system, power management system, water ballast system, mooring and towing system, mechanical system. The visual model includes the ship external visual, internal visual, wheelhouse, radar geometry, collision geometry, navigation light 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 datum is based on WGS84 and according to the last updated navigation charts and port design drawings.

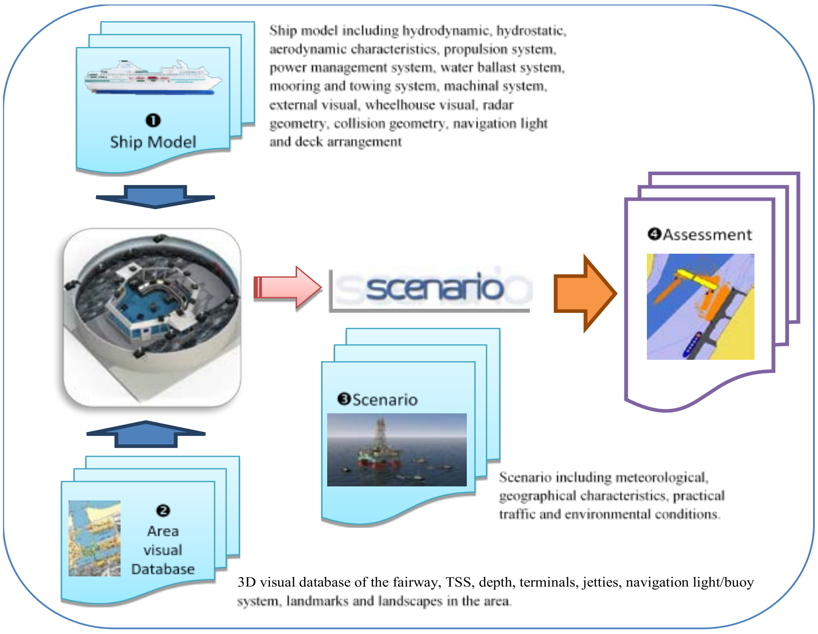

Figure 3. *The process of simulator test on ship manoeuvring.*

Step 3 – Simulator scenario development: This work involves to 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. Storms, currents, waves, tides, depths, weather conditions such as rain, snow, ice, look, day or night are added to the scenarios if applicable.

Step 4 – Assessment: Based on the design and simulation development in step 1, 2 and 3, the scenario will be run in the bridge simulators under the assessment of navigators, pilots, tugboat captains, VTS's operators, assessors and concerned parties. The output of the simulator runs, and 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.

4. Practical applications

During the duration from 2016 to 2018, the study group conducted several applied research projects requested by both international and domestic organisations for the feasibility study of the port and ship designs with the application of the above-mentioned method and process.

Facilities used for the researches included the Full mission bridge (FMB) simulator of the Maritime Education and Human Resource Center, the University of Transport in Ho Chi Minh City, Vietnam and the advanced Kongsberg's K-Sim simulator platform of the Maritime Centres of Excellence (Simwave), the Netherlands. Simwave is the biggest Maritime simulator centre in the world located in Barendrecht, the Netherlands. The projects were involved and cooperated with many experts and authorised personnel of related organizations including maritime institutes, maritime administrations, port authorities, pilot companies, tugboat companies, port consultancies and design companies, maritime safety companies, port operators, shipowners.

Project 1: Feasibility study for the calling of 14,000 TEU container ship at Tan Cang - Cai Mep with FMB simulator (2016).

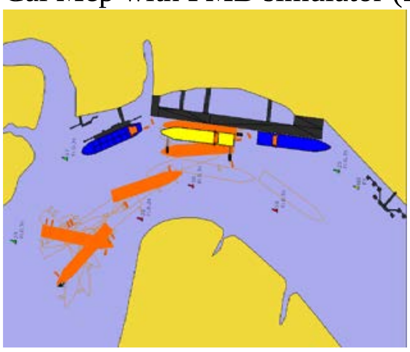

Figure 4. *Plotting track of a run test on simulator.*

This project was conducted at the request of Tan Cang Pilot Company (Tancang Pilot), Saigon New port in the simulator location of UT-STC. 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 by Tancang Pilot in December 2016 [20].

Figure 5. *Manoeuvring assessment test by Tan Cang pilot.*

Project 2: An overall study of the whole fairway Vung Tau - Cai Mep – Thi Vai (2016). This project was fund by the Ministry of Transport (MOT) of Vietnam and conducted by Portcoast Consultant Corporation. The feasibility test was carried out in bridge simulator system of the UT-STC in Ho Chi Minh City. Apart from the visual database for the whole fairway, more than 20 ship models of different real ocean and inland water vessels were modelled. The project included a complex traffic separation scheme (TSS), which is the first one 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 [21].

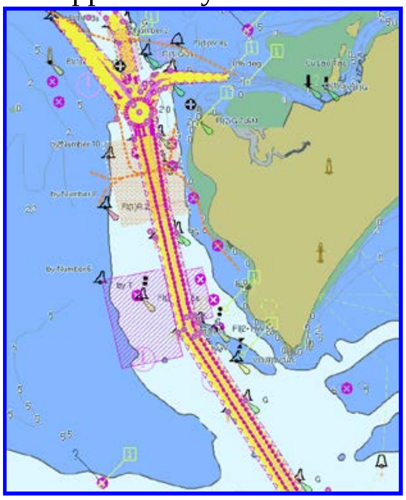

Figure 6. *The overall development of the fairway Vung Tau TSS simulated in the simulator.*

Figure 7. *Conducting simulator test in UT-STC.*

Project 3: The feasibility study for calling of 18000 TEU container ship at CMIT port with FMB simulator (2017). 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 big Maersk's Container ship 18,000TEU Triple-E at the CMIT port in Vung Tau, Vietnam.

Figure 8. *The Triple-E was modelled and deployed in the simulator*

After creating the ship mathematical and area visual model, many scenarios with various environmental conditions and traffic situation were simulated according to the recommendations of the local maritime management organizations.

The simulation test was conducted by experienced captains of Maersk Lines, Vung Tau pilots, Pilot company No. 1, Hai Van Tugboat company with the supervision of Vietnam Maritime administration, Vung Tau port authority, Vung Tau VTS, Southern Maritime Safety Corporation, the University of Transport in Ho Chi Minh city's lectures and experts. The project was approved satisfactorily by the authorized and concerned parties in December 2016 [22].

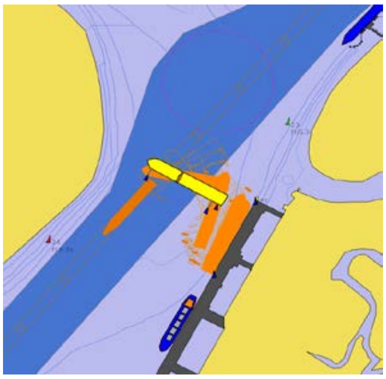

Figure 9. *A successful turning and unberthing of the Triple-E.*

Figure 10. *Assessment of the manoeuvring ability of Triple-E in the simulator.*

Figure 11. *Participants listening to the presentation of the author in the study results.*

Project 4: Real-time simulations regarding safe berthing and unberthing of an under-designed bulk carrier in the Port of Conakry in Guinea (2018). This is a special project requested by Concordia. The Netherlands to model a ship in the design stage. The ship is of new design and the area of the Port of Conakry, Guinea, South Africa is also under construction. With the designed data and drawings provided by the shipbuilder and the port designer, a new ship model was developed and a 3D visual model for the port and jetty was also created. The final test on February 2018 showed that the mathematical model and visual design were satisfactory. This convinced that the method can be applied to ships and areas under design stage [23], [24].

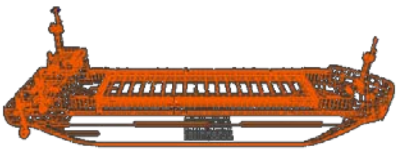

Figure 12. *The ship was modelled according to the design.*

Figure 13. *Visual model of the ship with twin azipod propellers.*

Figure 14. *The FMB 360^0 used for the testing*

Figure 15. *The full ship model and 3D visual design deployed in Simwave Kongsberg platform for assessment*

Figure 16. *Plotting track of a run test with support of mooring lines*

5. Conclusion

With the application of the mathematical modelling of ships and the visual modelling of fairway and water areas, the assessment of manoeuvring ability of ships can be done in bridge simulation system by applying the mentioned method.

By using proper mathematical model, the ships, environmental conditions and traffic situations can be simulated and deployed in simulation for assessment of the ships and ports, fairways in the design stage. To ensure the accuracy and reality of the simulation scenarios, the mathematical model can be simulated in 6DOF and in real-time mode. This work includes the suitable equations, formulas for calculating hydrostatics, hydrodynamics, propulsion system and external forces such as tugboat, mooring lines, anchors and the environmental effects including current, wave, wind, shallow water.

6. Acknowledgement

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