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Free running ship model tests of interaction between a moored ship and a passing ship

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Abstract

For many reasons, ship model interaction tests are performed in experimental towing tanks. This paper presents research on the hydrodynamic forces acting on a ship tied up at the solid berth, which is produced by other ships passing by using free-running ship models with much larger dimensions than those used in towing tanks. A passing ship model was controlled by a human operator – an experienced master. This enabled a study of the influence of the interaction impact on the course of the maneuver. The research was carried out at the Ship Handling Research and Training Centre in Iława. The ship model was moored alongside and equipped with multi-directional force sensors linking the ship model with a solid berth. Forces were measured as a function of the passing ship speed, side distance between both ships, ship sizes, and depth-to-draft ratio (H/T). Forces were measured in two planes: the longitudinal (surge) and the transversal (sway). A numerical database was processed and ordered according to the variables. The fuzzy model was created within a "Matlab" computing environment using a Sugeno-type self-learning neuron network model. The proposed Sugeno model was evaluated with other methods presented by Flory (2002), Seelig (2001), and PASS-MOOR by Wang (1975). The ultimate goal of this study was to simplify the method of predictive calculations for adjusting speed and distance when passing by the moored ship, which ensures compliance with safe port mooring requirements.

Introduction

It is commonly known that when a moored ship is passed there are hydrodynamic forces such as surge forces F_x, sway forces F_y as well as yaw moments M acting upon it. These forces trigger movements of the moored ship that causes tensions on the mooring lines, which can lead to the rupture of the mooring ropes. If the passing ship sails at high speed and the distance between the ships is small, and the ships have a minimum clearance under the keel, the berthing loads can be considerable, and in the case of exceeding their admissible values, damage can occur to the moored ship, its mooring equipment, the dock, and the fenders (Vasudevan & Seeninaidu, 2017). There are many descriptions of serious accidents resulting from this interaction; despite this, there are no guidelines on how these effects should be assessed and how to include them in the designs of mooring systems and operational practice (Pinkster, 2011).

Literature review

Figure 1 shows the hydrodynamic forces that act upon a moored ship when it is passed by another vessel.

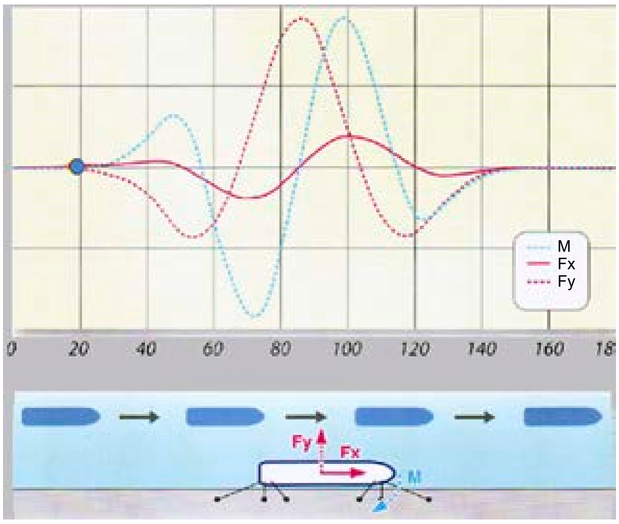

Figure 1. Forces acting on a moored ship

These forces can be calculated using the formulas:

$$F_x = C_x \cdot 0.5 \cdot \rho \cdot T \cdot L \cdot V^2 \quad (1)$$

$$F_y = C_y \cdot 0.5 \cdot \rho \cdot T \cdot L \cdot V^2 \quad (2)$$

where C_x represents the coefficient for the peak surge force, C_y denotes the coefficient for the peak sway force, ρ signifies the density of water, T is the draft of the moored ship, L is the length of the moored ship, and V is the speed of the passing ship. Both formulas contain the parameters of the moored ship and the speed of the passing ship. The other variables are hidden within the coefficients C_x and C_y. Most researchers focus on determining coefficients C_x and C_y.

Wang (Wang, 1975) determined the forces and moments occurring as a result of a ship passing by; he worked out an analytical method. He calculated the forces and moments as a function of time for an infinite depth of water. He also used correction coefficients to consider the effect of shallow water. Seeling (Seeling, 2001) used the figures found for deep water from Wang (Wang, 1975). Here, in the case of shallow water, correction coefficients were formulated with the use of the reanalyzed results of the test in a scaled model carried out previously. For estimating moments and peak forces, he created an Excel calculation sheet. Flory (Flory, 2002) worked out simple formulas to estimate forces and moments that arise due to the passing of ships with the use of a few published results and models. In his calculations, he used scale factors according to Froude's Model Law and considered the coefficient of clearance under the keel. Kriebel (Kriebel, 2005) carried out a few laboratory tests in scaled models and formulated simple empirical formulas for calculating forces and moments. Apart from this, he also studied Seeling's and Flory's methods and compared them with the experimental data he obtained. Based on his research, he re-derived Seeling's correction coefficients and introduced a set of new empirical formulas for the correction coefficients. All the methods discussed above consider Bernoulli's suction effect to be the main cause of the forces and moments that arise.

The main parameters that affect the system in all the above-mentioned papers are the speed of a passing ship, the separation distance, the displacement of the ship, and the water depth. The courses of the forces and moments are related to the relative variability of the position of the passing vessel against the moored vessel. The effect of the passing vessel begins roughly at a distance twice longer than the length of the ship (Flory, 2001). Variability at every time step takes place according to a similar pattern in all cases. This research aims to simplify the predictive calculation method to enable an adjustment of the speed and distance while passing along a moored vessel, so that compliance with safe mooring requirements at the harbor is maintained.

Description of model tests

This paper presents research on the hydrodynamic forces that act on a moored vessel at the permanent berth, which are produced by another vessel passing the former one in a parallel direction. The models used for the research were free-running ship models with far larger sizes than those used in towing tanks. In addition, the passing vessel model was controlled by a person – an experienced master.

The variables in the tests contained: the speed of the passing vessel, the passing distance between the ships, the sizes of vessels, and the ratio of depth-to-draft (H/T). Forces were measured in two planes: longitudinal (surge) and transversal (sway). A further step was used to determine the peak values for surge and sway forces. The numeric database, which was formed as a result, was processed and ordered. The database was implemented onto the fuzzy logic panel of the computing environment Matlab 2021 and a self-learning neural network of Sugeno type was created.

Test configuration and sign convention

All the tests use the parallel configuration indicated in Figure 1, in which the passing ships moves parallel to, and in the same direction as, the moored ship. A clockwise coordinate system has been adopted, the origin ($x = 0$, $y = 0$) of which is located amidships the moored vessel. The sign convention follows the right-hand rule: $+x$ – the bow, $+y$ – portside.

Facility, test rigs, and ship models

The research was carried out at the Ship Handling Research and Training Centre in Iława in the area presented in Figure 2.

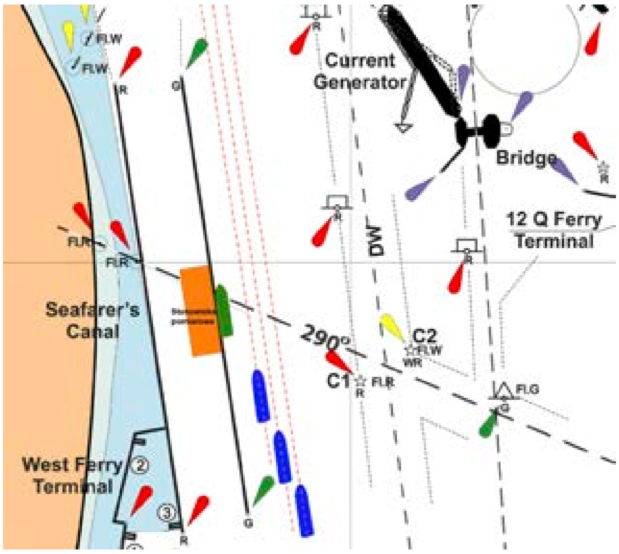

Figure 2. Test area at the Ship Handling Research and Training Centre in Iława

The moored vessel model was equipped with multi-directional force sensors, which at the same time linked the model with the berth. The exact arrangement of the sensors is provided in Figures 3 and 4, and the dimensions of the moored vessel can be found in Table 1.

Figure 3. A measuring station was installed at the deep-water harbor

Table 1. Parameters of the moored ship

Item	Symbol	Moored ship	Moored ship model
Length overall	L_{OA} [m]	218.85	9.17
Beam	B [m]	30.50	1.26
Draft	T [m]	12.09	0.51

The computer measured the recorded data from the measuring sensors for the forces F_x and F_y, and the speed of the vessel in motion, connection scheme shown in Figure 5. On the basis of the GPS position, it computed dynamic longitudinal and transversal distances between the vessels.

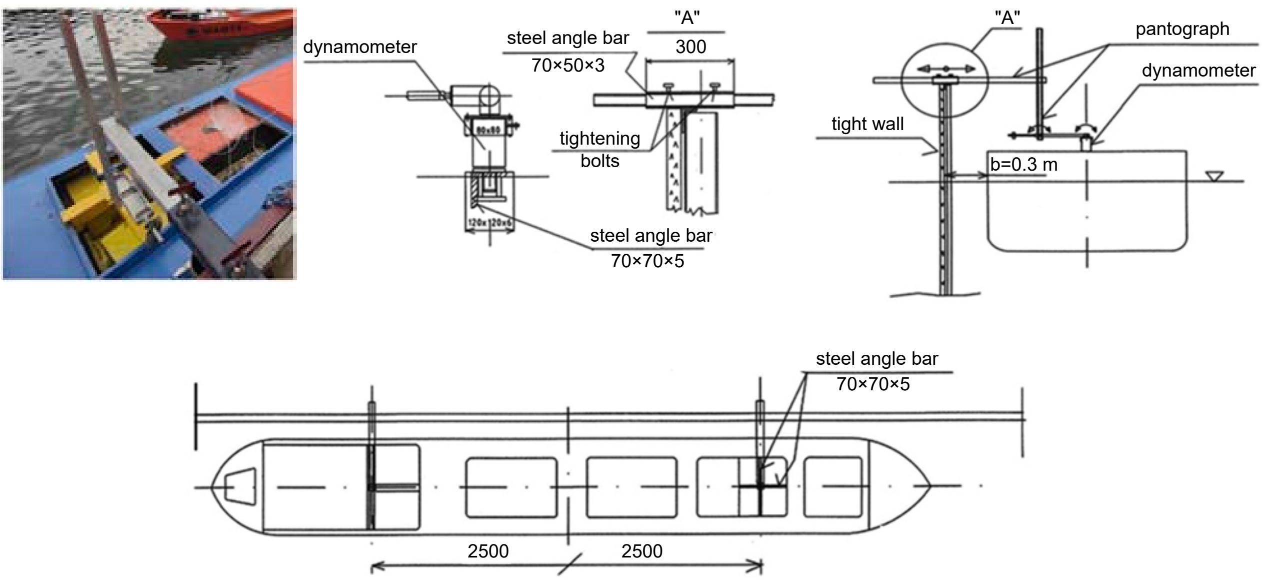

Figure 4. Depiction and dimensions of the moored ship

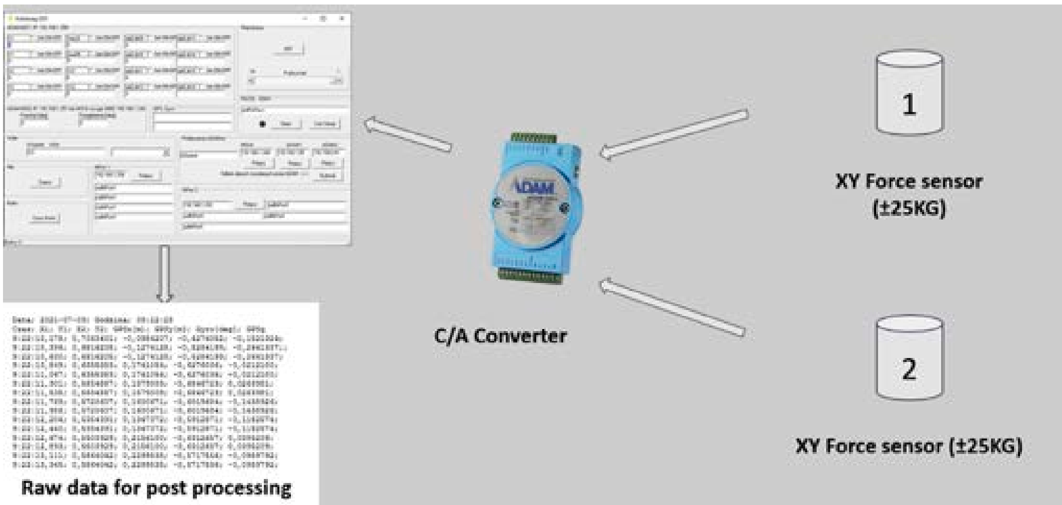

Figure 5. A measuring system on the moored ship model

Item	Symbol	Ship	Model
Length overall	L_{OA}	292.93 m	12.21 m
Length between perpendiculars	L_{BP}	278.00 m	11.58 m
Beam	B	48.00 m	2.00 m
Draft	T	15.33 m	0.64 m
Max. speed	V	15.5 kn	3.2 kn
Displacement	Δ	176 967 T	12.49 T
Block coefficient	C_B	0.844	0.844
Rudder area ratio	$A_P/(L_{BP}\times T)$	1.76%	1.76%

Other information:
- Main engine: Diesel, optional Turbine;
- Single 5-bladed right-handed propeller;
- Conventional rudder;
- 2 anchors + 2 cables 12 shackles each;
- Tug simulator – two 55 tons bollard pull tugs working on a line are available;
- GPS;
- Scale 1:24.

Figure 6. Model No. 1 – WARTA (LCC)

Item	Symbol	Ship	Model
Length overall	L_{OA}	227.76 m	9.49 m
Length between perpendiculars	L_{BP}	217.00 m	9.04 m
Beam	B	32.10 m	1.34 m
Draft	T	12.50 m	0.52 m
Max. speed	V	16.0 kn	3.1 kn
Displacement	Δ	75 550 T	5.46 T
Deadweight	DWT	66 200 T	n.a.
Block coefficient	C_B	0.86	0.86
Rudder area ratio	$A_P/(L\times T)$	1.86%	1.86%

Other information:
- Main engine: Diesel;
- Single 4-bladed right-handed propeller;
- 2 anchors + 2 cables 12 shackles each;
- Bow thruster;
- Tug simulator. Two 40 tons bollard pull tugs are available;
- Rudder: conventional (35° of max. deflection angle), optional single Schilling rudder (70° of max. deflection angle) or Becker rudder (55° of max. deflection angle);
- Scale 1:24.

Figure 7. Model No. 2 – BLACK LADY (panamax bulk carrier)

Two test models for the two vessels of different sizes were used. These are scaled replicas of the particular vessels at full scale. The parameters of the vessel models are provided within the tables in Figures 6 and 7.

Model vessels were equipped with the following:
- GPS Leica Viva GS10 with reference station. Accuracy of position: ±0.01 m;
- Anschütz Gyro Compass System Standard 22. Accuracy of HDG < 0.4°.

Test conditions and data analysis

Four key variables were identified during the measurements:
- the ship size ratio (DWT_1/DWT_0) – defined as the deadweight of the passing vessel in relation to that of the moored vessel;
- the depth-to-draft radio (H/T) – defined as the draft of the moored ship relative to the water depth;
- the separation distance (s [m]) – the side distance;
- the moving ship velocity (V [m/s]).

Ship size ratios included only two values:
- 1.15 – the size of the passing vessel was the same as the size of the moored vessel;
- 2.71 – the size of the passing vessel was smaller than the size of the moored vessel.

Water depths in the tests were selected to obtain two sizes for the *depth-to-draft ratio*: 1.20 (for shallow water) and 2.0 (for deep water).

Separation ratios were successively: 30.24 m, 60.48 m, 75.60 m, and 90.72 m, that is approximately: 1B, 2B, 2.5B, and 3B (B is the beam of a moored ship). *Moving ship velocity* ranged from approximately 4 kn to 20 kn in the following passes. For the above-mentioned parameters, combinations of passes were carried out during which the following were measured: the surge force and sway force. Then, the peak values for these forces were extracted: $F_{x\ min}$, $F_{x\ max}$, $F_{y\ min}$, and $F_{y\ max}$. Selected examples of peak force values, for particular variables, are presented in Tables 2–4.

Table 2. Tabulation of the test conditions and results for deep water and same-size ships

DWT_1/DWT_0	H/T	s [m]	v [m/s]	$F_{x\ min}$ [T]	$F_{x\ max}$ [T]	$F_{y\ min}$ [T]	$F_{y\ max}$ [T]
1.15	2.00	30.24	2.73	–22.86	–54.85	21.84	28.66
1.15	2.00	30.24	5.35	–68.47	–108.46	41.55	70.01
1.15	2.00	30.24	5.45	–97.07	–145.43	58.68	107.91
1.15	2.00	30.24	6.53	–149.97	–202.78	98.24	138.04
1.15	2.00	30.24	6.74	–157.15	–249.78	106.42	161.44
1.15	2.00	60.48	2.26	–5.87	–25.40	9.93	17.49
1.15	2.00	60.48	3.70	–22.14	–31.54	12.80	19.15
1.15	2.00	60.48	5.50	–39.96	–71.27	32.36	32.97
1.15	2.00	60.48	5.55	–50.16	–81.48	40.45	59.08
1.15	2.00	60.48	7.20	–86.00	–129.72	78.52	99.52
1.15	2.00	90.72	2.88	–8.34	–43.29	24.31	31.40
1.15	2.00	90.72	3.91	–17.82	–70.77	12.54	35.67
1.15	2.00	90.72	4.83	–29.03	–35.94	24.79	28.45
1.15	2.00	90.72	5.76	–32.96	–52.38	33.94	40.74
1.15	2.00	90.72	6.89	–55.24	–71.81	42.37	52.52

Table 3. Tabulation of the test conditions and results for deep water and LCC vs. small ship

DWT_1/DWT_0	H/T	s [m]	v [m/s]	$F_{x\ min}$ [T]	$F_{x\ max}$ [T]	$F_{y\ min}$ [T]	$F_{y\ max}$ [T]
2.71	2.00	30.24	2.93	–33.10	–62.52	35.90	44.04
2.71	2.00	30.24	3.09	–43.13	–74.05	43.56	64.52
2.71	2.00	30.24	3.65	–59.23	–110.28	78.16	83.95
2.71	2.00	30.24	4.27	–80.90	–121.04	89.22	93.52
2.71	2.00	30.24	5.04	–124.52	–162.60	145.87	124.13
2.71	2.00	60.48	2.52	–17.64	–29.81	21.53	39.45
2.71	2.00	60.48	3.50	–36.32	–62.23	42.36	37.99
2.71	2.00	60.48	4.22	–60.10	–80.36	59.54	58.07
2.71	2.00	60.48	4.99	–80.45	–113.43	71.32	83.59
2.71	2.00	60.48	6.22	–112.12	–183.76	140.52	171.97
2.71	2.00	90.72	2.26	–13.93	–19.26	11.41	23.78
2.71	2.00	90.72	3.14	–28.51	–26.41	22.47	33.85
2.71	2.00	90.72	4.32	–34.80	–59.98	36.42	29.33
2.71	2.00	90.72	4.94	–52.73	–78.86	53.32	36.94
2.71	2.00	90.72	6.17	–79.25	–132.18	90.43	59.61

Table 4. Tabulation of the test conditions and results for shallow water and same-size ships

DWT_1/DWT_0	H/T	s [m]	v [m/s]	$F_{x\ min}$ [T]	$F_{x\ max}$ [T]	$F_{y\ min}$ [T]	$F_{y\ max}$ [T]
1.15	1.20	30.24	3.87	–2.83	–40.57	14.86	49.65
1.15	1.20	30.24	4.36	–5.51	–65.50	–5.51	–65.50
1.15	1.20	30.24	6.22	–2.87	–134.33	44.46	82.10
1.15	1.20	30.24	6.95	1.55	–134.32	67.24	101.18
1.15	1.20	30.24	9.11	–8.07	–271.73	116.19	232.56
1.15	1.20	60.48	3.87	–0.85	–32.48	11.00	27.58
1.15	1.20	60.48	6.02	–1.34	–60.88	24.42	60.97
1.15	1.20	60.48	7.05	2.68	–100.14	38.53	71.84
1.15	1.20	60.48	9.11	0.43	–190.41	62.88	186.22
1.15	1.20	60.48	11.17	–9.71	–244.82	114.18	238.34
1.15	1.20	75.60	3.23	–2.17	–30.64	7.46	20.48
1.15	1.20	75.60	5.63	–2.70	–59.68	21.48	56.48
1.15	1.20	75.60	6.32	–4.34	–55.76	25.73	57.51
1.15	1.20	75.60	6.90	–0.47	–90.29	31.17	62.49
1.15	1.20	75.60	8.08	–0.04	–110.35	34.94	62.24
1.15	1.20	75.60	9.60	3.77	–156.28	62.09	101.54

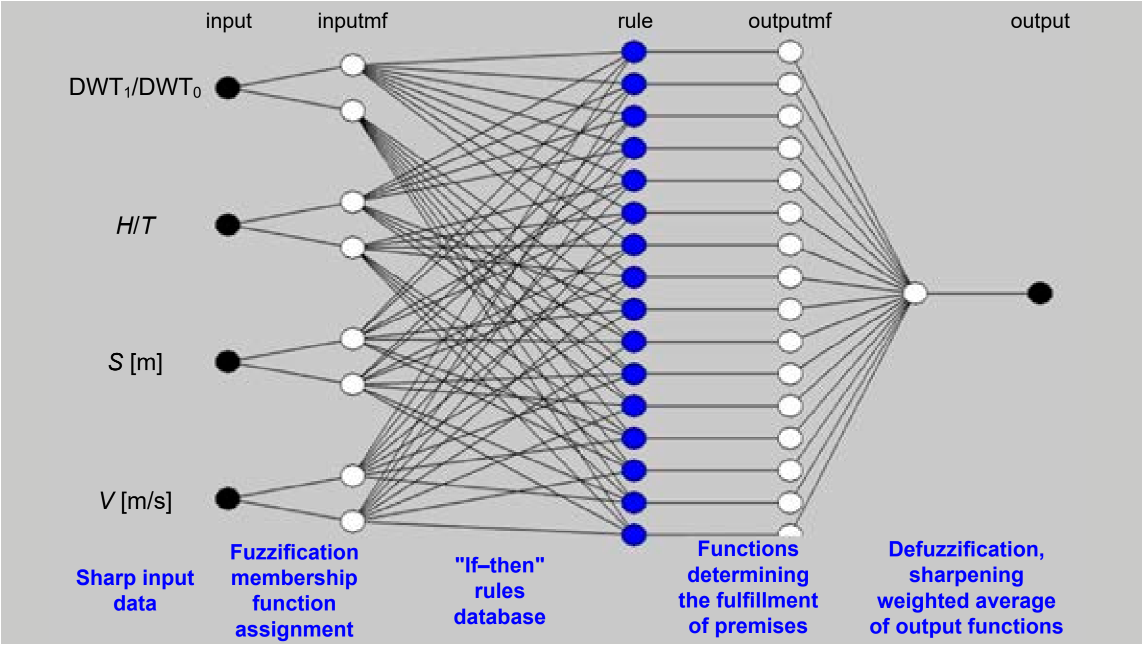

Figure 8. Screenshot of SUGENO model structure

The variables and force peaks described above constituted the input database for the Matlab (Matlab R2021b) computing environment (the "if-them" rules database). A self-learning neural network was created in the Matlab environment (see Figure 8), where four fuzzy models were created, one for each force $F_{x\,\min}$, $F_{x\,\max}$, $F_{y\,\min}$, and $F_{y\,\max}$ (Piegat, 1999).

Figures 9–12 show the interface of the Sugeno model and the sample calculations of $F_{x\,\min}$, $F_{x\,\max}$, $F_{y\,\min}$, and $F_{y\,\max}$ for the variables $DWT_1/DWT_0 = 2.71$, $H/T = 2$, and $s = 1B$, and for the speed in turn: $V = 2.66$ m/s, $V = 2.88$ m/s, $V = 3.21$ m/s, and $V = 3.42$ m/s.

Figure 9. Interface of the SUGENO model with $V = 3.42$ m/s ($DWT_1/DWT_0 = 2.71$, $H/T = 2$, and $s = 1B$)

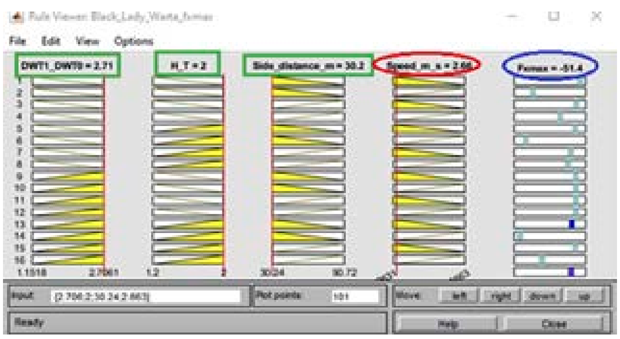

Figure 10. Interface of the SUGENO model with $V = 2.66$ m/s ($DWT_1/DWT_0 = 2.71$, H/T = 2, and $s = 1$B)

Figure 11. Interface of the SUGENO model with $V = 3.21$ m/s ($DWT_1/DWT_0 = 2.71$, $H/T = 2$, and $s = 1B$)

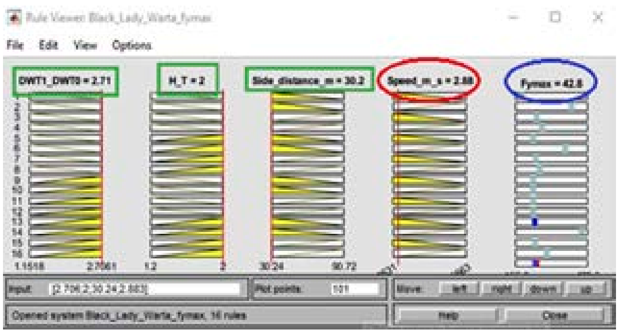

Figure 12. Interface of the SUGENO model with $V = 2.88$ m/s ($DWT_1/DWT_0 = 2.71$, $H/T = 2$, and $s = 1B$)

The user-friendly interface of the SUGENO model enables the easy modeling of the speed and side distance using sliders or typing the numerical values; the values of the maximum forces are thus instantly seen (Świercz, 2015). Based on expert knowledge, considering average mooring construction, we find the following:

- ships mooring devices and equipment (SWL);
- energy absorbing ability of port fenders and solid berths;
- mooring set up in average 2 lines + 1 spring line fore and aft.

It can be concluded that the maximum and minimum surge and sway forces should not exceed 50 T.

It should be noted that the DWT_1/DWT_0 and H/T variables appeared in the research only in the form of two values; therefore, the Sugeno model adopted a linear interpolation for these variables. The remaining variables, such as velocity and lateral distance, were measured in a sufficient amount for the Sugeno model to use three membership functions for them in the fuzzification process, which makes interpolation and extrapolation much more accurate (Trojanowska & Małopolski, 2005).

Results and conclusions

This article presents and discusses the results of the research carried out at the Ship Handling Research and Training Centre in Iława. The purpose of which was to simplify the method of predictive calculations in order to adjust the speed and distance when passing a moored ship, which ensures the safety of both vessels. The established database enables the answering of key questions for the passing of a moored ship, such as: Where does the interaction between the moored and passing ships begin? and What is the most dangerous relative position of ships?

A fuzzy model based on the Matlab computing environment was created, with the help of which it is possible to quickly determine the peak values of the hydrodynamic forces that arise during the interaction of a moored ship and a ship passing by. The study shows that fuzzy models enable the creation of stable, adaptive control systems without the need to conduct a large number of model tests. In addition, neural networks allow a correction and supplementation with expert knowledge of inaccurate fuzzy models.

The presented fuzzy model is based on the Sugeno model, a self-learning neural network that is characterized by high flexibility. Fuzzy models can be used for calculations for data outside the scope of the empirical research results. The proposed method can be implemented in the maritime transport safety management system in order to simulate the interaction of ships, and to determine the maximum permissible speed and distance to safely bypass moored ships in normal port traffic conditions.

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