Ship Speed Prediction in Real Sea Environment Using Advanced Technologies

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Abstract: - The paper presents some possibilities of practical use of advanced computing technologies applied to the prediction and modelling of ship speed in very hard and different environment conditions. The emphasis is put on two well recognised techniques, fuzzy logic and artificial neural networks. We propose here an effective method of ship speed prediction of bulk currier ship under different external hydro meteorological disturbances (wind, waves and sea current) at open sea.
The implementation of new adaptive neuro-fuzzy inference system (ANFIS) in ship speed prediction model creating have been shown in the paper. Navigational simulator Transas Marine Navy Trainer was used for collecting data needed in ship speed prediction model training and testing. The obtained results using ANFIS model point to very good prediction possibilities.

Key-Words: - ship speed, prediction, modelling, neuro-fuzzy inference, ANFIS model.

1 Introduction

Ship speed is one of the most significant variables for ship's mission. Therefore it's very important to predict ship's speed in all sailing conditions. The wind, waves and sea current as a part of environmental disturbances to the ship, are highly nonlinear. Wind is defined as horizontal movement of air to the surface on the sea and generates waves. The nonlinear dynamic equations of marine vessel motion can be expressed as follow [1]:

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau_c + g_0 + w \qquad (1)$$

where:
M - system inertia matrix (including added mass), v - ship speed, $C(v)$ - Coriolis-centripetal matrix (including added mass), $D(v)$ – damping matrix, $g(\eta)$ - vector of gravitational/buoyancy forces and moments, τ_c - vector of control inputs, g_o - vector for pretrimming (ballast control), w - vector of environmental disturbances (wind, waves and sea currents).

In recent years, there have been a growing number of papers in this and similar fields that are based on artificial intelligence algorithms, and especially on artificial neural networks and fuzzy logic when dealing with issues closely connected to prediction and/or estimation. Adaptive Neuro-Fuzzy Inference System (ANFIS) in maritime affairs is getting wider in use [2,3,4].

This paper analyzes and examines the possibility of facilitating ANFIS for reasons of a more accurate speed prediction of bulk carrier with regard to the effect of external hydrometeorological disturbances, i.e. with regard to wind, waves and sea current effects in predefined ship's encounter angles.

MathWorks MATLAB & Simulink was used as a software support in creating model for ship speed prediction in real sea conditions[1].

2 Collecting Data for Ship Speed Prediction Model

For the realization of the ANFIS model in ship speed prediction, it was necessary to ensure a certain quantity of input and output (experimental, simulated, …) data that are vital for its training and testing. From the reason that it was almost impossible to acquire real measurements for all the

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initial hydrometeorological conditions taken into consideration while developing this model, the Transas navigational simulator was used as a basis for collecting data and developing the needed data base. The influence of the external disturbances on a fully loaded bulk carrier at open sea with displacement of 202.000 dwt was analyzed.

Concerning the external disturbances in the used navigational simulator Transas NTPRO 4000, wind is described as a uniform flow of air around the ship with a constant direction and speed, and all is defined at the height of 6 meters above the sea level. Structural formula for all aerodynamic hull and superstructure characteristics are defined by functions expressed by partial sums of the Fourier series [5].

Sea currents are modelled as a constant flow with a given speed distribution. Sea current speed variation related to sea depth is not taken into consideration. Forces and moments caused by the effect of the sea current on the ship are defined as a sum of two components: forces and moments of the sea current in a steady constant flow, and forces and moments of the sea current caused by its irregular flow [5,7].

In the simulator, the sea state (waves) is modelled as a stationary process with spectral characteristics that correspond to the real sea waves states. For the wave energy spectral density function, a generalized Pierson-Moskowitz spectrum [6] is used with the parameters of which adapt to the navigation area selection [5]. A 3D polyharmonic irregular wave model is used with the sea state described by the significant wave height $H_{1/3}$, and the general sea direction φ_{WV}. The surface of the waves is defined as the sum of harmonics [5]:

$$\zeta(x_g, y_g, t) = \sum_{i=1}^{N} A_i \cdot \cos[k_i(x\cos\mu + y\sin\mu) - \omega_i t + \varepsilon_i] \quad (2)$$

where:

ζ - wave surface z-coordinate, i – the ordinal number of the harmonics, N – the total number of the harmonics, A_i – the amplitude of the i-th harmonic, k_i – the wave number, μ – angle of wave propagation relative to ship's heading, ω_i – the frequency of the i-th harmonic, ε_i – the phase of the i-th harmonic, x_g and y_g – coordinate axes of the motion plane. Because of the particularities of the sea roughness, the model used on the simulator consists of $N = 20$ harmonics. On the simulator, the effect of the waves on the ship is defined by calculating longitudinal, lateral and vertical forces, and roll, trim and yaw moments.

The simulations of various hydro meteorological effects on the ship speed were performed with certain limitations. All the values are simulated so that all the external disturbances come from the same direction, which assumes that the waves are formed as wind waves and that the sea currents are generated by wind. The initial course of the ship in each simulation was 0° (N direction), and the direction of the external disturbances varies. It was assumed that the ship retains its given course regardless of the external disturbances, thus the ship's autopilot option for tracking the planned voyage was used. With the final determination of the ship speed, ship speed over the sea bed was taken into consideration, i.e. the ship speed with respect to the sea bed which is gained as a resultant of the speed through the water and the effect of the sea current, wind and waves on the ship. In all the simulations, the basic assumption was that the ship constantly navigates along open part of the Adriatic Sea at full speed ahead (v).

In the analyzed simulation scenarios, initial values of the predefined hydrometeorological scenarios (*wind, waves, current*) were selected by varying their values from the following sets:

wind – simulated wind speed: {0, 10, 20, 30, 40} (knots)

waves – simulated wave height: {0, 1, 2, 3, 4} (m)

current – simulated sea current speed: {0, 1, 2} (knots).

The defined discrete values of wind speed, wave height and sea current speed were selected according to the Scale of Sea State for the Adriatic Sea with respect to the World Meteorological Organization (WMO).

Due to symmetry reasons, directions of external disturbances effect that were taken into consideration vary from 0° to 180°, and are from the following sets of encounter angles (see fig. 1.):

$\beta \in \{0°, 45°, 90°, 135°, 180°\}$. The reasons for such choice are of merely practical nature and are closely related to the manner in which the encounter angle is defined for the wind, waves and sea current on the Transas navigational simulator.

For the values of the encounter angle β, only several combinations of the before mentioned values of wind speed, significant wave height and sea current were taken into consideration, because it is clear that many of them do not have physical meaning. Therefore, the combinations for wind speed and wave height were taken according to table 1.

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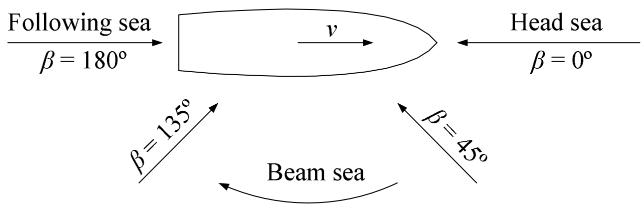

Figure 1. Encounter angles of ship's-disturbance for ANFIS model

Table 1. Combinations of wind speed and wave height used for developing ship speed ANFIS model

Wind speed [knots]	0		10		20			30			40	
Wave height [m]	0	1	0	1	1	2	3	2	3	4	3	4

The combinations in table 1 were generally determined according to the already mentioned Scale of Sea State for the Adriatic Sea with respect to the WMO. The only exceptions are the combinations (*wind, wave*) with the corresponding values (0 knots, 1 m) and (10 knots, 0 m) that represent swell (no wind, but present waves) and a sudden impact of wind (there is wind, but the waves have not developed yet) respectively. Twelve combinations (*wind, wave*) from (0 knots, 0 m) to (40 knots, 4 m) can easily be formed from table 1. If those combinations are also additionally combined with the values of the sea current speed from the set {0, 1, 2} knots, a total of 36 combinations (*wind, wave, current*) from (0 knots, 0 m, 0 knots) to (40 knots, 4 m, 2 knots) is acquired.

In this manner, 180 simulations of the effect of wind speed, wave height and sea current speed on the speed of bulk carrier are performed on the simulator for all the values of the encounter angle β so that the external disturbances reach the ship in the angles from the set {0°, 45°, 90°, 135°, 180°} clockwise with respect to the ship's longitudinal axis (Figure 1).

Each of the defined scenarios was simulated within a period of 10 minutes, and the average speed of the considered ship in the simulated scenario was determined from the last 5 minutes. The readings of all the parameters were performed every 10 seconds, and the simulation itself started with the defined values of the given scenario every time.

In the end, additional 20 different scenarios were simulated, but in the manner that the values of the wind speed, significant wave height, sea current speed and encounter angles were randomly selected. Although the selection of those scenarios was random, special attention was given so that an already used scenario does not appear among the values of external disturbances, and also that the values remain within the boundaries set according to WMO. These values were used for the final verification and evaluation of the prediction possibilities of the acquired ANFIS model for every encounter angle and for every value of external disturbances from the defined sets.

3 Ship Speed Prediction using Neuro-Fuzzy Approach

The emphasis in this paper has be done on testing the possibilities of developing a model for ship speed prediction depending on external hydro meteorological disturbances by means of ANFIS method.

Generally speaking, ANFIS is an algorithm for automatic adjusting of the Sugeno (Takagi-Sugeno-Kang) fuzzy inference system based on the training data. The first two parts of the fuzzy inference process, fuzzification of the input parameters and the application of the membership functions (MF) are practically identical with Mamdani model. The only difference is that the output membership functions of the Sugeno system can be either linear or constant.

By using the input-output data set, ANFIS creates a Fuzzy Inference System (FIS). The membership functions parameters are adjusted with backpropagation learning algorithm or combined with the method of least squares (hybrid learning method). This kind of adjusting enables FIS system learning from the data used for training [8].

In order to demonstrate the ANFIS architecture more easily, let us assume that the following fuzzy rules can be applied to two input parameters x and y, and one output parameter z:

Rule 1: IF x is A_1 AND y is B_1 THEN $f_1 = p_1x + q_1y + r_1$,

Rule 2: IF x is A_2 AND y is B_2 THEN $f_2 = p_2x + q_2y + r_2$,

where x and y are inputs, A_i and B_i are fuzzy sets, f_i linear input functions, p_i, q_i and r_i are parameters adjusted during the network training phase. The structure of the ANFIS network for the implementation of these two rules is shown in Figure 2.

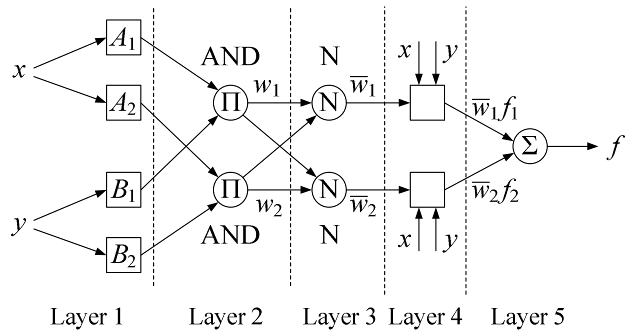

Figure 2. Network structure of ANFIS model.

In the first layer, all the nodes are adaptive. The outputs of the first layer are inputs to which the membership functions are associated (usually two on each input), and can be expressed as:

$$O_i^1 = \mu_{A_1}(x), \quad i = 1,2 \tag{3}$$

$$O_i^1 = \mu_{B_1}(y), \quad i = 1,2 \tag{4}$$

where μ_{A_1} and μ_{B_i} can be any membership functions.

ANFIS is exquisitely implemented and supported within the MATLAB & Simulink software package. The eight input and two output membership functions are at the user's disposal. In this work we used a bell-shaped input membership function (*gbellmf*). In the second layer, the nodes are fixed and marked by Π for reasons of simple multiplication. The outputs of this layer are calculated in the following manner:

$$O_i^2 = w_i = \mu_{A_1}(x)\mu_{B_1}(x), \quad i = 1,2. \tag{5}$$

In the third layer, the nodes are also fixed and marked by N. The outputs of this layer represent input normalization, and are calculated as follows:

$$O_i^3 = \overline{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1,2. \tag{6}$$

In the fourth layer, the nodes are again adaptive. The outputs of this layer are acquired as the products of the normalized inputs and first-degree polynomials (for the first-order Sugeno model). In other words, it stands that:

$$O_i^4 = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i y + r_i), \quad i = 1,2,.. \tag{7}$$

where p_i, q_i and r_i are the so called consequential parameters.

In the fifth layer, there is only one fixed node labelled with Σ in which a final output as a superposition of all input signals is calculated. In other words, the total output is calculated as:

$$O_i^5 = \sum_{i=1}^{2} \overline{w}_i f_i = \frac{\sum_{i=1}^{2} w_i f_i}{w_1 + w_2} \tag{8}$$

The goal of training (learning) is to obtain the least difference between the real and predicted values by adjusting the assumed (Layer 1) and the consequential (Layer 2) parameters.

The learning algorithm adjusts the parameters $\{a_i,b_i,c_i\}$ and $\{p_i,q_i,r_i\}$ in order to determine the optimum between the ANFIS output and the training output. When the assumed parameters $\{a_i,b_i,c_i\}$ are determined, the ANFIS output model can be written as:

$$\begin{aligned} f &= (\overline{w}_1 x)p_1 + (\overline{w}_1 y)q_1 + (\overline{w}_1)r_1 + \\ &\quad (\overline{w}_2 x)p_2 + (\overline{w}_2 y)q_2 + (\overline{w}_2)r_2 \end{aligned} \tag{9}$$

which is a linear combination of the adjustable consequential parameters p_1, q_1, r_1, p_2, q_2 and r_2. After this phase, the optimal values of these parameters are set by the method of least squares. In order to avoid problems concerning the oversized area for results searching or slow converging when the assumed parameters aren't fixed, a hybrid learning algorithm that combines the method of least squares with the backpropagation learning algorithm is used. Once the optimal values of consequential parameters are set by the method of least squares, the assumed parameters adjustment is performed by the gradient descent method. Finally, the ANFIS output is calculated by means of consequential parameters. The residuals between the calculated ANFIS output values and the real outputs is used to adjust the assumed parameters for the next epoch based on the standard learning algorithm with error backpropagation.

4 Test case: Results and Analysis

In order to create and test the ANFIS model described in the previous section, it is needful to classify the obtained data described in the section 2. From the total of 252 simulated scenarios of the effect of the external disturbances on the speed of bulk carrier ship, a matrix **M** of the 252x5 format was formed first. The rows of that matrix represent the values of the arranged 5-tuple (*wind speed, wave height, current speed, encounter angle, ship speed*) of the corresponding simulated scenarios.

During the initial testing phase, all the combinatorial ship speed interdependences with respect to the external disturbances were done. That also includes the second order combinations that provide a 3D graphical display that demonstrates the way the trained ANFIS gives a prediction for any initial condition. The combinations that include the encounter angle alternation and any of the other disturbances are particularly interesting and are shown in Figure 3, 4 and 5. The obtained responses are not to be taken without precaution being that the dependence of the ship speed is modelled with only two external disturbances at the same time.

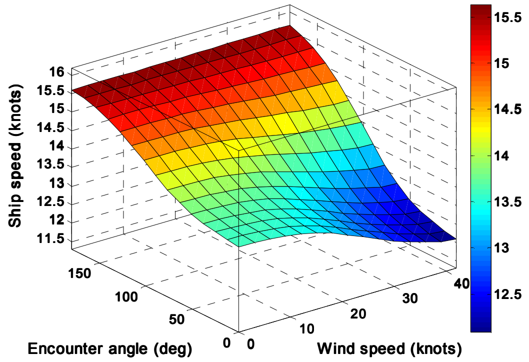

Figure 3. Influence of wind speed with change of encounter angle to ship speed

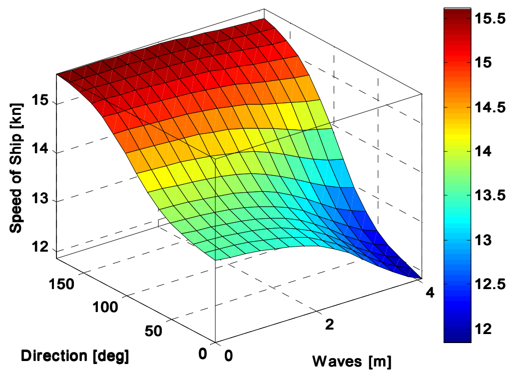

Figure 4. Influence of waves height with change of encounter angle to ship speed.

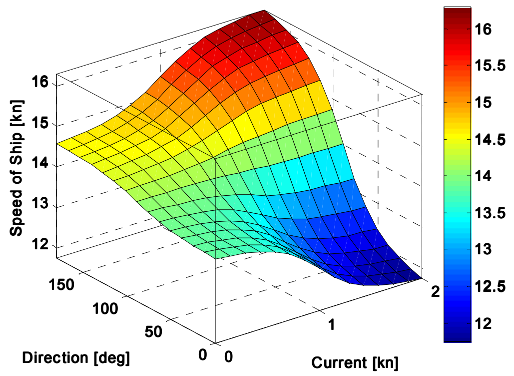

Figure 5. Influence of sea current with change of encounter angle to ship speed.

Figures 3, 4 and 5 show that all three disturbances have the same influence trend on ship speed. Ship speed decreases with an increase in an external disturbance and a simultaneous turning of the encounter angle from the stern towards the bow. On the other hand, the increase in the ship speed due to the effect of the external hydrometeorological factors has somewhat different trends. Thus, in case of wind and waves, this trend is dependent almost entirely upon the encounter angle, and in case of sea current, it is equally dependent upon the encounter angle as it is on the sea current speed. It was analyzed how the selection of different membership functions influences the quality of the response of the created ANFIS model. For validity assessment of the ship speed prediction model under the influence of external disturbances, root mean squared error (*rmse*) between the expected and the estimated values of the ship speed was used as a goal function and was calculated by the expression:

$$rmse = \frac{1}{N}\sqrt{\sum_{k=1}^{N}[n(k)-\hat{n}(k)]^2} \tag{10}$$

where N is the total number of the discrete values, $n(k)$ is the expected value, $\hat{n}(k)$ is the value estimated by the prediction model. The obtained results with respect to the selected performance measure are presented in figure 6.

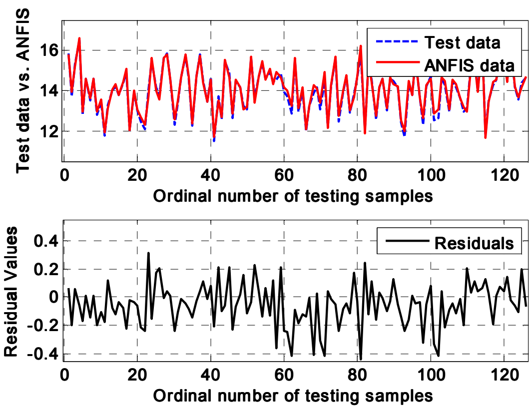

Figure 6. Test values of the ship speed and those obtained by ANFIS model with the corresponding residual diagram.

The best result of the 126 scenarios used for training and 126 scenarios used for testing was obtained using the bell-shaped input membership function (*gbellmf*) and the constant as the output membership function (*rmse*=0,161).

5 Conclusion

The possibility of application of a new ANFIS based approach to the ship speed prediction of type bulk carrier in very hard and different environment conditions was shown in this paper. The obtained results point to exceptionally good prediction possibilities of models created in this manner, which

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could result in a wide variety of practical applications such as increasing the accuracy and efficiency of logistical planning of ports and other resources (pilots, tugboats, operational quays, agents, forwarding agents...), ship position prediction, etc.
Concerning the recommendations for further research, the need for the model's generalization to a greater number of different types and dimensions of merchant ships should be emphasized as well as the other world seas and oceans regions.

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