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ON HARBOUR MANOEUVRING AND NEURAL CONTROL SYSTEM FOR BERTHING WITH TUG OPERATION

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ABSTRACT

Discussions on the mathematical model of harbour manoeuvring of a ship and on an artificial neural network (ANN) suitable for automatic berthing control including tug operation are made. Current, wind and tug forces are treated as well as precise mathematical model of a ship for low advance speed, including stopping behaviour. An ANN is designed to berth a ship automatically by her thruster and rudder. Another ANN controller is designed for tug boat manipulations. Finally, automatic berthing system using these two ANN's is confirmed by simulation.

Keywords: Berthing control, tug operation, neural network, ship manoeuvre, low advance speed

INTRODUCTION

Safety at sea is one of the most hottest topics now in the world. In this meaning, ship manoeuvrability is very important. IMO (International Maritime Organization) has just resolved its 'manoeuvrability standard' criterion for the newly constructed ships. However, this is just for normal ship operations, like turning ability, zig-zag manoeuvres and stopping ability. Actual ship operation is more and more complicated. Especially, berthing is one of the most difficult operation even for veteran pilots.

Authors are trying to make an automatic berthing system using artificial neural network (ANN) for a couple of years. In the first trial (Hasegawa and Kitera 1993a, 1993b, Hasegawa 1993), three-layer ANN is designed and examined by simulation. It is found the system works well for various situations of approach to the berth, by providing only several patterns as teaching data and by selecting suitable variables as input neurons. The system also works well against wind disturbances.

Thus, the system was planned to be expanded for more realistic operation; tug manipulation. In this paper, mathematical model and ANN configuration suitable for automatic berthing system including tug operation are made.

HARBOUR MANOEUVRING

MMG model

Manoeuvring motion of a ship at moderate speed is well represented by so-called MMG model (Ogawa et al. 1977, Hamamoto et al. 1977, Kasai et al. 1977, Kose et al. 1977, Ogawa et al. 1980) or other similar models developed following the MMG model. MMG model was developed in Japan by a group called "Mathematical Model Group", so the model name came from the group name.

However, the model is standing on a concept like

$$\begin{aligned} F &= F_H + F_P + F_R \\ &= + F_{H0} + F_{H(P)} + F_{H(R)} + F_{H(PR)} \\ &+ \; + F_{P0} + F_{P(H)} + F_{P(R)} + F_{P(HR)} \\ &+ \; + F_{RO} + F_{R(H)} + F_{R(P)} + F_{R(HP)} \end{aligned} \tag{1}$$

where F total force or moment such as X, Y and N

where

X	longitudinal force acting on a ship
Y	lateral force acting on a ship
N	moment about C.G. acting on a ship

subscripts are;

H	force or moment acting on a hull
P	force or moment acting on a propeller
R	force or moment acting on a rudder
O	open characteristics

and subscripts in parentheses are;

H	interaction force affected by the existence of a hull
P	interaction force affected by the existence of a propeller
R	interaction force affected by the existence of a rudder
PR	interaction force affected by the existence of combination of a propeller and a rudder
HR	interaction force affected by the existence of combination of a hull and a rudder
HP	interaction force affected by the existence of combination of a hull and a propeller

but the expression of each component is not officially standardized. There exist wide variation of the model now. Introduction of some standard models can be found in several literatures available in English (e.g. Inoue et al. 1981, Kose 1982). By their efforts, the model is now widely spread in the world and these models are sometimes referred as modular models in Europe.

Manoeuvring Motion at Low Advance Speed

Though the group MMG broke up after publishing its reports, it is proceeded to the new projects; JAMP (Japanese Manoeuvrability Prediction Working Group) (Fujii et al. 1985) and MSS (Manoeuvrability at Shallow Water and/or Slow Advance Speed Working Group) (Fujino et al. 1989, Kijima et al. 1989, Hamamoto et al. 1989). In the latter group, the mathematical model at low advance speed was discussed, although in the report, detail model was not proposed. Kijima et al. (1987) summarized mathematical models at low advance speed and Hasegawa and Kitera (1993a) reviewed them again with quoted applications.

Roughly speaking, the discussions are focused on how to represent non-linear hydrodynamic forces spreading wide range of sway angle. There are three ways; (1) polynomial model, (2) Fourier expansion model and (3) cross-flow model. Another difficulty in the model used for slow advance speed is how to avoid zero-division error when ship speed is zero, because normal non-dimension convention uses ship speed. In this paper, the model proposed by Kose et al. (1984) is used.

Stopping Manoeuvres

It is well known a ship becomes unstable during stopping. This is caused by asymmetrical force and moment acting on a hull by reversing rotation of a propeller. This phenomenon is well represented by the model;

$$
Y_{p'} = \begin{array}{l} A_1 + A_2 J_s \\ A_3 + A_4 J_s \\ A_5 \end{array} \qquad N_{p'} = \begin{array}{lll} B_1 + B_2 J_s & \text{for} & J_{syn} \le J_s < J_{syn0} \\ B_1 + B_4 J_s & \text{for} & J_s < J_{syn} \\ B_5 & \text{for} & J_{syn0} \le J_s \end{array} \qquad (2)
$$

where

$Y_{p'} N_{p'}$	asymmetrical lateral force and moment acting on a hull by reversing rotation of a propeller, non-dimensionalized by $(p/2)\ Ld(nD)^2$ and $(p/2).L^2 d(nD)^2$ respectively
Js	apparent advance ratio defined as

$$J_s = U \mid nD \qquad (3)$$

where

U	ship speed (m/s)
n	propeller revolution (rps)
D	propeller diameter (m)
$A_1 \sim A_5, B_1 \sim B_5, J_{syn}, J_{syn0}$	coefficients obtained from experiments

Longitudinal component of force is of course induced by reversing rotation of a propeller, and also well modelled by the following equation;

$$
X_p' = \begin{cases} C_1 + C_2 Js & \text{for} \quad J_s \ge C_{10} \quad \text{and} \quad n > 0 \\ C_8 + C_9 J_s & \text{for} \quad J_{st} < J_s < C_{10} \quad \text{and} \quad n > 0 \\ C_6 + C_7 J_s & \text{for} \quad J_s \ge C_{10} \quad \text{and} \quad n < 0 \\ C_3 & \text{for} \quad J_{st} < J_s < C_{10} \quad \text{and} \quad n < 0 \end{cases} \qquad (4)
$$

longitudinal force acting on a hull induced by a propeller (i.e. = (1-t)T), non-dimensionalized by pn^2D^4 thrust deduction T propeller thrust coefficients obtained from experiments

where

t	thrust deduction
T	propeller thrust
$C_1 \sim C_3, C_6 \sim C_{10}, J_{st}$	coefficients obtained from experiments

Figures 1 ~ 3 shows a typical result of experiments with approximation by equations (2) ~ (4) measured on a 3-metre model of a tanker "Exxon Osaka" (Hamamoto and Hasegawa 1986). Coefficients obtained from these figures are shown in Table 1.

Table 1. Coefficients Related to Propeller Reversing Forces and Moment

item	value	item	value	item	value
C_1	0.315	A_1	$-0.079\text{x}10^{-3}$	B_1	$0.035\text{x}10^{-3}$
C_2	-0.200	A_2	$7.99\text{x}10^{-3}$	B_2	$0.035\text{x}10^{-3}$
C_3	-0.251	A_3	$-4.93\text{x}10^{-3}$	B_3	$-3.17\text{x}10^{-3}$
C_6	-0.175	A_4	$-5.87\text{x}10^{-3}$	B_4	$1.96\text{x}10^{-3}$
C_7	0.330	A_5	$-0.558\text{x}10^{-3}$	B_5	$2.33\text{x}10^{-3}$
C_8	0.457	J_{syn}	-0.35	J_{syn0}	$0.225\text{x}10^{-3}$
C_9	0.408				0.06
C_{10}	-0.233				
J_{st}	-0.64				

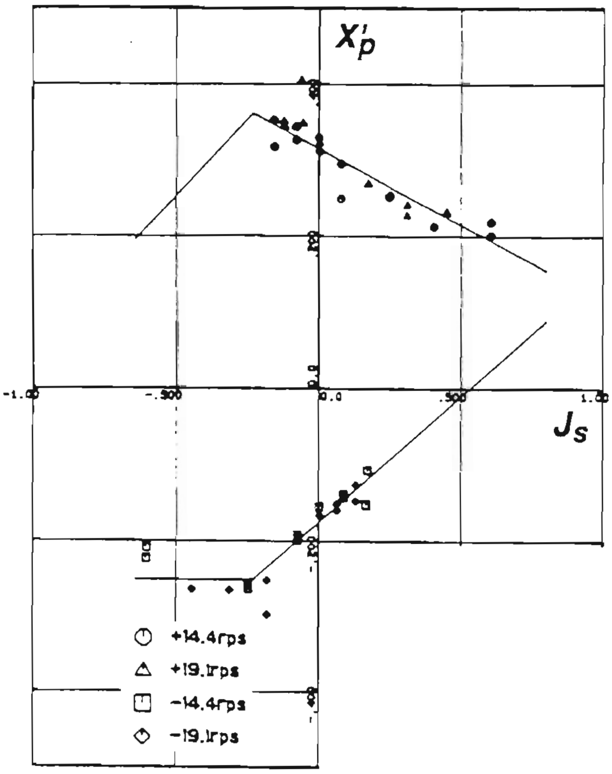

Fig.1 Longitudinal Force Due to Propeller Revolution

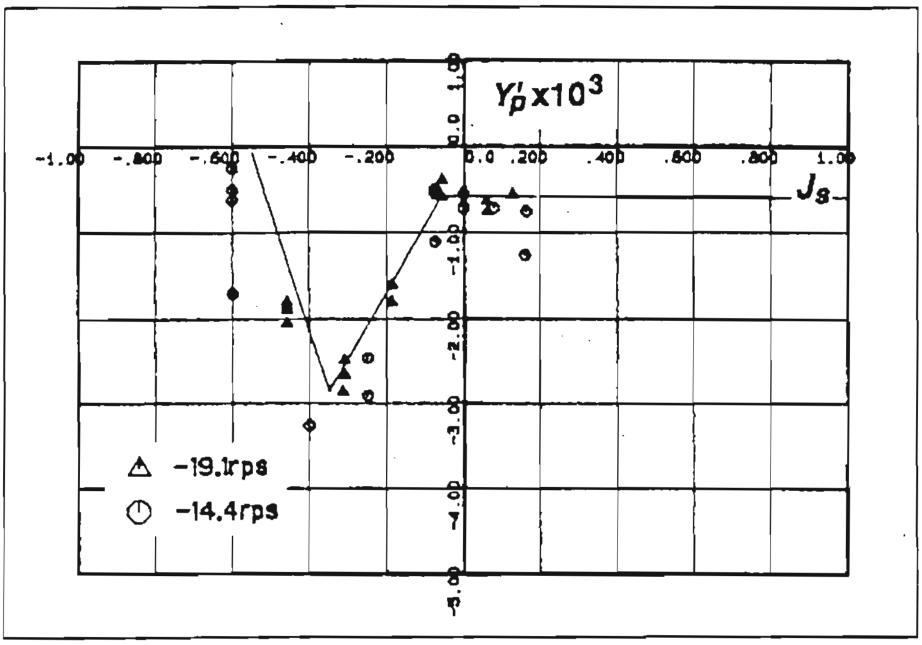

Fig.2 Lateral Force due to Propeller Revolution

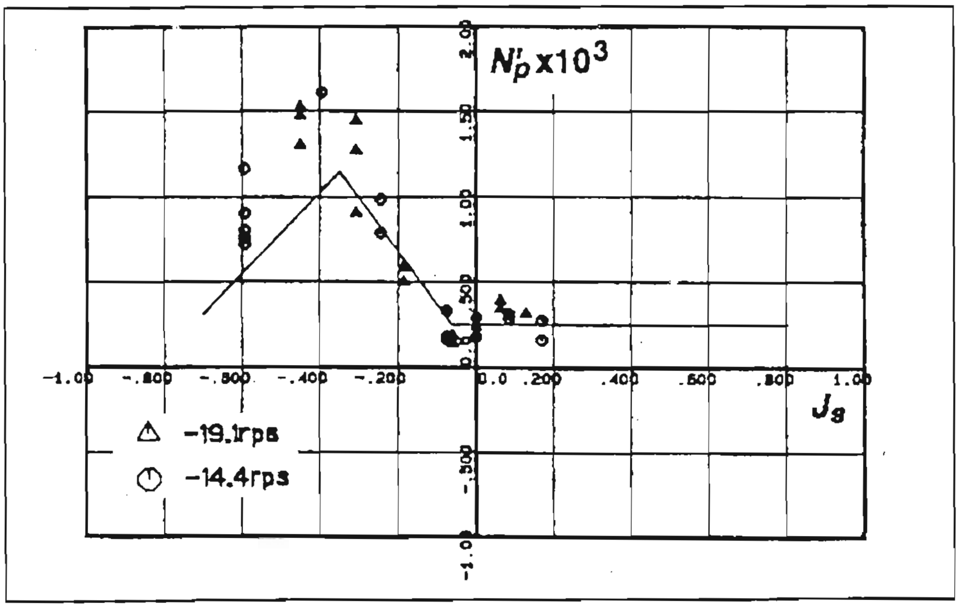

Fig.3 Moment About C.G. due to Propeller Revolution

Tug Forces

At berthing control, usually tug boats are used. Tug forces can be added to the right-hand side of equation (1) as another component with subscript T respectively.

These component forces are normally affected by the speed of the towed ship, if it is high enough, as suggested by Kose et al. (1987). In this paper, bollard pull/push forces are applied in the condition that these forces will be used only the speed of the towed ship is less than 6 knot. Besides, though a tug boat may pull or push the towed ship at an arbitrary direction and at an appropriate point of the towed ship, fixed points (l_{tf} and l_{ta} defined in **Figure 4**) and directions (0° for x-direction tugs and -90° for y-direction tugs) are assumed only from the simplicity purpose.

Lastly, the maximum thrust of a tug boat is assumed 60 tons but 140 tons maximum are applied in the simulation. This means that three tug boats are applied at each pushing/pulling point together.

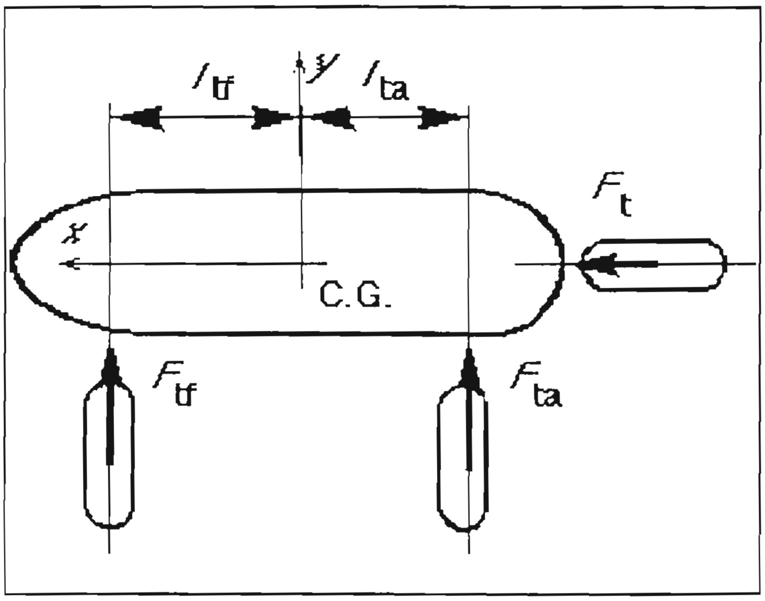

Fig.4 Layout of Tug Boats and Other Definitions

$$X_T = F_t,$$
$$Y_T = F_{tf} + F_{ta}$$
$$N_T = F_{tf} \times l_{tf} - F_{ta} \times l_{ta} \qquad (5)$$

where	X_T, Y_T N_T	longitudinal and lateral forces and moment about C.G. due to tug boats
	F_t, F_{tf} F_{ta}	x-direction, y-direction (fore and aft) tug forces (bollard pull/push)
	l_{tf}, l_{ta}	pull/push point (fore and aft)

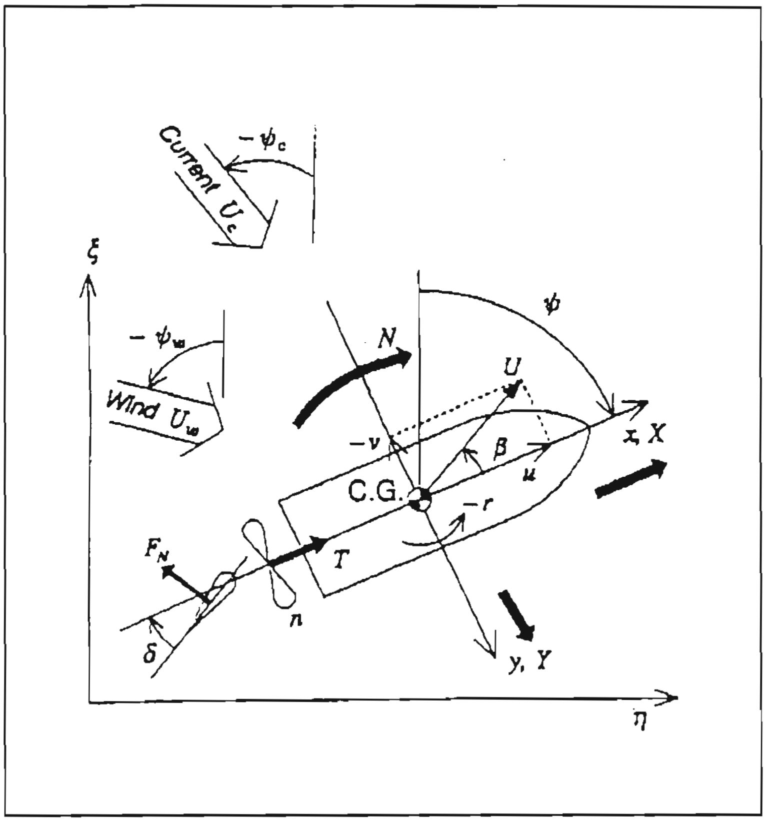

Figure 5. Coordinate System.

Wind and Current Forces /Moment

Wind disturbance and current effect become relatively large, when ship speed becomes low. Especially, in berthing these effects may not be neglected.

Wind forces and moment are calculated using Isherwood's formulae (Isherwood 1972, quoted by Hasegawa and Kitera 1993a), and added to equation (1) as X_w, Y_w and N_w

The treatment of current forces and moment, on the other hand, is different from other forces and moments. They should be accounted as relative velocity and rate of turn. In this paper, uniform current locally is assumed as

$$\begin{aligned} u_{ca} &= u + U_c \cos(\psi_c - \psi) \\ v_{ca} &= v + U_c \sin(\psi_c - \psi) \end{aligned}$$

$$\dot{u}_{ca} = \dot{u} + U_c r \sin(\psi_c - \psi)$$

$$\dot{v}_{ca} = \dot{v} + U_c r \cos(\psi_c - \psi) \tag{6}$$

where :

U_c	current velocity (m/s)
ψ_c	current direction (rad)
u, v	longitudinal and lateral components of ship velocity (m/s)
ψ	heading angle of a ship (rad)
r	rate of turn of a ship (rad/s)
u_{ca}, v_{ca}	longitudinal and lateral components of apparent current velocity (m!s)

Mathematical Model For Harbour Manoeuvring

For other notations, MMG model conventions are used as referred as in **Figure** 5. Summing up equations (1) ~ (5) and taking account some modification for slow advance speed, final mathematical model can be summarized as follows:

$$\begin{aligned}(m + m_x)\, \dot{u}_{ca} = {} & (m + m_y + X_{vr})\, v_{ca}\, r \\ & + X_{uu} | u_{ca} | u_{ca} + X_{uvv}\, u_{ca}\, v_{ca}^2 \mid U + X_{vvr} \mid v_{ca} \mid v_{ca}\, r \mid U \\ & - (m + m_x)\, U_c r \sin(\psi_c - \psi) \\ & + (1 - t)\, T - R \\ & - (1 - t_R)\, F_N \sin\delta \\ & + X_w + X_T \end{aligned} \tag{7}$$

$$\begin{aligned}(m + m_y)\, \dot{v}_{ca} - Y_{\dot{r}}\, \dot{r} = {} & Y_v\, U\, v_{ca} + Y_{vv} | v_{ca} | v_{ca} + Y_{vvvvv}\, v_{ca}^5\, U^3 \\ & + Y_r\, r + Y_{ur}\, u_{ca}\, r + Y_{uvvr}\, u_{ca}\, v_{ca}^2\, r / U^2 + Y_{vrr}\, v_{ca}\, r^2 / U \\ & + (m + m_y)\, U_c\, r \cos(\psi_c - \psi) \\ & - (1 + a_H)\, F_N \cos\delta \\ & + Y_P + Y_w + Y_T \end{aligned} \tag{8}$$

$$\begin{aligned}(I_{zz} + J_{zz})\, \dot{r} - N_{\dot{v}}\, \dot{v}_{ca} = {} & N_{uv}\, u_{ca}\, v_{ca} \\ & + N_r\, r + N_{rrr}\, r^3 \\ & + N_{ur}\, u_{ca}\, r + N_{vvr}\, v_{ca}^2\, r \\ & - N_v\, U_c\, r \cos(\psi_c - \psi) \\ & - (x_R + a_H x_H)\, F_N \cos\delta \\ & + N_P + N_w + N_T \end{aligned} \tag{9}$$

where

m, m_x, m_y	mass, x- and y-direction components of added masses
I_{zz} J_{zz}	moment of inertia and added moment of inertia about z-axis
R	ship resistance
F_N	rudder normal force, defined by MMG model
δ	rudder angle
t_R, a_H, x_R, x_H	empirical coefficients defined by MMG model
other coefficients	

such as X_{uu}, Y_v and N_{uv}	so-called hydrodynamic coefficients, modified for low advance speed

BERTHING CONTROL

Berthing control is one of the most difficult operation, and directly affected to ship safety. The automation is long-term desire. Conventional control theory, however, cannot solve the problem easily. Recently, several researchers have tried its automation using several methods.

(1) feedback and feedforward combined control (Kose et al. 1986, Takai and Ohtsu 1990)
(2) optimal control (Koyama et al. 1987, Shouji and Ohtsu 1992, 1993a, 1993b, Shouji et al. 1992)
(3) predictive fuzzy control (Takai and Yoshihisa 1987)
(4) artificial neural network (ANN) control (Yamato *et al.* 1990, Hasegawa and Kitera 1993a, 1993b, Hasegawa 1993)
(5) knowledge-base control (Yamato et al. 19∼2, 19g3)

Hasegawa and Kitera (1993a, 1993b) and Hasegawa (1993) have configured an ANN for berthing control as shown in **Figure C** for a tanker whose particulars are described in Table 2. Error-back-propagation method is used for learning. It works satisfactorily as shown in **Figure 7,** even if the ship is controlled only by her own main thruster and rudder. This is partially because the mathematical model installed didn't include the model for the stopping behaviours. So the ship easily stop straight without the assistance of tug boats.

Table 2 Principal Particulars of a Tanker.

Item	*Symbol*	*Value*	*Unit*
Ship length	L	304.0	m
Length overall	L_{OA}	310.5	m
Ship breadth	B	52.5	m
Mean draught	d_m	17.4	m
Block coefficient	C_b	0.827	-
Mass	m	2.350×10^8	kg
Moment of inertia	I_{zz}	1.018×10^{12}	kgm^2
Wetted surface area	S	2.259×10^4	m^2
Propeller diameter	D_P	8.5	m
Propeller pitch	P	5.16	m
Rudder area	A_R	98.0	m^2
Rudder height	h	12.94	m
Rudder aspect ratio	Λ_R	1.709	-

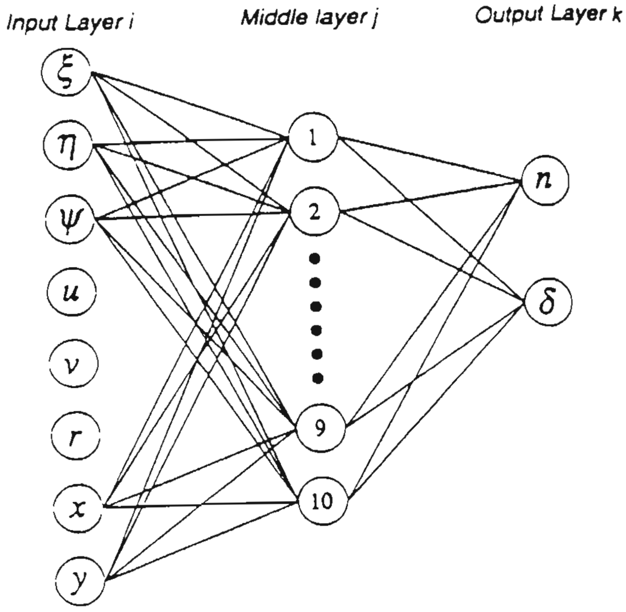

Figure 6. Configuration of Three-Layer Network for Berthing
(Hasegawa and Kitera 1993a, 1993b).

In this paper, their method is further expanded suitable for tug boats operation, using more practical mathematical model described in equations (7) ~ (9).

As for the ANN, another network including F_t, F_{tf} and F_{ta} as additional neurons in the output layer in **Figure** G is designed. These two ANN's are switched based on the ship's position and velocity. Firstly, the ship starting from the point A in **Figure** 8 is approaching to the point B by the ANN shown in **Figure** 6. Secondly, the ANN is switched to the tug included ANN between B and C. In **Figure** 8, tug boats are plotted as A. White triangle mark means the tug boat is pushing the ship, while black triangle mark means pulling. Though the approaching angle at the point A, wind velocity and direction are different between **Figures** 7 and 8, it is obviously observed the different manner of berthing control.

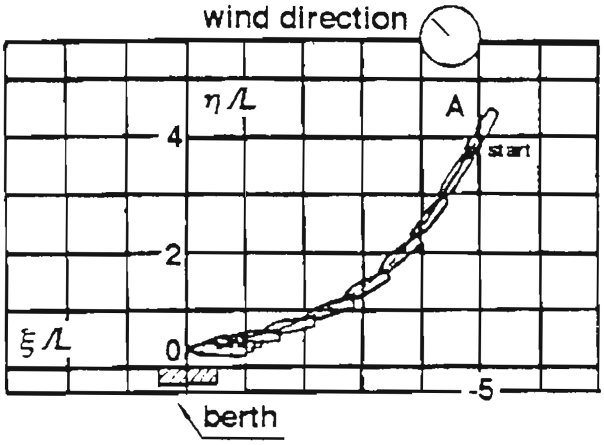

Figure 7. Sample Result of Berthing Control Using Main Truster and Rudder Only by Artifcial Neural Network
$A(\xi,\eta,\psi)$ = (-5L, 4L, -60deg) Wind (U_w, ψ_w) = (5m/s, 45deg)
(Hasegawa 1993)

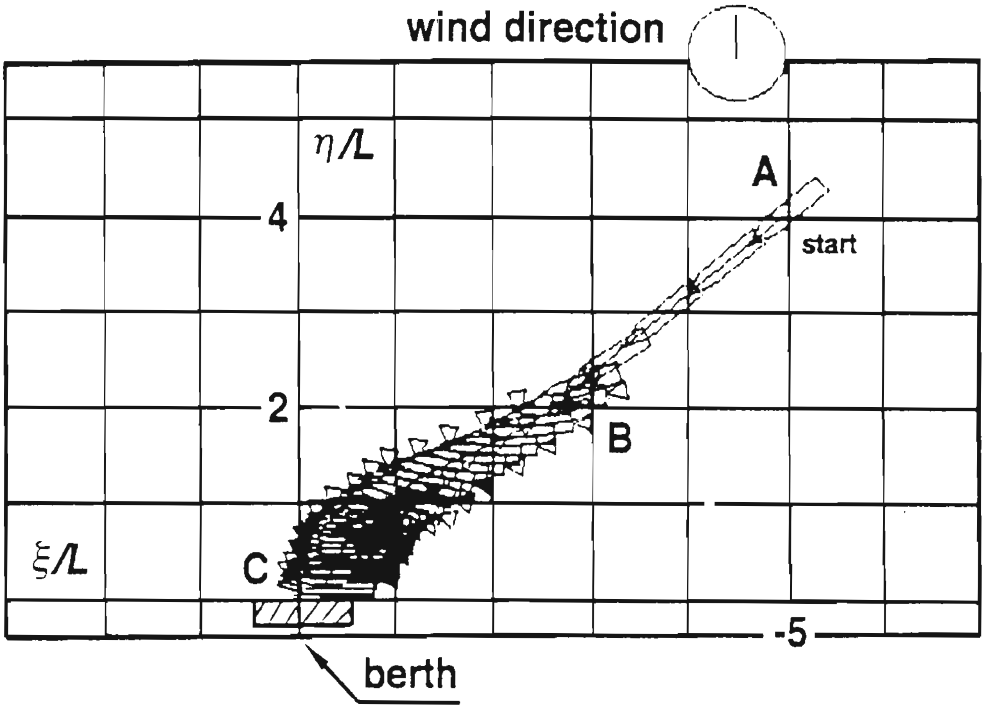

Figure 8. Berthing Control Using Tug Boats by Artificial Neural Network.
$A(\xi,\eta,\psi)$ = (-5L, 4L,-30deg), Wind (U_w,ψ_w) = (3m/s, 90deg)

CONCLUSIONS

In this paper, the authors are describing mainly on two points; on harbour manoeuvring and on berthing control using tug boats. Main conclusions obtained through the study can be summarized as follows.

(1) Mathematical models suitable for harbour manoeuvring are described.

(2) Artificial neural network (ANN) is configured both for approaching and berthing to a berth.

(3) Further study is necessary for verification of the mathematical model at low advance speed, including free-sailing tests.

(4) It is still difficult to setup the efficient patterns for getting teaching data for tug operation, though the detail description is omitted.

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