MATHEMATICAL MODEL AND ALGORITHMS CONTROL OF SHIP IN MEETING MOTION WHEN PASSING THROUGH THE CHANNEL

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ABSTRACT

In this paper, the author devotes the development of mathematical model and algorithms control of ship in meeting motion when passing through the channel. The research object is the adaptive control, the algorithm of auto pilot regulator and the programs of ship control based on the fuzzy control that assure the accuracy and the navigational quality in the narrow water with the infinite of external impacts.

Keywords: The adaptive control, fuzzy control, ship in meeting motion.

INTRODUCTION

The problem of ship control with the program complex in the real time is impossible to obtain the solution, when using of auto pilot regulator with convention PID unit and current adjust method. Because of the operation time of system, the parameter and the external effects are contingently varied in wide range. In this research, it's considered the subject of synthesis of mathematical model and algorithms control of ship incoming traffic at the channel where the space for maneuvering is confined, i.e. the interaction between two ships in meeting motion.
Firstly, it's considered the subjects related to the development of mathematical model of ship motion such as: direction and force of wind, high and length of wave, the characteristic of ship's hydrodynamic, draft and under keel clearance, speed. In playing the modelling role, M.V HAI DUONG 101 (IMO number 9697727) registered under Vietnamese flag, owned by HAI DUONG COMPANY LIMITED (HADUCO), is chosen as the model ship. This is anchor handling, tug and supply ship with LOA 65m, GT2281, equipped with DPS-2, built by Focal Ship Building, China in 2014.

Figure 1: M.V HAI DUONG 101

LITERATURE REVIEW

In this field, there are many research works such as A. Lebkowski, R. Smierzchalski, W. Gierusz and K. Dziedzicki (2008), Zadeh LA (1974); Bolnokin VE, Uy DV and Manh DX (2005); Loc HD (2002), Chai TY and Zhang Tao (1981); Chan PT, Xie WF and Rad AB. (2000); Chang HC, Wang MH (1995); Chang SS, Zadeh LA (1972); Chen CL, Chen WC (1994); Chen FC, Liu CC (1996); Cheng SJ, Chow IS, Malik OP and Hope GS (1986); Krasovsky A.A (1999); Peshekhonov V.G (2000); Kolesnikov A.A (2002); Astana Y.M (2002); V.S Medvedev et al. (2005); Hecht-Nielsen r. (2007); Stone M. (2009); Weierstrass K (2010). They have focused on the research of the adaptive control for application in the objective control. In this research, the author devotes the development of method and algorithms to model and optimize the ship control system in meeting motion. The research object is to design the method and the navigational equipment, the auto ship control. They are the adaptive control, the method of assurance of the accuracy and the navigational quality in the narrow water with the infinite of external impacts.

METHODOLOGY

A Statement of Problems of the Ship Control in the Meeting Motion

The following systems of co-ordinates are used [1]:

Terrestrial - O^n, Z^n, x^n, y^n

Connected - O, Z, x, y

High-speed - O, x^0, Z^0, y^0

It is possible to consider O^n, Z^n, x^n, y^n inertial system as the ship's speed is less than circular speed of the earth.

The equations of a ship complex with Ship Propulsion System (SPS) will be such:

$$\left.\begin{aligned}
&(m+\lambda_{11})\frac{dU_x}{dt}-(m+\lambda_{22})U_y\Theta_z-\lambda_{26}\Theta_z^2=F_x\\
&(m+\lambda_{22})\frac{dU_y}{dt}+(m+\lambda_{11})U_x\Theta_x+\lambda_{66}\frac{d\Theta_z}{dt}=F_y\\
&(I_z+\lambda_{26})\frac{d\Theta_z}{dt}+(\lambda_{22}-\lambda_{11})U_xU_y+\lambda_{26}U_x\Theta_z+\lambda_{26}\frac{dU_y}{dt}=M_z\\
&(I_i+\lambda_i)\frac{d\omega_i}{dt}=M_{g_i}-M_{c_i},\quad i=1,\dots,n
\end{aligned}\right\}\qquad(1)$$

Where:

m - Weight of a vessel;

λ_{11} - The weight of water at movement on axis X;

λ_{22} - The weight of water at movement on axis Y;

λ_i - The inertia moment of weight of water;

λ_{66} - The inertia moment of water when the vessel moving around axis Z;

U_x, U_y - Ship's speeds by the axes X and Y;

Θ_z - The rotational speed of a vessel round the vertical axis passing through the center of gravity;

ω_i - Angular rotational speed of i rowing screw;

λ_{26} - The static moment;

F_x - Projection of the forces affected to ship by axis *X*;

F_y - Projection of the forces affected to ship by axis *Y*;

M_z - The moments affected to ship by axis *Z*;

M_{g_i} - The moment developed by *i* diesel engine;

M_{c_i} - The resistance moment to *i* diesel engine;

I_i - The inertia moment of rotating parts of *i* engine and the screw.

Supposedly, vessel contours are symmetric concerning a plane midsection, i.e. concerning plane *OXY* the size λ_{26} can be neglected [2, 3]:

$$\left.\begin{aligned} (m+\lambda_{11})\frac{dU_x}{dt} &= (m+\lambda_{22})U_y\Theta_z + F_x \\ (m+\lambda_{22})\frac{dU_y}{dt} &= -(m+\lambda_{11})U_x\Theta_z + F_y \\ (I_z+\lambda_{66})\frac{d\Theta_z}{dt} &= (\lambda_{11}+\lambda_{22})U_xU_y + M_z \\ (I_i+\lambda_i)\frac{d\omega_i}{dt} &= M_{g_i} - M_{c_i}, \quad i=1,\dots,n \end{aligned}\right\} \tag{2}$$

As forces and the moments are considered in high-speed system of co-ordinates, their projections to axes of the connected system will be [3]:

$$\left.\begin{aligned} (m+\lambda_{11})\frac{dU_x}{dt} &= (m+\lambda_{22})U_y\Theta_z + F_x \\ (m+\lambda_{22})\frac{dU_y}{dt} &= -(m+\lambda_{11})U_x\Theta_z + F_y \\ (I_z+\lambda_{66})\frac{d\Theta_z}{dt} &= (\lambda_{11}+\lambda_{22})U_xU_y + M_z \\ (I_i+\lambda_i)\frac{d\omega_i}{dt} &= M_{g_i} - M_{c_i}, \quad i=1,\dots,n \end{aligned}\right\} \tag{3}$$

Where:

α - A drift corner;

P_{e_i} - An emphasis force of *i* screw;

A - A drift force;

R - A resistance force of vessel movement;

M - The moment of the hydro-mechanical forces affected ship hull by axis *Z*;

M_q - The moment of transversal force q;

M_{n_i} - The moment concerning axis *Z*, arisen by *i* propeller thrust.

The moment from transversal force q is defined so:

$$M_q = \Theta_q l_q \tag{4}$$

where l_q - distance between rudder stock and the center of gravity.

The considered equations are nonlinear mathematical models of ship complexes, as a control objects. It's difficult to use these equations for the analysis and synthesis of algorithms control. Normally, these equations are not linearized by means of classical ways or by mean of multidimensional extrapolation.

Objectives of Meeting Motion

The ship will be considered in the form of dynamic system with a status $x(t)$, an output $y(t)$ and the control $u(t)$, defined by the equations [4]:

$$\dot{x}(t) = f\left[x(t),t\right] + B\left[x(t),t\right]u(t) \tag{5}$$

$$y(t) = h\left[x(t)\right] \tag{6}$$

It's assumed that:

$$\left.\begin{array}{r} x(t) - n \textit{ dimension vector} \\ x(t) - m \textit{ dimension vector} \\ u(t) - r \textit{ dimension vector} \end{array}\right\} \tag{7}$$

Also that:

$$n \geq r \geq m > 0 \tag{8}$$

Where: f - the function of n dimensional vector; $B\left[x,t\right]$- the matrix-function of the size $n \times r$; h - the function of m dimensional vector. It's considered that components of a vector of control $u(t)$ are limited on size by inequalities

$$\left|u_j(t)\right| \leq m_j, \quad j = 1, 2, ..., r \tag{9}$$

Supposing $z(t)$ - a vector with m components, it's agreed to name $z(t)$ as desirable output. Let $e(t) = y(t) - z(t)$ - Error vector; t_0 - initial time; $x(t_0)$ - starting state of dynamic system.
It is required to find the control, which:

- Satisfies to restrictions (8);
- How to control the system that finally there is:

$$e(T) \in E \tag{10}$$

  where E - the given subset in R_m;
- Minimizes transitional time $T - t_0$.

If the dynamic system described by the equations (5) and (6), is completely observable, at every $y(T)$ there corresponds a unique status $x(t)$. Hence, area S in status space can be defined by the relation:

$$S = \left\{x(T) : y(T) = h\left[x(T)\right]; y(T) \in Y\right\} \tag{11}$$

Using of the minimum principle of Pontriagina LC, it's obtained the system method to solve the optimum problem. Received results in the analytical form can be used for numerical representation of decisions. It's considered the optimum control for mobile area S_t. The system is given

$$\left.\begin{array}{c} \dot{x}(t) = f_i\left[x(t),t\right] + \sum_{j}^{r} b_{ij}\left[x(t),t\right]u_j(t); \\ i = 1, 2, ..., n \\ \textit{or in the equivalent vector } \dot{x}(t) = f\left[x(t),t\right] + B\left[x(t),t\right]u(t) \end{array}\right\} \tag{12}$$

The given smooth area S is defined by relation

$$\left.\begin{array}{c} g_a\left[x,t\right]=0,\ \alpha=1,2,...,n-\beta;\ \beta\geq 1 \\ or\ by\ the\ equivalent\ way: \\ g\left[x,t\right]=0 \\ is\ the\ n\ dimension\ vector\ with\ the\ parts\ g_a \end{array}\right\} \qquad (13)$$

Components $u_1(t), u_2(t),...,u_r(t)$ are limited on size by a relation

$$\left.\begin{array}{c} \left|u_j(t)\right|\leq 1,\ j=1,2,...,r\quad for\ any\ t \\ or\ by\ the\ briefer\ method: \\ u(t)\in\Omega \end{array}\right\} \qquad (14)$$

The function is defined as:

$$J(u)=\int_{t_0}^{T}dt=T-t_0 \qquad (15)$$

Where T - free selected.

It's necessarily the control $u(t)$, that:

- Satisfied to restrictions (14);
- Transferred $x(t_0)$ of systems (12) in area S;
- Minimized the function $J(u)$.

On the basis of a minimum principle it is possible to confirm that there is an (optimum) additional vector $p^*(t)$ corresponding to optimum control $u^*(t)$ and an optimum trajectory $x^*(t)$. Existence $p^*(t)$ is a necessary condition. It is necessary that components $x_k^*(t)$ and $p_k^*(t),\ k=1,2,...,n$ satisfied to the initial equations.

$$\left.\begin{array}{l} \dot{x}_k^*(t)=\dfrac{\partial H\left[x^*(t),p^*(t),u^*(t),t\right]}{\partial p_k^*(t)} \\ \dot{p}_k^*(t)=\dfrac{\partial H\left[x^*(t),p^*(t),u^*(t),t\right]}{\partial x_k^*(t)} \end{array}\right\} \qquad (16)$$

Proximity Control for Linear Features

It developed a set of control models for ships in closed approach. The linear production is considered that there is a dynamic system [4, 5, 6, 7 and 8].

$$\dot{x}(t)=Ax(t)+Bu(t) \qquad (17)$$

Where:

- Status of system $x(t)$ is an n dimensional vector;
- Mmatrix A of the system is a constant matrix size $n\times n$;
- The coefficient matrix of the control functions ("gain") B is a constant matrix size $n\times r$;
- The control $u(t)$ is an r-dimensional vector

It's considered that the system is completely controllable and components $u_1(t), u_2(t),...,u_r(t)$ limited in size.

$$\left|u_j(t)\right|\leq 1,\quad j=1,2,...,r \qquad (18)$$

At a given initial time $t_0=0$ the initial state of the system is equal to

$$x(0) = \xi \tag{19}$$

Find the control $u^*(t)$ transforming the system from ξ to 0 at the minimum time.

It's denoted $\lambda_1, \lambda_2, ..., \lambda_n$ the eigenvalues of the matrix system A, and through $b_1, b_2, ..., b_r$ - column vectors of the matrix B

$$B = \begin{bmatrix} \uparrow & \vdots & \uparrow & \vdots & & \vdots & \uparrow \\ b_1 & \vdots & b_2 & \vdots & \cdots & \vdots & b_r \\ \downarrow & \vdots & \downarrow & \vdots & & \vdots & \downarrow \end{bmatrix} \tag{20}$$

The system is fully controllable. This means that the control transferring system (17) from any initial state ξ and the origin 0, exist. This occurs if the matrix size $n \times (rn)$:

$$G = \left[B \vdots AB \vdots A^2 B \vdots \ldots \vdots A^{n-1} B \right] \tag{21}$$

contains n linearly independent column vectors.

The input $y(t)$ in (17) is connected with its state $x(t)$ and the control $u(t)$ by the equation:

$$y(t) = Cx(t) + Du(t) \tag{22}$$

The algorithm for calculating the optimal control is shown in the following block diagram in Figure 2.

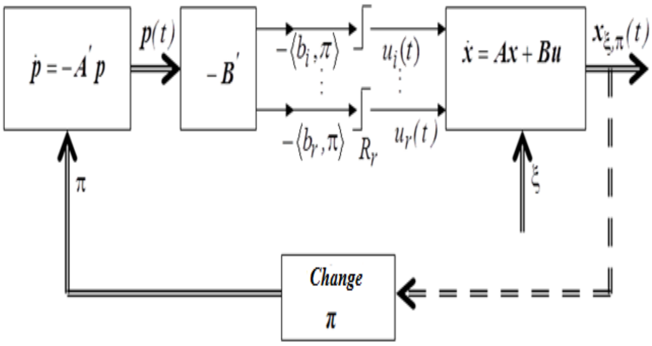

Figure 2: The structure of the algorithm is an open problem of optimal high-speed

Block diagram of an optimal feedback system is shown in Figure 3. Functions $x_1(t), x_2(t), ..., x_n(t)$ are measured at each time and introduced into a subsystem that is signed C ("computer"). The outputs RF are switching functions $h_1[x(t)], h_2[x(t)], ..., h_r[x(t)]$ which are then fed to the ideal relay $R_1, R_2, ..., R_r$ for the variables time-optimal control. Receiving and developing of functions $h_1[x(t)], h_2[x(t)], ..., h_r[x(t)]$ is the basis of the problem of optimal control.

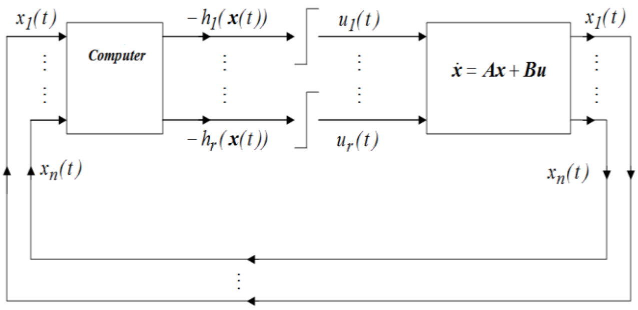

Figure 3: Structure of the time-optimal control systems with feedback

Programs for the Ship Control in Meeting Motions

It's considered the way of decisions based on the Mayer's approach in the minimum principle that allows bringing the interesting analytical solutions to numerical values [9].
It's used the system of equations:

$$\left.\begin{aligned} \frac{dl}{dt} &= v_c - v_l \\ \frac{dv_c}{dt} &= -a_c v_c + k_c \omega_c \\ \frac{dv_l}{dt} &= -a_l v_l + k_l v_l \end{aligned}\right\} \tag{23}$$

Where: l -the distance between the leader ship and the own vessel;
v_c - The speed of own ship;
v_l - The speed of the leader;
ω_l - Manipulated leader (speed of diesel engine);
ω_c - Manipulated vessel (speed of diesel engine);
a_c, a_l, k_c, k_l - Constant coefficients.
The impact of restrictions are applied on the ship control

$$|\omega_l| \le \Omega_{l\max}; \ |\omega_c| \le \Omega_{c\max} \tag{24}$$

The value ω_l is determined by a fixed subsystem based on a predetermined motion technology of ships. The control ω_c is selected by the captain of vessels. It must be such that the time interval $t = 0 \div t_k$ the following conditions are met the requirement $v_l = v_c$, $l \cong 0$.
Where t_k - the finishing time of controlled motion of ship.
It's found a control law for speed of ship's diesel engine, which provides a minimum time to achieve the equality of speeds $v_l = v_c$ and the distance between the "leader" and the following ship $l \cong 0$. The characteristics for the development of a mathematical model of the ship fuel consumption power plant.

With a decrease in the degree of automation, i.e. the ship-master himself control the ship on the basis of the program generated a stationary system, the dimension of the problem can be reduced by excluding from the general equation of a diesel engine, and the time constant is small in comparison with the time constant of the vessel.

Ship Control in Avoidance by the Fuzzy Logic Regulator

It's considered the theoretical questions of ship in avoidance on the basis of a fuzzy logic regulator. The description of structure of linguistic logic regulators (LLR) is resulted. Such regulators contain fuzzy sets, logic operations of union, intersection and a combination with variables linguistic values, the fuzzy relation formed by one or several logic operations, and a rule of fuzzy extrapolation based on the known data input.

It's noted that the important advantage of all LLR. LLR is similarly the multi-stages relay that the stages are selectively operated by the characteristic of the controlled object. Thereby it is possible to compensate appreciably the influence of nonlinearity of object that is appreciable worsening work of control systems with linear regulators P, PI and PID.

A special place is occupied by the so-called fuzzy model Tanaka and Sudzhenko or TS-model [10, 11 and 12]. First, analytical way, and then to the specific problems of modeling and control were demonstrated its high approximation ability. Fuzzy TS-model consists of a set of production rules containing the right side of the linear differential equation:

$$\begin{gathered} If\ \ y(t-1)\ is\ Y_1^{\theta},\dots,y(t-r)\ is\ Y_r^{\theta}, \\ x(t)\ is\ X_0^{\theta},\dots,x(t-s)\ is\ X_s^{\theta}, \\ then\ \ y_0(t)=a_0^{\theta}+\sum_{k=1}^{r}a_k^{\theta}y(t-k)+\sum_{l=1}^{s}b_l^{\theta}x(t-l), \\ \theta=\overline{1,n} \end{gathered} \tag{25}$$

Where:

$a^{\theta}=(a_0^{\theta},a_1^{\theta},\dots,a_r^{\theta}),\ b^{\theta}=(b_0^{\theta},b_1^{\theta},\dots,b_s^{\theta})$ - The vectors of the customizable parameters;

$y(t-r)=(1,y(t-1),\dots,y(t-r))$ - The state vector;

$x(t-s)=(x(t),x(t-1),\dots,x(t-s))$ - The input vector;

$Y_1^{\theta},\dots,Y_r^{\theta};X_0^{\theta},\dots,X_r^{\theta}$ - The fuzzy sets.

The appearance of TS-model had an enormous influence on the subsequent development of the theory of fuzzy control systems:

- Among the fuzzy models for the first time it was a legitimate use of the traditional parametric identification;
- Despite the presence in the right part of the rules of linear differential equations to TS-model, by specifying the parameters of c, the order of r,s and increase in the number of rules n can be described with very high accuracy nonlinear dynamic processes;
- Averaging properties of the output mechanism and a specific kind of membership functions make it possible to model TS-little sensitive to noise and measurement errors;

Being a non-linear and continuous function of the input variables and parameters, TS-model provides the opportunities of the analytical study of stability of nonlinear systems with its presence and subsequent training to achieve the desired quality of transients.
The structure of the generalized TS-model with n rules and m inputs, carrying the role of the mechanism output y is considered. The analysis of possibility of use LLR for synthesis of Ship Auto Pilot Regulator is resulted.

Mathematical Model and Algorithms Control of Ship Motion in Coming Traffic

The functions of forces and moments effected to ship are described by the following expression [13]:
The function of forces effected to ship by the *OY* axis (the drift function of wind pressure):

$$A_1(p)\beta+B_1(p)\theta+C_1(p)\varphi=D_1(p)\delta+E_1(p)u+Y_b \tag{26}$$

The function of moments by the *OX* axis:

$$A_2(p)\beta+B_2(p)\theta+C_2(p)\varphi=D_2(p)\delta+E_2(p)u+L_{xb} \tag{27}$$

The function of moments by the *OZ* axis:

$$A_3(p)\beta+B_3(p)\theta+C_3(p)\varphi=D_3(p)\delta+E_3(p)u+L_{zb} \tag{28}$$

Where:

- $p=\dfrac{d}{dt}$

- L_b : the sum of external forces effected longitudinally by OY axis;
- L_{xb} : the sum of external forces effected longitudinally by OX axis;
- L_{zb} : The sum of external forces affected longitudinally by OZ axis.

If the impact of the yaw and heave forces are small, it can be skipped, then there is:

$$B_1(p) = B_3(p) = D_1(p) = D_3(p) = 0 \tag{29}$$

In this case, the equations (26), (27) and (28) can be rewritten as the following forms:

$$\left.\begin{array}{c} A_1(p)\beta + C_1(p)\varphi = E_1(p)u + Y_b \\ A_2(p)\beta + B_2(p)\theta + C_2(p)\varphi = D_2(p)\delta + E_2(p)u + L_{xb} \\ A_3(p)\beta + C_3(p)\varphi = E_3(p)u + L_{zb} \end{array}\right\} \tag{30}$$

In the equations (30), the first and third equation depends on the second one. In order to research the controllable ability of the system in the stable course, it can be used the following equations:

$$\left.\begin{array}{c} A_1(p)\beta + C_1(p)\varphi = E_1(p)u + Y_b \\ A_3(p)\beta + C_3(p)\varphi = E_3(p)u + L_{zb} \end{array}\right\} \tag{31}$$

The above-said relations allow developing the transfer matrix of ship for the different processes. For example, the transfer function of yaw angle and rudder angle has the form:

$$W_{\phi u}(p) = \frac{\phi(p)}{u(p)} = \frac{A_1E_3 - A_3E_1}{A_1C_3 - A_3C_1} \tag{32}$$

In corresponding to each impact of disturbance, it can be found the transfer function as:

$$W_{\phi Y_B}(p) = \frac{\phi(p)}{Y_B(p)} = \frac{A_3}{A_1C_3 - A_3C_1} \tag{33}$$

$$W_{\phi L_{ZB}}(p) = \frac{\phi(p)}{L_{ZB}(p)} = \frac{A_3}{A_1C_3 - A_3C_1} \tag{34}$$

If all the impacts of disturbance can be presented by the relation:

$$f_\varphi = A_1L_{zb} - A_3Y_b \tag{35}$$

Then the transfer function of yaw angle and the disturbance forces in equation (34) can be presented as the form:

$$W_{\phi f}(p) = \frac{\phi(p)}{f_\varphi(p)} = \frac{1}{A_1C_3 - A_3C_1} \tag{36}$$

If the frequent impact of wave can be present as the form of sinusoid complex, then:

$$\left.\begin{array}{l} Y_b = Y_{bm}\sin\omega_k t, \\ L_{xb} = L_{bm}\sin\omega_k t, \\ L_{zn} = L_{zbm}\cos\omega_k t, \end{array}\right\} \tag{37}$$

Where Y_{bm}, L_{bm}, L_{bz} - the functions of wave intensity and the angle φ_b created by the ship motion under the wave impact.

In many cases, the transfer function of yaw angle and rudder angle can be also present as the form:

$$W_{\phi u}(p) = \frac{k_{ou}}{p(Tp+1)} \tag{38}$$

And

$$W_{\phi f}(p) = \frac{k_{of}}{p(Tp+1)} \tag{39}$$

Where k_{ou}, k_{of} - the brake coefficients in corresponding to the impact of rudder and the above-said disturbance force; T is the time constant.

In order to find the transfer function in referent to the sway and heel of ship, it's necessary to consider the fact that heel is not influence of the ship displacement but also its drift. The transfer function of heel will have the form:

$$W_{\theta\delta}(p) = \frac{\theta(p)}{\delta(p)} = \frac{D_2(p)}{B_2(p)} \tag{40}$$

$$W_{\theta Y_B}(p) = \frac{\theta(p)}{Y_B(p)} = \frac{A_3C_2 - A_2C_3}{B_2(A_1C_3 - A_3C_1)} \tag{41}$$

$$W_{\theta L_{XB}}(p) = \frac{\theta(p)}{L_{XB}(p)} = \frac{1}{B_2} \tag{42}$$

$$W_{\theta L_{ZB}}(p) = \frac{\theta(p)}{L_{ZB}(p)} = \frac{A_2C_1 - A_1C_2}{B_2(A_1C_3 - A_3C_1)} \tag{43}$$

The above transfer functions are used to establish and analyze the controllable motion of the ship under the stable disturbance impacts.

As the above said mention, the dynamic disturbances have always static property. Therefore, the auto pilot regulator should have the ability to optimize its operation that adapts with the received information. When solving of the optimization problem of parameter of the auto pilot regulator, it can be divided into two sub problems. In the first problem, it should be synthesized the tuning unit exactly for each number and in the second one, it should be established the optimization algorithm of the parameters of the auto pilot.

Supposedly, the basic structure of considered object is described by the transfer functions (38), (39), the transfer function of the feedback relation has the form:

$$W_{goc}(p) = S_1 p + S_0 \tag{44}$$

The transfer function of the tuning unit PI has the form:

$$W_{reg}(p) = \frac{u(p)}{u_1(p)} = \frac{k_{reg}}{T_{reg}p + 1} \tag{45}$$

Where:

$$k_{reg} = \frac{1}{k_{oc}}, T_{reg} = \frac{1}{k_{oc}k} \tag{46}$$

And the equation will be presented by the expression:

$$\Delta u = (\Delta\phi_{task} - \Delta\phi W_{g_{oc}})\frac{k_{reg}}{T_{reg}p + 1} \tag{47}$$

At the stable mode $\Delta_{\varphi task} = 0$, then:

$$\Delta u = \Delta\phi(S_1 p + S_0)\frac{k_{reg}}{T_{reg}p + 1} = \frac{S_0\frac{1}{k_{oc}}}{\frac{1}{kk_{oc}}p + 1}\Delta\phi - \frac{S_1\frac{1}{k_{oc}}}{\frac{1}{kk_{oc}}p + 1}p\Delta\phi \tag{48}$$

With understanding that, the quality of control is mainly influence of the time constant value of the tuning unit T_{reg}. The optimized parameters are $S_0, S_1, k\ and\ k_{oc}$. The transfer function of the tuning unit at $T_{reg} \approx 0.5\sec$ has the form:

$$\Delta u = -S_0\frac{1}{k_{oc}}\Delta\phi - S_1\frac{1}{k_{oc}}p\Delta\phi \tag{49}$$

The relation between the parameters S_0, S_1, k *and* k_{oc} is defined by the following relation:

$$S_0 = \frac{1}{4Tk_p k_{ou}}(1 + k_p k_{ou} S_1)^2 \quad (50)$$

With playing the role of the selected standard for choosing of the optimized algorithm of the parameters of the tuning unit, it's often selected the expression that consists of the following format:

- Minimization of the defined errors;
- Minimization of the differential error or total.

However, the criteria may be different for each other at the different mode of the ship control. The adjustment of the parameters can be carried out by the computer program or automated fine-tune (lookup). The computer program of the parameter changing requires the knowledge of the varied rule of the external parameters as well as the varied rule of the objective parameters. In this case, it can be synthesized the self-adjusted optimized algorithm in the meaning of any given criteria. Further by means of the fuzzy logic and neuron network technology, it'll be subsequently considered two basic subjects, as following:

- To keep the ship route stably as the expected trajectory (programed);
- To synthesize the ship control to the expected trajectory (given).

It's presented the ship motion by the model:

$$\left.\begin{array}{c} \dot{V}_y(t) = a_{11}^x(t)V_y(t) = a_{12}^x(t)\gamma(t) = b_1^x(t)u(t) \\ \dot{\gamma}(t) = a_{21}^x(t)V_y(t) + a_{22}^x(t)\gamma(t) + b_2^x(t)u(t) \\ \dot{\psi} = \gamma \end{array}\right\} \quad (51)$$

Where V – the speed vector; V_x, V_y - the speed component V by the axes x, y; ψ, γ - the corresponding angles.

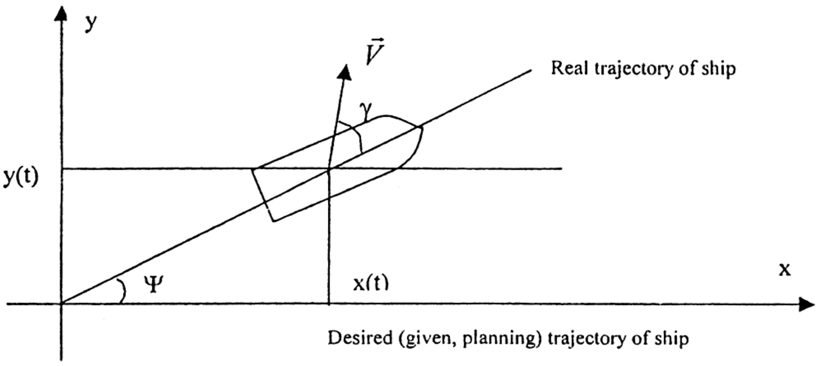

Figure 4: The Model of the Ship Motion

$$\left.\begin{array}{l} a_{11}^x = V_x \dfrac{a_{11}}{L}, \ a_{12}^x = V_x a_{12}, \ a_{21}^x = V_x \dfrac{a_{21}}{L^2} \\ a_{22}^x = V_x \dfrac{a_{22}}{L}, \ b_1^x = V_x^2 \dfrac{b_1}{L^2}, \ b_2^x = V_x^2 \dfrac{b_2}{L^2} \end{array}\right\} \quad (52)$$

Where: L – ship's length; $a_{11}, a_{12}, a_{21}, a_{22}, b_1, b_2$ - the given coefficients.

By this mean, it's obtained the standard establishment of the synthetic problem of the optimized equation, as:

$$\dot{x}(t) = f(x,u,t), \ x_0 = x(t_0), \ u(t) \in U \subset R^m, \ x(t) \in R^n \quad (53)$$

With the quality function:

$$J(x,u) = F\left[x(T),T\right] + \int_{t_0}^{T} L(x,u,t)dt \qquad (54)$$

It should be entered here the angle φ - the angle between the real course and the expected course (figure 5), and established the continuous control $u(t)=\varphi(t)$ with the help of the approximated discrete diagram, as [11, 14]:

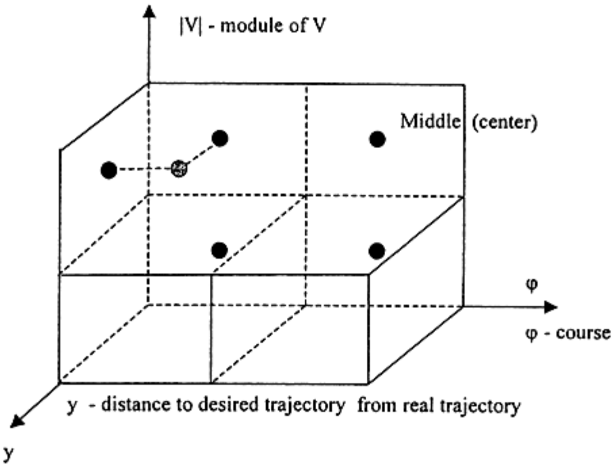

Figure 6: the Approximated Discrete Diagram

By using of chain of quantitative changes of $\varphi(t)$:

$$u_0 = \varphi(t_0),\ u_1 = \varphi(t_1), ...,\ u_k = \varphi(t_k) \qquad (55)$$

It will be established the required control. The ship sails in the condition with the contingent dynamic disturbances ξ as:

$$\dot{x} = f(x,u,t) + \xi \qquad (56)$$

After applying of the physical operation, there will be the 3-D space of the discrete control (the discrete set of control mode) $\{y,\varphi,|V|\}$ and the corresponding set of the 3-D cubes $\{y_i,\varphi_i,|V_i|\}$. Subsequently, it's considered that the point inside the cubes is not subdivided, i.e. they are only defined by their numeric value center. The varied linguistic parameters of the system will be connected with the co-ordinate of the center point of the cubes.

Structurally, the diagram of the algorithm control is:

1. By the navigation equipment, it will be obtained the ship position and calculated $\{y,\varphi,|V|\}$. Thence, it is defined the cube position of present ship position.
2. Solve the problem of the ship control: $\dot{z}(t) = f(z,u,t),\ \ z(t_0) = z_0$

Where: $z(t)\in R^n$, $u(t)\in U \subset R^m$; U - the set of the control functions with $z=(x,y,\psi,r)$, z_0 - the quantity of center point of cube where the object is.

In corresponding to the quality function of control, it should be established the control as:

$$u = -R^{-1}B^{T}Sz$$
$$u(t) = -R^{-1}B^{0}S(t)z(t)$$
$$u(t) = -R^{-1}B^{T}\left[S(t)z(t) - K(t)z_M(t)\right]$$

The control $u(t)$ in the discrete rounded operation will be established by chain $\varphi_1 = \varphi(t_1),\ \varphi_2 = \varphi(t_2), ...,\ \varphi_k = \varphi(t_k)$. This chain presents the moment by time and the yaw of the ship trajectory. After t_k, it should be kept value $\varphi(t_k)$ unchanged.

The subsequent application of the above method may be repeated, if the ship is continuously deviated far from the desired value in comparison with the desired trajectory. It can be illustrated the difference between the optimum control and the fuzzy logic control by the result of math model.

During the ship's navigation, the operation time of diesel engines with high loading significantly decreases, also maintains the ship's trajectory as the desired course.
Let's consider a case of control of two ships in avoidance oncoming traffic of in the confined channel (figure 7).

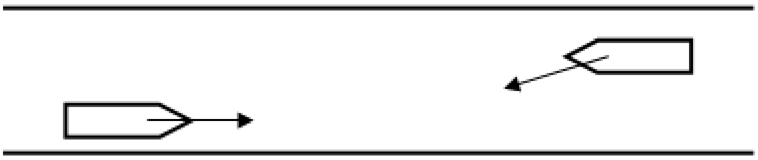

Figure 7: Two ship in avoidance during navigating in confined channel

Co-ordinates of a trajectory of mutual movement look like:

$$\bar{x}^1 = x^1, y^1, \Psi^1, v^1, ...$$
$$\bar{x}^2 = x^2, y^2, \Psi^2, v^2, ...$$
$$u_{opt}(\bar{x}^1, \bar{x}^2, t) = \left[u^1_{opt}(t), u^2_{opt}(t)\right]$$

The conventional optimum trajectories in avoidance $u^{-1}_{opt}(t), u^{-2}_{opt}(t)$ are resulted on figure 8.

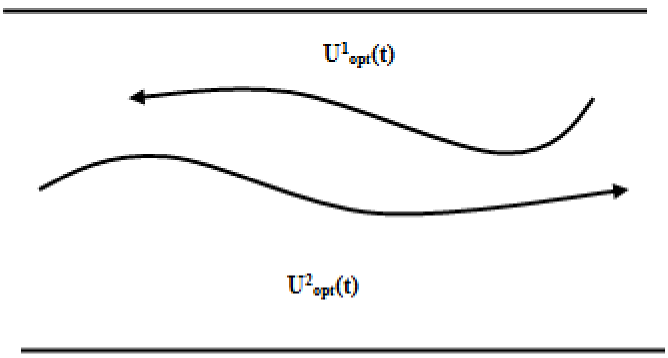

Figure 8: The conventional optimum trajectories in avoidance

In the given case of the fuzzy control is formed similarly on the Cartesian product $\Pi = \left[(\bar{x}^1, \bar{x}^2)\right]$ of trajectories of movement of two ships. Accordingly, the control functions are formed by means of Cartesian products (6-dimensional space) of the time quantized control functions (discrete set of control solution) $\{y, \varphi, |V|\}$ and corresponding set of 3-D cubes $\{y_i, \varphi_i, |V_i|\}$ corresponding to each ship (figure 9).

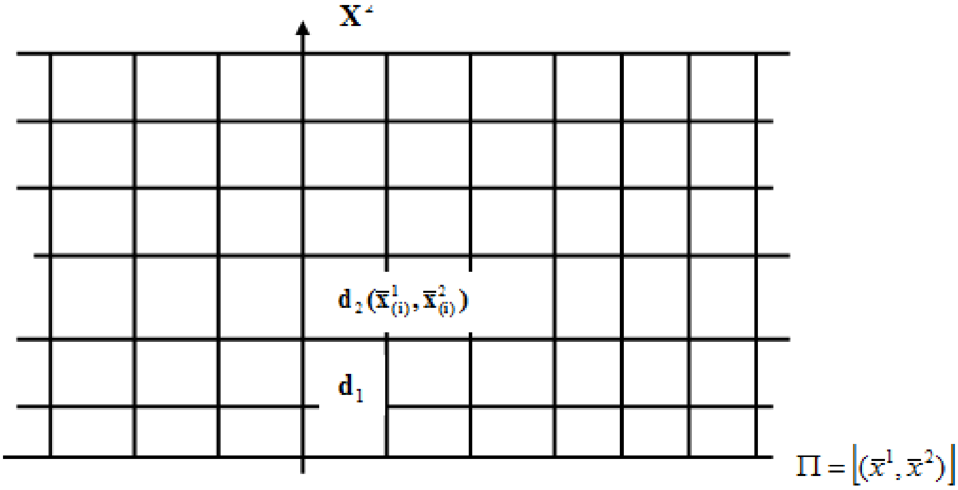

Figure 9: The Cartesian product of trajectories of movement of two ships

RESULTS

The results of modelling of process of two ships in avoidance in the channel as the form of diagram of motion trajectories is shown as following:
Usual (optimum) control

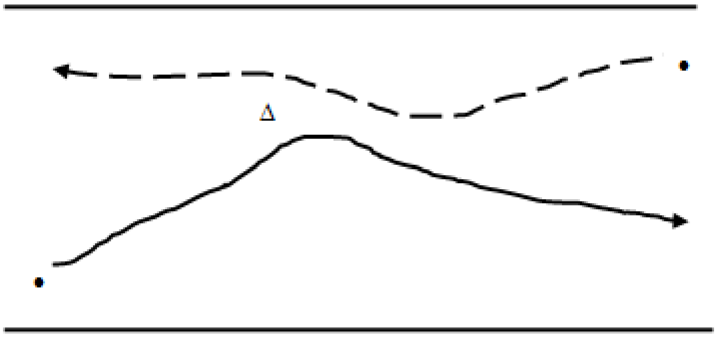

Figure 10: The model result of the optimum control

Fuzzy control

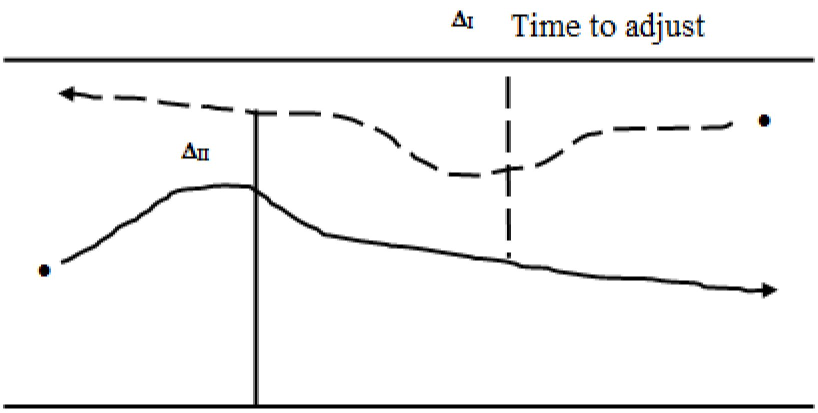

Figure 11: The model result of the Fuzzy control

The results of modelling show that in case of fuzzy control of vessel carry out a mutual divergence in the narrow channel with a large distance (in one and a half time concerning optimum control model), also it allows the ships avoiding each other at the safe distance.

DISCUSSION

The major importance of application of the fuzzy logic is to achieve the purposes:

- Minimizing of the operating time of ship engines on peak modes, i.e. with raising of fuel consumption;
- Synthesis of ship control is simulated as the behavior of the person (helmsman) for the purpose of reception enough of simple algorithms control when the vessel passing the channel or avoiding each other at oncoming traffic.

CONCLUSIONS

On the basis of systematizing and generalizing of available theoretical, it's applied the results of the actual problem of the system analysis, modelling and optimizing of control systems by oncoming traffic of ships is solved. The conducted researches allow inferring the following basic conclusions:

1. Mathematical models of a vessel are developed at lateral and longitudinal movement, both in linear, and in a nonlinear form that are considered the navigational conditions and the external influences. Also, they allow solving the problems about meetings motion of ships. The developed mathematical models of the vessel movement consider:
   - The quantities and dimensional parameters of a vessel;
   - The parameters of a power-plant and vessel's control system;
   - The disturbance influences of waves, wind and currents;
   - The requirements and logician condition of navigation in the narrow channels.
2. The basic control problems of the vessel arising in a number of special areas are formulated, particularly at the narrow channels. Application of optimum and adaptive control systems is proved.
3. On the basis of the offered applying technologies of the minimum principle it is solved a number of private control problems which are used for maintenance of a meeting motion as: ship control in following of the "leader" vessel, control of lateral motion, ship control of coming into the given mobile areas, ship control on the basis of nonlinear mathematical models which provide decisions of tasks in view for various navigational conditions are defined;
4. On the basis of a principle of a maximum of Pontrjagina LC., mathematical and algorithmic maintenance is developed for the decision of problems on a meeting motion. Procedures of a finding of optimum control in an analytical form and the approached algorithms are developed;
5. On the basis of the developed mathematical models and principles of fuzzy logic, it is synthesized the general scheme and algorithms control of ships in avoidance in the limited water spaces. Mathematical modelling of the closed control system is spent. Transitive characteristics of processes are resulted. The analysis of the received results allows inferring a conclusion on expediency of application of the approach of fuzzy logic at designing of ship control systems.
6. Mathematical and semi-natural modelling of the offered algorithms (it is particularly conducted research on modelling of ship navigating on the Vung Tau channel).

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- In practical applying of Hai Duong Company Limited (Vietnam);
- In course “Automatic control and navigation” at Ho Chi Minh City University of transport (Vietnam).

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