Fuzzy Control of Underwater Vehicle’s Motion

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Abstract: - In the paper some aspects of steering an underwater vehicle in vertical plane have been developed. The fuzzy logic properties have been applied for compensation of the vehicle's model parametrical uncertainties and viscous environment influence. It has enabled to calculate command signals driving the vehicle along the desired trajectory in case of using not full information about behaviour of the vehicle. The results of computer simulations are inserted.

Key-Words: - Underwater vehicle, Fuzzy logic, Intelligent control, Automation

1 Introduction

The steering and manoeuvring performance of underwater vehicles have been treated in various papers [1,2,3]. Modelling of vehicle dynamics with taking into consideration all real world conditions of operation is a very complicated process due to description of forces operating on the vehicle, the evaluation of coefficients of state equations, the external perturbations of waves and current. The full model of motion of a marine vehicle in 6 degrees of freedom is required only if a displacement in any direction and violent changes of a trajectory are considered. In case when stationary operating conditions are considered, such as motion and stabilisation of the vehicle on demanded depth, direction, constant distance to or above the target, etc. the simplified model may be applied [4].

The mathematical model of the underwater vehicle for control purposes is usually the reduced complexity model, but it has to be able to describe precisely enough the dynamical responses of vehicle’s motion caused by the power transmission system, stern deflection and environment perturbations.

2 Mathematical model of the underwater vehicle

Non-linear multidimensional model of motion of the underwater vehicle is usually described through Newton’s laws of linear and angular momentum in a form (1).

$$\begin{cases} m_x \frac{du}{dt} + m_z qw - m_y ru + l_{35} q^2 - l_{26} r^2 = X \\ m_y \frac{du}{dt} + l_{26} \frac{dr}{dt} + m_x ru - m_z pw - l_{35} pq = Y \\ m_z \frac{dw}{dt} + l_{35} \frac{dq}{dt} + m_y pu - m_x qu + l_{26} pr = Z \\ I_x \frac{dp}{dt} + (l_{26} + l_{35})(qu - rw) = K \\ I_y \frac{dq}{dt} + l_{35} \frac{dw}{dt} + pq(I_x - I_z) + uw(m_x - m_z) - l_{26} pu - l_{35} qp = M \\ I_z \frac{dr}{dt} + l_{26} \frac{du}{dt} + pq(I_y - I_x) + uu(m_y - m_x) + l_{35} pw + l_{26} ru = N \end{cases} \quad (1)$$

where:

u, u, w -linear velocities in a body-fixed reference frame (coincided with body axes),

p, q, r - angular velocities in a body-fixed reference frame,

m - vehicle‘s mass,

$m_x = (1 + k_{11})m, \quad m_y = (1 + k_{22})m, \quad m_z = (1 + k_{33})m,$

k_{ij} - dimensionless coefficients being function of main vehicle‘s dimensions,

I_x, I_y, I_z - moments of inertia,

X, Y, Z - external forces,

K, M, N - moments of external forces,

l_{ij} - coefficients of added mass and added inertia moments.

A right side of the equations (1) is determined by hydrodynamic forces and moments reacting on the vehicle and values of its mass, displacement and thrust of propellers.

In this paper motion of underwater vehicle in vertical plane is regarded. In such case the diving equations of motion include the heave velocity w, the angular velocity in pitch q, the pitch angle q, the depth z and the stern plane deflection d_S. Under assumption that the forward speed is constant and the sway and yaw modes are neglected, the non-linear mathematical model of the vehicle (1) can be transformed to the following linear set of equations,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u \tag{2}$$

where:

A - state matrix,

b - control vector,

$\mathbf{x} = [w, q, q, z]^T$ - state vector,

w - heave velocity (m/s),

q - angular velocity in pitch (rad/s),

q - pitch angle (rad),

z - depth (m),

$u = d_S$ - command signal (rad),

d_S - stern plane deflection (with limitation $|d_S| \le 0{,}436 rad$),

PID controllers are most widely used for control purposes in dynamical systems. Parameters of a conventional PID controller are fixed so such controller is inefficient under conditions of external disturbances. In recent years fuzzy theory has been successfully applied in the control of wide variety of engineering systems [5, 6, 7, 8]. In comparison to classical control techniques, precise information about the system is not necessary to design a suitable fuzzy controller. Beneath, the controller to steering of the underwater vehicle is described.

3 Fuzzy control law

A fuzzy Proportional Derivative (PD) Mamdani's controller working in configuration presented in Figure 1 was designed for the depth control.

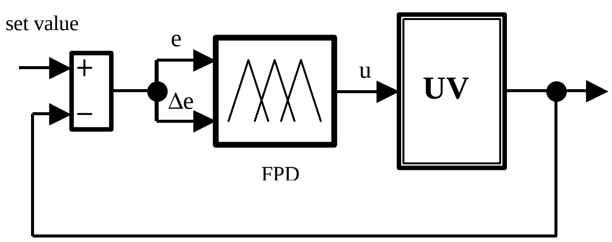

Fig. 1. Fuzzy control system

The design was based on the linearized model of the vehicle given in (2).

Membership functions for linguistic input variables (error signal $e = (z_0 - z(k))$, z_0 – desired value of draught and derived change in error $\Delta e(k) = (e(k) - e(k-1))$ were tuned, while the system suffered some disturbances in the process. These functions are shown respectively in Figures 2 and 3. The singletons presented in Figure 4 were used as the membership function for the command signal.

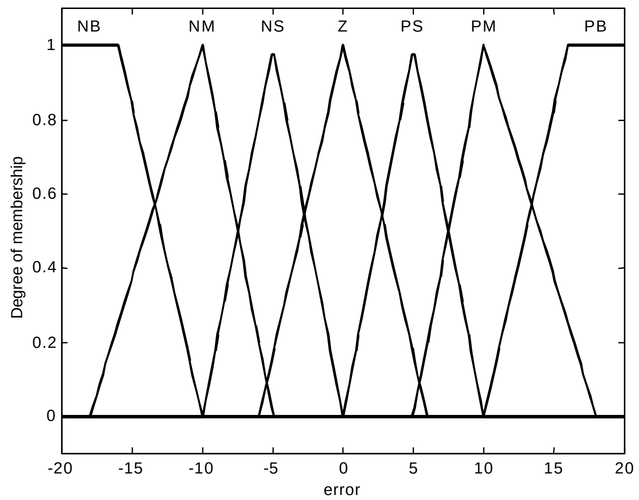

Fig. 2. Fuzzifier membership functions of error signal *e*

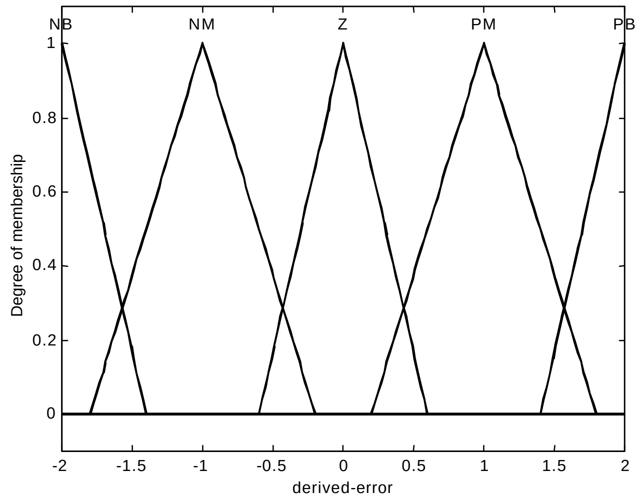

Fig. 3. Fuzzifier membership functions of derived change in error *De*

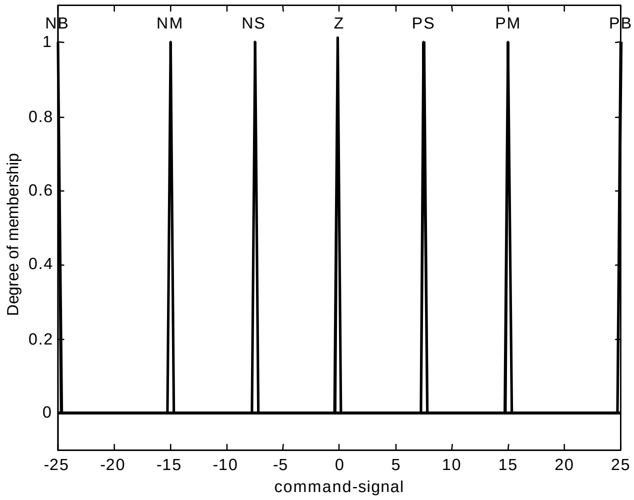

Fig. 4. Fuzzifier membership function of command signal *u*

Rules from the Mac Vicar-Whelan's standard base of rules [5, 9] were chosen as the control rules. The obtained non-linear control surface is shown in Figure 5.

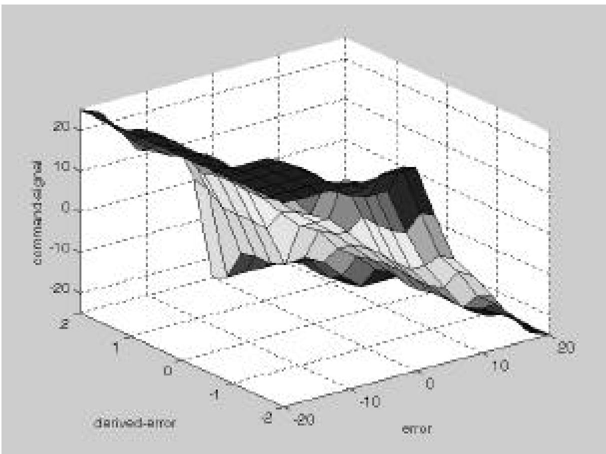

Fig. 5. Control surface generated by fuzzy controller

4 Simulation Study

Some computer simulations were realised to compare control quality in case of using the proposed fuzzy controller and a classical one. The simulations were based on the model of vehicle's motion in vertical plane given in (2) with matrices,

$$\mathbf{A} = \begin{bmatrix} -0.483 & -10.8 & -1.45 & 0.0 \\ -0.54 & -1.45 & -89.3 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 \\ 1.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} -0.365 & -1.11 & 0.0 & 0.0 \end{bmatrix}^T$$

and the following control law,

$$u = -k_2 q - k_4 (z - z_o)$$

where $k_2 = -22.6$ and $k_4 = -2.07$ are values of feedback gain vector computed by means of the pole placement algorithm.

The Runge-Kutta's 4th-order method was used to compute parameters of the above model. Values of the state vector were calculated every 0.1(s) and stern plane deflection was changed every 1(s).

Results of simulations for both types of controllers are shown in Figures 6, 7 and 8. (the fuzzy controller is denoted as FPD and the classical one as CPD) The upper plot illustrates courses of trajectories of the vehicle's motion in case of using the CPD controller (No. 1) and the FPD one (No. 2). In the medium and lower plots are presented command signals respectively for CPD and FPD controllers.

The behavior of the vehicle without interaction of disturbances is illustrated in Figure 6. The CFD controller assures shorter time of reaching a required draught. A main advantage of using the FPD controller is smoothness of the trajectory and much less changes of deflection of stern plane.

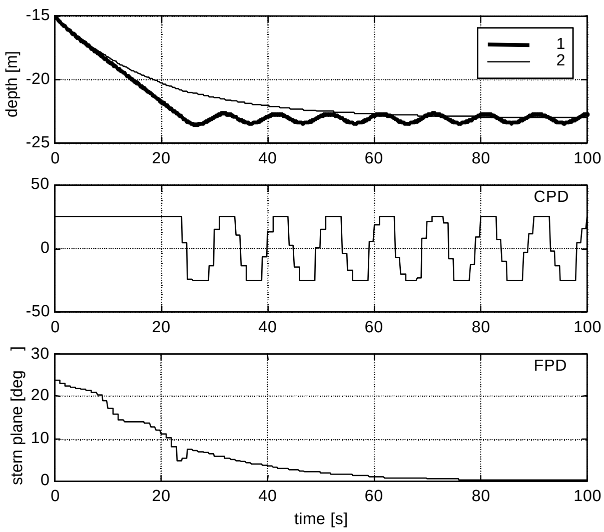

Fig. 6. The trajectories of vehicles' motion (1 – CFD controller, 2 – FPD controller) and command signals (without disturbances)

Next figures show the vehicle's motion under conditions of disturbances. Before experiments the mathematical model (2) was modified to the following form,

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{b}u(t) + \mathbf{N}\mathbf{d} \quad (3)$$

where:

N - disturbance matrix (being function of white noise),

$\mathbf{d} = [d_1, d_2, 0, 0]$ - constant vector,

d_1 - disturbance from residual buoyancy (N),

d_2 - disturbance from pitch moment (Nm).

The simulations were carried out for different levels of disturbances. Two examples for medium and strong influence of disturbances are presented below.

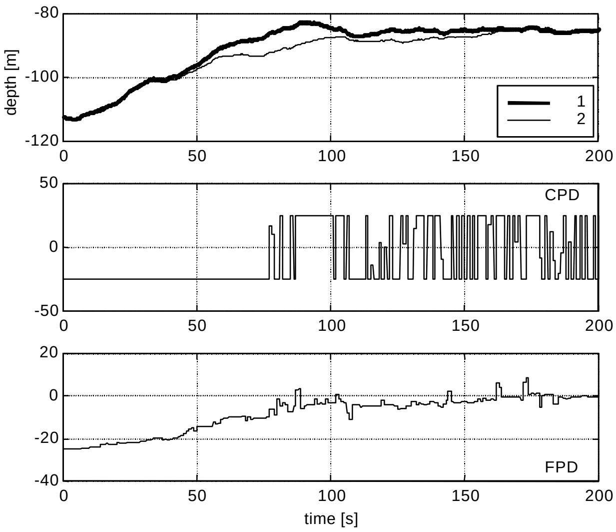

Fig. 7. The trajectories of vehicles' motion (1 – CFD controller, 2 – FPD controller) and command signals for medium disturbance effect

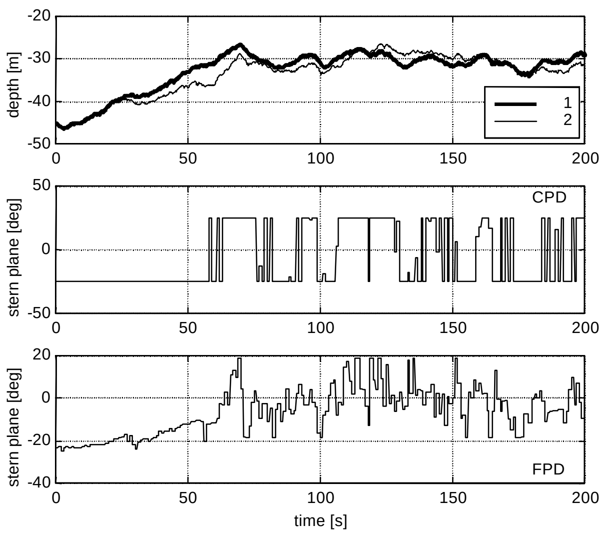

Fig. 8. The trajectories of vehicles' motion (1 – CFD controller, 2 – FPD controller) and command signals for strong disturbance effect

Disturbances have significant impact for expenditure of energy in the underwater system due to necessity of continuous compensation deviation from fixed value of depth. The comparison of stern plane deflections shows that energy consumption is less in case of applying the fuzzy control law.

5 Conclusion

The carried out computer simulations, for variety of operating conditions, showed that fuzzy control law can be successfully used to steer the underwater vehicle along the earlier planned trajectory. It is our firm belief, that the fuzzy controller is useful, not only for motion in vertical plane, but also for other manoeuvring problems.

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