Active Reconfigurable Control of a Submarine with Indirect Adaptive Control

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Abstract-An indirect adaptive controller is designed for submersibles. The design is developed using a linearized MIMO model of a submarine. Standard recursive least squares estimation method is used to estimate the parameters. Depth and pitch angle of the submarine is controlled by means of the well-known indirect self-tuning method. In case of a system fault, estimated parameters of the submarine model have been used to update the controller coefficients.

I. INTRODUCTION

The purpose of this paper is to present some results obtained for the indirect adaptive control of a linear MIMO submarine model in case of system faults. The depth control of a submarine at shallow submergence under sea wave disturbances and system faults is investigated. Shallow water operation has vital importance for conventional submarines to use their periscope and charge batteries while cruising in diesel-engine mode. However the depth control becomes more difficult when the vessel is close to the surface due to adverse effects of sea conditions.

The submarine beneath the sea waves is subject to sea forces and moments. These forces are composed of first and second order parts of sinusoidal wave patterns. The first order forces tend to cancel each other along the hull of the vehicle and can be neglected for the controller design. Second order part of the wave effect tends to pull the vehicle towards to surface [6]. The latter one which is also called suction force becomes smaller as the depth increases.

Equations of motion of a submarine consist of nonlinear differential equations. These equations are derived in six degrees of freedom. Since the control action is not performed for yaw and roll axes. The pitch and heave equations are used for the controller design. Since working with a linear model is much simpler than a nonlinear one. The nonlinear equations of the submarine for the pitch and heave axes has been linearized around an equilibrium point. The adverse effects of the sea waves are modeled to include in the overall submarine model for a more realistic controller design.

The proposed fault tolerant control scheme is implemented for the depth control of the submarine. The unanticipated system faults are compensated and the depth control of the controller is performed by means of the updated controller coefficients with respect to estimated system parameters. System faults are detected by using recursive least square estimator [3]. Threshold values are defined by trial and error. In case of a fault the controller informs the operator and carries on the depth control with the updated controller coefficients.

It is aimed to keep the vehicle at submerged depth in order to avoid detection due to approaching to surface in case of unanticipated system faults.

II. MODEL

A. Submarine Model

Equation of motion along z-axis (Normal force) is given

$$\dot{w}(t) = \frac{Z'_w U}{L m'_3} w(t) + \frac{1}{m'_3}(z'_{\dot\theta} + m')U\dot\theta(t) + \frac{Z'_{\ddot\theta} L}{m'_3}\ddot\theta(t) + \frac{Z'_{\delta B} U^2}{L m'_3}\delta B(t) + \frac{Z'_{\delta S} U^2}{L m'_3}\delta S(t) + \frac{2}{\rho L^3 m'_3}(Z_{wave}(t) + W_e(t)\cos\theta) \quad (2.1)$$

and $Q(t) = \dot\theta(t)$.

Equation of motion along y-axis (Pitching Moment) is given

$$\ddot{\theta}(t) = \frac{M'_{\dot{w}}}{LI'_2}\dot{w}(t) + \frac{M'_w U}{L^2 I'_2} w(t) + \frac{M'_{\dot{\theta}} U}{LI'_2}\dot{\theta}(t) + \frac{M'_{\delta B} U^2}{LI'_2}\delta B(t) + \frac{M'_{\delta S} U^2}{L^2 I'_2}\delta S(t) + \frac{2mg}{\rho L^5 I'_2}(z_G - z_B)\theta + \frac{m_{wave}}{\frac{\rho}{2} L^5 I'_2} \quad (2.2)$$

These equations are the states of the submarine dynamics, namely, pitch acceleration and heave velocity. However, the depth of the submarine is also required as a state. The depth of the submarine can be written for small angles as

$$\dot{h}(t) = w(t) - U(t)\theta(t) \quad (2.3)$$

From (2.1), (2.2) and (2.3), the state-space realisation of the submarine dynamics together with system fault effect can be written as

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{F}\mathbf{d}(t) + \mathbf{R}\mathbf{f}(t), \\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t). \end{aligned} \quad (2.4)$$

and

$$\begin{aligned} \mathbf{x}(t) &= [w(t), Q(t), \theta(t), h(t)], \\ \mathbf{u}(t) &= [\delta B(t), \delta S(t), M_e(t)], \\ \mathbf{d}(t) &= [Z_{wave}(t), M_{wave}(t)]. \end{aligned}$$

where $\mathbf{x}(t) \in \Re^n$ is the state vector, $\mathbf{u}(t) \in \Re^r$ is the control input vector and $\mathbf{y}(t) \in \Re^m$ is the measurement vector, $\mathbf{f}(t) \in \Re^g$ represents the fault vector which is considered as an unknown time function. **A**, **B** and **C** are system parameter matrices. Here **R** matrix is the fault distribution matrix. $\mathbf{d}(t) \in \Re^h$ represents sea force component along the submarine' s z-axis and moments of sea waves about submarine' s y-axis. **F** matrix is the disturbance distribution matrix of sea wave effects.

The discrete-time state space representation of the submarine model for 0.2 sec. sampling time turns out to be,

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}_d\mathbf{x}(k) + \mathbf{B}_d\mathbf{u}(k) + \mathbf{F}_d\mathbf{d}(k) + \mathbf{R}_d\mathbf{f}(k), \\ \mathbf{y}(k) &= \mathbf{C}_d\mathbf{x}(k). \end{aligned} \quad (2.5)$$

B. Sea Model

The adverse effects of the sea waves are modelled to include in the overall submarine model for a more realistic controller design. The sea model given in this paper is the one accepted in International Towing Tank Conference (ITTC). There is only one single parameter in that model, the significant wave height,

$$S(\omega) = \frac{8.1\times10^{-3}\cdot g^2}{\omega^5}\cdot\exp\left[\frac{-3.11}{H_s^2\cdot\omega^4}\right] \quad (2.6)$$

where H_s is the significant wave height in meters, ω is the frequency in rad/sec and $g = 9.81\frac{m}{\sec^2}$. It is clear from these units that the dimension of the sea state turns out to be $(m^2 - \sec)$. But this dimension is converted into $(ft^2 - \sec)$ to be consistent with the submarine model.

Sea waves have two types of effects on ship dynamics as disturbance, one is the disturbance on force dynamics Z_{wave} and the other one is the disturbance on moment dynamics M_{wave}. They are expressed in terms of instantaneous sea elevation v the sea state may be represented by a five state variable model forced by a white noise w.

$$x_s(k+1) = A_s x_s(k) + B_s w_s(k) \quad (2.7)$$

where

$$x_s(k) = [x_{s1}(k), x_{s2}(k), x_{s3}(k), x_{s4}(k), x_{s5}(k)]^T$$

here $x_{s1}(k) = v(k)$. The wave force Z_{wave} and moment M_{wave} can be approximated by

$$\begin{aligned} Z_{wave}(k) &= a\cdot v(k) + b, \\ M_{wave}(k) &= c\cdot v(k) + d \end{aligned} \quad (2.8)$$

where a, b, c, d are constants for different wave heights.

C. Actuator Dynamics

The submarine simulation model also includes actuator dynamics. There are three control inputs and three actuators. Two of the actuators are used as bow and stern hydroplanes which are electro-hydraulic systems. The actuator for the third input is a pump to fill or empty the auxiliary tank. As the actuators are mechanical devices their control action is limited. Limit values for bow and stern hydroplanes are $\pm 30^\circ$. A digital filter can represent the dynamics of the bow and stern hydroplanes as,

$$X_h(k+1) = 0.885X_h(k) + 0.115U_o(k) \quad (2.9)$$

where

X_h Ordered Hydroplane Deflection

U_o Real Hydroplane Deflection

III. CONTROL RECONFIGURATION

A. Estimation of the Submarine Parameters

The autopilot design by implementing the indirect adaptive control method requires satisfactory online estimates of parameters. Dynamics of the submarine changes with respect to the environmental conditions and will change in case of possible system faults.

Ignoring the effects of the waves and system faults in (2.5), the model of the submarine can be expressed as,

$$\mathbf{A}(z^{-1})\mathbf{Y}(k) = \mathbf{B}(z^{-1})\mathbf{U}(k-d) \qquad (3.1)$$

There are two inputs, namely bow and stern hydroplane deflections, and two outputs; depth value measured by a hydrostatic pressure sensor and pitch angle measured by a gyro sensor. Therefore **A** and **B** have components which are matrices of dimension two by two. Hence,

$$\mathbf{Y}(k) = \mathbf{X}\cdot\mathbf{\Theta} \qquad (3.2)$$

where $\mathbf{\Theta}$ is the parameter vector and $\mathbf{X}$ is the data vector.

The estimator is required to estimate the parameters of the submarine model in case of excessive sea wave effects and unanticipated system faults. It is well-known that the parameters of most deterministic time-varying systems can be estimated satisfactorily by implementing the RLS estimator with exponential forgetting [4].

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \mathbf{K}(k)\varepsilon(k),$$
$$\mathbf{P}(k) = (1-\mathbf{K}(k)\varphi(k-1))\mathbf{P}(k-1)/\beta,$$

β is the forgetting factor which is found by trial and error for the main propulsion system fault and different sea states.

B. Predictive Control

A predictive control technique [2] is implemented in order to calculate the predicted output values as

$$y_i^*(k+d) - w_i(k+d) = 0 \qquad (3.3)$$

where $y_i^*(k+d)$ is the predicted value of the output i at d-step ahead. Since for the submarine model $d = 1$, it is required to find $y(k+1)$.

Certainty equivalence principle [1] can be implemented by using the estimated parameters of the submarine model in order to calculate the predicted output. This output value can be used to minimise the following cost function vector in order to calculate the bow and stern hydroplane deflections,

$$\mathbf{J} = \mathbf{R}\cdot\left\|\mathbf{Y}^*(k+1) - \mathbf{W}(k+1)\right\|^2 + \mathbf{Q}\cdot\left\|\mathbf{U}(k)\right\|^2 \qquad (3.4)$$

The predicted depth and pitch angle values are inserted into the cost function and the derivative of the cost functions with respect to bow and stern hydroplane inputs are taken and equated to zero in order to calculate the optimal control inputs as follows;

$$\frac{\delta\mathbf{J}}{\delta\mathbf{U}(k)} = \mathbf{Q}\cdot\mathbf{U}(k) + \mathbf{R}\cdot\frac{\delta\mathbf{Y}^*(k+1)}{\delta\mathbf{U}(k)}\cdot(\mathbf{Y}^*(k+1) - \mathbf{W}(k+1)), \qquad (3.5)$$

$$\mathbf{Q}\cdot\mathbf{U}(k) + \mathbf{R}\cdot\frac{\delta\mathbf{Y}^*(k+1)}{\delta\mathbf{U}(k)}\cdot(\mathbf{Y}^*(k+1) - \mathbf{W}(k+1)) = 0 \qquad (3.6)$$

The control input vector can be found as

$$\begin{aligned}\mathbf{U}(k) = [\mathbf{R}\hat{\mathbf{B}}_0^T\hat{\mathbf{B}}_0 + \mathbf{Q}]^{-1}\cdot\mathbf{R}\hat{\mathbf{B}}_0\cdot[&\mathbf{W}(k+1) + \mathbf{A}_1\mathbf{Y}(k) \\ &+\mathbf{A}_2\mathbf{Y}(k-1) + \mathbf{A}_3\mathbf{Y}(k-2) + \mathbf{A}_4\mathbf{Y}(k-3) \\ &-\hat{\mathbf{B}}_1\mathbf{U}(k-1) - \hat{\mathbf{B}}_2\mathbf{U}(k-2) - \hat{\mathbf{B}}_3\mathbf{U}(k-3) - \hat{\mathbf{h}}_d]\end{aligned} \qquad (3.7)$$

C. Fault Detection

System faults effects the parameters of the submarine model. In this case the main propulsion system of the submarine becomes out of order hence the forward speed of the submarine U in (2.1) and (2.2) decreases and the parameters of the submarine model change drastically.

In order to detect this fault the sequences of $\theta(k)$ is used. In case of a system fault the derivative of the $\theta(k)$ changes, and if this function exceeds a threshold value a fault can easily be detected. Here the threshold value requires knowledge about the fault a priori. In a way all possible fault scenarios are taken into consideration during the design phase of the controller. The fault detection scheme based on the RLS is [3],

1.- Estimate $\theta(k)$ and $\Delta\theta(k) = \theta(k) - \theta(k-1)$ with RLS algorithm.

2.- Calculate the derivative of the estimated parameter vector $\frac{d\theta_i}{dt} \approx [\theta_i(k+1) - \theta_i(k)]/\tau_s$ for each component of the vector in every sampling instant τ_s.

3.- Compare the derivative of each component with a priori defined threshold value κ_i. Note that the threshold values are found by trial and error.

IV. SIMULATION RESULTS

Matlab-SIMULINK software has been used for simulations. Main propulsion system fault has been inserted into the dynamics of the submarine model. Forward speed of the submarine has been gradually decreased from 8.43 ft/sec. to 2.43 ft/sec. for the sea state 1. Mentioned fault inserted at 250^{th} sec. into the nominal system and this fault has been removed at 350^{th} sec. of the simulation.

It is observed that the indirect adaptive control method can cope with this fault when the suction force caused by sea waves is minimum. The depth and pitch angle of the submarine can be seen in Fig. 1. Bow and stern hydroplane deflections can be seen in Fig. 2. Bow hydroplane is saturated at the beginning of the diving operation and once depth of 30m reached for faulty situation.

Depth and pitch angle outputs throughout the simulations give satisfactory results. It can be stated that the proposed active reconfigurable controller compensates system fault effects.

Sea state of the submarine model is changed to sea state 6 and simulations are repeated when the adverse effect of the suction force is greater. In the mean time, forward speed of the submarine has been gradually decreased from 8.43 ft/sec. to 4.43 ft/sec. Mentioned fault inserted at 250^{th} sec. into the nominal system and this fault has been removed at 350^{th} sec. of the simulation.

It has been observed that the proposed controller can hardly control the submarine. Depth and pitch angle outputs of the submarine are not satisfactory. Depth and pitch angle outputs for sea state 6 can be seen in Fig. 3. Bow and stern hydroplane deflections for the same case can be seen in Fig. 4.

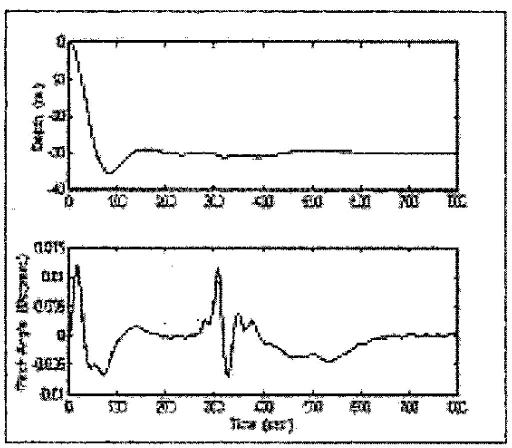

Fig. 1. Actual Depth and Pitch Angle for Sea State 1

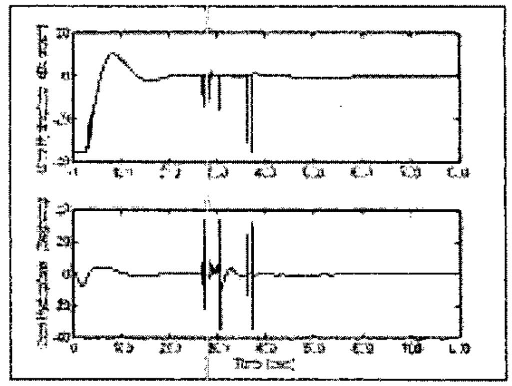

Fig. 2. Bow and Stern Hydroplanes for Sea State 1

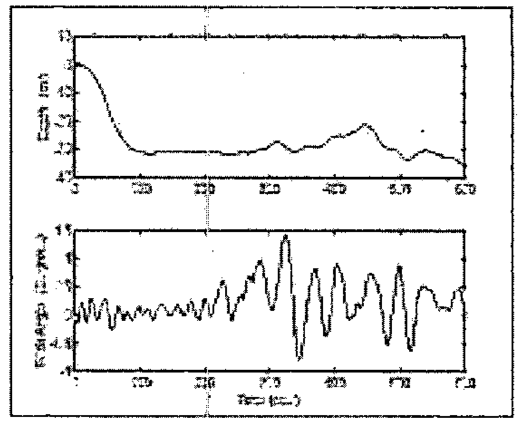

Fig. 3. Depth and Pitch Angle for Sea State 6.

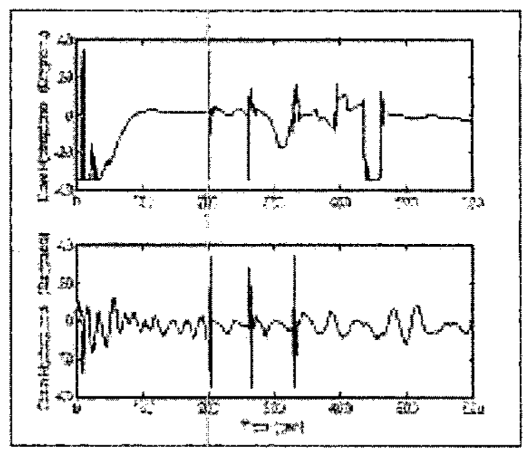

Fig. 4. Bow and Stern Hydroplanes for Sea State 6.

Actuators are saturated for both sea states. Nevertheless the response of the system gives satisfactory results. Reconfiguration activity can be seen clearly from Fig. 2 and 4 for both cases. RLS estimator with exponential forgetting method provided the actual estimates of the system parameters to converge to real parameters.

V. CONCLUSIONS

In this work an indirect adaptive control technique is applied to the depth and pitch angle control of a submarine in case of system faults in order to perform active reconfiguration. Satisfactory results obtained for sea state 1 but the performance degraded when the effects of the sea waves increased in case of sea state 6.

Parameter estimation for time-varying parameters due to sea wave and system fault effects is performed with RLS algorithm. Estimated parameters converged to true parameters of the submarine model. Same forgetting factor 0.98 has been used throughout the simulations. Forgetting factor is defined by trial and error. Fault detection is not required but performed by using parameter estimation algorithm.

A detailed investigation of parameter estimation algorithm can increase the performance of the controller when operation at higher sea states required. Forgetting factor can be updated with respect to the residual information of the fault detection mechanism. Other active reconfiguration controller can be investigated for comparison and further research.

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