Biologically-Inspired Adaptive Pectoral-Like Fin Control System For CFD Parameterized AUV

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Abstract- **This paper treats the question of adaptive control of a biorobotic autonomous underwater vehicle (BAUV) in the yaw plane using biologically-inspired pectoral-like fins. The fins are assumed to be oscillating harmonically with a combined linear (sway) and angular (yaw) motion. The bias (mean) angle of the angular motion of the fin is used as a control input. Oscillatory fins produce periodic time-varying control forces and moments. It is assumed that the physical parameters, the hydrodynamic coefficients, and the fin force and moment are not known to the designer. Using a discrete-time state variable representation of the BAUV, an adaptive sampled data control system for the trajectory control of the yaw angle using state feedback is derived. The parameter adaptation law is based on the normalized gradient scheme. In the closed-loop system, time-varying yaw angle reference trajectories are tracked and all the signals in the closed-loop system remain bounded. Simulation results for the set point control and sinusoidal trajectory tracking are presented, which show that the control system accomplishes precise trajectory control in spite of the parameter uncertainties, and the inter sample segments of the yaw angle trajectory remain close to the discrete-time reference trajectory.**

I. INTRODUCTION

Aquatic animals have splendid ability to move smoothly through water using a variety of control surfaces for propulsion and maneuvering [1, 5, 16, 23, 24]. Increasing demand for efficient maneuvering of autonomous underwater vehicles has led researchers to investigate the potential for incorporating control surfaces resembling those of biological systems. As such presently there exists considerable interest in designing flapping foils for propulsion and control of BAUVs [2, 3, 4, 10, 19].

Several studies have been conducted on fish morphology, locomotion, and application of biologically inspired control surfaces for the control of AUVs [10, 20, 24, 25]. Laboratory experiments have been performed to measure forces and moments produced by oscillating foils [4, 8, 20, 25]. These experimental results confirm that pectoral fins undergoing simultaneous lead-lag, feathering, and flapping motions have the ability to produced large lift, side force, and thrust, which can be used for the propulsion and control of AUVs. Attempts have also been made to characterize the forces and moments produced by oscillating fins using computational methods [11, 14, 22]. An analytical representation of unsteady hydrodynamics of flapping foils has been obtained using Theodorsen theory [7].

An oscillating fin propulsion control system using neural network has been developed and tests have been performed [25]. The guidance and control of a fish robot equipped with mechanical pectoral fins has been considered and rule-based fuzzy control system has been tested in laboratory experiments [8, 9]. An adaptive control law for the control of undersea vehicles using dorsal fins have been considered, in which the control force is generated by cambering the fin [12]. The optimal and inverse control laws have been designed for regulation, and depth and yaw angle trajectory control using mechanical pectoral fins [17, 13]. For the derivation of these control laws, a parameterization of periodic fin forces using the CFD analysis has been obtained. But the pectoral fin control laws of [17] and [13] have been derived on the assumption that the model parameters are completely known. This is rather a stringent requirement since, in a real case, the vehicle parameters and the hydrodynamic coefficients are not precisely known. Especially the precise knowledge of the forces and moments of unsteadily moving foils is extremely difficult. Furthermore, the parameterization of the fin forces using the Fourier series of [17] and [13] depends on the order of truncation of the Fourier expansion, and as such different input matrices are obtained as the additional harmonic functions are included in the series representation. Apparently, it is important to design control systems for the control of AUVs using oscillating foils in the presence of parametric uncertainties.

The contribution of this paper lies in the design of an adaptive control system for the yaw plane maneuvering of a biorobotic AUV using biomimetic mechanism resembling the pectoral fin of fish. The pair of fins attached to the AUV are assumed to undergo combined oscillatory linear (sway) and angular (yaw) motion, and consequently generate periodic forces and moments. In this paper, the bias (mean) angle of the yaw motion of the fin is treated as a control variable. The model of the AUV considered here is similar to that of [17] and [13], in which the fin forces and moments are parameterized using computation fluid dynamics (CFD) analysis. For the purpose of design, it is assumed that the vehicle's physical parameters, the hydrodynamics coefficients, and the fin forces and moments are not known. It may be pointed out that the control laws [17] and [13] have been developed by assuming that the systems parameters are completely known. A discrete-time model of the vehicle is obtained and a sampled-data adaptive control law is derived for the trajectory control of the yaw angle. Unlike the derivation of [17] and [13], the control law is independent of the number of harmonics retained in the truncated Fourier expansion of the fin force and moment. The adaptation law for tuning the controller parameters is derived using the normalized gradient method. In the closed-loop system, the yaw angle asymptotically tracks time-varying reference trajectories, and all the signals in the closed-loop system remain bounded. Simulation results for the set point and sinusoidal trajectory control are presented. These results show that the adaptive control system accomplishes precise yaw angle trajectory control in spite of the parameter uncertainties, and the yaw angle trajectory remains close to the discrete reference trajectory between the sampling periods.

The organization of the paper is as follows. The AUV model and the problem formulation are presented in Section II. An adaptive law for yaw angle control is derived in Section III, and Section IV presents the simulation results.

II. AUV MODEL AND CONTROL PROBLEM

Figure 1 shows the schematic of a typical AUV. Two fins resembling the pectoral fins of fish are symmetrically attached to the vehicle. The vehicle moves in the yaw plane ($X_I - Y_I$ plane), where $O_I X_I Y_I$ is an inertial coordinate system. $O_B X_B Y_B$ is body-fixed coordinate system with its origin at the center of buoyancy. X_B is in the forward direction. Each fin has two degrees of freedom (sway and yaw) and oscillates harmonically.

A. Fin force and moment

We assume that the combined sway-yaw motion of the fin is described as follows:

$$\delta(t) = \delta_m sin(2\pi f t)$$
$$\theta_y(t) = \beta + \theta_{ym} sin(2\pi f t + \nu) \quad (1)$$

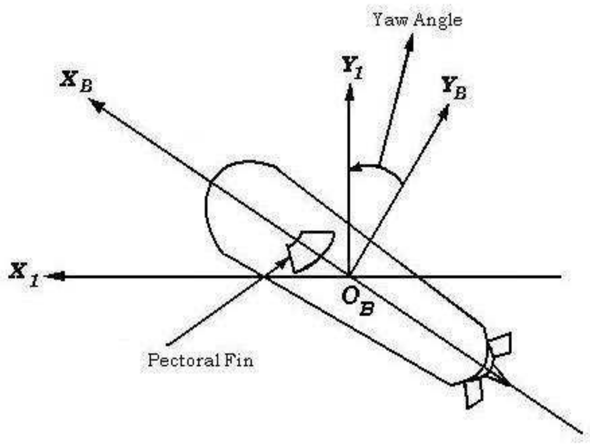

Figure 1: **AUV model with pectoral fins**

where δ and θ_y correspond to sway and yaw angle of the fin, δ_m and θ_{ym} are the amplitudes of linear and angular oscillations, β is the bias (mean) angle, f (Hz) is the frequency of oscillations, and ν is the phase difference between the sway and yaw motion. Based on the CFD analysis, it has been shown in [17] and [13] that the periodic lateral force (f_y) and yawing moment (m_y) generated by the oscillating fin can be described by the Fourier series given by

$$f_y(t) = \sum_{n=0}^{N} [f_n^s(\beta) sin(n\omega_f t) + f_n^c(\beta) cos(n\omega_f t)]$$

$$m_y(t) = \sum_{n=0}^{N} [m_n^s(\beta) sin(n\omega_f t) + f_n^c(\beta) cos(n\omega_f t)] \quad (2)$$

where f_n^a and f_n^b, $a \in \{s, c\}$ are the Fourier coefficients, and N is an arbitrarily large integer such that the neglected harmonics have insignificant effect. (The control law designed here does not depend on N.) The Fourier coefficients are nonlinear functions of the bias angle. Assuming that β is small, fin force and moment can be approximated as (k = 1,2,3.....).

$$f_k^a(\beta) = f_k^a(0) + (\frac{\partial f_k^a(0)}{\partial \beta})\beta$$

$$m_k^a(\beta) = m_k^a(0) + (\frac{\partial m_k^a(0)}{\partial \beta})\beta \quad (3)$$

where a $\in \{s, c\}$. Defining a vector ϕ(t) of sinusoidal signals

$$\phi(t) = [1, sin\omega_f(t), cos\omega_f(t), ..., sinN\omega_f(t), cosN\omega_f(t)]^T$$
$$\in R^{2N+1} \quad (4)$$

and using (2) - (4), one obtains

$$f_y(t) = \phi^T(f_a + \beta f_b)$$
$$m_y(t) = \phi^T(m_a + \beta m_b) \quad (5)$$

where f_a, f_b, m_a, and m_b are approximate vectors, which can be obtained from (2) and (3).

B. Yaw Dynamics

We assume that vehicle's forward speed U is held constant by some control mechanism. The equations of motion of a neutrally buoyant vehicle is described by Fossen [6]

$$m(\dot{v}+Ur+X_G\dot{r}-Y_Gr^2) = Y_{\dot{r}}\dot{r}+(Y_{\dot{v}}\dot{v}+Y_rUr)+Y_vUv+F_y$$

$$I_z\dot{r} + m(X_G\dot{v} + X_GUr + Y_Gvr) = N_{\dot{r}}\dot{r} + (N_{\dot{v}}\dot{v} + N_rUr) + N_vUv + M_y$$

$$\dot{\psi} = r \tag{6}$$

where ψ is the heading angle, $r = \dot{\psi}$ is the yaw rate, v is the lateral velocity along the Y_B-axis, (X_G, Y_G) = $(X_G, 0)$ is the coordinate of the center of gravity with respect to O_B, m is the mass, and I_z is the moment of inertia of the vehicle. $Y_{\dot{\nu}}, N_{\dot{r}}, Y_{\nu}$, etc are the hydrodynamic coefficients, and F_y and M_y are the net fin force and moment.

For small motion of the vehicle, linearizing (6) gives

$$\begin{bmatrix} m - Y_{\dot{v}} & mX_G - Y_{\dot{r}} & 0 \\ mX_G - N_{\dot{v}} & I_z - N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} Y_vU & Y_rU - mU & 0 \\ N_vU & N_rU - mX_GU & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} F_y \\ M_y \\ 0 \end{bmatrix} \tag{7}$$

Defining the state vector $x = (v, r, \psi)^T \in R^3$ and using (7) gives the state variable form

$$\dot{x} = Ax + B_v \begin{bmatrix} F_y \\ M_y \end{bmatrix} \tag{8}$$

where A and B_v are appropriate matrices. The net lateral force and moment due to two fins is given by $F_y = 2f_y$ and $M_y = 2(d_{gf} \cdot f_y + m_y)$, respectively, where d_{gf} is the moment arm due to the fin location. Then substituting the fin force and moment from (5) in (8), gives the state variable representation

$$\dot{x} = Ax + B\Phi(t)f_c + B\Phi(t)f_v\beta$$

$$y(t) = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} x(t) = Cx(t) \tag{9}$$

where y=ψ is selected as the controlled output variable, B is an appropriate matrix satisfying $B[f_y, m_y]^T = B_v[F_y, M_y]^T$, $f_c = (f_a^T, m_a^T)^T \in R^{4N+2}$, $f_v = (f_b^T, m_b^T)^T \in R^{4N+2}$ and

$$\Phi(t) = \begin{bmatrix} \phi^T(t) & 0 \\ 0 & \phi^T(t) \end{bmatrix} \tag{10}$$

For the purpose of design, we assume that the system matrices A and B, and the parameter vectors f_c and f_v are not known. We assume that the state vector is available for feedback. Let $y_m(t)$ be a given yaw angle reference trajectory. We are interested in designing an adaptive control law such that in the closed-loop system, all the signals are bounded, and the yaw angle ψ asymptotically tracks $y_m(t)$.

III. ADAPTIVE CONTROL LAW

This section presents the derivation of an adaptive control law using the state variable feedback. The system (9) is time-varying but periodic. The design of control system for a time-varying unknown system is not simple. Moreover, in order to obtain a meaningful use of the parameterization of the fin force and moment using the CFD analysis, we proceed to design a sampled-data adaptive control system.

We assume that the bias angle changes at a regular interval $T = m_oT_o$, where m_o is an integer and $T_o = 1/f$ is the fundamental period. That is, the bias angle switches after the completion of m_o cycles of the oscillation of the fins, and is kept constant between the switching instants. Discretizing the state (9) yields a time-invariant system given by

$$x[(k+1)T] = A_dx(kT) + B_d\beta_k + d_u$$

$$y(kT) = Cx(kT) \tag{11}$$

where A_d, B_d and d_u are constant vectors, β_k (a constant) is the bias angle over $t \in [kT, (k+1)T)$, and k = 0,1,2,.... We assume that the matrices A_d, B_d and d_u are unknown to the designer. Here we treat d_u as a constant disturbance input vector.

In the sequel, z denotes the z-transform variable or an advance operator (i.e. $zq(kT) = q[(k+1)T]$). Solving (11), the output y(z) can be written as

$$y(z) = C(zI - A_d)^{-1}B_d\beta_k(z) + C(zI - A_d)^{-1}d_u(z)$$

$$\triangleq k_p\frac{n(z)}{d(z)}\beta_k(z) + \frac{n_d(z)}{d(z)}d_u(z) \tag{12}$$

where $n(z)$ and $d(z)$ are monic polynomials of degree 2 and 3, respectively, and $n_d(z)$ is a polynomial. For the derivation of the control law, the following assumptions are needed:
Assumption 1:
(A.1) The discretized system (A_d, B_d, C) is controllable and observable.
(A.2) The system is minimum phase.
(A.3) The sign of k_p is known and the upper bound k_p^o of $|k_p|$ is known.

For the vehicle model $n(z)$ is a stable polynomial (i.e. its both the roots are strictly within the unit disk in the complex plane), but the denominator polynomial $d(z)$ is unstable. Furthermore, $n(z)$ and $d(z)$ are coprime, and therefore, the pair (A_d, B_d) is controllable and (C, A_d) is observable. We point out that the stability of the polynomial $n(z)$ depends on the choice of fin location on the vehicle, and it is found that for small d_{gf} (distance from point of attachment of fin to center of gravity) the system is minimum phase. The Assumption 1 can be verified by computing $A_d, B_d, k_p, n(z)$ and $d(z)$ for some nominal values of the parameters. Then the assumption remains valid for the perturbations around the nominal condition.

The relative degree of the system is one, therefore we choose a reference model of the form.

$$y_m(kT) = W_m(z)r(kT), \quad k = 0, 1, 2, ... \tag{13}$$

where $r(kT)$ is a discrete-time command input and

$$W_m(z) = \frac{1}{z} \quad (14)$$

is the delay operator (i.e., $y_m[(k+1)T] = r[kT]$).

First we consider the existence of the control law assuming that the system parameters are exactly known. Then this control law is modified for the case when the parameters are known. The design of the control law follows the steps described in [18]. Consider a control law

$$u^*(kT) = \theta_1^{*T} x(kT) + \theta_2^* r(kT) + \theta_3^* \quad (15)$$

where $\theta_1^* \in R^3$, and $\theta_2^*, \theta_3^* \in R$ are to be chosen properly. Then in the closed-loop system (11) and (15), solving for $y(kT)$ gives

$$y(kT) = C(zI - \bar{A}_d)^{-1} B_d \theta_2^* r(kT) + \Delta(z)$$
$$+ C{A_d}^{-k} x(0) \quad (16)$$

where

$$\Delta(z) = [C(zI - \bar{A}_d)^{-1} B_d \theta_3^* + C(zI - \bar{A}_d)^{-1} d_u] \frac{z}{z-1}$$

and θ_1^* is chosen such that $\bar{A}_d = (A_d + B_d \theta_1^{*T})$ has stable eigenvalues.

Now the computation of θ_i^* for the yaw angle trajectory control is done. This is accomplished by model matching. Let us choose the feedback gains θ_i^* $(i = 1, 2)$ such that $\theta_2^* = k_p^{-1}$ and

$$C(zI - A_d - B_d \theta_1^{*T}) B_d \theta_2^* = W_m = z^{-1} \quad (17)$$

This is possible because the system (11) is controllable and minimum phase. Then in the closed-loop system, (16) takes the form

$$y(kT) = W_m(z) r(kT) + \Delta(z) + C{\bar{A}_d}^k x(0) \quad (18)$$

where $\Delta(z)$ simplifies to

$$\Delta(z) == [\theta_2^{*-1} \theta_3^* W_m(z) + C(zI - \bar{A}_d)^{-1} d_u] \frac{z}{z-1} \quad (19)$$

Note that (17) has been used to obtain (19). Since $\bar{A}_d$ is a stable matrix, as $k \to \infty$, (19) gives

$$\Delta(\infty) = lim_{z \to 1} [(z-1) \ \Delta(z)]$$
$$= (\theta_2^*)^{-1} \theta_3^* + C(I_{3\times3} - \bar{A}_d)^{-1} d_u \quad (20)$$

From (20), it follows that $\Delta(\infty)$ becomes zero if one chooses

$$\theta_3^* = -\theta_2^* C(I_{3\times3} - \bar{A}_d)^{-1} d_u \quad (21)$$

Using these values of θ_i^*, and ignoring the exponentially decaying signals,(18) gives

$$y(kT) = W_m r(kT) \quad (22)$$

This implies that the tracking error $e(kT) = y(kT) - y_m(kT) = W_m[0]$ tends to zero as $k \to \infty$.

For the system with unknown parameters, the control law is chosen as

$$u(kT) = \theta_1^T(kT) x(kT) + \theta_2(kT) r(kT) + \theta_3(kT) \quad (23)$$

where $\theta_1(kT) \in R^3, \theta_2(kT) \in R$, and $\theta_3(kT) \in R$ are the time-varying estimates of θ_i^*, $i = 1, 2, 3$. We are interested in deriving an adaptation law such that the tracking error asymptotically tends to zero. With the control law (23), the closed-loop system takes the form

$$x[(k+1)T] = A_d x(kT) + B_d[\theta_1^T(kT) x(kT)$$
$$+ \theta_2(kT) r(kT) + \theta_3(kT)] + d_u$$
$$= [A_d + B_d \theta_1^{*T}] x(kT) + B_d \theta_2^* r(kT)$$
$$+ B_d \theta_3^* + B_d \tilde{\theta}^T(kT) w(kT) + d_u \quad (24)$$

where

$$\theta^* = [\theta_1^{*T}, \theta_2^*, \theta_3^*]^T \in R^5,$$
$$w(kT) = [x^T(kT), r(kT), 1]^T \in R^5,$$

$\theta(kT) = (\theta_1^T(kT), \theta_2(kT), \theta_3(kT))^T$, and $\tilde{\theta}(kT) = (\theta(kT) - \theta^*)$ is vector of parameter error. In view of (16), (17) and (19), the output computed from (24) takes the form

$$y(kT) = W_m r(kT) + W_m \rho^* \tilde{\theta}(kT) w(kT) + \Delta(z)$$
$$+ C{\bar{A}_d}^k x(0) \quad (25)$$

where $\rho^* = k_p = \theta_2^{*-1}$. Since $\Delta(z)$ tends to zero as $kT \to \infty$, ignoring the exponential decaying signals, (25) yields

$$e(kT) = \rho^* W_m[\tilde{\theta}^T(kT) w(kT)] \quad (26)$$

For the derivation of the adaptation law according to [18], one needs to obtain an augmented error beginning from (26). Define a signal

$$\xi(kT) = \theta^T(kT) w[(k-1)T] - \theta^T[(k-1)T] w[(k-1)T] \quad (27)$$

and the augmented error

$$\epsilon(kT) = e(kT) + \rho(kT) \xi(kT) \quad (28)$$

where $\rho(t)$ is an estimate pf $\rho^* = k_p$. Then substituting the tracking error (26) in (28) and using (27) gives

$$\epsilon(kT) = \rho^* \{W_m(\theta^T(kT) w(kT)) - \theta^{*T} w[(k-1)T]\}$$
$$+ \rho(kT) \xi(kT)$$
$$= \rho^* \{\theta^T(kT) w[(k-1)T] - \xi(kT) - \theta^{*T} w[(k-1)T]\}$$
$$+ \rho(kT) \xi(kT)$$
$$= \rho^* \tilde{\theta}^T(kT) w[(k-1)T] + \tilde{\rho}(kT) \xi(kT) \quad (29)$$

where $\tilde{\rho}(kT) = \rho(kT) - \rho^*$ is the parameter error. This linearly parameterized augmented error equation is important for the derivation of the adaptation law.

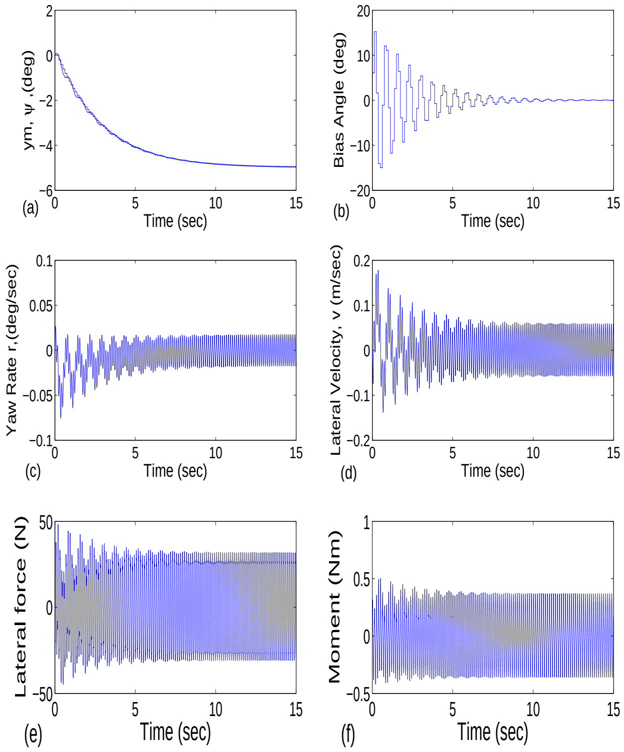

Figure 2: **Adaptive set point control: Frequency of flapping 8Hz for $\psi^* = -5$ (deg) and Parameter uncertainty 50%**
(a) Yaw angle, ψ, (solid) and reference yaw angle (staircase) (deg) (b) Bias angle (deg) (c) Yaw rate (deg/sec) (d) Lateral velocity (m/sec) (e) Lateral force(N) (f) Moment(Nm)

Now following [18], the normalized gradient based control law is chosen as

$$\theta[(k+1)T] = \theta(kT) - \frac{sign(\rho^*)\Gamma w[(k-1)T]\epsilon(kT)}{m^2(kT)}$$

$$\rho[(k+1)T] = \rho(kT) - \frac{\gamma\xi(kT)\epsilon(kT)}{m^2(kT)} \qquad (30)$$

where the symmetric positive definite adaptation gain matrix Γ satisfies $0 < \Gamma = \Gamma^T < \frac{2}{k_p^o} I_{5\times5}$, $0 < \gamma < 2$, and

$$m^2(kT) = 1 + w^T[(k-1)T]w[(k-1)T] + \xi^2(kT)$$

For the stability analysis one chooses the Lyapunov function

$$V(\tilde{\theta}, \tilde{\rho}) = |\rho^*|\tilde{\theta}^T(kT)\Gamma^{-1}\tilde{\theta}(kT) + \gamma^{-1}\tilde{\rho}^2(kT) \qquad (31)$$

and following [18] shows that

$$V[(k+1)T] - V(kT) \le -\alpha_1 \frac{\epsilon^2(t)}{m^2(t)} \qquad (32)$$

where $\alpha_1 > 0$. This implies that $\theta(kT), \rho(kT), \frac{\epsilon(kT)}{m(kT)} \in L^\infty$ (the set of bounded functions), and $\frac{\epsilon(kT)}{m(kT)}, (\theta[(k+1)T] - \theta(kT)), (\rho[(k+1)T] - \rho(kT)) \in L^2$ (the set of square integrable functions). Furthermore, one can show that $e(kT) \to 0$ and all the signals in the closed-loop system are bounded. This completes the derivation of the adaptive control law for the yaw plane maneuvering.

IV. SIMULATION RESULTS FOR YAW MANEUVERS

In this section, simulation results using the MATLAB/SIMULINK for yaw angle control are presented. Various time-varying reference trajectories are considered for tracking, and the performance of the adaptive controller in the presence of parameter uncertainties is examined.

The parameters of the model are taken from [15]. The AUV is assumed to be moving with a constant forward velocity of 0.7 (m/sec). The vehicle parameters are $l = 1.391$ (m), mass=18.826 (kg), I_z= 1.77 (kgm^2), $X_G = -0.012$, $Y_G = 0$. The hydrodynamic parameters for a forward velocity of 0.7 m/sec derived from [15] are $Y_{\dot{r}} = -0.3781$, $Y_{\dot{v}} = -5.6198$, $Y_r = 1.1694$,$Y_v = -12.0868$, $N_{\dot{r}} = -0.3781$, $N_{\dot{v}} = -0.8967$, $N_r = -1.0186$, and $N_v = -4.9587$. It is assumed that d_{fg}=0.01 (m) and the fin oscillation frequency is $f = 8Hz$. The vectors f_a, f_b, m_a, and m_b are found to be [13]

$$\mathrm{f}_a = (0, -40.0893, -43.6632, -0.3885, 0.6215, 6.2154, -10.17, -0.1554, 0.6992)$$

$$\mathrm{f}_b = (68.9975, 0.4451, -16.4704, 64.1009, -19.5864, -0.8903, -2.2257, 2.2257, 4.8966)$$

$$\mathrm{m}_a = (0.0054, 0.6037, 0.4895, 0, -0.0054, 0, -0.0925, 0, -0.0054)$$

$$\mathrm{m}_b = (-0.5297, -0.3739, -0.0935, -0.2493, 0.1246, 0.0312, -0.0312, 0.0935, 0)$$

It is pointed out that these parameters are obtained using the Fourier decomposition of the fin force and moment, and are computed by multiplying the Fourier coefficients by $\frac{1}{2}\rho.W_a.U_\infty{}^2$ and $\frac{1}{2}\rho.W_a.chord.U_\infty{}^2$, respectively, where W_a is the surface area of the foil. For simulation, the initial conditions of the vehicle are assumed to be $x(0) = 0$.

The closed-loop system (9) and (23) with the update law (30) is simulated. The bias angle is changed to a new value every $T = T_o$ seconds, where $T_o = 1/f$ is the fundamental period of f_p and m_p. For the set point control, the terminal value of the yaw angle is taken as $\psi^* = -5$ deg. Thus one desires to control the BAUV to a heading angle of -5 deg. For the update law, the adaptation gains are selected as $\Gamma = 0.4(2/k_p^o)I_{5\times5}$ and $\gamma = 1$, where $k_p^o = 0.08 \ge |k_p|$. Using the values of AUV model, it is found that the actual feedback gains are $\theta_1^* = (1.2139 - 13.0228 - 104.6334)^T, \theta_2^* = -104.6334$

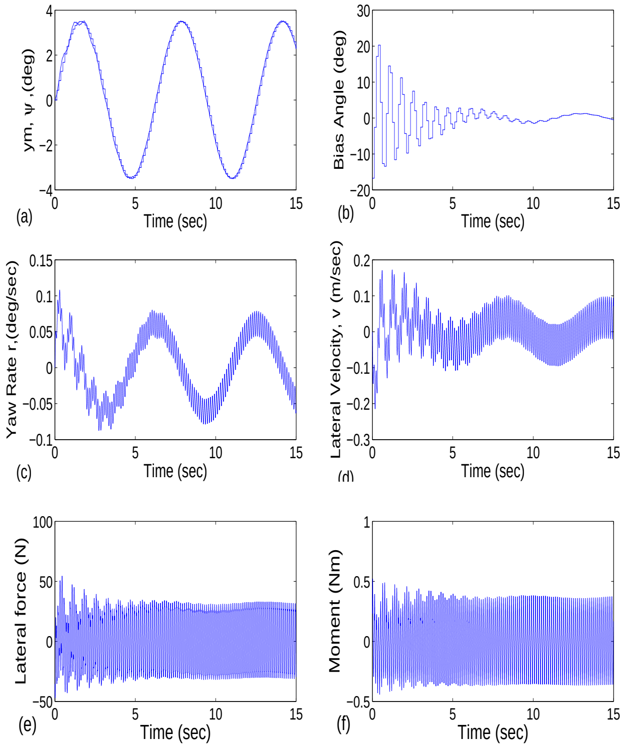

Figure 3: **Adaptive sinusoidal trajectory control: Frequency of flapping 8Hz for $y_m = 3.5\ sin\ 2\pi fkT$ (deg) and Parameter uncertainty 50$\%$**
(a) Yaw angle, ψ (solid) and reference yaw angle (staircase) (deg) (b) Bias angle (deg) (c) Yaw rate (deg/sec) (d) Lateral velocity (m/sec) (e) Lateral force(N) (f) Moment(Nm)

and $\theta_3^* = 0.2122$ and $\rho^* = k_p = -0.0096$. The open-loop zeros and poles of the discretized system are (-0.8990, 0.4667) and (1.0000, 1.0864, 0.8715), respectively. Therefore, the transfer function is minimum phase. Simulation results are presented for the parameter uncertainty of 50 $\%$.

Case A: Adaptive set point control: Parameter uncertainty 50$\%$ off-nominal for Yaw angle -5 (deg).
For smooth control, the reference input $r(kT)$ (in rad) is selected as

$$r(kT) = [1 - exp(-0.35(k-1)T)](-5\pi/180)$$

where the sampling time is $T = 0.125$ (sec). Thus the control law is is updated at the completion of each cycle of oscillation. Assuming 50 $\%$ uncertainty, the initial estimates $\theta(0)$ and $\rho(0)$ are set to $0.50\theta^*$ and $0.50\rho^*$. This way the control law gains are 50 $\%$ lower than the exact θ^*. Fig. 2 shows the simulated results. It can be seen that the adaptive controller achieves accurate heading angle control to the target set point in about 15 sec. The control input (bias angle) magnitude required is about 15 deg, which can be provided by the pectoral fins. The plots of the lateral force and moment produced by the fins are also provided in the figure. In the steady-state, the lateral fin force and moment exhibit bounded periodic oscillations. It is found that the control magnitude can be reduced by using slower command $r(kT)$ if desired.

Case B: Adaptive sinusoidal trajectory control: Parameter uncertainty 50 $\%$ off-nominal
In order to examine, time-varying tracking ability of the controller, a sinusoidal reference trajectory is generated using the command input $r_m(kT) = 3.5\times\ (\pi/180)\ sin(kT)$ (rad). It is assumed that $\theta(0) = 0.50\theta^*$ and $\rho(0) = 0.50\rho^*$ giving 50$\%$ uncertainty. The responses are shown in Fig. 4. It is seen that, after the initial transients, the heading angle smoothly tracks the sinusoidal command trajectory. The control input (bias angle) magnitude required is about 20 deg.

Simulations for other off-nominal choices of $(\theta(0), \rho(0))$ have been performed. It is found that although, theoretically, asymptotic tracking can be accomplished for any choice of initial estimates of $(\theta(0), \rho(0))$, larger control inputs are required for higher uncertainties. Furthermore, the control system performs relatively well for the choice of underestimated initial values of the control gains $(\theta(0), \rho(0))$. Of course, the responses also depend on the choice of the command generator and the adaptation gain matrix Γ and γ of the update law.

CONCLUSION

In this paper, the design of an adaptive control system for the yaw plane control of a BAUV using pectoral-like fins was considered. The bias angle was treated as the control input. The periodic fin force and moment were parameterized using CFD analysis, and a discrete-time AUV dynamic model was used for control system design. The systems parameters were assumed to be unknown. A sampled-data adaptive control law was derived for the control of the yaw angle. The control system included a normalized gradient adaptation law for tuning the controller gains. In the closed-loop system, it was shown that the yaw angle asymptotically follows prescribed time-varying yaw angle trajectories. The performance of the designed control system was examined using numerical simulations. From these results, one concludes that in the closed-loop system precise yaw angle trajectory control can be accomplished in the presence of model uncertainties. This is important because in a real situation, one does not have the knowledge of the system parameters. Especially, the precise characterization of the pectoral fin forces, and moments is not easy. There exist flexibility in the choice of the design parameters, which can be selected to obtain desirable response characteristics in the closed-loop system.

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