The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Study and Implementation of Station-holding Performance on a Fish Robot in Adverse Unsteady Flow

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Abstract—**In the present work we study the station-holding performance exhibited by real fish and implement the similar performance onto a biomimetic fish robot. The aim is to make the swimming of a fish robot capable of holding its station in one-dimensional unsteady adverse flow, i.e. to obtain adaptation to the variations of flow rate. With the sensory feedbacks including water environment information and the displacement of fish robot, a closed-loop swimming control scheme is developed. Firstly, inspired by a real carp fish swimming in adverse flow, control laws that regulate the tail beat frequency and amplitude of fish robots are formulated. A non-linear oscillator is applied to model the periodic swimming gaits. As controlling parameters of the oscillator, frequency and amplitude are dynamically tuned by the feedback control laws. The output of the oscillator that generates the adaptive swimming gaits is adjusted accordingly. The control method is verified through simulation and experiments on a BCF type fish robot.**

I. Introduction

TRANSIENT swimming movements in fish such as fast starting and sharp turning have been implemented on fish robots in current literatures [1, 2]. Studies and experiments of such locomotion are inevitably conducted in still water or steady flow environment. Normally, the existing solutions adopt predefined gaits and open-loop control schemes [2-4]. The swimming gaits are obtained through off-line based approach such as observation of real biological system and computational fluid dynamics (CFD) simulation [2, 5, 6]. Current closed-loop swimming control focuses mostly on the motion planning problems with the help of external cameras providing the environment feedback. The key issue is to develop proper methods that generate coordinated swimming gaits and hence achieve desired performance, for example, obstacle avoidance and path tracking [7-9]. In [10], an online swimming gait generation without machine vision feedback is discussed. The fish robot can perform smooth gait transition from crawling to swimming according to the feedback provided by a water detection sensor. This on-off sensory feedback is only used to switch the motion pattern completely decided by the gait generator [10]. Although closed-loop control and the online motion planning are conducted in these studies, the adaptation to the flow variation is still absent.

In this paper, a control method that enables the swimming of robotic fish systems adaptive to variational flow is presented. As a case of transient swimming, station-holding performance exhibited by real fish is implemented onto a biomimetic fish robot. Station-holding in fish is a remarkable example of adaptation to unsteady flow, which has been well documented in biology area [11]. The aim of the present research is to control swimming of robotic fish system adaptive to the adverse flow with varying speed and capable of holding its position. Instead of solving problem in still water, we develop a closed-loop scheme to control the swimming in unsteady flow.

Two issues exist in the station-holding control. Firstly, the adaptive swimming control needs feedback of water environment, which is hardly obtained due to the lack of proper sensors [12, 13]. Secondly, the current study on the adaptive swimming control method is not sufficient yet. In this paper, we place the attention on the online generation of adaptive swimming gaits. The sensing of flow information is not a topic of this paper. Some external sensors are used to provide feedbacks. Nonlinear oscillators that produce harmonic patterns are applied to model the gaits as one-dimensional fish swimming always exhibits symmetrical and periodic patterns. Feedback control laws are designed to dynamically tune parameters of the oscillator and in turn adjust the swimming gaits. The station-holding performance on robotic fish is achieved through this closed-loop control.

II. Fish Swimming In Adverse Unsteady Flow

We do not intend to develop a control system that can deal with all kinds of flow conditions but conduct the research in the flow with the following properties: 1) the flow rate is variable; 2) the flow is one-way and one-dimensional; and 3) laminar flow is assumed. We firstly observe this process of a real carp fish in a water tunnel. The fish sample belongs to typical BCF (body and/or caudal fin) type species. It makes use of the caudal fin as propulsor to generate thrust through oscillatory motion [14], which is also a major way of propulsion in current fish robots [2]. The motion of fish in still water shows steady patterns with approximately constant tail beat frequency and amplitude in a relatively long time period (here we define the amplitude and frequency as

Manuscript received on July 15, 2010. The financial support by the NTU-Mindef/06/01 and MoE AcRF RG23/06 Research Grants (Singapore) are acknowledged.

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controlling parameters). If there is a sudden increase of incoming flow rate, i.e. the fish have to swim against the water current, it can quickly perceive this change and make adjustments on the swimming pattern. Both controlling parameters are augmented with the increase of flow rate. At low flow rate, the fish can adapt itself to the flow immediately. At relatively high flow rate, the adjustment of gaits exhibits three stages. At first, the fish is washed away from its original place along the flow direction. Then the fish gets adaptive to the flow environment and swims back with the two controlling parameters increased. As it approaching the original place, the fish reduces the amplitude slightly and maintains the beat. After short period of regulating, the gait is gradually changed to a new steady pattern and the swimming comes to the third stage.

As implied by the real fish, a BCF-type robotic fish can achieve the similar adaption to unstable flow by real-time adjusting two controlling parameters. Feedback control laws that regulate the controlling parameters can be employed to guide the tuning. In this initial study, we do not intend to develop a sensing system for fish robot but focus only on the generation of adaptive swimming gaits. The sensory signals are obtained through normal displacement and velocity sensors passed to the gait controller. The adaptive gait generator and the controller design are discussed in the following part of the paper.

III. Control Laws for Adaptive Swimming Gaits

The ability of adaptation to unsteady flow can be achieved through dynamical adjustment of swimming gaits according to the flow information. In the following sections, we discuss the application of a nonlinear oscillator in generating of swimming gaits and the control laws that tunes its parameters. The method can help the robotic fish hold its position and keep stable in fluctuations of flow.

A. A Non-linear Gait Generator

The swimming gaits of the fish are routinely modeled as consecutive harmonic oscillations when swimming along a straight path and decomposed from fish body motion functions [1, 2, 15]. Here the term *gait* is borrowed from the legged locomotion or robotic arms to define the control input for the actuator that drives individual robotic body elements involved in thrust generation. To handle the variation of flow, the swimming gait must be dynamically tuned according to the flow. However, the amplitude and phase of these gaits are completely determined by the known body motion functions [3, 12]. A mathematic model that generates on-line steady harmonic gaits is necessary. The gaits are also required to be adjusted continuously and smoothly according to environment feedback. Note that the normal sine generator cannot perform this task because if there is a sudden change in amplitude or frequency which is associated to the sudden change of flow rate, the motion may not be smooth, even not continuous, as illustrated by Fig. 1. It can result in the instability of control. The smooth transition of swimming gaits is important for robot because it ensures that there is no jerk or discontinuity in locomotion. The actuators therefore get free from the potential damage caused by the jerk. To satisfy the above-mentioned requirements, a nonlinear oscillator is applied to model the swimming gait. Here the Hopf oscillator is selected, which is defined by:

$$\dot{x} = k(A^2 - x^2 - y^2)x - 2\pi f y \tag{1}$$

$$\dot{y} = k(A^2 - x^2 - y^2)y + 2\pi f x \tag{2}$$

where x and y are two state variables of the oscillator which are all functions of time t ($t \geq 0$), A is a positive number that determines the amplitude of the steady state oscillation, f is the oscillation frequency and k is a positive constant which regulates the speed of convergence.

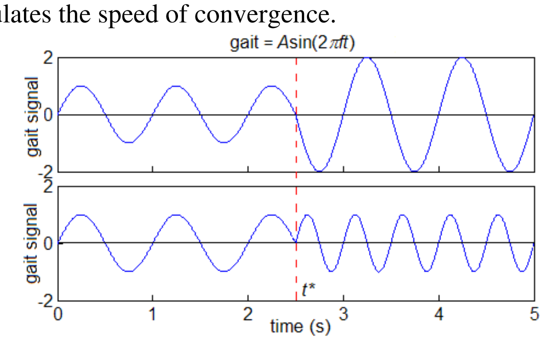

Fig. 1. Outputs of the sine generator where amplitude A is changed from 1 to 2 (upper) and frequency f is changed from 1 to 2 (lower). All changes of parameters occur at time t^*=2.5s. At other time (t^* is random), discontinuity may also appear.

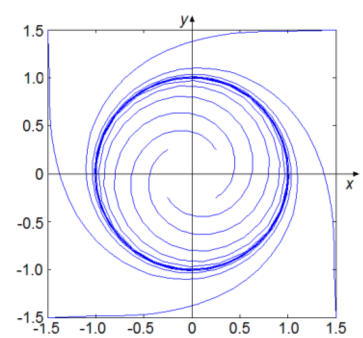

Fig. 2. The phase portrait of the oscillator. The limit cycle behavior is illustrated. The radius and frequency are all normalized to 1. In both cases that the states start from both inside and outside they always converge to the limit cycle.

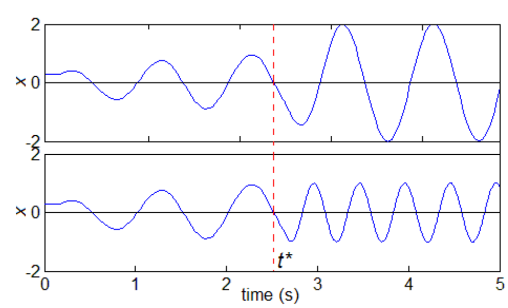

Fig. 3. Output of the nonlinear oscillator given by (1) and (2). At t=2.5s the radius is changed from 1 to 2 (upper) and frequency is changed from 1 to 2 (lower). We can see that the oscillations naturally become stronger or faster with smooth transition, which is different from the case in Fig. 1.

Many different oscillators can be used for modeling the motion pattern of oscillatory motion of caudal fin [10, 16]. We choose Hopf oscillator because of its harmonic steady state output, which is suitable for modeling the swimming gaits along straight path. Another attraction of this oscillator is its limit cycle behavior. It can be seen in Fig. 2 that the states always asymptotically converge to a limit cycle with radius A as time gets large. Robustness of the oscillator is also a significant property. After perturbation (parameters of the oscillators are changed), the system can also continuously converge to a new stable state. The output of the oscillator is still smooth due to the integration in solving the nonlinear differential equations, as shown in Fig. 3. When used in control of swimming, this asymptotic stability provides possibility to generate gradually changing gait signals, which makes the adaptive swimming gaits generation feasible.

B. Feedback Control Laws for Station-holding Control

We are now going to control the swimming of the fish robot to perform a specific task: hold its original position in unsteady adverse flow (see Fig. 4). It is naturally assumed that the controlling parameters all rise when the adverse flow rate increases. In the beginning, the fish augments both parameters for larger thrust to overcome the drag. Then as the swimming becomes adaptive to the flow, the frequency or amplitude may be slightly decreased to save the energy. Additionally, the evolving of both parameters is coupled. We also observed that the frequency is changed more significantly in variational flow. So we can assume that the regulation of the frequency is in the first place and the amplitude is changed subsequently.

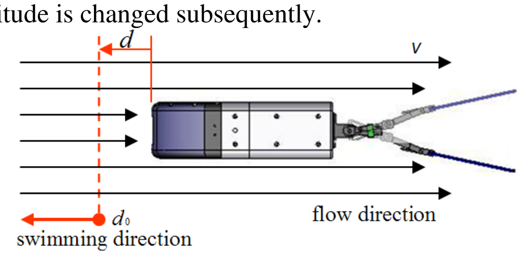

Fig. 4. Definitions of parameters. This is a top view of fish in adverse current. d is the actual displacement. d_0 denotes the original position of the fish. v is the flow velocity

Several assumptions are made. Firstly, we assume that once the fish senses the increase of incoming flow, its tail beat frequency jumps to a certain value proportional to the flow rate. Secondly, as the fish is washed away by water flow, the frequency gets larger with the distance increment with respect to its original position. Thirdly, we assume that the frequency becomes larger as the relative speed between fish locomotion and the water flow rises. This is apparent because the drag increases proportionally to square of relative speed [14]. Finally as the fish is flushed away from the origin, the controller should 'memorize' this position error and try to reduce the distance. Therefore, the controller for the frequency should also contain the information of the integration of position errors. Given that the desired input position is zero (d_0=0) in station-holding problem (position error is e=d_0-d), the control law for frequency can be interpreted as:

$$f = -k_1 d - k_2 (v - \dot{d}) - k_3 \int_{t_0}^{t} d\,\delta t \qquad (3)$$

where k_1, k_2 and k_3 are positive constants; t_0 is the time instance that fish detects the nonstationary flow (We can assume that t_0=0. See Fig. 4 for definition of other variables). Rewrite (3) and obtain

$$f = -(k_1 d - k_2 \dot{d} + k_3 \int_{0}^{t} d\,\delta t) - k_2 v \qquad (4)$$

If we look into (4) we can find that the regulation of frequency is equivalent to a Proportional Integral Derivative (PID) type controller. The last term of (4) can be seen as a feedforward of the flow information.

The control law for the amplitude can also be structured in a similar manner. The value of amplitude is proportional to the adverse flow rate and the distance d. With the coupling of frequency, the control law can be given by the following equation.

$$A = -k_4 d - k_5 v - k_6 f \qquad (5)$$

where k_4, and k_5 are positive coefficients; k_6 represents the coupling strength with the frequency. Note that the coupling coefficient, k_6 is necessary because it ensures that the actuator will not reach its power limitation easily when frequency increases. For a practical physical system, the value of A and f are bounded by the maximum allowable power. Given that the steady state output of the Hopf oscillator is $x \approx A\sin(2\pi ft)$, its first order and second order derivatives are limited by the maximum speed and acceleration of an actual actuator respectively. Therefore we have the following conditions for A and f (by differentiating x):

$$Af \le \omega_m \text{ and } Af^2 \le \alpha_m \qquad (6)$$

where ω_m and α_m are velocity and acceleration limits determined by the actuator of the fish tail.

IV. Simulation of Station Holding Control

We conduct a simulation to test the control effect by using some fundamental dynamics. The model is a one-DOF BCF-type swimming robot, as shown in Fig. 5 (Actually there are two DOFs in the tail of this prototype. Only one is under control. Another is a passive one). This robot mimics the swimming of a carangiform swimmer. The first tail joint of the robot is driven by a DC motor. The second joint is a passive one with a spring connection to increase the compliance.

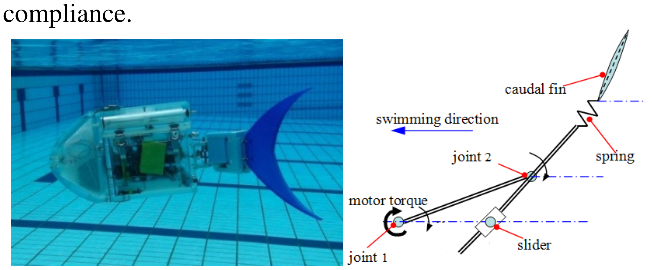

Fig. 5. A two-DOF BCF fish robot (a) and the schematic of tail mechanism (b) [17]. The picture was taken in the swimming pool of Nanyang Technological University.

Let M denote the mass property of the robotic fish, F_D be the body drag and F_T be the thrust generated by tail. Then the dynamics of the fish can be simply interpreted by:

$$M\ddot{d} = F_T - F_D \qquad (7)$$

By assuming that the fish tail is a pure propulsor and the drag totally comes from the fish body, F_D is then given by:

$$F_D = \frac{1}{2}\rho C_d S(\dot{d} - v)^2 \quad (8)$$

where ρ is the water density, C_d is the drag coefficient and S is the cross-sectional area of fish body. To evaluate the thrust force, a semi-empirical model, $F_T = F_T(A, f, v)$, is developed in our previous work to model the thrust [18]. The dynamics of the swimming robots can then be given by:

$$\ddot{d} = \frac{1}{M}\left[F_T(A, f, v) - \frac{1}{2}\rho C_d S(\dot{d} - v)^2\right] \quad (9)$$

$$F_T(A, f, v) = 0.063abf\left(2\sin\frac{A}{2} + \sin\frac{\sqrt{3}A}{2} + \sin A\right) \quad (10)$$

where a and b are two empirical parameters obtained from experiments and defined by:

$$a = \frac{6.4A^{0.8}f}{(v + 0.28Af)^{0.3}} \text{ and } b = \frac{3.9A^{6.5}f^{0.9}}{(v + 0.28Af)^4} + 0.65$$

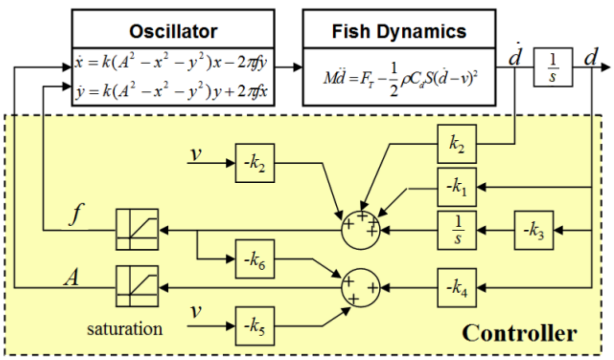

Fig. 6. Overview of the control scheme. The Hopf oscillator generates the periodic tail motion pattern. A feedback control scheme is applied to regulate the frequency and amplitude. The amplitude is also coupled with frequency by a proportional coefficient k_6. Flow rate is a feedforward quantity to the controller.

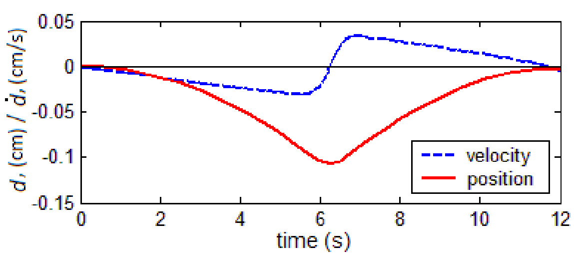

Fig. 7. Simulated results of station-holding control. The displacement and the absolute velocity are shown. The parameters in (9) are M=6.8kg, ρ=1000kg/m^3, C_d=0.63 and S=0.02 m^2.

Equation (10) solves for such a problem that at given controlling parameters and the flow speed the thrust force can be predicted. We just use it in the simulation to find the some general trend of coefficients for (4) and (5). Details of (10) are discussed in [18]. Better coefficients will be determined according to actual experiments. The control scheme is illustrated in Fig. 6. The problem of station-holding in water flux is actually a position control with zero input. Fig. 7 shows a result of the simulation. Initially the fish keeps unmoving in stationary water. Then the flow rate steps to a certain value and the robot swims in the adverse current. The robot begins to regulate the tail oscillation patterns, i.e. the controlling parameters governed by (4)-(6). It can be seen that in the first stage the fish is washed away from zero position. The absolute swimming is toward the negative direction. After several seconds setting, the robot adapts itself to the adverse current and approaches to its origin gradually. The evolving of the controlling parameters is illustrated in Fig. 8. The robot keeps tuning the motion of its tail continuously and smoothly until the oscillation evolves to a new stable pattern.

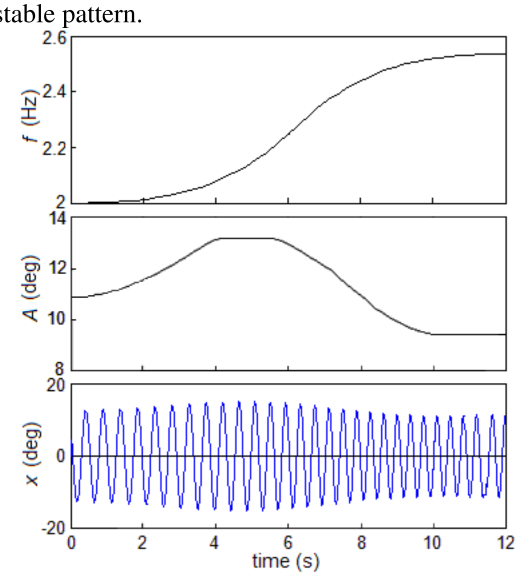

Fig. 8. Evolving of the tail beat frequency，amplitude and the swimming gait control signal. The paramters in (3)-(5) are chosen as k=1, k_1=2.0, k_2=0.8, k_3=25.0, k_4=0.5, k_5=28.0 and k_6=0.02.

V. Experiments on A One-DOF Fish Robot

A. Experiment Setup

The experiment is conducted in a water tunnel apparatus (Fig. 9). The configuration of the experiment is shown in Fig. 10. A linear conductive plastic resistance sensor is mounted on the fish robot through a rigid bar connection to measure its actual position. The absolute swimming velocity is obtained from the derivative of the position (upon application, we use the forth-order backward derivative to achieve high precision velocity). The flow information is passed by a volumetric flow rate meter (Fig. 9) to the control hardware.

Equations (1)-(10) are solved in Labview™ development environment and implemented with the CompactRIO™ embedded controller. The sampling period of control loop is chosen as 20ms, which is proved sufficient to maintain the real-time property in the experiment. The non-linear equations of the oscillator are solved with the fourth-order Runge-Kutta method. Given that (0, 0) is a stable equilibrium point (It is a point attractor) of the Hopf oscillator the initial value should avoid this point. They can be theoretically set as any values near the limit cycle. The whole control philosophy is that the non-linear oscillators work as an oscillatory swimming pattern generator. The feedback controller given by (4) tunes this frequency and the controller given by (5) modulates the shape of the output.

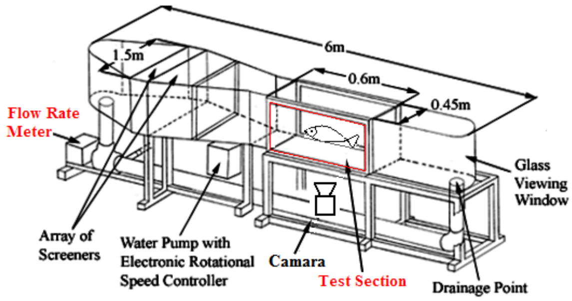

Fig. 9. A water tunnel apparatus. The observation of fish sample [19] and the robotic fish experiment are conducted in the Test Section. The flow rate is measure through a volumetric flow rate sensor.

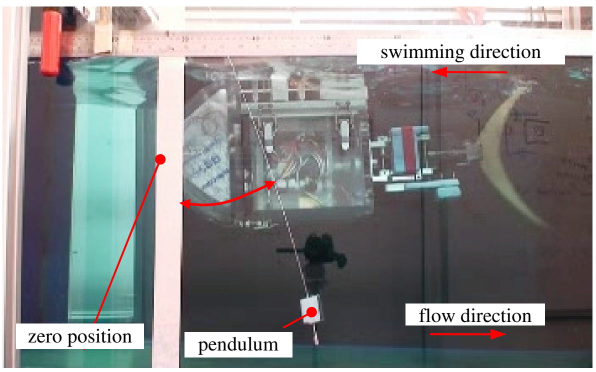

Fig. 10. The configuration of experiment in water tunnel. The fish swims against one-dimensional adverse flow in the water tunnel. The absolute displacement versus the zero position is measured through a linear sensor mounted with a slider on the top of fish. The flow velocity is provided by the flow rate meter mounted in the water tunnel. A pendulum dragged by a soft string and submerged in water is used to visually indicate the strength of flow speed by its deflection angle.

B. Experiment Results

We first evaluate parameters k_2 and k_5 for feedforward terms in (4) and (5). It is assumed that the fish robot in the following two scenarios swims with the same controlling parameters: 1) water is still and robot moves forward at constant absolute speed v with respect to the ground; and 2) water moves at constant speed v and the robot swims against flow while keeping stationary with respect to the ground. We can test the fish robot in free run mode in still water. Find the relation between the swimming speed and controlling parameters. Then values of k_2 and k_5 are obtained through dividing frequency/amplitude by flow velocity respectively. For our fish robot, we can also use the predictive model in [18] to find the value of these parameters. One way to evaluate k_1-k_6 is to use the Bode diagram, as suggested in [20]. This method relies too much on the mathematical model of the fish dynamics. Although we have a predictive model in our simulation, it is not so accurate for finding the proper parameters. In our implementation, we tune those parameters manually by using some rule based methods according to input-output relationship obtained in actual experiments [21].

The step responses of the control system are tested, which is depicted in Fig. 11. The example of swimming t_2 to t_3 is illustrated in Fig. 12. Firstly, we set a low adverse flow rate and the robot easily gets adaptive to the flow (the fish robot quickly adjust its swimming gaits to hold its original position). Then the flow speed is increased to 10cm/s at time t_1. At first the robot is flushed away from the original position. The controlling parameters increase correspondingly to generate higher thrust against the adverse flow. After about ten seconds setting process, the robot gets back to zero position and maintains stable. At t_2 the flow rate is increased to 15cm/s (this flow rate is equivalent to the 0.8BL/s, which is large for the present fish robot). The setting process is similar except that the there is an obvious overshoot (t=35-38s) and the fluctuation near the zero position is relatively large (t=40-55s). At t_3 a decreasing step response is tested by reducing the flow rate. As shown from t=55s to 70s, after short period of overshooting, the robot gets stable again. The evolving of the controlling parameters is shown in Fig. 13.

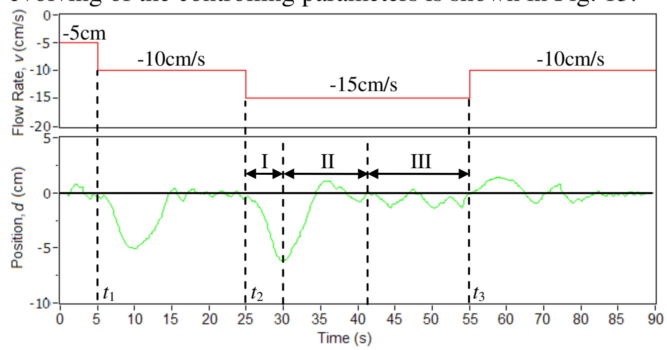

Fig. 11. The step response of the station-holding control. The coefficients in (1)-(6) are k=8.0, λ=1.0, k_1=16, k_2=1.5, k_3=12, k_4=28, k_5=105, k_6=1.6, ω_m=0.785rad/s and α_m=2.36 rad/s^2. Note that the actual flow may not be changed so sharply as described in the figure. The figure only shows an ideal case.

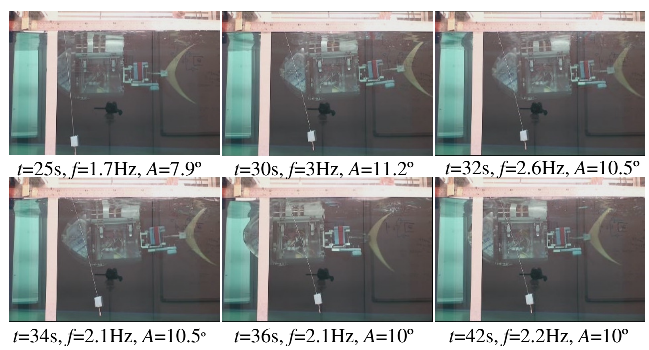

Fig. 12 Snapshots of the adaptive swimming from t_2 to t_3. The locomotion experienced three stages: I) both controlling parameters increase as the robot is flushed away in t=25-30s; II) swims back in t=30-42s and II) get stable when t>42s.

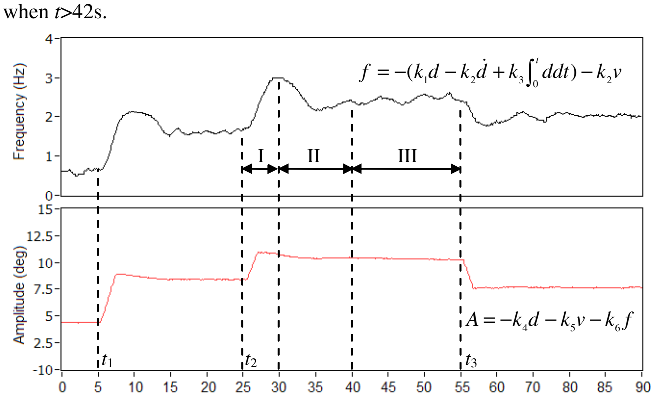

Fig. 13. The evolving of the tail beat frequency and amplitude. The definition of the time line is the same as that in follows Fig. 11.

It can be seen from Figs. 11-13 that the station-holding control system is stable. The controlling parameters are convergent as time gets large. However, there are obvious gap between the actual coefficients for control laws obtained from experiments and those from the simulation. This suggests that the model in (9) is not sufficient to describe the dynamics of the robot-water interaction. This equation provides only a static description of thrust and controlling parameters. In transient swimming condition, the accuracy of these this model may not be sufficient. However, the simulation can provide a qualitative understanding of the controller design. In experiments, we try the coefficients starting from those suggested in the simulation. After some modification according to the observations, better results are obtained. The station-holding is achieved. But a small fluctuation of the position is also observed, which is not as ideal as what is shown in the simulation.

VI. Concluding Remarks

In this paper, swimming adaption to one-dimensional unsteady flow is studied and implemented on a fish robot. This work is beneficial for improving the locomotion performance of biologically inspired swimming robots. Feedback control laws that help the fish robot performing station-holding in unsteady flow are presented. Nonlinear oscillators are used to model the fish tail motion. By dynamically tuning the controlling parameters, the fish robot can adjust its swimming gaits adaptive to the variation of flow. We analyze and test the control laws on a BCF type fish prototype in water tunnel. The inspirations from this simple illustration are fundamental for more complex adaptive swimming control.

Several works can be explored in future study. Firstly, the control method can be extended on multi-DOF fish robot combined with multiple coupled nonlinear oscillators. Secondly, the energy efficient swimming will be investigated by applying closed-loop swimming control and online adaptive gait generation. Thirdly, more complex flow situation will be considered, for example, three-dimensional, laminar or turbulent flow. The success of these works will further improve the locomotion performance of current underwater swimming machines.

Acknowledgment

The authors would like to express thanks to Professor Srigranrom Sutthiphong and Mr. Vincent Chai for their help in doing the experiments. Mr. Chee Wee Chong, a research student in our research team and all technicians in the Robotics Research Center of the Nanyang Technological University are acknowledged for their assistance during the prototype constructing.

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