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Phase controller for a robotic fish to follow an oscillating source

Wei-Kuo Yen, Jenhwa Guo *

Department of Engineering Science and Ocean Engineering, College of Engineering, National Taiwan University, Taipei, Taiwan, ROC

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ABSTRACT

This work develops a method for controlling a robotic fish, as it swims in a school, by following periodic stimuli generated by a neighboring robot. To track the motion of a periodically oscillating neighboring source, the hydrodynamic pressure around the body of the robotic fish is measured by a PVDF sensor attached to the robot. The pressure induced by the source is obtained by subtracting the predicted pressure generated by the robotic fish from the measured pressure. The controlled fish tail mechanism is represented as an oscillator, and a moving oscillating sphere is considered to be an external source. A dipole model based on the potential flow theory is used to predict the hydrodynamic pressure close to the fish tail. The relative phase between the tail and the oscillating source is estimated from the pressure measurements of the PVDF sensor. The difference in phase angle between the tail and the oscillating source is used to determine the torque used to drive the tail mechanism. The proposed method is demonstrated by the tank experiments that involve a captured model of a robotic fish that swims close to an oscillating source.

1. Introduction

Robotic fish are designed to mimic the motion of real fish. Given their ability to hover precisely and turn swiftly, the robotic fish are also expected to mimic real fish behaviors, such as shoaling and schooling. Fish obtain many benefits from shoaling/schooling behavior including time saving in finding prey and defence against predators (Shaw, 1978). Hydrodynamic efficiency is also increased as schooling fish swim in a diamond pattern due to fish extracting energy from the Kármán vortex street generated by the leading fish (Weihs, 1973). In fish schools the 'preferred' distance between a fish and its nearest neighbor is around one body length (Partridge, 1982). One possible method for a fish staying in the moving school is to employ the lateral line organ distributed from its head to its tail to sense the displacement of water (Pitcher et al., 1976). To understand how the lateral line system can help real fish to school, scientists analyzed environmental stimuli to the system under different situations. Studies show that by calculating the distributions of the pressure difference and pressure gradient of adjacent pores on the surface of a fish body, near-field information such as location and movement of a source, as well as the existence of a plane surface can be encoded (Hassan, 1992; Coombs and Braun, 2003; Windsor et al., 2010). Thus, a pressure sensor array is devised to determine the pressure gradient of Kármán vortex street (Venturelli et al., 2012). The position of a robotic fish in a Kármán vortex street behind an object in a flow was controlled, using the feedback of pressure signals measured by the sensor array installed in the robot's head (Salumäe and Kruusmaa, 2013). A recent study also utilizes the measured pressure variations in the surrounding of the robotic fish to sense the kinematic conditions of an adjacent robotic fish (Zheng et al., 2018).

From the above, a robotic fish is expected to have the ability to measure pressure signals that are generated by periodic movements in its nearby environment to enable it to swim properly in a school. It has also been found that while swimming in a Kármán vortex street, real fish alternate their body motions to synchronize with the vortices and to maintain their positions (Liao et al., 2003). Similarly, robotic fish should adjust their body motion in response to environmental pressure signals obtained using some forms of pressure sensing (Yen et al., 2018). Although previous research showed that real fish could guide themselves by sensing the pressure variations of the surrounding flow field to move, there are few studies on robotic fish formation using pressure feedback control.

The present work suggests that the school formation, for a robotic fish to follow a neighbor, depends on maintaining their relative distance, and that relative phase rather than pressure intensity determines the torque command sent from the controller to the tail fin for speed control. The speed of a robotic fish can be controlled by adjusting the beating frequency of the tail (Guo, 2009; Kopman et al., 2015). When two robotic fish swim in parallel and keep the same phase of their tail motions, the

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* Corresponding author.
E-mail address: jguo@ntu.edu.tw (J. Guo).

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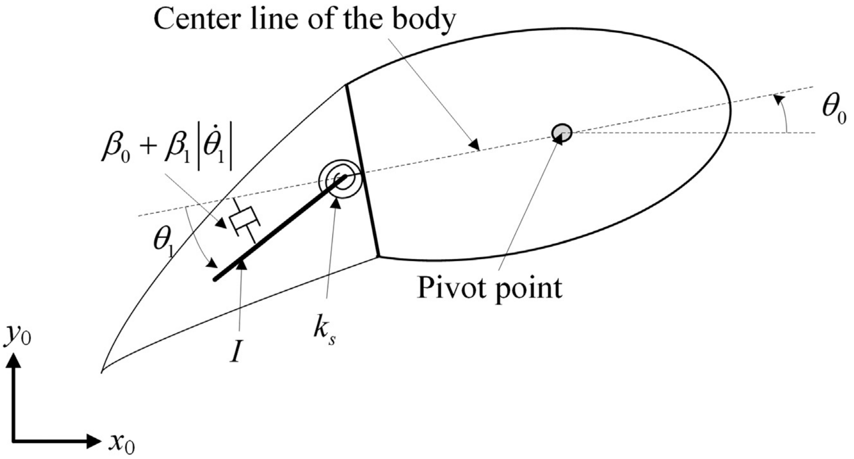

Fig. 1. Representation of dynamic model of the tail fin. θ_0 indicates the orientation of the robot in a space-fixed coordinate $o - x_0y_0$; θ_1 indicates orientation of the tail relative to the center line of the body; I is the moment of inertia, which comprises the moments of inertia of the tail and added mass; k_s is the stiffness of the tail; β_0 and β_1 are the linear and quadratic damping coefficients, respectively.

speed for following can be achieved. The speed-following strategy presented here is to control the relative phase of the oscillating tail to that of an adjacent neighbor. As the distance is close enough to detect the neighbor, it is only phase that needs to be controlled.

This work proposes a controller design for robotic fish to follow an oscillating source. An oscillator-based method is used to model the fin oscillation. Another oscillator model is used to represent the oscillating source. The objective is to control the phase difference between the tail motion of a robotic fish and the oscillation of the source. First, the motions of the tail fin and the source are described as nonlinear oscillators with a constant frequency ratio. To obtain information about the motion of the source, a polyvinylidene fluoride (PVDF) pressure sensor is placed on the surface of the robot to measure the hydrodynamic pressure generated by the oscillating source. In experiments, a mechanism drives a small ball to generate the oscillating source, and the robotic fish is constrained but not restricted to exhibit yaw motions. According to the potential flow theory, the hydrodynamic pressure signals generated by the oscillating source are related to its motion, and can be used as the phase control input to the tail oscillator. Control of the tail to follow the oscillating source, which moves with different forward velocities, is tested to evaluate the effectiveness of the phase control. The experimental results reveal that control using the desired phase difference between the tail of the robotic fish and the oscillating source can be achieved, presenting the possibility of synchronizing the motions of two robotic fish. This paper is organized as follows. Sections 2 and 3 introduce the modeling and the design of the control system, respectively. Section 4 provides experimental data and Section 5 provides concluding remarks.

2. Modeling of hydrodynamic pressure

The dynamic model of the robotic fish is nonlinear and can be derived using Euler-Lagrange equations (Guo and Joeng, 2004). To control the tail motion of the robot, the tail is assumed to oscillate with small amplitudes and the coupling terms between the tail angle and other state variables are assumed to be relatively small. The dynamic model of the tail can thus be decoupled from the whole dynamic model of the robotic fish and represented as follows (Seo et al., 2010).

$$I\ddot{\theta}_1 + \beta_0\dot{\theta}_1 + \beta_1|\dot{\theta}_1|\dot{\theta}_1 + k_s\theta_1 = \tau_a + \delta, \tag{1}$$

where θ_1 is the angular motion of the tail relative to the center line of the body, as shown in Fig. 1; I is the moment of inertia, which comprises the moments of inertia of the tail and added mass, and k_s is the stiffness of the tail. $\beta_0 + \beta_1|\dot{\theta}_1|$ is the nonlinear damping term, and δ is the small perturbation that arises from errors in the modeling of the mass and damping. To provide a stable limit cycle oscillation (Seo et al., 2010), the input torque is set to

$$\tau_a = -P\theta_1 + \gamma_0\dot{\theta}_1 - \gamma_1|\dot{\theta}_1|\dot{\theta}_1 + g_h(\theta_0 - \theta_h) + I\tau_s(t), \tag{2}$$

where P, γ_0, and γ_1 are input parameters; g_h is the heading control gain; θ_0 is the heading angle of the robot in a space-fixed coordinate $o - x_0y_0$, and θ_h is the desired heading angle; $\tau_s(t)$ is the input that generates a torque on the tail that causes it to respond to an environmental stimulus. Substituting Eq. (2) into Eq. (1) yields,

$$\ddot{\theta}_1 + (\sigma_1|\dot{\theta}_1| - \sigma_0)\dot{\theta}_1 + \omega_0^2\theta_1 = g_h(\theta_0 - \theta_h)/I + \tau_s(t), \tag{3}$$

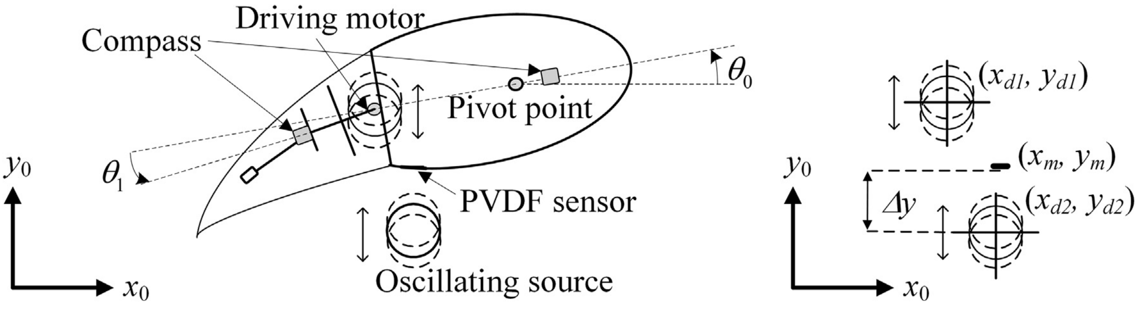

Fig. 2. Models of a robotic fish and an oscillating source. θ_0 and θ_1 are the orientations of the head and tail of the robot, respectively, in a space-fixed coordinate $o - x_0y_0$. The oscillating tail of the robot and the oscillating source are simply modeled as dipoles 1 and 2, oscillating in the y_0-direction and are located at points (x_{d1}, y_{d1}) and (x_{d2}, y_{d2}), respectively. The pressure sensor on the robot is located at (x_m, y_m) and $\Delta y = y_m - y_{d2}$.