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The Numerical Modeling and Sliding Mode Control of A New Submersible Fish Cage

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Abstract: The purpose of this paper is to develop a new submersible fish cage operated by a pneumatic system for offshore aquaculture. Although some researchers have investigated modeling and control of fish cages, such cages consist of variable ballast tanks that with closed cylinders and thus present a maintenance issue. In solving the issue the new submersible fish cage investigated consists of bottom-opening cylinders. Accordingly, we designed a mathematical model of the concept and applied Sliding Mode Control for nonlinear angle control. Some experiments conducted under assumed conditions indicate that the angle of the system converges to zero under all conditions and the control has the stability to balance the fish cage.

1. Introduction

As population increased, the need of essential nutrients abundantly contained in fish and seaweed is also being increased steeply. Coastal region to crop the seafood is, however, restricted by many systems already installed including fish cages, vacation spots and power plants. These limited conditions force aquacultural systems to be displaced from coastal to offshore region.

As many offshore aquacultural systems are operated by farmers on ferry and placed in water for a long time, pneumatic systems are suitable for reasons related to their good power/weight ratio, easy maintenance and assembly operations, clean operating conditions and low cost1). However, compressibility of air and highly nonlinear flow through pneumatic system components make pneumatic devices have bad controllability and occupy small space in industrial applications.

Nevertheless, submersible fish cage operated by pneumatic system had been studied by many researchers as the one of offshore aquacultural systems. Recent researches mostly have, however, been focused on modeling of net cage structure and feeding2-5).

Although some researchers investigated modeling and control of fish cage system, they overlooked physical properties of air including compressibility and nonlinearity. The fish cage was, moreover, made up of variable ballast tanks that consist of closed cylinders6-10). As fish cage in offshore is placed in water for a long time, it is unsuitable to use hydraulic valves that sea water pass through in terms of maintenance.

For solving the problem above mentioned new fish cage is made up of bottom-opened cylinders. The characteristics of air makes, however, opened system become more complex to control.

Therefore, we design analytically mathematical model of the newest submersible fish cage system has open cylinders in detail, and then utilize the Sliding Mode Control (SMC) theory for nonlinear angle control implementation, considering its robustness and high performance characteristics even for highly nonlinear

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systems[11]. The validity of the modeling and control logic is finally verified by experiments based on real situations.

2. System Description and Modeling

The current section provides brief explanation of how the fish cage works and how numerical modeling is derived. Details of system structure and derivation of basic equations are omitted for the sake of brevity.

2.1 System Description

The submersible fish cage system consists of float, mooring system, anchor system and fish cage having four open cylinders as shown in Fig. 1. The fish cage is usually located in water and stretched by mooring system in order to preserve the fish stock from the destructive environmental events[8]. As the need to feed fish, pneumatic system equipped in ferry can raise the fish cage.

In the ordinary way, due to the absence of power source it is efficient to use mooring system, float and auxiliary cylinders to maintain descended position of fish cage. Inserting little air into open cylinders, the cage can be ascended. In this process, inequality of air volume put in each cylinder and wave affect an angle of the cage.

The angle of bottom-opened cage makes the system unstable and must be controlled. What we have to consider is, therefore, only angle control of fish cage in the process of ascending and descending.

We will treat the control problem in section 3.

2.2 Mathematical Modeling

The differential equation for the rates of change of the pressure in each cylinder is[1]

$$\dot{P}_i = \frac{P_i k}{V_i}\left(G_{In,i}\frac{RT_{in}}{P_i} - G_{O,i}\frac{RT_i}{P_i} - A\dot{x}_i\right),\ i = 1,2,3,4 \tag{1}$$

where P_i is the absolute pressure of each cylinder, k is the specific heat ratio, V_i is the air volume of each cylinder, R is the gas constant, T_{in} is the inlet temperature of the air going into the cylinder, T_i is the temperature of the air in each cylinder, A is the area of cylinder, $\dot{x}_i$ is the time derivative of the inside water level of cylinder, $G_{o,i}$ $G_{in,i}$ is the input air mass flow to cylinder and $G_{o,i}$ is the output air mass flow from cylinder. The standard equation describing mass flow of air is[12]

$$G = \begin{cases} C_d A_o C_{in} \dfrac{P_u}{\sqrt{T_u}} & \text{if } \dfrac{P_d}{P_u} \le P_{cr} \\ C_d A_o C_o \dfrac{P_u}{\sqrt{T_u}} \left(\dfrac{P_d}{P_u}\right)^{1/k} \sqrt{1 - \left(\dfrac{P_d}{P_u}\right)^{1-1/k}} & \text{if } \dfrac{P_d}{P_u} > P_{cr} \end{cases} \tag{2}$$

where C_d is the dimensionless, discharge coefficient of the orifice, A_o is the orifice area, P_u is the upstream pressure, T_u is the upstream temperature, P_d is the downstream pressure and

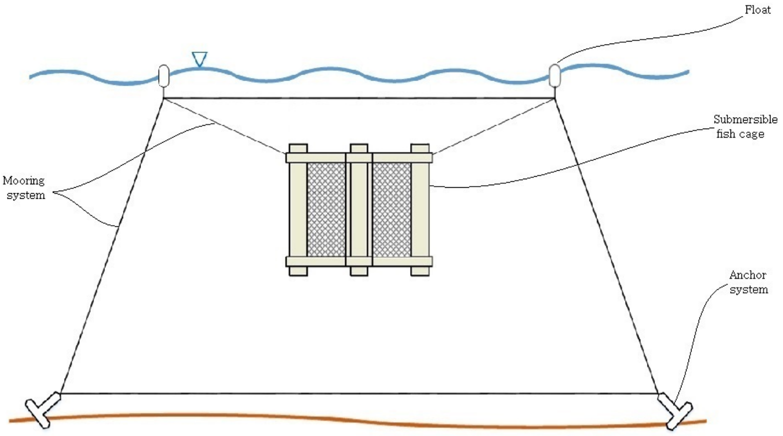


Fig. 1 Submersible fish cage system

$$C_{in} = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{k+1/k-1}} \; ; \; C_o = \sqrt{\frac{2k}{R(k-1)}} \; ; \; P_{cr} = \left(\frac{2}{k+1}\right)^{k/k-1}$$

are constant for a given fluid13). For air we have C_{in} =0.040418, C_o=0.156174 and P_{cr}=0.52

Now we present the dynamic equation of the experimental model of fish cage shown in Fig. 2. The dynamic equation describing vertical motion of cage is

$$\ddot{z} = \frac{1}{M}\left(Mg - \rho_w g \sum_{i=1}^{4} V_i - F_{buoy} - 4\alpha hA - \frac{C_f \rho_w A_f}{2}\dot{z}^2\right) \qquad (3)$$

where z is the depth of cage from sea level, M is the mass of cage, ρ_w is the density of water, g is the gravitational acceleration, F_{buoy} is the auxiliary force by other components, h is the height of cylinder, α is the pressure gradient by depth of water, C_f is the dimensionless drag coefficient and A_f is the frontal area, the projected area seen by a person looking toward the object from a direction parallel to the upstream velocity, of total system. The fourth term of (3) represents the constant force arising from pressure increment depending on depth and the fifth term of (3) is the drag, reaction force for speed of system and the approximate value of C_f is determined by means of a simplified analysis or an appropriate experiment 14).

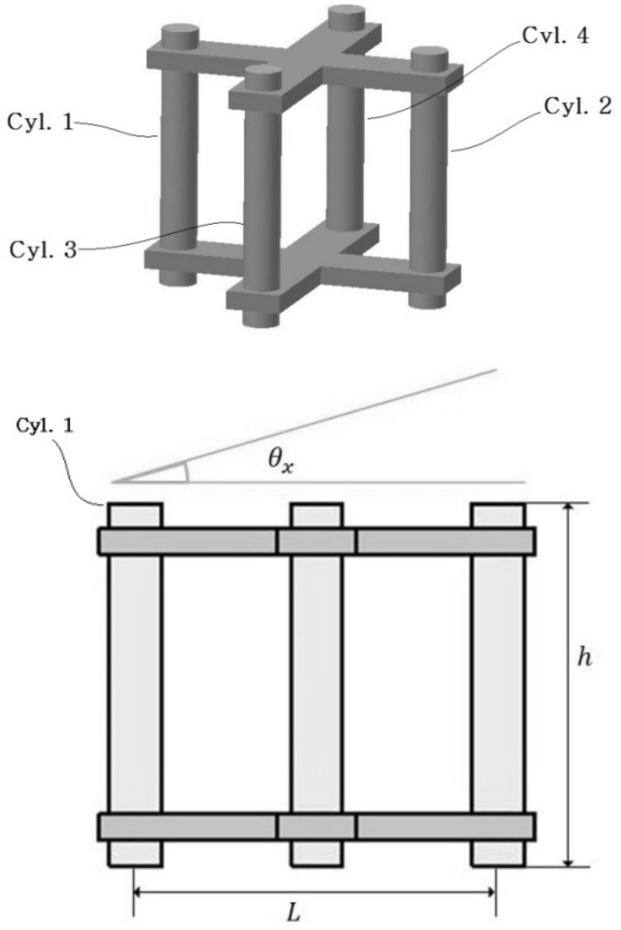


Fig. 2 The fish cage model

As cylinders opened, the equation about movement of water level inside cylinder is expressed as

$$\ddot{x}_i = \frac{1}{m_{w,i}}\left[m_{w,i}g + P_i A - \{P_{atm} + \alpha(z + h \pm \frac{L}{2}\sin\theta_n)\}A\right] \quad (4)$$

where x_i is the inside surface of water of each cylinder, $m_{w,i}$ is the weight of water filled in cylinder, L is the horizontal length of cage, θ_n is the angle of system, n is the x or y meaning axis and P_{arm} is the atmospheric pressure that added in equation to match absolute pressure. The terms in brace of (4) represent the water pressure acting on bottom area of each cylinder.

Finally, using moment equation we can describe rotation of cage as follows

$$\ddot{\theta}_x = \frac{1}{I}\left(\frac{L}{2}\rho_w g A x_2 - \frac{L}{2}\rho_w g A x_1\right) \qquad (5)$$

$$\ddot{\theta}_y = \frac{1}{I}\left(\frac{L}{2}\rho_w g A x_4 - \frac{L}{2}\rho_w g A x_3\right) \qquad (6)$$

where I is the moment of inertia of system and is obtained by experiment for covering the reaction force about rotational motion. It makes the calculation of control law concise.

3. Controller Design

As explained previously, what we only consider is angle control of cage in the process of ascending and descending. Since the use of level sensor is constrained from maintenance problem, we replace the level of water inside cylinders with mass using ideal gas equation in control logic. Thus we utilize SMC, a kind of robust control. The detailed derivation of following equations is in the Appendix for the sake of brevity.

Hoping zero angle of cage $(\theta_x, \theta_y = 0)$ sliding surfaces are defined as

$$S_x(t) = C_1\theta_x + C_2\dot{\theta}_x + C_3\ddot{\theta}_x \tag{7}$$

$$S_y(t) = C_1\theta_y + C_2\dot{\theta}_y + C_3\ddot{\theta}_y \tag{8}$$

where C_1, C_2, C_3 are constants decided by the trial and error method.

Substituting Eq. (5), (6) and ideal gas equation and using few assumptions, differentiation of Eq. (7) and (8) can be written as follows

$$\begin{aligned}\dot{S}_x(t) = C_1\dot{\theta}_x + C_2\frac{\rho_w gRTL}{2I}\left(\frac{m_2}{P_2} - \frac{m_1}{P_1}\right) + \\ C_3\frac{\rho_w gRTL}{2I}\left(\frac{u_2}{P_2} - \frac{u_1}{P_1} - \frac{m_2\dot{P}_2}{kP_2^2} + \frac{m_1\dot{P}_1}{k\,P_1^2}\right)\end{aligned} \tag{9}$$

$$\begin{aligned}\dot{S}_y(t) = C_1\dot{\theta}_y + C_2\frac{\rho_w gRTL}{2I}\left(\frac{m_4}{P_4} - \frac{m_3}{P_3}\right) + \\ C_3\frac{\rho_w gRTL}{2I}\left(\frac{u_4}{P_4} - \frac{u_3}{P_3} - \frac{m_4\dot{P}_4}{kP_4^2} + \frac{m_3\dot{P}_3}{k\,P_3^2}\right)\end{aligned} \tag{10}$$

Setting Eq. (9) and (10) equal to zero and solving for u, we can take equivalent control u^{eq}.

For satisfying the sliding condition, $SS < 0$, the control law of fish cage is defined as

$$\mathrm{sign}(-S_x)u_2 + sign(S_x)u_1 = u^{eq} + Ksat(S_x/\varphi) \tag{11}$$

$$\mathrm{sign}(-S_y)u_4 + sign(S_y)u_3 = u^{eq} + Ksat(S_y/\varphi) \tag{12}$$

where K is the controller gain defined as a function of the state variables, φ is the thickness of a thin boundary layer introduced to avoid chattering[11] and sign and sat are functions expressed as follows

$$\mathrm{sign}(\delta) = \begin{cases} 1 & if\ \delta > 0 \\ 0 & if\ \delta \le 0 \end{cases}$$

$$\mathrm{sat}(\varepsilon) = \begin{cases} 1 & if\ |\varepsilon| > 1 \\ |\varepsilon| & if\ |\varepsilon| \le 1 \end{cases}$$

The controller gain K can be chosen function of angle as follows

$$\mathrm{K} = K_0|\theta| + K_1|\dot{\theta}|$$

where K_0 and K_1 are the constants obtained by the trial and error method[15-17].

4. Simulation and Experimental Verification

The validity of the numerical model and control logic is verified by experiment in this section. The simulation of modeling is carried out using Simulink in MATLAB and Runge-Kutta method. We set fixed step size $1ms$ and neglected time delay. The pneumatic circuit of total system is briefly depicted in Fig. 3 and Fig. 4 represents the real test rig. Discharge coefficient of each 2-way valve (TV2W03) was found by experiment, $C_d = 0.59$. The control logic is conducted by online processing of transmitted data from pressure sensor (PSE543) and angle sensor (MSENS) every sampling time.

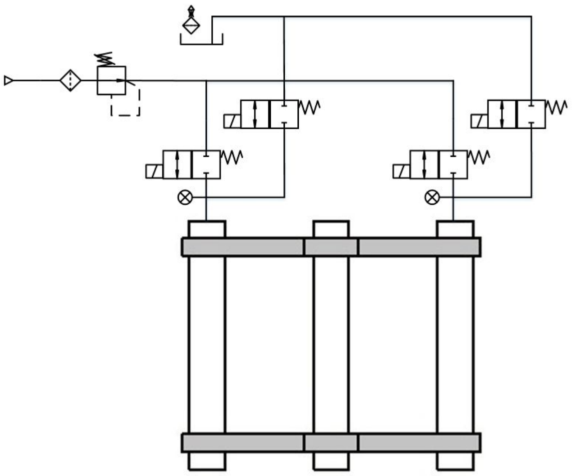


Fig. 3 The experimental setup: pneumatic circuit

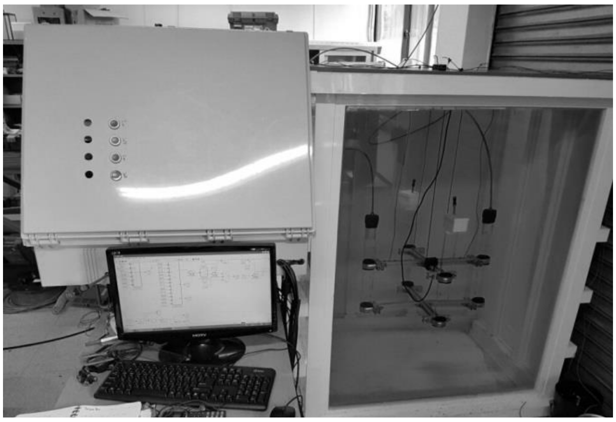
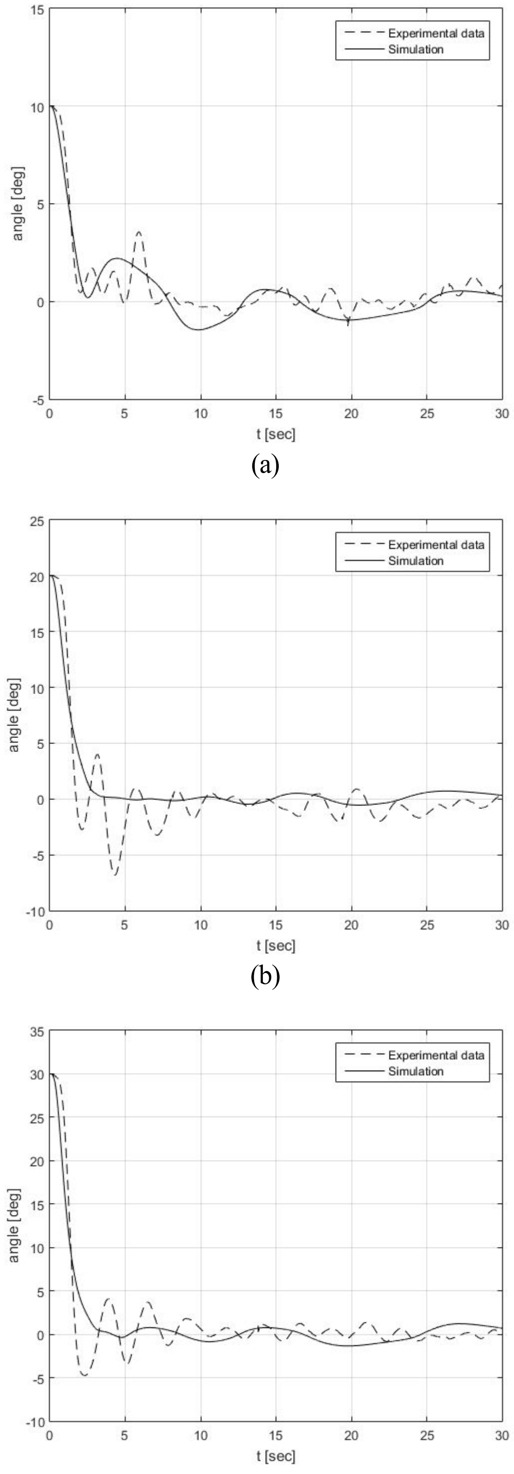


Fig. 4 The experimental setup: test rig

Fig. 5 depicts comparison of numerical simulation and experiment. Initial point of inside water level of each cylinder is identical ($x_i = 0.1\mathrm{m}$) to describe the circumstance affected by wave and each graph is classified by initial angle of system.



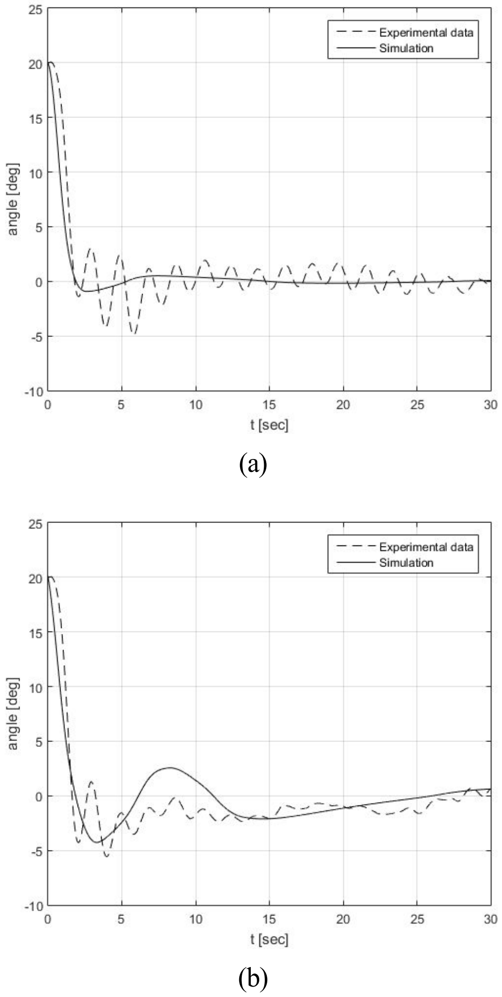
(a)

(b)

(c)

Fig. 5 The test results, initial degree
(a) $\theta_x = 10°$, (b) $\theta_x = 20°$, (c) $\theta_x = 30°$

Fig. 6 depicts another comparison of numerical simulation and experiment. Initial point of inside water level of each cylinder is different ($x_1 = 0.1\mathrm{m}$, $x_2 = 0.2\mathrm{m}$ or $x_2 = 0.3\mathrm{m}$ respectively) to describe the circumstance affected by inequality of magnitude of put air.



(a)

(b)

Fig. 6 The test results, water level difference
(a) $\Delta x = 0.1\mathrm{m}$, (b) $\Delta x = 0.2\mathrm{m}$

Quite big difference between simulation and experiment is observed. Even if LPF eliminated noise of pressure sensor, the differential of signal made noise amplified and affected magnitude of equivalent control. The differential of angle signal influenced, furthermore, sliding surface and made control of system change frequently. These observational errors aggravated accuracy of the level of water inside cylinders substituted with mass in control logic.

5. Conclusion.

In this article numerical modeling of the newest submersible fish cage consists of open cylinders was carried out in detail by considering nonlinearity of air and the SMC was conducted to keep angle of fish cage stable. From a conservational point of view the inside water level of cylinders was substituted in control logic, but this effected a degradation of modeling accuracy. Furthermore, the differential of sensor signal aggravated control logic. Nevertheless, we observed that the angle of system converges to zero and the control logic of system is stable under all assumed circumstances.

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Appendix

In this section we derive the control method expressed as Eq. (11). The procedure of derivation of Eq. (12) is omitted owing to similarity.

Differentiation of Eq. (7) is described as

$$\dot{S}_x(t) = C_1\dot{\theta}_x + C_2\ddot{\theta}_x + C_3\dddot{\theta}_x. \qquad \text{(A.1)}$$

Substituting Eq. (5) in Eq. (A.1), the differential of sliding surface is represented as

$$\dot{S}_x(t) = C_1\dot{\theta}_x + C_2\frac{\rho_w g A L}{2I}(x_2 - x_1) + C_3\frac{\rho_w g A L}{2I}(\dot{x}_2 - \dot{x}_1) \qquad \text{(A.2)}$$

Assuming temperature of inlet and outlet is same and using simple notation, Eq. (1) can be expressed as

$$\dot{P}_i = \frac{P_i k}{V_i}\left(\frac{RT_{in}}{P_i}u_i - A\dot{x}_i\right) \qquad \text{(A.3)}$$

and the ideal gas equation is

$$P_i A x_i = m_i RT \qquad \text{(A.4)}$$

By substituting Eq. (A.3), (A.4) in Eq. (A.2) we can take Eq. (9) and setting Eq. (9) equal to zero and solving for u, u^{eq} is defined as

$$u^{eq} = \begin{cases} \frac{P_1}{C_3}\left[C_1\frac{2I}{\rho_w g RTL}\dot{\theta}_x + C_2\left(\frac{m_2}{P_2} - \frac{m_1}{P_1}\right)\right. \\ -\frac{P_2}{C_3}\left[C_1\frac{2I}{\rho_w g RTL}\dot{\theta}_x + C_2\left(\frac{m_2}{P_2} - \frac{m_1}{P_1}\right)\right. \end{cases}$$
$$+C_3\left(\frac{m_1\dot{P}_1}{kP_1^2} - \frac{m_2\dot{P}_2}{kP_2^2}\right)\Big] \quad if\ S_x > 0$$
$$+C_3\left(\frac{m_1\dot{P}_1}{kP_1^2} - \frac{m_2\dot{P}_2}{kP_2^2}\right)\Big] \quad if\ S_x < 0. \qquad \text{(A.5)}$$

From Eq. (A.5) the control method Eq. (11) always satisfy sliding condition, $S\dot{S} < 0$.

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