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Design and Mechanism Analysis of Paddlewheel Aerator with Movable Blades

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Abstract. The successful of intensive aquaculture is strongly influenced by the ability of the farmers to overcome the deterioration of water quality. The problem is low dissolved oxygen through aeration process. The aerator device which widely used in pond farming is paddle wheel aerator because it is the best aerator in aeration mechanism and usable driven power. However, this aerator still has a low performance of aeration, so that the cost of aerator operational for aquaculture is still high. Up to now, the effort to improve the performance of aeration was done by two-dimensional blade design. Obviously, it does not provide an optimum result due to the power requirements for aeration is directly proportional to the increase of aeration rate. The development of movable blade is based on fact that power is required only when blade of paddle wheel aerator entering water and in contrary action of aeration effect only when the blade is about leaving the water. This study was carrier out to design paddle wheel aerator with movable blade which will open when entering water and close when leaving water. Wheel closed at quadrant I to IV (entering water surface) and was about to open at quadrant III to II (leaving water surface). The blade was designed referring to commonly used Taiwan wheel model. The size of the blade was 15 cm of width, 20 cm of length, trapezoid-shape with 15° of bottom side and 30° of top side, had 40 holes with diameter of 1.6 cm. The component of mobable blade mechanism consisted of cam and shaft, rim, rim cap, blade holder, follower, spring and bearing. Follower was able rotate with angle of rotation was 125°, rotational displacement was 50 mm, maximum velocity was 0.55 m/s and acceleration was 6.09 m/s². The largest angle of pressure occurred between cam and follower was 40.12° and the maximum torque required to rotate movable wheel was 80.09 Nm. The result shows that the testing without a load at 115 rpm, the torque that occured is 43.05 N·m and the electric power consumption is 511.72 Watt. However, the electrical consumption is still higher comparing with Taiwan paddlewheel aerator model due to the friction occured on the follower and cam.

1. Introduction

Aeration is a mechanism of adding some amount of oxygen into water to provide sufficient amount of oxygen. Aeration is carried out by increasing water and air contact using aerator device. One type of aerator device which widely used in pond farming is paddle wheel aerator [1]. Paddle wheel aerator is considered as the most appropriate aerator device due to aeration mechanism and wide usable driven power [2].

Some of parameters including water and air surface contact, differential oxygen concentration, film surface coefficient and turbulence influence aeration rate [3]. Aeration performance was influenced by geometry, size and wheel velocity [4]. Higher size tends to have higher aeration which simultaneously followed by higher driven power needs due to higher drag force. This condition creates certain problem in utilizing paddle wheel aerator as it may increase operational cost including electrical and fuel consumption.

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Various models of paddle wheel aerator are offered in market. Aerator based on Taiwan design is widely used by consumers due to affordable price, light in weight and corrosion-resistant but has low efficiency as shown Figure 1 [1][5]. Aerator that was designed and fabricated by Taiwan has SAE (standard aeration efficiency) value of $1.063 \text{ kg O}_2 \text{ kW h}^{-1}$ [6]. Bhuyar *et al.* designed aerator with SAE value $2.269 \text{ kg O}_2 \text{ kWh}^{-1}$ [7]. The most appropriate paddle wheel aerator was designed by Moore and Boyd with SAE value $2.54 \text{ kg O}_2 \text{ kWh}^{-1}$. Some of fabrications use aerator design with specification $2.25\text{-}7.5 \text{ kW}$ and $\text{SOTR } 17.4\text{-}23.2 \text{ kg O}_2 \text{ h}^{-1}$ and average value of SAE was $2.2 \text{ kg O}_2 \text{ kW h}^{-1}$ [8].



Figure 1. Paddlwheel aeator based of Taiwan design

The development of movable blade is based on fact that power is required only when blade of paddle wheel aerator entering water and in contrary action of aeration effect only when the blade is about leaving the water. This study was carrier out to design paddle wheel aerator with movable blade which will open when entering water and close when leaving water, also the torque and power consumption assessment its done.

2. Materials and methods

2.1. Materials and functional design

The size of the blade was 15 cm of width, 20 cm of length, trapezoid-shape with 15° of bottom side and 30° of top side, had 40 holes with diameter of 1.6 cm. The wheel was designed to rotate clockwise with movable blade that enabled to open and close. The blade was about to close at quadrant I to IV (entering water surface) and open at quadrant III to II (leaving water surface). Blade opened to 45° from its close position which parallel to rim. Wheel dimension was designed similarly with commonly used wheel size i.e. 20 cm width, 30 cm rim diameter and 60 cm total dimension.

2.2. Measurment methods

2.2.1. Torque measurement. Torque measurement was done by using a strain gauge mounted on the wheel shaft. The sensor was connected to the strain amplifier (DAS-406B DC Strain Amp) through the slip ring and the bridge box were recorded by using data loggers (minilab 1008) and stored in the computer (Figure 2). Measurement data in the form of voltage (mVolt) was converted to strain (μst) and torque measurement values ($\text{N}\cdot\text{m}$) with calibration values that have been done before.

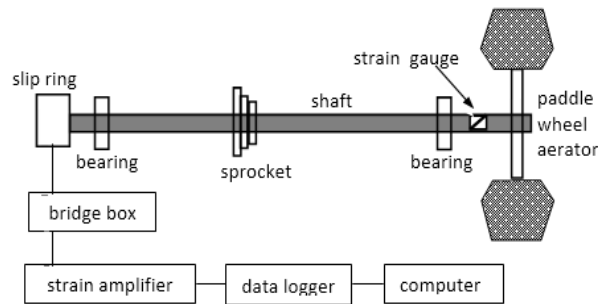


Figure 2. Torque measurement scheme

2.2.2. Power measurement. Paddlewheel power measurement was done by measuring the electrical power consumption of electric motors using Ammeter (DO2A) which was connected to an electrical outlet. Reading the power measurement value (Watt) was done by using a digital video camera recording on display Ammeter. Rated power was taken on the average value that often was showed from the reading video playback recording for each treatment testing.

3. Results and discussion

The blade was designed referring to commonly used Taiwan wheel model. The structural design based of functional design. The design paddle wheel aerator with movable blade which will open when entering water and close when leaving water. Wheel closed at quadrant I to IV (entering water surface) and was about to open at quadrant III to II (leaving water surface). The blade was designed referring to aerator based on Taiwan design.

3.1. Structural design

The wheel structure consisted of two main components i.e. stationary and rotary component as shown in Figure 3.

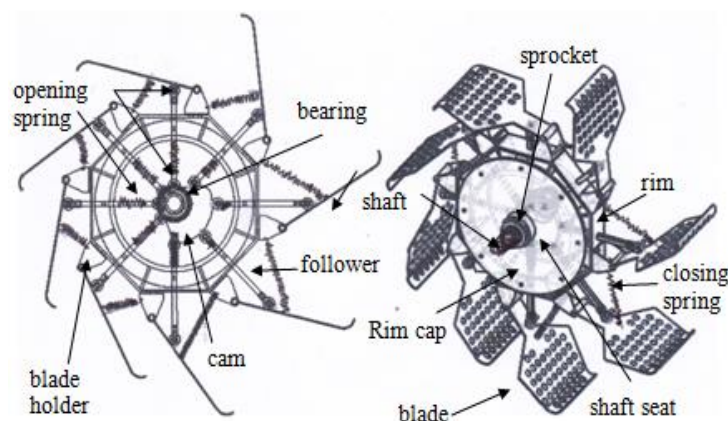


Figure 3. Wheel structure with movable blade

Stationary component consisted of cam and shaft. The longest and shortest radius of cam were 680 mm and 17.5 mm, respectively. Cam was mounted to shaft with diameter of 25 mm and attached to machine frame.

Rotary component consisted of the rim, rim cap, blade holder, follower, bearing and spring. The rim was octagonal-shape encircling tube with diameter of 218 mm and height of 30 mm. One side of the tube was enclosed with metal sheet, shaft seat and bearing with diameter of 25 mm. Outside the shaft seat,

sprocket that engage onto chain was attached for transmission purpose. The rim cap was a shaft seat made from metal sheet and similar bearing with rim tube which mounted to rim tube using bolt. Blade was used to directly bursting up water. Blades formed 30° of angle towards rim with radius of curvature was 40 cm. The size of the blade was 15 cm of width, 20 cm of length, trapezoid-shape with 15° of bottom side and 30° of top side, had 40 holes with diameter of 1.6 cm.

Blade holder was used to place blade with shaft of 8 mm and height of 25 mm and bolted at the end side of rim. The follower stem was used to push blade to open and close adjusting to cam profile. The follower stem was 150 mm of height and bearing with 19 mm of external diameter was attached on the two end-sides. Spring consisted of opening blade and closing blade. The opening spring was inserted to follower stem with diameter of the spring was 10.5 mm, length was 60 mm, wire diameter was 1 mm and spring constant was 0.35 Nm. The closing spring of blade was attached on the front blade holder with diameter of 10 mm, length of 45 mm, wire diameter of 1 mm and spring constant of 0.5 Nm.

3.2. Movable component mechanism

3.2.1. Motion mechanism. Movable blade were driven using cam mechanism. The cam is a simply mechanism that can provide almost all types of follower movement. The movement analysis of cam mechanism is shown in Figure 4.

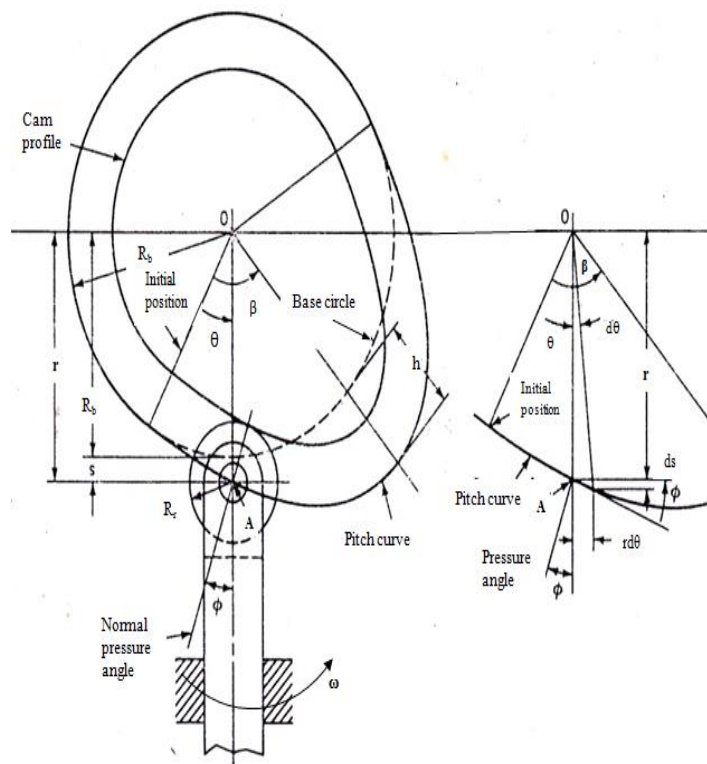


Figure 4. Profile analysis of cam-follower

Diagram of displacement, velocity and acceleration of cam is important factors in determining cam design [9]. Equation of cam displacement is written as follows:

$$\text{for } \frac{\theta}{\beta} \leq 0.5 \quad s = 2h \frac{\theta^2}{\beta^2}$$

$$\text{for } \frac{\theta}{\beta} \geq 0.5 \quad s = h \left[1 - 2 \left(1 - \frac{\theta}{\beta} \right)^2 \right] \quad (1)$$

Equation of cam velocity is written as follows:

$$\begin{aligned} \text{for } \frac{\theta}{\beta} \leq 0.5 \quad \frac{ds}{dt} &= \frac{4h\omega\theta}{\beta^2} \\ \text{for } \frac{\theta}{\beta} \geq 0.5 \quad \frac{ds}{dt} &= \frac{4h\omega}{\beta} \left(1 - \frac{\theta}{\beta} \right) \end{aligned} \quad (2)$$

Equation of cam acceleration is written as follows:

$$\begin{aligned} \text{for } \frac{\theta}{\beta} \leq 0.5 \quad \frac{d^2s}{dt^2} &= \frac{4h\omega^2}{\beta^2} \\ \text{for } \frac{\theta}{\beta} \geq 0.5 \quad \frac{d^2s}{dt^2} &= -\frac{4h\omega^2}{\beta^2} \end{aligned} \quad (3)$$

The maximum displacement of follower for one rotation 50 mm with angle of rotation 125° is shown in Figure 5.

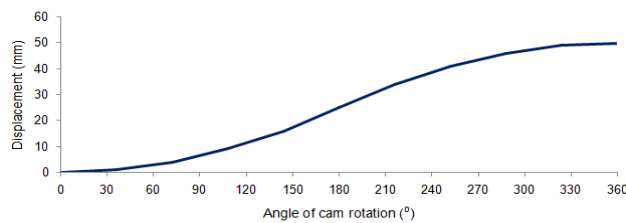


Figure 5. Displacement of follower

The maximum velocity of follower was 45.84 m/s as shown in Figure 6.

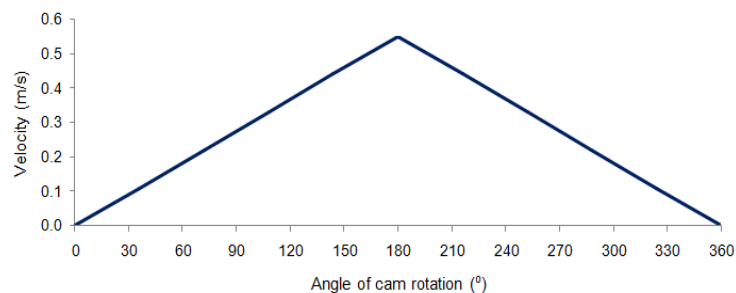


Figure 6. Velocity of follower

The constant acceleration was 6.09 m/s^2 as shown in Figure 7.

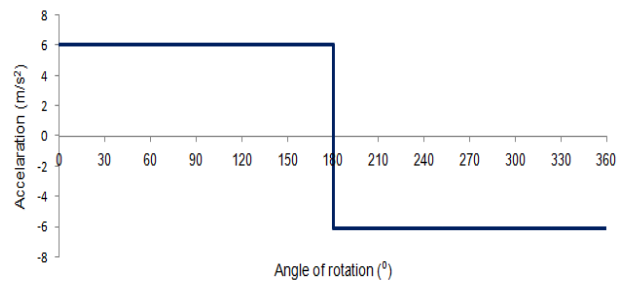


Figure 7. Acceleration of follower

3.2.2. Angle of pressure. Angle of pressure determines the smoothness of cam movement. The analysis of angle of pressure was illustrated in Figure 3. Angle of pressure (ϕ) for every angular position was equated as follows:

$$r = R_b + s \quad \tan \phi = \frac{ds}{r d\theta} \quad (4)$$

The magnitude of pressure angle for every angle of rotation is shown in Table 1.

Table 1. Pressure angle of follower

θ (deg)	$r=R_b+s$	$\tan\theta=ds/r(d\theta)$	$ds/d\theta$	ϕ (deg)
0	27	0.00	0.00	0.00
36	28	9.17	0.33	18.13
72	31	18.33	0.59	30.60
108	36	27.50	0.76	37.38
144	43	36.67	0.85	40.46
180	52	45.84	0.88	41.40
180	52	45.84	0.88	41.40
216	61	36.67	0.60	31.01
252	68	27.50	0.40	22.02
288	73	18.33	0.25	14.10
324	76	9.17	0.12	6.88
360	77	0.00	0.00	0.00

The largest angle of pressure between cam and follower was 41.40° . This magnitude was too large and not necessary for cam-follower mechanism as it required high force and caused mechanism failure that led to machine damage.

3.2.3. Spring mechanism. Each blade had two types of spring i.e. blade-closing spring and blade-opening spring. Blade-closing spring (s_1) worked against drag force (F_d) and gravity of the blade (w), while blade-opening spring (s_2) worked against force of blade-closing spring from cam pressure due to wheel rotation. Analysis of spring force is shown in Figure 8.

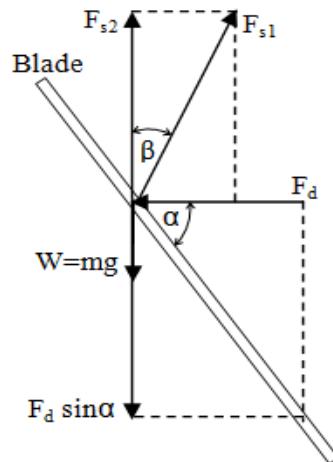


Figure 8. Spring force analysis

Based on the calculation, some of spring data were collected, including installed length, operating length, operating force, springs material, wire diameter, average diameter, inside diameter, outside diameter, free length, number of coils and allowable shear stress for blade-opening springs. The magnitude was 75 mm, 25 mm, 2.45 N, 49.05 N, chromium-vanadium A231, 2 mm, 2 mm, 10.5 mm, 14.5 mm, 80 mm, 12 coils and 922.74 MPa, respectively. The magnitude for blade-closing spring was 124 mm, 38 mm, 2.45 N, 264.50 N, chromium-vanadium A231, 2 mm, 2 mm, 8 mm, 125 mm, 130 mm, 20 coils and 815.75 MPa, respectively.

3.2.4. Inertia and torque. Inertia and torque analysis are shown in Figure 9. The influencing parameters consisted of force acting on follower (P), inertia force of follower (f), force of gravity on follower (W), shear stress acting on follower (F), normal force on rim towards follower (F_1, F_2), normal force of cam toward follower (N), follower overhang (a), distance between bearing surface (b), diameter of follower stem (d), pressure angle (ϕ) and friction coefficient between follower (μ).

$$F = P + f + W + F_s \quad (5)$$

Total vertical force was:

$$N \cos \phi = F + \mu (F_1 + F_2)_s \quad (6)$$

Total horizontal force was:

$$F_1 = F_2 + N \sin \phi_s \quad (7)$$

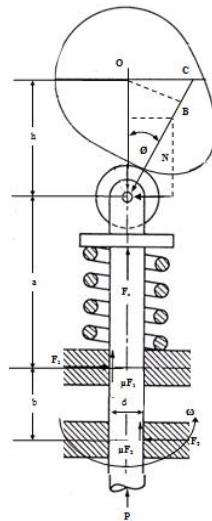


Figure 9. Free body diagram for analysis of angle of pressure

Summing moments to a point where F_1 works, gave:

$$F_2(b - \mu d) = N_a \sin \phi + \frac{d}{2}(F - N \cos \phi) \quad (8)$$

By neglecting F_1 and F_2 at the last 3 equations, normal force of cam acting on follower was:

$$N = \frac{F_b}{b \cos \phi - (2\mu a + b\mu - \mu^2 d) \sin \phi} \quad (9)$$

Torque required to rotate paddle wheel was calculated as follow:

$$T = N(OB) \quad (10)$$

The results of normal force, vertical force and horizontal force are shown in Table 2. The maximum torque required to activate blade mechanism was 80.09 N·m.

Table 2. Normal force cam-follower

θ (deg)	$2\pi\theta/\beta$ (deg)	ϕ (deg)	N (N)
0	0	0	239.64
12.5	36	18.13	-380.96
25	72	30.60	-146.87
37.5	108	37.38	-120.09
50	144	40.46	-122.97
62.5	180	41.40	-144.87
62.5	180	41.40	-144.87
75	216	31.01	-324.70
87.5	252	22.02	-3141.54
100	288	14.10	612.74
112.5	324	6.88	328.35
125	360	0	239.64

3.3. Torque and power consumption

Testing without a load at 115 rpm showed the torque that occurred 43.05 N·m and the electric power used 511.72 Watt. Torque occurring reduction compared with calculation results due to modification follower. Follower rod are to be bent to minimize the contact angle that happened. That torque still high and not proportional to torque reduction of simulation result effect of using moveable blade 31.51% (Bahri *et al.* 2015). Thus, the electric power consumption was still high compared with Taiwan model paddlewheel aerator was 451 Watt. However, the results showed that the friction force still high occurred between the cam and the follower that are caused by a cam profile which must follow the functional design of the paddlewheel aerator.

4. Conclusions

The blade of aerator is able to open when entering water and close when leaving water. Structure of the wheel consisted of two main components i.e. stationary and rotary component. Stationary component consisted of cam and shaft. Rotary component consisted of a rim, a rim cap, blade holders, followers, bearings and springs. The follower was able to rotate with angle of rotation was 125°, rotational displacement was 50 mm, maximum velocity was 0.55 m/s and acceleration was 6.09 m/s². The follower had constant acceleration. Testing without a load at 115 rpm shows the torque that occurred 43.05 N·m and the electric power used 511.72 Watt. These test results showed the friction force still high occurred between the cam and the follower that are caused by a cam profile which must follow the functional design of the paddlewheel aerator. It is suggested that to overcome the friction by increasing the dimension of mechanism construction and reduce the angle contact between cam and follower.

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