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The Fundamental Study to Reduce The Settled Area of The Fish Aggregation Devices on The Sea Floor Thrown from A Ship

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ABSTRACT

This study aims at clarifying the effective method to set up the fish aggregation device (FAD) thrown down from a ship on the designed position most accurately. The numerical simulation technique is developed to analyzed the behavior of the settling FAD in consideration of the effect of vortices generated behind it. From the systematic calculations for the change of the initial condition on the posture of the FAD at throwing, the effective initial posture of the FAD which reduces the settled area on the sea floor most is investigated. Furthermore, the added-mass coefficient of the settling FAD is numerically analyzed from the kinetic energy of the fluid induced by the settling FAD. The FAD treated in this study is the structure to gather fishes.

1. INTRODUCTION

The fish aggregation device is usually placed on the sea floor of a depth from about 30m to 100m to gather fishes. The most common shape of the FAD is the cubic type of 2mx2mx2m with a hollow inside and a gap in individual surfaces as shown Fig.1. Although the reason why and how the FAD can gather fishes has not been enough clarified yet, vortices formed at the FAD and their shedding behind the FAD have been pointed out to be the major reason to gather fishes around it. The FAD supplies for fishes not only a hiding place but also nourishing materials which are flung up from the sea bed by the vortex induced. The multi-FAD system in which the FADs are arrayed with a constant interval along a dominant flow in planned sea area has been adopted to activate the mentioned properties of the FAD. The multi-FAD system is mainly constructed by throwing them down from a ship to lay out on the fishing ground. It is difficult to set up the FAD in the fluid is consisted by following three complex motions (i.e. an oscillatory motion in horizontal direction, a rotational motion and vertical

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Fig.1 Illustration of fish aggregation device

drop). As a result of the position errors induced in the set up, the work of the system on gathering fishes may not be demonstrated sufficiently. Hence, to make it clear the settling behaviors of the FAD becomes urgent to carry out their accurate settling on the designed position.

On the other hand, from the strength point of view, the impulsive force exerted on the FAD at landing on the sea bottom must be evaluated accurately. The impulsive force F is given by

$$\int_{\Delta t} F dt = (M + C_{MA}M') v_0(1+e)$$
(1)

where M and M' are the mass of the FAD and the liquid displaced by FAD respectively, C_{MA} is the coefficient of the added-mass coefficient, v_0 is the speed of the settling FAD at immediate time before landing, e indicates the repulsion factor between the FAD and the sea bottom. In general, the added-mass coefficient of the settling body is affected by the distance between the body and the bottom. Therefore, in order to evaluate the stability of the FAD against the impulsive force at landing efficiently, the affection of the sea bottom on the added-mass coefficient should be taken into account when we determine the design impulsive force on the FAD.

This study aims to clarify the following points; (1) the numerical simulation technique to analyze the behaviors of the settling FAD considering the effect of vortices generated behind it, (2) the initial condition of posture of the FAD at throwing to set up the FAD thrown down from a ship on the designed position most accurately, (3) the change of the added-mass coefficient of the settling FAD.

2. NUMERICAL SIMULATION TECHNIQUE OF THE SETTLING FAD

The oscillatory motion of the settling FAD in a periodic wave is induced by the instantaneous fluctuations of the pressure distribution around it, which is induced by the vortices generated from it and the wave motion. Hence, in the present numerical simulation technique, the fluid resistance exerted on the settling FAD is estimated firstly by integrating the pressure distribution around its surface. This surrounding pressure distribution is numerically analyzed with both the discrete vortex approximation method (see Sarpkaya 1968, Clements 1973) for the simulation of the vortex formation behind the FAD and the source-sink points method (see Chakrabarti 1987) for the formulation of the boundary condition on the surface of it. Secondly, the oscillatory motion of the settling FAD at every moment is numerically calculated from the equation of horizontal, vertical and rotational motion for the settling FAD.

2-1 DESCRIPTION OF THE FLUID FIELD AROUND THE SETTLING FAD

In the case of two-dimensional wave field as shown in Fig.2, applying the small amplitude wave theory to the incident wave, the free surface in the wave field can be approximately replaced by the fixed rigid surface. Then, the appropriate complex velocity potential for the flow around the settling FAD can be determined by using the Schwartz-Christoffel transformation to project the interior region



Fig.2 Schematic figure of flow field around the settling FAD



Fig.3 (a) physical plane z ; (b) transformed plane λ

between the boundaries in the z-plane into an upper half of the λ -plane with the boundary along the real axis (see Fig.3). The λ -plane is transformed into the physical z-plane by the function

$$z = x + iy = K \log(-\lambda) + C$$
⁽²⁾

where K is the constant determined by the water depth, and C is a integral constant. Since λ =-1 at z=0 and λ =1 at z=-ih in which i= $\sqrt{-1}$ and h is the water depth, Eq.(2) is rearranged in term of z as,

$$\lambda = -\exp(C_{\Omega}z) \qquad (C_{\Omega} = \pi/h) \tag{3}$$

The complex velocity potential $(\omega_{V\lambda k})$ of the discrete vortex (λ_k) in λ -plane (see Fig.3) is given by the following equation in terms of the imaginary discrete vortex which is necessary to maintain the boundary condition of zero flow across the real axis in λ -plane.

$$\omega_{V\lambda k} = \frac{i\Gamma_k}{2\pi} \left[\log(\lambda - \lambda_k) - \log(\lambda - \overline{\lambda_k}) \right]$$
(4)

where Γ_k and λ_k are the circulation and the complex coordinate of the vortex respectively, the circulation is defined as positive being clockwise, and the over bar denotes the complex conjugate. Substituting Eq.(3) into Eq.(4), the complex velocity potential (ω_{Vzk}) in z-plane is introduced as

$$\omega_{Vzk} = \frac{i\Gamma_k}{2\pi} \left[\log(e^{C_0 z_k} - e^{C_0 z}) - \log(e^{C_0 \overline{z}_k} - e^{C_0 z}) \right]$$
(5)

where z_k is the complex coordinate of the vortex in z-plane. With the same way that used for the discrete vortex (Eq.(5)), the complex velocity potential (ω_{Rzc}) of the source point in z-plane is given by

$$\omega_{Rzk} = \frac{D(z_c)}{2\pi} [\log(e^{C_0 z_c} - e^{C_0 z}) + \log(e^{C_0 \overline{z_c}} - e^{C_0 z})]$$
(6)

where z_c and $D(z_c)$ are a location and a strength of the source point respectively.

When the flow around the settling FAD in z-plane consists of a periodic wave, N discrete vortices with some circulations generated from P separation points and the flow from the source points on the FAD surface, the complex velocity potential ω_z at the point z in z-plane is given by

$$\omega_z = \phi_z + i\psi_z = \omega_W + \omega_V + \omega_R \tag{7}$$

where ϕ_z and ψ_z are the velocity potential and the stream function for the total flow in the z-plane respectively, ω_W , ω_V and ω_R are the complex velocity potential of the incident wave, the discrete vortices and the source points, these are derived as follows with Eq.(5) and Eq.(6).

$$\begin{split} & \omega_{W} = \frac{\sigma H}{2k \sinh kh} \sin[k(ih+z) - \sigma t] \\ & \omega_{V} = \frac{i}{2\pi} \sum_{j=1}^{P} \sum_{k=1}^{N} \Gamma_{jk} [\log(e^{C_{0}z}jk - e^{C_{0}z}) - \log(e^{C_{0}\overline{z}}jk - e^{C_{0}z})] \quad (9) \\ & \omega_{R} = \frac{1}{2\pi} \oint_{C} D(z_{c}) [\log(e^{C_{0}z_{c}} - e^{C_{0}z}) + \log(e^{C_{0}\overline{z}}c - e^{C_{0}z})] dc \quad (10) \end{split}$$

Here H, σ and k are a wave height, angular frequency and wave number respectively, \oint_C represents the contour integral along the surface c of the settling FAD. In the numerical calculation of Eq.(10), the surface c of the FAD is divided into M sections of length ΔC_m (m = 1 \sim M) and the source point is set on the center of the each section. Then the corner of the FAD is approximated with a circular arc of a radius 0.02a, in which a is the side length of the FAD. The integration in Eq.(10) is evaluated as

$$\omega_{\mathrm{R}} = \frac{1}{2\pi} \sum_{m=1}^{\mathrm{M}} \mathbb{D}(z_{\mathrm{m}}) [\log(\mathrm{e}^{\mathrm{C}_{0} z_{\mathrm{m}}} - \mathrm{e}^{\mathrm{C}_{0} z}) + \log(\mathrm{e}^{\mathrm{C}_{0} \overline{z}_{\mathrm{m}}} - \mathrm{e}^{\mathrm{C}_{0} z})] \Delta \mathrm{m} \quad (11)$$

The strength of the individual source point in Eq.(11) is determined by the boundary condition on the FAD surface (i.e. the fluid velocity normal to the FAD surface is equal to the settling velocity normal to the FAD surface). When the FAD is settling with speed (u_C, v_C) and with an angular velocity ω_r as shown in Fig.4, the identical equation of the strength $D(z_m)$ of the source point becomes as

$$\mathbf{R}\left[\frac{\partial \omega_{W}}{\partial n}\right] + \mathbf{R}\left[\frac{\partial \omega_{V}}{\partial n}\right] + \mathbf{R}\left[\frac{\partial \omega_{R}}{\partial n}\right] = (\mathbf{u}_{C} + \mathbf{u}_{r})\mathbf{n}_{x} + (\mathbf{v}_{G} + \mathbf{v}_{r})\mathbf{n}_{y} \quad (12)$$
(on the surface of the FAD)



Fig.4 Fluid resistance on the settling FAD

where $\partial/\partial n$ denotes the derivative taken normal to the surface of the FAD, n_x and n_y are the x and y components of the unit vector taken outward normal to the FAD surface respectively, u_r and v_r are the x, y components of the velocity induced by the FAD rotation with angular velocity ω_r , R[] denotes the real part.

 w_r , K[] denotes the real part. In Eq.(9), the velocities of the vortices are decided from the kinematic condition for the discrete vortices (i.e. a marked vortex is affected only from the incident wave, the other vortices and the source points on the FAD surface). Therefore, the velocity components u_{jk} , v_{jk} of the j-th vortex generated from the k-th separation point are expressed as

$$u_{jk} - iv_{jk} = \frac{d}{dz} [\omega_z - \frac{i\Gamma_{jk}}{2\pi} log(e^{C_0 z_{jk}} - e^{C_0 z})] \Big|_{z=z_{jk}}$$
 (13)

If there are PN pieces of discrete vortices simultaneously around the settling FAD, a set of PN ordinary differential equations are derived as equations of the kinematic conditions for the discrete vortices.



Fig.5 Initial positions of nascent vortices

In Eq.(13), the unknown initial position of the nascent vortex and the circulation of the vortices are included. There have been no established method, however, to calculate the initial position of a nascent vortex, its position has been determined with (A) the Kutta condition at the edge of the body or (B) the boundary layer thickness. In this study, (B) is adopted, and the initial positions are located at the distance of δ (boundary layer thickness which is determined by $\delta = \sqrt{T/\pi}$ in which ν is the kinematic viscosity coefficient and T is the period of the wave) from the edges of the settling FAD as shown in Fig.5. Each initial position between the angle of the FAD and the settling direction. The three separation patterns are treated in this study as shown in Fig.5. Secondly, the circulation of the nascent vortex is calculated with the Roshko's approximate equation (Roshko 1954). Taking the direction of the nascent vortex is given by

$$\partial \Gamma / \partial t = U_{c} |U_{c}| / 2$$

where U_s is a fluid velocity at the initial position of the nascent vortex. Although some vortices induce large velocities when they approach each other because we neglect the viscosity, this phenomenon is avoided by replacing the distributed discrete vortices with the Rankine vortex. The core radius of the Rankine vortex is given by $|\Gamma_{jk}|/2\pi U_s$ (Stansby 1977) in this study.

2-2 FLUID RESISTANCE ON THE SETTLING FAD

The fluid resistance exerted on the settling FAD can be obtained by integrating the pressure distributions around it, which is given in terms of $\partial \phi_z / \partial t$, u and v on the FAD surface $(z=z_n)$ as

$$P(z_p) = -\rho \left[\left. \frac{\partial \phi_z}{\partial t} + \frac{1}{2} (u^2 + v^2) \right] \right|_{z=z_p}$$
(15)

where ρ is the fluid density. Since the position z_{jk} of the discrete vortices, the strength $D(z_m)$ and the location z_m of the source points; and the position z_p on the FAD surface are functions of time, the first term of Eq.(15) is given by

$$\frac{\partial \Phi_{z}}{\partial t}\Big|_{z=z_{p}} = \left[\mathbf{R} \left[\frac{\partial \omega_{W}}{\partial t} \right] + \mathbf{R} \left[\frac{\partial \omega_{W}}{\partial z} \frac{dz}{dt} \right] + \mathbf{R} \left[\frac{\partial \omega_{V}}{\partial z_{jk}} \frac{dz_{jk}}{dt} \right] + \mathbf{R} \left[\frac{\partial \omega_{V}}{\partial z_{jk}} \frac{dz_{jk}}{dt} \right] \right] + \mathbf{R} \left[\frac{\partial \omega_{R}}{\partial z_{m}} \frac{dz_{m}}{dt} \right] \right] \right|_{z=z_{p}}$$

In Eq.(16), dD/dt can be calculated by differentiating Eq.(12) with respect to time t, the differentiated equation is analyzed in the same manner as the above-mentioned method for the strength of the source point. The horizontal and the vertical fluid resistance F_x , F_y exerted on the settling FAD are given as follows lastly

$$F_{x} = -\sum_{p=1}^{M} P(z_{p}) n_{xp} \Delta C_{p} , \quad F_{y} = -\sum_{p=1}^{M} P(z_{p}) n_{yp} \Delta C_{p}$$
(17)

2-3 THE EQUATIONS OF MOTION OF THE SETTLING FAD

Referring to Fig.4, the equations of horizontal, vertical and rotational motion for the settling FAD are give as

$$M_{a} \frac{du_{G}}{dt} = \sum_{i=1}^{4} F_{xi} , \quad M_{a} \frac{dv_{G}}{dt} = \sum_{i=1}^{4} F_{yi} - (M_{a} - M_{w})g$$

$$I_{r} \frac{d\omega_{r}}{dt} = \sum_{i=1}^{4} (x_{i}'F_{yi} - y_{i}'F_{xi})$$
(18)

(14)

where $\rm M_{a}$ is a mass of the FAD per unit thickness, $\rm M_{w}$ is the liquid (per unit thickness) displaced by the FAD, g is the gravity acceleration, and $\rm I_{r}$ is an inertia moment of the FAD around the gravitational center axis of the FAD. x₁' and y₁' are the distance from the center of the FAD cross section to the center of an i-th piece in the x and y direction as illustrated in Fig.4.

3. APPLICATION OF THE NUMERICAL SIMULATION TECHNIQUE

rotational motion of the settling FAD.

The application of the numerical simulation technique for the settling behavior of the FAD was investigated by comparing the calculated and experimented results. The experiments were carried out by using the wave tank of 30m long, 60cm wide and 1m depth to observe the behaviors of the settling FAD. The FAD model used in the experiments was consisted of four pieces of slender rectangular (lcmxlcm in the cross section) bodies. This study restricted the FAD motion on the vertical plane. Therefore, to prevent the FAD from 3-dimensional motion, a long model which had the same cross section was used in the experiments. Size of the model section is 3cmx3cm, length is 56cm, the void ration per unit thickness is 55.6%. The photographs of the settling figures of the FAD model were taken on a same film by using a strobe flash, the interval time of the flash is 0.2s. 2-dimensional motion is strictly inspected through the experiments. Since the behaviors of the settling FAD model were very irregular in the experiments, it was difficult to compare the simulated FAD behaviors with the measured behaviors. Therefore, we compared the simulated and measured horizontal fluctuation of FAD and the angular velocity of the



Fig.6 Definition of the fluctuation of the settling FAD



Fig.7 Measured and calculated oscillatory motion of the settling FAD

Fig.6 shows the definitions of the fluctuation of the settling FAD, $D_{\rm x}$ and $D_{\rm y}$ are the horizontal fluctuation and the settling distance from the simulated position. The angular velocity $\omega_{\rm r}$ is defined as positive being anticlockwise. When $\omega_{\rm r}$ is positive, since the FAD moves in the positive direction of horizontal axis in Fig.6, the relative horizontal fluctuation to the settling distance $D_{\rm x}/D_{\rm y}$ becomes positive.

Fig.7 shows examples of the experimented and calculated oscillatory motions of the settling FAD, x/a and y/a are the normalized x, y positions of the center of the FAD cross-section at each measured and calculated position. From the experiment (Fig.7(A)), the dominant behaviors of the settling FAD are the fluctuation in the horizontal direction which corresponds to a change in the rotational direction and the time lag between the inflection points of D_x/D_y and ω_r . This time lag may come from the change in the direction of the horizontal fluctuation which can not instantly correspond to the change in the rotational direction, because a motion of the settling FAD is the inertia motion. On the other hand, in the calculated results (Fig.7(B)), the present simulation technique can simulate also the dominant settling behaviors which are recognized in the experiments, i.e., the fluctuation. From these investigations, we may conclude that the settling behavior of the FAD can be evaluated with this numerical simulation technique.

4. RELATION BETWEEN INITIAL ANGLE OF FAD AT THROWING AND SETTLING BEHAVIOR

To investigate the effective initial posture of the FAD at throwing to reduce the settled area on the sea floor most, the systematic calculations for the change of the initial angle from the still water surface at throwing were carried out by using the present simulation technique. Fig.8 shows the calculated behaviors of the settling FAD for

Fig.8 shows the calculated behaviors of the settling FAD for three kinds of the initial angles, $\theta_0=0^\circ$, 22.5°, 45°. In these cases, wave period of T=1s is applied. From the settling figures, it is found that the fluctuation of the settling FAD in the horizontal direction has close relation to the initial angle of the FAD at throwing. Therefore, the initial angle is the important factor to dominate the scatter range of the landing FAD on the sea floor. In Fig.8(A) and (B), the ω_r takes the positive value for the major part of water depth, D_x/D_y also takes the positive values. From these results, it can be seen that the FAD settles in the positive direction of the horizontal axis. When θ_0 is 45°, the period of the change in the rotational direction is shortest among these three cases, and the horizontal fluctuation becomes very small. This situation for the settling FAD becomes the most stable, i.e., less oscillation may take place. From this result, it may be estimated that this situation reduces the settled area on the sea floor most. Furthermore, Fig.9 shows the calculated behaviors of the settling FAD in the case of T=1.5s. When θ_0 is 45° (Fig.9(C)), the period of the change in ω_r becomes the shortest, and the most stable situation for the settling



Fig.8 $\rm D_X/D_y,~\omega_r$ and behaviors the settling FAD with respect to the initial angle $\rm \theta_0$ (T=1s)



Fig.9 $D_{\rm x}/D_{\rm y},~\omega_{\rm r}$ and behaviors the settling FAD with respect to the initial angle θ_0 (T=1.5s)

FAD can be observed again. From these investigations, it can be concluded that the initial posture of the FAD at throwing with the angle of 45° from the still water surface reduces the settled area on the sea floor most.

5. ADDED-MASS COEFFICIENT OF THE SETTLING FAD

The added-mass coefficient of the settling FAD is evaluated from the kinetic energy of the fluid induced by the settling FAD (see Milne-Thomson 1968). The kinetic energy T_w of the flow induced by the settling FAD is given by

$$T_{w} = -\frac{1}{2} \rho \oint_{C} \phi \frac{\partial \phi}{\partial n} dc \qquad (19)$$

where Φ is the velocity potential. If V is the volume (per unit thickness) of the FAD, the kinetic energy E_w of the fluid replaced by the settling FAD is

$$E_{w} = \frac{1}{2} C_{MA} \rho V v_{0}^{2}$$
 (20)

Since the added-mass $C_{MA}V$ is defined as the mass such that the kinetic energy E_w becomes equivalent to the kinetic energy T_w , the added-mass coefficient C_{MA} becomes from Eq.(19) and Eq.(20) as

$$C_{MA} = -\oint_{C} \phi \frac{\partial \phi}{\partial \pi} dc / (Vv_0^2)$$
(21)

In the numerical calculation technique of the added-mass coefficient, the source-sink points method is adopted for the formulation of the boundary condition on the surface of the settling FAD. The velocity potential of flow around the settling FAD is given by

$$\Phi = \mathbf{R} \left[\frac{1}{2\pi} \oint_{C} \mathbb{D}(z_{c}) \left[\log(e^{C_{0} z_{c}} - e^{C_{0} z}) + \log(e^{C_{0} \overline{z}_{c}} - e^{C_{0} z}) \right] dc \right]$$
(22)

The second term of Eq.(22) is the imaginary part which is necessary to maintain the bottom boundary condition of zero flow across the sea floor. The calculations are carried out for the settling FAD in a still water, the horizontal and the rotational motion for the settling FAD are neglected for simplicity.

Fig.10 shows the change of the added-mass coefficient of the settling FAD with respect to the relative distance h_q/a from the sea bottom. When $h_q/a>4$, C_{MA} is less affected by h_q/a . When $h_q/a<4$, however, C_{MA} is affected by the "bottom" effect, and in the region of $h_q/a<1$ the shorter the relative distance becomes, C_{MA} starts to increase very quickly in spite of the void ratio of the FAD. Furthermore, from Table-1 which shows the C_{MA} at landing on the sea bottom $(h_q/a=0.5)$ and that in the infinite fluid field $(h_q/a=\infty)$, it



Fig.10 Change of the added-mass coefficient of the FAD with settling

Table-1 $\ \mbox{C}_{\mbox{MA}}$ at landing and $\mbox{C}_{\mbox{MA}}$ in the infinite field

	γ	(%)	0	30.5	55.5	75.0	88,9
CMA	at	hq∕a≃ ∞	1.19	1,15	1.18	1.22	1,24
CMA	at	hq/a=0.5	2.74	2.08	1.84	1.82	1,78



Fig.11 Relation between C_{MA} and the posture of the FAD at landing on the sea bottom

can be found that $\rm C_{MA}$ at landing on the sea bottom reaches about 1.4 to 2.3 times of that in the infinite fluid field. Fig.11 shows the relation between the C_{MA} and the posture of rig.11 shows the relation between the $\rm C_{MA}$ and the posture of the FAD at landing on the sea bottom, $\theta_{\rm f}$ is the angle between the FAD surface and the bottom, $\rm C_{MA}$ is the value at landing on the sea bottom. From this figure, it is seen that the added-mass coefficient of the settling FAD is affected by $\theta_{\rm f}$ and $\rm C_{MA}$ in the case of $\theta_{\rm f}{=}0^\circ$ becomes the largest among these five angles.

6. CONCLUSION

Concluding remarks are as follows.

(1) The present simulation technique for the settling behaviors of the FAD can successfully simulate the dominant behaviors of the settling FAD in the experiments (i.e. the fluctuation of the settling FAD in the horizontal direction corresponding to the change of its rotational direction, the time lag between the inflection points in the relative horizontal fluctuation to the settling distance and those in the angular velocity in the rotational motion).

(2) The fluctuations of the settling FAD in the horizontal direction are closely related to the initial angle of the FAD at throwing. The most stable situation for the settling FAD is achieved when the initial posture of the FAD is thrown with the angle of 45° from the still water surface. This situation may reduce the settled area on the sea floor most.

(3) The added-mass coefficient of the settling FAD may be evaluated through the calculation of the kinetic energy of the flow around the settling FAD using the potential theory with a sufficient accuracy. The added-mass coefficient at landing on the sea bottom reaches about 1.4 to 2.3 times of that in the infinite field. When the settling FAD lands on the sea bottom with zero angle, the added-mass coefficient becomes the largest.

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