Dolphin Kick Swimmer using the Unstructured Moving Mesh Method

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Abstract. The dolphin kick assumes a vital role in swimming competitions, as it is used after dives and turns in several swimming styles. To improve the swimmer's dolphin kick performance, flows around him were simulated. Using video footage of a male swimmer's joint angles, a 3D model simulation was created. The flows were computed using the unstructured moving grid finite volume method to express the complicated motion of swimmers. The mesh around the swimmer is moved according to his motion. In this method, a geometric conservation law is satisfied as well as a physical one. Furthermore, the moving computational domain method is also adopted for calculation efficiency. The numerical swimmer is finally completed by a coupled computation between motion of human and fluid. In this paper, the simulation results revealed that the influence of the maximum knee oscillation angles affect the speed of the swimmer.

Keywords: Computational fluid dynamics, Unstructured moving mesh, Dolphin kick swimming.

1 Introduction

The dolphin kick is the swimming style that a swimmer creates wave by wiggling its body like a dolphin in order to propel. As the feature, both arms are fixed on top of its head, and both legs are also drawn up. The surge of its body goes on increasing from fingertip to toe. The style assumes a vital role in swimming competition, because it is adopted after dives and turns in several swimming style. Thus, to clarify the detail mechanism of its movement and to improve are very important.

Against such a background, the measurement of the drag of a swimmer who is pulled under the water with stretching posture was reported [1]. Then, the drag of a swimmer having arm stroke at the crawl swimming style was measured using the MAD system [2] and using the dynamics analysis [3]. However, it would be difficult to produce their detail environment because the experimental apparatus and the measurement method themselves would restrict the movement of a swimmer. The visualization for flows around swimmer were also reported using the approach filming artificial bubbles [4] and using tuft put on skin of a swimmer [5]. But their approaches would affect to its performance of a swimmer. Furthermore, it would be difficult to catch detail phenomena like small vortices around it. While the visualizations for wake of the dolphin kick

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using PIV were reported [6]. By using PIV, that a couple of vortices around hands generated by arm stroke at the crawl influence the generation of unsteady fluid force were shown [7]. But it was restricted in the two-dimensional measurement.

On the other hand, a lot of results using computational simulation instead of experimentations were reported. The propulsion of the dolphin kick swimmer were estimated [8] using the swimmer model:SWUM [9]. Using the same model, an influence to propulsive speed and efficiency by waviness of swimmer's body was shown [10]. Although this model can capture a tendency of the influence, the human body shape is simplified. Furthermore, the fluid dynamics itself is not calculated in the paper. Therefore, it would be difficult to know a detail force from fluid to human body. While, 3-D computational simulation was carried out for a flow around hand and arm [11], and then it was expended to a flow around a whole body [12]. Comparing the depth of a body from water surface and drag of a swimmer with force during glide swim, the influence of a flow condition around the swimmer by the depth from the surface was reported [13]. The detail human shape and the detail motion of swimming were modeled using 3-D scanner and Autodesk MAYA, then the flow around the model with dolphin kick was calculated using the immersed boundary method [14]. The results showed that the ring vortex created by a motion of kicking lower affects the majority of the propulsion caused by dolphin kick. However, these computations were estimated in constant speed flows only. Since the swimming speed of dolphin kick changes dynamically, it is important to take acceleration and deceleration into consideration to know the detail of the flow mechanism around a swimmer. The flow around a swimmer accelerated and decelerated by fluid force was calculated using the smoothed particle hydrodynamics. The computation [15] showed that an increase of the frequency of dolphin kick cycle boosts the propulsion speed linearly. However, the motion of the human model has not been verified, thus there is doubt about the validity of the result.

In this study, the swimmer shaped model was generated by unstructured mesh. Then, the flows were computed using the unstructured moving grid finite volume method [16, 17] to express the complicated motion of swimmers. This method satisfies both geometric and physical conservation laws using four dimensional space-time unified control volume. Furthermore, the moving computational domain method [18, 19] was adopted to express acceleration and deceleration of the swimmer. The position of the swimmer is decided by a coupled computation between motion of human and fluid. The objective of this paper is to specify the mechanism the flow around the dolphin kick swimmer and to investigate influence which the maximum knee oscillation angles affect the speed of the swimmer.

2 Numerical Approach

2.1 Governing Equations

Governing equations are the continuity equation and the incompressible Navier–Stokes equations. These are written as follows:

$$\nabla \cdot \mathbf{q} = 0, \tag{1}$$

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{E}_a}{\partial x} + \frac{\partial \mathbf{F}_a}{\partial y} + \frac{\partial \mathbf{G}_a}{\partial z} = -\left(\frac{\partial \mathbf{E}_p}{\partial x} + \frac{\partial \mathbf{F}_p}{\partial y} + \frac{\partial \mathbf{G}_p}{\partial z}\right) + \frac{1}{\mathrm{Re}}\left(\frac{\partial \mathbf{E}_v}{\partial x} + \frac{\partial \mathbf{F}_v}{\partial y} + \frac{\partial \mathbf{G}_v}{\partial z}\right), \tag{2}$$

where $\boldsymbol{q}$ is the velocity vector, $\boldsymbol{E}_a$, $\boldsymbol{F}_a$, and $\boldsymbol{G}_a$ are advection flux vectors in the x, y, and z direction, respectively, $\boldsymbol{E}_v$, $\boldsymbol{F}_v$, and $\boldsymbol{G}_v$ are viscous-flux vectors, and $\boldsymbol{E}_p$, $\boldsymbol{F}_p$, and $\boldsymbol{G}_p$ are pressure terms.

2.2 Numerical Schemes

To express the motion of a swimmer, the unstructured moving grid finite volume method was adopted. The method assures a geometric conservation law as well as a physical conservation law. Then, a control volume in the space-time unified domain (x, y, z, t), which is four-dimensional in the case of three-dimensional flows is used.

To express acceleration and deceleration of a swimmer, moving itself is required instead of general approach which calculates a fixed body in uniform flow. In several moving body approach, the moving computational domain method is suitable for the application. The method which moves the computational domain itself according to motions of a body can remove restrictions of the distance traveled. Furthermore, the method satisfies both geometric and physical conservation laws as it is based on the unstructured moving grid finite volume method. Thus the moving computational domain method is adopted in this paper.

3 Computational Model and Conditions

3.1 Numerical Swimmer Model

To obtain motions to the swimmer model, joint angles data is captured from video footage of a male swimmer as shown in Figure 1. The average speed of the swimmer in the video is 1.4m/sec. Then the dolphin kick cycle T is 0.65sec.

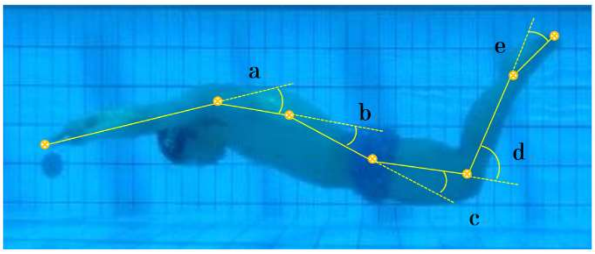

Fig. 1. Video footage of a male swimmer and positions of joint angles (a: shoulder, b: back, c: hip, d: knee, e: ankle)

The joint angles of shoulder, back, hip, knee and ankle shown in Figure 2. These relations of joint angles make a motion of dolphin kick. The sequence of movements for dolphin kick swimmer are shown in Figure 3.

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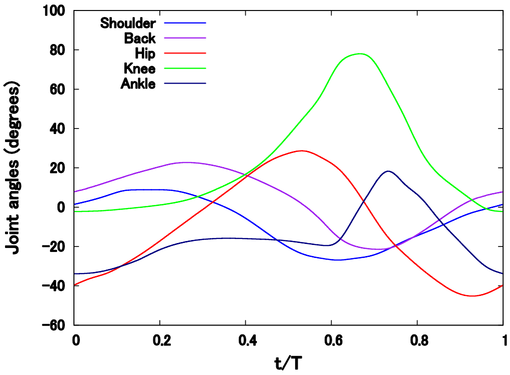
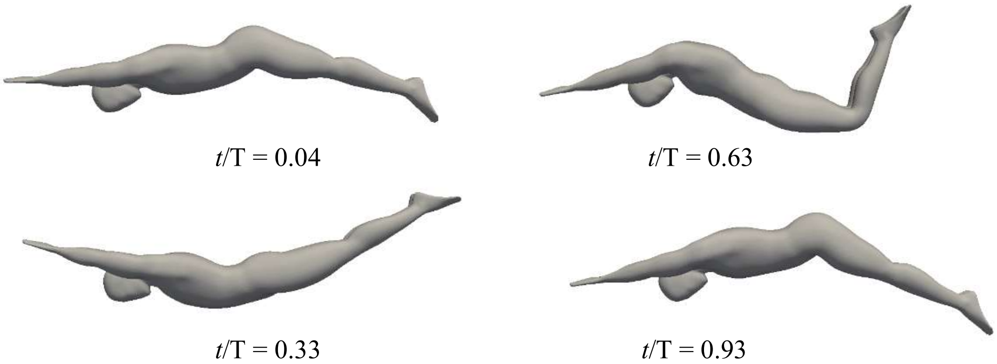


Fig. 2. Changes of five joint angles captured from video footage in a dolphin kick cycle



t/T = 0.04

t/T = 0.63

t/T = 0.33

t/T = 0.93

t/T = 0.48

Fig. 3. Dolphin kick movement reproduced

3.2 Computational Mesh and Conditions

The computational mesh is generated using unstructured type. Here, 1,420,617tetrahedron and 726,499 prisms are used. The prism mesh is for boundary layer. Their elements are created by MEGG3D [20].

Dolphin kick motion stars at the speed of the swimmer 1.4m/sec. Then, a coupled computation between motion of human and fluid also starts simultaneously. Reynolds number is 5×10^4. Then number of time steps of a dolphin kick cycle is 17800.

4 Results

4.1 Dolphin Kick Swimming

Under the computational conditions, a flow around the swimmer was calculated. Figure 4 shows isosurface of Q-criterion around the swimmer. At *t*/T=0.33, vortices around

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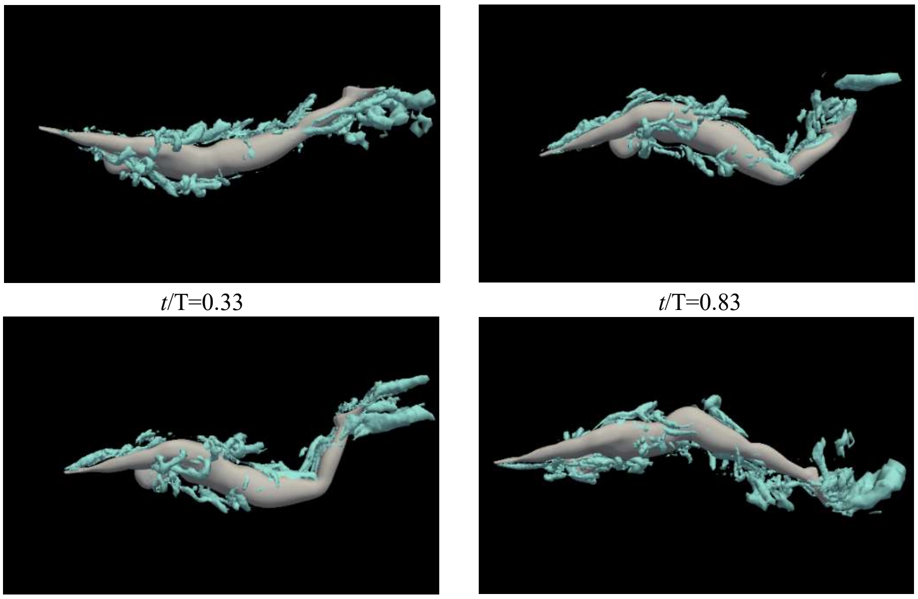
and under legs generated by raising the legs are seen. The feet reach the highest point at *t*/T=0.58, the long vortices are discharged from feet and toes. In the downward of legs, vortices are created upper legs as seen at *t*/T=0.83. An average speed in a cycle with dolphin kick is 1.49m/sec. Comparing with the practical speed 1.4m/sec, the difference is equivalent to 6.43% of the speed. The result shows the validity of the computations using this numerical swimmer model with dolphin kick.



t/T=0.33 *t*/T=0.83

t/T=0.58 *t*/T=0.93

Fig. 4. Isosurface of Q-criterion around the swimmer

4.2 Influence of Maximum Knee Oscillation Angles

To improve the swimming style with dolphin kick, the influence which the maximum knee oscillation angles affect the speed of the swimmer is investigated. Six different knee oscillation angles (Variant1:80 degrees, V2:70, V3:60, V4:50, V5:40, V6:30) are estimated and their results are compared.

As the results, the average speed of 6 variants are shown in Table 1. The highest speed is taken in Variant 3, then the lowest one is Variant 6. On the other hand, the history of thrust in 6 variants is shown in Figure 5. So the highest average speed Variant 3 doesn't get the highest thrust. Then the lowest average speed Variant 6 also doesn't take the lowest one. The highest thrust is made by Variant 1 which has the maximum knee angle among the investigation. However Variant 1 also have the lowest thrust because it would have the maximum drag. The drag is made from the resistance of the flow occurred the surface area of the swimmer's body changed by the high angle of knee.

Table 1. Comparison of Average speed of 6 variants

Variant Number	Average speed
1	1.078
2	1.108
3	1.132
4	1.100
5	1.085
6	1.047

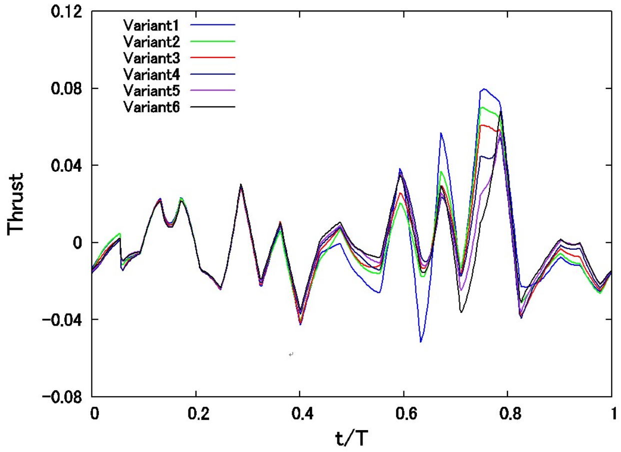


Fig. 5. History of thrust in 6 variants

5 Conclusions

In this paper, flows around the dolphin kick swimmer were computed using unstructured moving mesh method. Furthermore, by combing a moving computational calculating approach and a coupled computation between motion of a swimmer and fluid with the unstructured mesh, the numerical swimmer was structured. Comparing with the practical speed data, the speed of the numerical swimmer made the error less than 7%. Furthermore, around the swimmer's feet, the result could show similar pressure distribution and velocity vectors with the experimentation data. Thus, the validity of the computations using this numerical swimmer model with dolphin kick were shown. To improve the dolphin kick, 6 maximum knee oscillation angles were estimated using the numerical swimmer. In the case of 60 degrees at knee oscillation angle, it was found that the swimmer can take the highest average speed.

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