Development of a Simulation Model for Monofin Swimming

Motomu NAKASHIMA**, Shingo SUZUKI** and Kenji NAKAJIMA**
** Graduate School of Information Science and Engineering, Tokyo Institute of Technology
2–12–1 Ookayama, Meguro-ku, Tokyo 152–8552, Japan
E-mail: motomu@mei.titech.ac.jp

Abstract
The objective of this study was to develop a simulation model for monofin swimming which considers the mechanical interaction between the monofin and swimmer. For this objective, the swimming human simulation model SWUM was extended to the monofin swimming. In order to identify the bending stiffness and damping coefficient of the monofin, the static and dynamic bending tests of a monofin were conducted. From the identification process, it was found that the simulation using the identified parameters reproduced the experiment well. This suggests the validity of the modeling of the monofin itself. The body geometry and joint motion of the swimmer were acquired from the experiment using a subject swimmer. In order to identify the fluid force coefficients of the monofin, the fluid force acting on the monofin was measured in the experiment which was conducted in a circulating water tank. The simulation with the identified parameters reproduced the experiment well. This suggests the validity of the fluid force model for the monofin. From the simulation of monofin swimming using the identified model parameters, it was found that the whole behavior of the swimmer and monofin in the simulation agrees well with that in the experiment, especially for the bending motion of the monofin. The velocities averaged in one kicking cycle in the simulation and experiment also agreed within a 10% error. These results sufficiently suggest the validity of the developed simulation model.

Key words : Swimming, Sports Biomechanics, Biofluid Dynamics, Monofin, Simulation

1. Introduction
A monofin is an elastic fin which the swimmer attaches for recreational and competitive purposes. Both feet of the swimmer are inserted into the footpockets of a single fin. Monofin swimming is interesting from many aspects. From a recreational viewpoint, the remarkably high swimming speed can be pointed out as its distinguished feature. The swimmer with a monofin generally can swim much faster than the one without it. The maximum speed of monofin swimming reaches 3 m/s, which is 1.5 times of that of swimming without fins. Monofin swimming is also interesting from a biomechanical viewpoint. The swimmer and monofin share a mechanical interaction, that is, the swimmer can transmit the force to the monofin to drive it, and the monofin returns the reaction to the swimmer. This interactive relationship determines the total swimming performance. Additionally, monofin swimming is interesting from the engineering viewpoint. Although there are rules in the competitive games, the monofin has many degrees-of-freedom for design, such as planform, thickness, stiffness, surface finishing and so on. It is a challenging task to design a monofin optimized for an individual swimmer’s specific purpose.

From the biomechanical and engineering aspects, many studies about monofin swimming have been conducted to date(1). As an example of recent studies, Rejman(2) measured the kinematic data of subject swimmers and discussed the influence of timing delay on intracycle...
swimming velocity. Rejman and Ochmann\(^{(3)}\) measured the strain of the monofin as well as the kinematic data, and attempted to utilize this information for the assessment of various swimming techniques. Matsuuchi et al.\(^{(4)}\) measured the flow field around the monofin using the PIV (Particle Image Velocimetry) method. Tamura et al.\(^{(5)}\) manufactured the mechanical equipment which drove the monofin in one degree-of-freedom, and proposed the optimized monofin which was expected to maximize the thrust. Luersen et al.\(^{(6)}\) proposed a numerical approach to optimize the monofin using a two-dimensional model. Bideau et al.\(^{(7)}\) developed a three-dimensional fluid-structure interaction model of the monofin using the finite element method.

By the previous studies, however, the mechanical interaction between the swimmer and monofin has not been sufficiently clarified. Also for the design of the optimized monofin, it is important to take the mechanical interaction into account. Therefore, an analysis tool which can take the mechanical interaction between the swimmer and monofin is necessary for further study. The study by Luersen et al.\(^{(6)}\) is yet insufficient for this purpose since the swimmer’s absolute motion was predetermined, the swimmer’s body was too simplified, and the simulation was not validated by comparing it with the experiments.

The objective of this study was to develop a simulation model for monofin swimming which considers the mechanical interaction between the monofin and swimmer, and which was validated by comparing it with an experiment. For this objective, the swimming human simulation model SWUM (SWimming hUman Model), which has been developed by the authors\(^{(8)(9)(10)(11)(12)}\), was utilized. In this paper, the outline of SWUM is briefly described first in §2.1. How to extend SWUM to the monofin swimming is explained in §2.2. The identification of model parameters based on experiments is described in §3. The results of monofin swimming simulation using the identified model parameters are discussed in §4.

2. Simulation Model

2.1. Outline of swimming human simulation model SWUM

The simulation model SWUM is designed to solve the six degrees-of-freedom absolute movement of the whole swimmer’s body as single rigid body by time integration, using the inputs of the swimmer’s body geometry and relative joint motion. Therefore, the swimming speed, roll, pitch and yaw motions, propulsive efficiency, joint torques and so on are computed as the output data. The swimmer’s body is represented by a series of 21 rigid body segments as follows: lower and upper waists, lower and upper chests, shoulder, neck, head, upper and lower hips, thighs, shanks, feet, upper arms, forearms, and hands. Each body segments is represented by a truncated elliptic cone. The unsteady fluid force and gravitational force are taken into account as external forces acting on the whole body. The unsteady fluid force is assumed to be the sum of the inertial force due to added mass of the fluid, normal and tangential drag forces and buoyancy. These components are assumed to be computable, without solving the flow, from the local position, velocity, acceleration, direction, angular velocity, and angular acceleration for each part of the human body at each time step. The coefficients in this fluid force model were identified using the results of an experiment with a limb model and measurements of the drag acting on swimmers taking a glide position in the previous studies\(^{(8)}\). As a result of the identification, the fluid force model was found to have satisfactory performance although it has a 10% error. For the simulation example of six beat crawl stroke in the previous study, the swimming speed of the simulation became a reasonable value, indicating the validity of the simulation model although it was 7.5% lower than the actual swimming. With respect to the six beat crawl stroke, the authors have already analyzed contributions of each fluid force component and of each body part to the thrust, effect of the flutter kick, estimation of the active drag, roll motion, and the propulsive efficiency\(^{(9)}\). Analyses of the other three strokes and a comparison among four strokes (including crawl stroke) have also been carried out\(^{(10)}\). In addition to these, analysis and optimization of the underwater dolphin kick have been conducted\(^{(11)}\). Their details are described in the references respectively. Some of the
2.2. Extension of SWUM to monofin swimming

In order to simulate the monofin swimming, an extension of SWUM was carried out. The schematic figure of the simulation model for monofin swimming is shown in Fig. 1. The swimmer was modeled as a series of 21 truncated elliptic cones, as described in the previous subsection. The monofin was divided into five rigid plates in order to represent its elastic deformation in the sagittal plane. The truncated elliptic cones were also employed in order to model the five rigid plates, and the plates were represented by flattening the cones, as shown in Fig. 2. The virtual springs and dampers were utilized in order to represent connections among the rigid plates. These springs, therefore, have to be set as sufficiently strong. In addition to these, rotational springs and dampers were employed in order to represent the elasticity of the monofin itself. The swimmer and monofin were also connected by a set of translational and rotational springs and dampers.

The dynamic behaviors of six rigid bodies (the swimmer and the five plates) were to be solved in the present simulation. Each rigid body has six degrees-of-freedom: three for translational and three for rotational. The equations of motion for the six degrees-of-freedom were solved using the time integration method, that is, the new translational and rotational velocities after one time step are computed using the quantities at the present time, and this procedure is repeated to advance the time. Since the six rigid bodies in the present simulation have the dynamic interactions through the springs and dampers, all the time integration among the bodies have to be advanced simultaneously, computing the interacting force among the bodies. For such a calculation, the extension of SWUM for ‘multi agent/object simulation’, which has been developed in the previous study(13), was utilized.

3. Identification of Model Parameters

3.1. Bending stiffness and damping coefficient of the monofin

In order to identify the bending stiffness and damping coefficient of the monofin, static
and dynamic bending tests of a monofin were conducted. The photograph of the monofin used in the test is shown in Fig 3(a). This monofin (WaterWay Company, Model 1 Stiffness Medium) is a very ordinary type. For the bending test, the footpockets of the monofin were fixed to a table as shown in Fig 3(b). The tip of the monofin was then loaded with a weight through strings, as shown in Fig 3(c). The mass of the weight was changed as: 0 kg, 1.0 kg, 1.5 kg and 2.0 kg. In the case of dynamic test, a string to the weight was cut with scissors so that the load became zero suddenly, and bending displacement of the monofin after cutting was measured. In order to measure the bending displacement of the monofin, tiny white markers were attached at the side of the monofin, as shown in Fig 3(d). The markers were filmed using a digital still camera (for the static test) or a CCD camera (for the dynamic test). The displacements of the markers in the vertical direction were computed from the taken pictures.

The bending test was reproduced by the simulation for the identification. The simulation image is shown in Fig 4. For this simulation, the geometry and density of the monofin were input first, based on direct measurements. The tip of the monofin was then loaded in the initial condition as it was in the experiment. The monofin in the simulation oscillated initially and converged to a static equilibrium state. This state was employed for the comparison with the static bending test. For the dynamic test, the load was programmed to be removed after the sufficient period to reach the equilibrium static state. The monofin in the simulation oscillated again after the load was removed. This oscillating state was employed for the purpose of comparison with the dynamic bending test. Note that all the fluid force coefficients for the
Table 1 Results of identification for the spring constants and damping coefficients

<table>
<thead>
<tr>
<th>(Fin element No.)–(No.)</th>
<th>Spring constant [Nm/rad]</th>
<th>Damping coefficient [Nms/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2</td>
<td>3.35×10^2</td>
<td>2.10</td>
</tr>
<tr>
<td>2–3</td>
<td>3.15×10^2</td>
<td>2.04</td>
</tr>
<tr>
<td>4–4</td>
<td>2.32×10^2</td>
<td>1.75</td>
</tr>
<tr>
<td>5–5</td>
<td>1.16×10^2</td>
<td>1.23</td>
</tr>
</tbody>
</table>

(a) Static test (displacements of all markers)  (b) Dynamic test (displacement of tip (No.1) marker)

Fig. 5 Experimental and simulated results of bending test

monofin were set to zero in these simulations, that is, no fluid force acted on the monofin. Although the actual dynamic test was carried out in the air, the fluid force due to the air was assumed to be negligible. The spring constants of the rotational springs and the damping coefficients of the rotational dampers among the five rigid plates were then determined as constant (not time-varying) values, so that the vertical displacements of the marker points in the simulation became as close as possible to those of the bending tests. In the actual procedure, all the spring constants were changed keeping a certain ratio. This ratio could be calculated from the width and thickness of the monofin at the corresponding position using the equation of the beam deformation, based on the assumption of the uniform material. The same method was used also for the damping coefficients.

The results of identification for the spring constants and damping coefficients are shown in Table 1. The experimental and simulated results of the bending test are shown in Fig. 5. The mass of the weight was 1.0 kg in this case. The static displacements of all markers are shown in Fig. 5(a). The dynamic displacements of tip marker (No.1 in Fig. 5(a) ) are shown in Fig. 5(b). It can be seen that the displacements of the simulation using the determined constants agrees well with those of the experiment. This suggests the validity of modeling of five rigid plates for the monofin.

3.2. Body geometry and joint motion of the swimmer

In order to identify the body geometry and joint motion of the swimmer, a volunteer subject swimmer was employed. The subject swimmer was a 26 years old healthy male (body height; 1.67 m). He was an experienced monofin swimmer and also a native previous record holder of the Japanese long distance competition.

In order to identify the body geometry, the pictures of the subject swimmer in several various postures were taken by a digital still camera. From these pictures, the body geometry of the subject swimmer in the simulation model was determined, modifying the existent body of geometric data based on an average of Japanese males.

In order to identify the joint motion, a swimming experiment was carried out. The schematic figure of the experimental setup is shown in Fig. 6. The subject swimmer swam with the monofin in a swimming pool. The swimming motion of the subject swimmer was filmed
Fig. 6  Schematic figure of the experimental setup for joint motion

Fig. 7  Markers attached to the subject and monofin

Fig. 8  Joint motion determined from the experiment
by two underwater CCD cameras. Fourteen markers were attached to the subject and monofin, as shown in Fig. 7. Before the swimming experiment, 168 markers for calibration were located at constant intervals in a three dimensional space of 0.9 m (width) × 6.0 m (length) × 1.53 m (depth) in the pool, and these markers were filmed by the underwater cameras. The calibration data for a motion analysis system were then obtained using the taken pictures and the coordinates of the markers. Using the obtained calibration data, the three-dimensional coordinates of the markers attached to the subject swimmer during the swimming experiment could be calculated using the motion analysis system. In the swimming experiment, the subject swimmer swam completely underwater (it is called ‘Apnea’ in monofin swimming) at his comfortable constant swimming speed. The joint angles were calculated from the three-dimensional coordinates of the markers. The obtained joint motion in one kicking cycle ($t^*$ is nondimensional time) is shown in Fig. 8. The one kicking cycle was 1.0 s.

### 3.3. Fluid force coefficients of the monofin

In order to identify the fluid force coefficients of the monofin in the simulation model, the fluid force acting on the monofin was measured in the experiment which was conducted in a circulating water tank. The photograph of the experimental setup is shown in Fig. 9(a). A driving device was mounted on the tank, which drove the four swords in the water. The underwater part of the experimental setup is shown in Fig. 9(b). The four swords drove the monofin which was used in the experiment of the subject swimmer. The two degrees-of-freedom motion of heave (vertical) and pitch (rotational) for the monofin was performed by moving each of the two swords in a vertical direction separately. The four dynamometers which could measure the forces in the propulsive (horizontal) and vertical directions were located at the bottom ends of the swords. The motion data of the monofin was determined based on the motion of the experiment of the subject swimmer. That is, from the coordinates of the monofin in the experiment of the subject swimmer, the corresponding vertical displacements of the swords were computed. Due to the limitations of the device’s driving force and the input range of the dynamometers, the amplitudes of the displacements were reduced to 20% of the actual motion and the kicking cycle was increased to 2.32 s. The peak-to-peak amplitudes of heave and pitch were 0.097 m and 15 deg, respectively. The flow speed of the circulating tank was 0.8 m/s.

This experiment was reproduced by the simulation for the identification. In this simulation, the geometry, bending stiffness and damping coefficients of the monofin which were identified in section 3.1 were employed. The fluid force coefficients in the model were determined by manually adjusting them so that the forces acting on the monofin in the simulation became as close as possible to those in the experiment. The identified fluid force coefficients are shown in Table 2. With respect to $C_n$, which is the coefficient of the inertial force of the added mass of fluid, the values of the root side became larger and those of the tip side smaller. The coefficients $C_n$ and $C_t$, which are employed for the normal and tangential drag forces,
Table 2 Results of identification of the fluid force coefficients

<table>
<thead>
<tr>
<th>Fin element No.</th>
<th>$C_a$ (added mass)</th>
<th>$C_n$ (normal drag)</th>
<th>$C_t$ (tangential drag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (root side)</td>
<td>0.75</td>
<td>5.5</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>0.30</td>
<td>5.5</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>5.5</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>0.10</td>
<td>5.5</td>
<td>0.03</td>
</tr>
<tr>
<td>5 (tip side)</td>
<td>0.05</td>
<td>5.5</td>
<td>0.03</td>
</tr>
</tbody>
</table>

(a) Horizontal direction (positive is thrust) (b) Vertical direction (positive is upward)

Fig. 10 Results of fluid forces acting on the monofin in the experiment and simulation using identified coefficients

were the same values among the five fin elements. Note that the coefficient $p$, which represents the effect of ellipse flatness on the fluid force for the normal drag, was zero for all the fin elements. This was because $p$ was not necessary for the simulation of monofin swimming since the kicking motion was confined to the sagittal plane. The results of fluid forces acting on the monofin in the experiment and simulation using identified coefficients are shown in Fig. 10. The experimental values were computed as the sum of the values measured by the four dynamometers. It can be seen that the simulation using the identified fluid force coefficients agrees well with the experiment, although the forces in the horizontal direction were small due to the small motion amplitude. This agreement suggests the validity of the fluid force model for the monofin.

4. Simulation of Monofin Swimming

The simulation of monofin swimming was carried out using the model parameters identified in the previous section. The other parameters used in the simulation are as follows: With respect to the fluid force coefficients of the swimmer, $C_a = 0.65$, $C_n = 1.08$, $C_t = 0.03$ and $p = 1.0$ are used. These values are the same as the simulation of underwater dolphin kick in the previous study.(11) The body density of the swimmer was set to 1.0 (equal to the surrounding water) for all body segments, although the actual density for the most part of the human body is slightly heavier than the water, and for the chest, it is lighter due to the air in the lung. This setting aimed to eliminate the effects of buoyancy and gravity on the swimming speed, since their inequality might cause an undesired acceleration. With respect to the joint motion, the constant offset value of 10 degrees was added to the hip joint angle in the extension direction so that the swimmer in the simulation propels straight in the pitch direction. The time step for the time integration was 1/2000, that is, one kicking cycle was divided into 2000 steps. Five cycles were computed in the simulation and the last fifth cycle was used for the evaluation since the swimming speed for one cycle converged to a constant value.

The photographs of the experiment and the swimming motion obtained in the simulation are shown in Fig. 11. The nondimensional time $t^*$ is normalized by the kicking cycle and the beginning of the fifth cycle was set to zero. It was found that the whole behavior of the swimmer and monofin in the simulation agrees well with that in the experiment, especially for the bending motion of the monofin. The comparison between the simulation and experiment for the velocity of the marker at the waist in the horizontal direction are shown in Fig. 12.
Fig. 11 Photographs of the experiment (left) and swimming motion obtained in the simulation (right)

(a) $t^* = 0.1$

(b) $t^* = 0.3$

(c) $t^* = 0.5$

(d) $t^* = 0.7$

(e) $t^* = 0.9$
Although the experimental value was very oscillatory due to the numerical differentiation of the measured coordinate data, the acceleration at $t^* = 0 - 0.3$ and gentle deceleration at $t^* = 0.3 - 1.0$ can be seen both in the simulation and experiment. The velocities averaged in one kicking cycle were 1.79 m/s (experiment) and 1.71 m/s (simulation), respectively. This small error (within 10%) as well as the agreement of the whole behavior in Fig. 11 suggest the sufficient validity of the developed simulation model.

Additional analyses were carried out using this validated simulation model. The simulation images for one kicking cycle are shown in Fig 13. The red lines emitting from the monofin represent the point of application, direction and magnitude of the fluid force acting on the monofin. When, where, and in which direction the fluid force acts on the monofin can be found from the figure. The time history of the thrust produced by the monofin is shown in Fig 14. The thrusts separated by five elements are shown in Fig 14(a). The black line (“All”) is the total thrust produced by the monofin which was computed as the sum of the thrusts of the five elements. It was found that the root side of the fin contributes to the thrust more than the tip side. It was also found that each peak by up and down kicks for each fin element has a phase lag to the adjacent root side element. The separated fluid force components of the thrust are shown in Fig. 14(b). It is found that the main component of the thrust is the inertial force due to the added mass of the fluid (red line). It is also found that the normal drag force also contributes to the thrust especially when the inertial force due to the added mass becomes negative ($t^* = 0.2 - 0.4$ and $0.6 - 0.8$). As the result, the monofin produces the positive thrust almost always through the cycle. The maximum thrust produced by the monofin reaches 300 N. The comparable thrust (200 - 400 N) was reported in the simulation analysis of the barefoot dolphin kick by Sugimoto et al. (14). The barefoot underwater dolphin kick, however, had the negative thrust phase in one kicking cycle. In the monofin swimming, the always positive thrust produced by the monofin will enable the swimmer to swim at the speed higher than that in the barefoot dolphin kick. The thrusts produced by the swimmer and monofin are shown in Fig. 15. The thrust of the monofin (blue line) is identical to the black lines in Fig 14. It was found that the thrust of the swimmer (red line) becomes always negative, that is, producing not the thrust but the drag. This drag is balancing with the thrust produced by the monofin. Those findings obtained by the simulation would be useful for the effective product design of the monofin, and also instructive for athletes and coaches of the monofin swimming.

5. Conclusions

In this study, the simulation model for monofin swimming was developed by extending the swimming human simulation model SWUM. The monofin was modeled as a series of five rigid plates in the model. The model parameters were identified using the results obtained in the experiments. The simulation of monofin swimming was carried out and the results were discussed. Findings are summarized as follows:
Fig. 13  Simulation images for one kicking cycle

Fig. 14  Time history of thrust produced by monofin for one kicking cycle
From the identification of the bending stiffness and damping coefficient of the monofin, it was found that the simulation using the identified parameters were consistent with the findings of the experiment. This suggests the validity of the modeling of five rigid plates for the monofin.

From the identification of the fluid force coefficients of the monofin, it was found that the fluid forces of the simulation using the identified parameters agreed well with those of the experiment. This suggests the validity of the fluid force model for the monofin.

From the simulation of monofin swimming using the identified model parameters, it was found that the whole behavior of the swimmer and monofin in the simulation agreed well with that in the experiment, especially for the bending motion of the monofin. The velocities averaged in one kicking cycle in the simulation and experiment also agreed within a 10% error. These results suggest the sufficient validity of the developed simulation model.

From the simulation of monofin swimming, it was found that the root side of the fin contributes to the thrust more than the tip side. It was also found that the monofin produces the positive thrust almost always through the cycle.

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