Effect of Flexibility of the Caudal Fin on the Propulsive Performance of Dolphins

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In this paper, the effect of flexibility of the caudal fin on the propulsive performance of bottlenose dolphins is studied using the numerical simulation technique. The fluid-structure interactions are computed using an assumed mode method together with the 3D modified doublet lattice method (MDLM) and the 3D Navier-Stokes (NS) code. As the first step, the necessary power for the standing swimming condition is determined via numerical simulation using the 3D NS code. With this necessary power, the propulsive performance of horizontal swimming is estimated using the 3D MDLM coupled with an optimum design technique and the 3D NS code. The results show that the power-mass-ratio of the standing swimming is 62.2 W/kg which is approximately 2.6 times larger than that of human athlete, and it is an 11% decrease compared with that obtained under the rigid fin assumption. As to the horizontal swimming, the propulsive efficiency increases approximately 2–4% compared with that of the rigid fin to attain the same amount of thrust according to the analysis using the 3D MDLM, while the analysis using the 3D NS code predicted an approximate 12% decrease in efficiency due to flow separation observed around the tip region. As the result of these analyses, the maximum speed of horizontal swimming is predicted to be 12 m/s which is a 1 m/s decrease from the 13 m/s estimated under the rigid fin assumption.

Key Words: Aeroelasticity, Dolphin, Standing Swimming, Numerical Simulation, Swimming Speed

1. Introduction

In a paper published in 1936, Gray\(^\text{1)}\) pointed out that the power generation capability of a dolphin’s muscle is seven times larger than that of a terrestrial mammal. This conclusion was derived on the basis of the assumptions that the maximum speed of the dolphin is 20 knots (10 m/s), that the friction drag of the body can be estimated by assuming that the boundary layer around the body is turbulent and that the propulsive efficiency is 100%. If these assumptions are correct, the conclusion he derived is contradictory to the fact that the dolphin is a mammal. Therefore, it is called “Gray’s paradox.” Gray\(^\text{1)}\) also pointed out in the same paper that the power generation capability of a dolphin’s muscle might be equivalent to that of other types of mammalian muscle if the boundary layer around the body is laminar. Numerous studies have been made on the nature of the boundary layer since then (see the extensive review by Fish and Rohr\(^\text{2)}\)). However, Fish\(^\text{3)}\) concluded, by examining the numerous studies on the nature of the boundary layer, that there is no special mechanism for drag reduction and dolphins appear to maintain a turbulent boundary layer. Fish\(^\text{3)}\) computed the thrust, efficiency and power using the theory of Chopra and Kambe\(^\text{4)}\) from the experimental data of the fin motion read from video footage of several trained dolphins swimming horizontally. Then he computed the drag coefficient from the computed power. However, the value of the drag coefficient and the power thus derived show considerable scatter depending on the data of the individual dolphin used for the analyses, making the accurate determination of the power generation capability of dolphins difficult. (The power thus determined around the maximum speed of 6 m/s was scattered from 1,900 W to 7,600 W.) On the other hand, there is no such uncertainty for the standing swimming performance shown in aquariums where the body (in the air) is supported by the caudal fin in the water (see Fig. 1). It is clear that the thrust generated by the fanning motion of the caudal fin is equal to the body weight, which

Fig. 1. Standing swimming of a dolphin.
can be measured accurately. Therefore, an accurate estimation of the power generation capability could be possible without having to include the body drag if we can analyze the standing swimming. Recently, Isogai\textsuperscript{5)} presented the results of the numerical simulation of the standing swimming using the 3D Navier-Stokes (NS) code. The power-mass-ratio (PMR; power per unit mass of body) obtained for the model dolphin (body length: 2.3 m; body mass: 138 kg) is 70.2 W/kg, which is three times larger than that of the human athlete. Based on this PMR, he estimated the maximum speed of the horizontal swim, obtaining 13 m/s. In his analysis, however, the caudal fin is assumed to be rigid. As pointed out by Fish et al.,\textsuperscript{6)} cetacean flukes are flexible and they could give some effect on the propulsive performance of dolphins including the standing swimming. Although some works on the effect of flexibility on the propulsive performance of the flapping fluke have been published so far, some\textsuperscript{7,8)} of them are confined to the two-dimensional airfoil, and one\textsuperscript{9)} of them treats only spanwise flexibility. It is clear that a more rigorous hydro-elastic analysis is necessary, that takes into account the chordwise and spanwise flexibility using the 3D unsteady aerodynamic theory to estimate the propulsive performance of dolphins including the standing swimming.

The purpose of the present study is to evaluate the effect of flexibility of the caudal fin on the power necessary for the standing swimming and on the propulsive performance of the horizontal swim.

2. Method of Analysis

2.1. Model dolphin

In the present paper, we consider one of the bottlenose dolphins (\textit{Tursiops truncates}) studied by Nagai\textsuperscript{10)} for the analytical model. The length ($l$), mass ($M$) and fineness ratio ($l/d$, $d$: maximum diameter of body) of the model dolphin are 2.3 m, 138 kg and 5.38, respectively. Figure 2 shows the planform of the caudal fin. The root chord length is 0.144 m, the full span length is 0.432 m and the area of the fin is 0.0377 m$^2$. The aspect ratio is 4.96. The airfoil section of the fin is assumed to be NACA0021.\textsuperscript{11,12)} Note that this analytical model is the same as that used in Ref. 5).

\[
E_{eq} = \frac{E_1}{2} \int_{0}^{T_f/2} E_2 y^2 dy + \frac{E_1}{2} \int_{T_f/2}^{T_f} E_2 y^2 dy
\]

For computing the hydro-elastic effects on the propulsive performance of the dolphin, we apply the modal approach used in Ref. 14). In taking this approach, we make the following assumptions:

1) The central part of the fluke which is mainly composed of the caudal vertebrae\textsuperscript{11)} is rigid and its motion is actively controlled by the hypaxial and the epaxial muscles.\textsuperscript{13,15)}

2) The other part of the fin which is composed of LL and DCT is a flexible beam which is connected to the rigid central part of the fluke.

In the modal approach, the generalized mass, the natural vibration modes and the natural frequencies of the tail fin are utilized for the hydro-elastic analyses. We employed the lumped mass method\textsuperscript{6)} for the vibration analysis using the elastic and mass data of the tail fin. Figure 4 shows the

2.2. Elastic properties of the caudal fin

In order to compute the effect of the flexibility, it is essential to know the elastic properties of the caudal fin. Although such data is very scarce, Sun et al.\textsuperscript{11)} measured the elastic property, especially Young’s modulus, of tissues of the tail fin of the bottlenose dolphin. They used the specimens taken from the tail fin of a dead dolphin (\textit{T. truncatus}). According to Sun et al.,\textsuperscript{11)} the tail fin is mainly composed of the outer ligamentous layer (LL) with a high tensile modulus and the inner dense connective tissue (DCT) with a high compressive modulus combined together acting as a sandwich composite beam (see Fig. 3). Sun et al.\textsuperscript{11)} found that there is a linear relationship between the thickness of the LL ($T_{LL}$ [mm]) and the thickness of the fluke ($T_F$ [mm]). That is,

\[
T_{LL} = 0.843 + 0.110T_F
\]

They obtained Young’s moduli $E_1$ and $E_2$ in the spanwise direction of LL and DCT via tensile and compression tests, respectively, as $E_1 = 166.54$ MPa and $E_2 = 12.05$ MPa. By applying these data of Young’s moduli and Eq. (1) to the present dolphin model, we obtain the equivalent Young’s modulus ($E_{eq}$) of the caudal fin as $E_{eq} = 108$ MPa. Here, $E_{eq}$ is defined by

\[
E_{eq} = 2\left(\int_{0}^{T_f/2} E_2 y^2 dy + \int_{T_f/2}^{T_f} E_1 y^2 dy\right)
\]
location and the sweep angle of the elastic axis (x: dimensionless coordinate defined by \(X/b_r, \bar{Y}/b_r, b_c: \) root semi-chord). In Table 1, the concentrated mass \((m_i)\), moment of inertia \((I_{ni})\), bending rigidity \((E_{li})\) and torsional rigidity \((G_{ji})\) at the spanwise stations of the elastic axis are shown. These inertial and mass properties are computed using Young’s modulus and mass density of the fin \((1,100 \text{ kg/m}^3)\) coupled with the fluke geometry. The natural frequencies and mode shapes up to 4th mode are shown in Fig. 5.

2.3. Hydro-elastic response computation

Figure 6 shows the definitions of the coordinates and the fin motion. In the modal approach, the displacement of the fin mean surface \(F(X, Y, t)\) in the \(Z\) direction is expressed using nine mode shapes as

\[ F(X, Y, t) = F_r(X, Y, t) + \sum_{i=1}^{9} \phi_i(X, Y)q_i(t) \]  

where \(F_r(X, Y, t)\) is the rigid displacement due to the forced oscillation, \(\phi_i(X, Y)\) is the \(i\)-th natural vibration mode of the fin and \(q_i\) is the unknown generalized coordinate of the elastic deformation. The rigid displacement \(F_r(X, Y, t)\) of the fin can be expressed as

\[
\begin{array}{cccccc}
1 & 0.0 & 0.102 & 1.469 \times 10^{-4} & 16.94 & 31.09 \\
2 & 0.19 & 0.102 & 1.469 \times 10^{-4} & 16.94 & 31.09 \\
3 & 0.63 & 0.089 & 1.118 \times 10^{-4} & 12.89 & 23.55 \\
4 & 1.06 & 0.067 & 0.640 \times 10^{-4} & 7.38 & 13.60 \\
5 & 1.49 & 0.051 & 0.370 \times 10^{-4} & 4.26 & 7.81 \\
6 & 1.92 & 0.036 & 0.187 \times 10^{-4} & 2.15 & 3.98 \\
7 & 2.36 & 0.024 & 0.083 \times 10^{-4} & 0.96 & 1.74 \\
8 & 2.78 & 0.015 & 0.034 \times 10^{-4} & 0.39 & 0.72 \\
9 & 3.21 & 0.009 & 0.011 \times 10^{-4} & 0.13 & 0.23 \\
10 & 3.40 & 0.005 & 0.003 \times 10^{-4} & 0.04 & 0.07 \\
\end{array}
\]
where \( H_r \) and \( \theta_r \) are the heaving and pitching displacements, respectively, and they are given as
\[
H_r = H_r \sin(\omega t) \quad (5)
\]
\[
\theta_r = \theta_r \sin(\omega t + \phi) \quad (6)
\]
where \( H_r \) and \( \theta_r \) are the amplitudes of the heaving and pitching oscillations, respectively, \( \omega \) is the circular frequency of forced oscillation and \( \phi \) is the phase advance angle of the pitching oscillation ahead of the heaving oscillation. Using Lagrange’s equations of motion, we obtain the ordinary differential equations of motion to determine \( q_i \) as follows:\(^{14}\)
\[
M_i \left( \frac{d^2 q_i}{dt^2} + \left( \frac{\partial^2}{\partial \phi^2} \right) q_i \right) = -\int f(X,Y) \phi_i(X,Y) \frac{d^2 F_r}{d\phi^2} \, dX \, dY
\]
\[
+ \int \left( \Delta P(X,Y,t) \phi_i(X,Y) \right) \, dX \, dY
\]
for \( i = 1, \ldots, 9 \) \( (7) \)

where \( M_i \) is generalized mass, \( \omega_i \) is the \( i \)-th natural circular frequency, \( m(X,Y) \) is mass per unit area of fin, \( \Delta P(X,Y,t) \) is the pressure difference between the upper and lower surfaces of the fin and \( q_i \) is the damping coefficient which is equivalent to the structural damping coefficient.\(^{16}\) Equations \( (3)–(7) \) are the basic equations for computing hydroelastic deformation of the flexible fin, that are used both for the NS simulations including the standing swimming and the horizontal swimming, and the propulsive performance computations using MDLM. Further details of the method of analysis can be found in Ref. 14.

3. Results

3.1. Standing swimming

For the numerical simulation of the standing swimming, the 3D NS equations are solved with Eq. \( (7) \). The 3D NS code used in the present study is a Reynolds averaged Navier-Stokes (RANS) code originally developed by Isogai.\(^{13}\) A body-fitted C-H type grid is used. The number of grid points used is 240 points (200 points on the wing and 20 points on the upper and lower surfaces of the wake region) in the chord-wise direction, 29 points in the span-wise direction (19 points on the semispan wing and 9 points on the off-wing region) and 51 points normal to the wing surface. The code employs a total variation diminishing (TVD) scheme (Yee and Harten\(^{18}\)) and the Baldwin and Lomax\(^ {19}\) algebraic turbulence model. To compute the standing swimming, for which the caudal fin oscillates in still water and no free stream exists, the Navier-Stokes equations are made non-dimensional by the root semi-chord \( b_r \), the maximum heaving velocity \( V_H \) and the far-field fluid density \( \rho_{\infty} \). Note that the \( Z \)-axis (direction of heaving motion; we call this direction the stroke-plane) coincides with the horizontal axis and the \( X \)-axis coincides with the vertical axis (direction of gravity) for the standing swimming condition. The fin motion given to the central part of the fin is almost the same as that of the rigid fin\(^5\) except in terms of the frequency (or \( V_H \); maximum heaving velocity).

\[
R_{ch} = 1.0 \times 10^6, \quad k_H = 0.199, \quad H_r/b_r = 5.03,
\]
\[
\theta_r = 58.9 \text{ deg}, \quad \phi = 75.8 \text{ deg}, \quad a = -0.617
\]
and
\[
g = 0.22
\]
\[
(V_H = 8.68 \text{ m/s}, \quad f = 3.82 \text{ Hz})
\]

where \( R_{ch} \) is the Reynolds number based on the root chord length and \( V_H \), \( k_H \) is defined by \( k_H = b_r \omega / V_H \) and \( a \) is defined by \( A/b_r \). (Note that the value of 0.22 is tentatively used as the damping coefficient since the experimental data of \( g \) for the dolphin’s tail fin is not available. However, the effect of \( g \) on the PMR of the standing swimming and the horizontal swimming is small; namely, approximately 5% for standing swimming and 2% for horizontal swimming for the range of \( g \) from 0.10 to 0.50. A detailed discussion on the effect of \( g \) to the propulsive performance is given in the appendix.)

The periodic solution is obtained at the third cycle of oscillation. Figure 7 shows the fin deformation and surface pressure distribution at the typical phases of the third cycle of oscillation. (\( t^* \) is dimensionless time defined by \( t^* = t(V_H/b_r) \)). In Fig. 8, the flow pattern (stream lines) around the 52% semi-span during the third cycle of oscillation is shown. As seen in the figures, large-scale flow separation around the leading edge region is observed. Figure 9 shows the heaving and pitching displacements of the rigid fin and those of the elastic deformations at the 52%, 74% and 92% semispan,
respectively. Note that the total displacement of the fin is the sum of the rigid and elastic displacements shown in the figures. In Fig. 9, it is identified that the maximum heaving elastic displacements occur at 103 deg phase delay from that of the maximum rigid heaving displacement, and the maximum values of the elastic heaving displacements become $H_e/h_r = 1.39, 2.10$ and $2.90$ at the 52%, 74% and 92% semispan, respectively. ($H_e$ is the elastic displacement of the fin.) From the figure, it is identified that the high-frequency elastic pitching deformation is included in the fundamental frequency of 3.8 Hz and the maximum pitching elastic deformation becomes approximately 10 deg.

As the result of the numerical simulation, we obtain the time-averaged thrust of 1,352 N (138 kgf) which can sustain the body weight of 138 kgf with the necessary power of 8,582 W. These results give PMR of 62.2 W/kg which is 2.6 times larger than that of a human athlete and it is an approximately 11% reduction compared with 70.2 W/kg which was obtained under the assumption of the rigid fin. In Fig. 10, the variations of thrust and power with respect to time during the third cycle of oscillation are shown.

It is interesting to see that the variations of thrust and power are almost sinusoidal despite the large-scale flow separation.
The maximum speed expected when the power predicted by the analysis of the standing swimming is used for the horizontal swimming is discussed in the next section.

3.2. Horizontal swimming

In this section, the propulsive performance of horizontal swimming of the present model dolphin is estimated using the MDLM coupled with an optimization technique. The optimization technique is used to find the optimum fin motion which attains the maximum propulsive efficiency. As the result of optimization, the thrust, power, propulsive efficiency and PMR at the optimum condition are determined. In order to evaluate the effect of the viscosity, especially the effect of flow separation, on the performance thus determined using the MDLM, the numerical simulations using the 3D NS code are also conducted.

In order to determine the optimum fin motion to attain the highest propulsive efficiency, we take the following steps that we also took in Ref. 5).

Step 1: We assume the forward velocity $V$ (m/s), and determine the Reynolds number based on the body length $R_{e,j}$. Step 2: Using $R_{e,j}$ thus determined and assuming the boundary layer around the body is fully turbulent (because $R_{e,j}$ is larger than $10^5$ when the forward velocity of the present model dolphin is larger than 6.0 m/s), the friction drag coefficient $C_f$ is computed by the following equation, valid for $R_{e,j} \leq 10^9$ (Schlichting21).

$$C_f = 0.455 / (\log R_{e,j})^{2.58} - 1700 / R_{e,j}$$  \hspace{1cm} (8)

Step 3: Using $C_f$ obtained in Step 2 and the following equation (Hoerner22), which gives a correction for pressure drag, we obtain the drag coefficient of the body $C_{D,w}$ based on the body surface area $S_w$.

$$C_{D,w} = C_f (1 + 1.5(d/l)^{1/2} + 7(d/l)^3)$$  \hspace{1cm} (9)

where $d/l = 1/F_r$; $F_r$: fineness ratio.

Step 4: We transform $C_{D,w}$ to the drag coefficient of the body $C_D$ based on the surface area of the caudal fin $S_f$.

$$C_D = (S_w/S_f) C_{D,w}$$  \hspace{1cm} (10)

where $S_w$ and $S_f$ for the present model dolphin are 2.45 and 0.0377 m$^2$, respectively.

Step 5: We determine the optimum fin motion; namely, the reduced frequency $k$ ($k = b_i \omega / V$, note that the definition of $k$ is different from the definition of $k_H$ used in the computation of the standing swimming in section 3.1), $H_{b_i} / b_i$, $\theta_{w_i}$, $\phi$ and $a$ that attain the maximum propulsive efficiency $\eta_p$ ($\eta_p = TV/P$; $T$: time-averaged thrust; $P$: time-averaged power) using the optimization technique. For this purpose, we employ 3D MDLM code (Isogai and Harino14) coupled with an optimization algorithm of the complex method (Box23). The 3D MDLM code can compute the thrust and power of the oscillating wing of an arbitrary planform for a given flapping wing motion. The accuracy and reliability of the code is examined (see Ref. 14)) by comparing with the theory of Chopra and Kambe.4) The complex method is a direct search method.
which can maximize or minimize the objective function without recourse to the derivatives of the objective and constraint functions with respect to the design variables. The present problem of finding the optimum fin motion which maximizes the propulsive efficiency can be set as follows.

Objective function: \( \eta_p = TV/P \)

Design variables: \( k, H_o/b_r, \theta_o, \phi, a \)

Constraints: \( C_T \geq C_D, H_o/b_r \leq 4.0 \)

where \( C_T \) is the thrust coefficient defined by

\[
C_T = T/((1/2) \rho_{\infty} V^2 S) 
\]

Further details of the optimization procedure using the 3D MDLM coupled with the complex method are given in Ref. 14). The number of iteration steps used to obtain the converged solution was approximately 200–300. When we assume a swimming speed of 12 m/s, the results obtained at each step are as follows.

\[ R_{e,l} = 2.11 \times 10^7, \quad C_f = 0.00259, \quad C_{D,W} = 0.00302, \quad C_D = 0.197 \]

As a result of the optimization, we obtain

\[ \eta_p = 0.917, \quad C_T = 0.197, \quad C_W = 0.215 \]

where \( C_W \) is the power coefficient defined by

\[
C_W = P/((1/2) \rho_{\infty} V^3 S) 
\]

The optimum fin motion obtained is

\[ k = 0.229, \quad H_o/b_r = 3.99, \quad \theta_o = 43.0 \text{ deg}, \quad \phi = 83.1 \text{ deg}, \quad a = -0.50 \]

\( C_T \) and \( C_W \) give a time-averaged thrust of \( T = 534.7 \text{ N} \) and power of \( P = 7,003 \text{ W} \) which is less than the power necessary for the standing swimming of 8,582 W. For the analysis using MDLM, the efficiency is increased approximately 4% from that obtained for the rigid fin assumption.\(^5\)

Since the optimum fin motion thus obtained does not reflect the viscous effect, there is a possibility of flow separation that might degrade the propulsive performance considerably. In order to examine the viscous effect, the numerical simulation using the 3D NS code is conducted. The flow condition and the caudal fin motion are the same as those of the optimum fin motion obtained using the MDLM except that the amplitude of heaving oscillation is slightly modified to satisfy the condition of \( C_T \geq C_D (=0.197) \).

Therefore, the flow condition and the fin motion used for the 3D NS simulation are as follows.

\[ V = 12.0 \text{ m/s}, \quad R_e = 1.32 \times 10^6, \quad k = 0.229, \]

\[ H_o/b_r = 4.07, \quad \theta_o = 43.0 \text{ deg}, \quad \phi = 83.1 \text{ deg}, \quad a = -0.50 \]

where \( R_e \) is the Reynolds number based on the root chord. We have obtained the periodic solution after the 3rd cycle of oscillation. The results are as follows.

\[ \eta_p = 0.757, \quad C_T = 0.213, \quad C_W = 0.281, \quad PMR = 61.4 \text{ W/kg} \]

Note that the efficiency decreases approximately 17% from that obtained by the MDLM analysis. The reason for this decrease of efficiency seems to come from the flow separation observed around the tip region of fin, that occurs at the upper and lower most positions (\( kt^* = 2\pi/3 \) and \( 5\pi/3 \); dimensionless time \( t^* \) is defined by \( t^* = t(V/b_r) \)) of the heaving displacement. Figure 11 shows the vorticity distributions around the 92% semispan. These figures clearly show the existence of the flow separation, that seems to be induced by the excessive chord wise (chamber) elastic deformation. Except for these small scale flow separation around the tip region, almost no flow separation is observed in other parts of the fin for the horizontal swimming conditions.

![Fig. 11. Vorticity distributions around the 92% semispan at the upper/lower most positions of the fin for \( V = 12 \text{ m/s} \).](image)

![Fig. 12. Rigid and elastic heaving and pitching displacements of the fin during one cycle of oscillation for horizontal swimming of \( V = 12 \text{ m/s} \) (rigid: – – – –, elastic: 52%; – – – –, 74%; – – – –, 92%; – – – –).](image)
Figure 12 shows the variations of the rigid and elastic heaving and pitching displacements of the fin at the 52%, 74% and 92% semispan with respect to time during the third cycle of oscillation, respectively. From the figures, it is identified that the maximum elastic heaving and pitching displacements at the 92% semispan become $H = 2.10 \text{ and } C_P = 23 \text{ deg}$ with the phase delay angles of 115 and 118 deg from the maximum rigid heaving and pitching displacements, respectively. It is also interesting to see that the phase advance angle of the elastic pitching displacement ahead of the elastic heaving displacement is approximately 80 deg, which might contribute to the efficient generation of thrust. Figure 13 shows the variations of thrust and power with respect to time during the third cycle of oscillation. As seen in the figure, thrust becomes negative during $t^* = 6.6–10.0$ and $t^* = 20.5–24.0$ when the fin reaches the upper and lower most positions where flow separation occurs around the tip region as shown in Fig. 11.

Note that the PMR of 61.4 W/kg predicted by the 3D NS simulation for $V = 12 \text{ m/s}$ is slightly less than the PMR of 62.2 W/kg of the standing swimming. This means that the present model dolphin can swim at the horizontal speed of 12 m/s, though the duration of the swim might be 6–10 s as discussed in Ref. 5).

The propulsive performance of the horizontal swimming at other speeds; namely, $V = 6.5 \text{ m/s}$, $9.43 \text{ m/s}$, and $11 \text{ m/s}$ are also computed following the same procedure (Steps 1–5). The results are summarized in Tables 2 and 3 including those obtained for $V = 12 \text{ m/s}$. These numerical data of PMR are also plotted in Fig. 14, where the results obtained using the MDLM are shown by the solid line and the results obtained using the 3D NS code are shown by the solid circles. (Note that the amplitudes of heaving oscillation in the NS simulation are slightly increased from those of the MDLM so that $C_T \approx C_D$.)

As seen in the figure, the PMR predicted by the 3D NS code is larger; namely, approximately 16% for $V = 6.5 \text{ m/s}$ and 21% for $V = 12 \text{ m/s}$, than that predicted by the MDLM. These discrepancies between the two can be attributed to the effect of flow separation as already discussed. From Fig. 14, the PMR of the maximum speeds of dolphins observed in the aquariums; namely, 6.5–9.5 m/s, are in the range 10–30 W/kg, far below the PMR of 62.2 W/kg estimated from the analysis of the standing swimming.

<table>
<thead>
<tr>
<th>Method</th>
<th>$V$ (m/s)</th>
<th>$f$ (Hz)</th>
<th>$H_o/b_o$</th>
<th>$\alpha$</th>
<th>$H_o/b_o$</th>
<th>$\beta_o$ (deg)</th>
<th>$\phi$ (deg)</th>
<th>PMR (W/kg)</th>
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<td></td>
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Table 3. Results obtained via the MDLM and the 3D NS code for the optimum fin motion.
4. Concluding Remarks

The effect of flexibility of the caudal fin on the propulsive performance of bottlenose dolphins was studied using the numerical simulation technique. The fluid-structure interactions were computed using the assumed mode method together with the 3D MDLM and the 3D NS code. As the first step, the necessary power for the standing swimming condition was determined via numerical simulation using the 3D NS code. With this necessary power, the propulsive performance of horizontal swimming was estimated using the 3D MDLM coupled with an optimum design technique and the 3D NS code. The results showed that the PMR of the standing swimming is 62.2 W/kg which is approximately 2.6 times larger than that of human athlete, and it is an 11% decrease compared with that obtained under the rigid fin assumption. As to the horizontal swimming, the propulsive efficiency increased approximately 2–4% compared with that of the rigid fin to attain the same amount of thrust according to the analysis using the 3D MDLM, while the analysis using the 3D NS code predicted an approximately 12% decrease in efficiency due to flow separation observed around the tip region. As the result of these analyses, the maximum speed of horizontal swimming was predicted to be 12 m/s which was a 1 m/s decrease from the 13 m/s estimated under the rigid fin assumption.

References


Appendix

In this appendix, the effect of damping coefficient (g) on the performance of the standing swimming and horizontal swimming are examined. All the data shown here are the results of the numerical simulations obtained using the 3D NS code. In Fig. 15, the variations of PMR, thrust coefficient $C_T = (L/(1/2pAV^2_S))$ and the power coefficient $C_W = (P/(1/2pAV^2_S))$ of the standing swimming with respect to $g$ are shown. As seen in the figure, the effect of $g$ on these coefficients are very small; namely, approximately 4–5% for $g = 0.1–0.5$. (Note that the amplitude of free oscillation decreases less than 1% of the first cycle after the 15th cycle for $g = 0.10$ while it decreases less than 1% after the 3rd cycle for $g = 0.50$, respectively. For $g = 0.22$, which is tentatively used for the present study, the amplitude of the free oscillation decreases less than 1% after the 7th cycle of oscillation.) In Fig. 16, the variations of PMR, $\eta_p$, $C_T$ and $C_W$ with respect to $g$ for the horizontal swimming of $V = 11$ m/s are shown. The fin motion is the same as that shown in Table 3. As seen in the figure, the effect of $g$ on PMR and $\eta_p$ is very small; namely, only 2%, while $C_T$ and $C_W$ increase approximately 15% with increasing $g$ from 0.10 to 0.50. However, their effect on PMR and $\eta_p$ remains small because $C_T$ and $C_W$ increase at almost the same rate with respect to $g$.  

Fig. 15. Effect of damping on standing swimming performance.

Fig. 16. Effect of damping on horizontal swimming performance.