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Propulsive Performance of Dolphins

- Estimation from Analysis of Standing Swimming -

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ABSTRACT

In the standing swimming of dolphins, which is often seen in aquariums, the total weight of the body is supported by the caudal fin in the water. It is clear that the thrust generated by the fanning motion of the caudal fin is equal to the body weight. In the study reported in this paper, a numerical simulation of the flow around the caudal fin (of the bottlenose dolphin) using the 3D Navier–Stokes code for the standing swimming condition was conducted and the necessary power was computed. The power thus determined is about 3–4 times larger than the power necessary for the cruising swimming condition, determined by the performances observed to date for trained dolphins in aquariums. With this necessary power, we have estimated the maximum speed the dolphin can attain, using the 3D MDLM (modified doublet lattice method) coupled with an optimum design method and the 3D Navier–Stokes code, obtaining about 13 m/s, which is considerably higher than those observed in aquariums.

Key Words: Dolphin, Standing Swimming, Numerical Simulation, Power Mass Ratio, Swimming Speed

1. INTRODUCTION

Numerous studies on the propulsive performance of dolphin have been published since the initial study of Gray (1936) (see the review by Fish and Rohr 1999)). Special attention has been paid to the maximum speed a dolphin can achieve, since there is a close correlation between a dolphin's maximum speed and its power generation capability. Fish (1993) measured the maximum speeds of several trained bottlenose dolphins (*Tursiops truncates*) in a large pool of an aquarium (Sea World) and reported a maximum speed of 6.0 m/s. Lang and Norris (1966) reported that the swimming speed of a bottlenose dolphin depends

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on the duration of the swim, namely, 3.08 m/s for indefinite duration, 6.09 m/s for 50 sec, 7.01 m/s for 10 sec and 8.3 m/s for 7.5 sec. Nagai (2002) reported a maximum speed of 7.47–9.41 m/s, observed in an aquarium (Okinawa Memorial Park Aquarium) by analyzing the high jumps of bottlenose dolphins. Rohr et al. (2002) examined the maximum swimming speeds, nearly 2,000 speed measurements obtained for both captive and free-ranging dolphins, concluding that the maximum horizontal speed of the trained *T. truncates* was 8.2 m/s and the upward swimming speed, prior to vertical leaps ranged from 8.2 to 11.2 m/s. They also reported that wild seven *truncates* demonstrated a maximum speed of 6.7 m/s, concluding that there was no evidence that the free-ranging dolphins have superior swimming capabilities to captive animals. In sharp contrast with these observations of maximum speed, Lockyer and Morris (1987) reported a maximum speed of 15 m/s (54 km/h) of a bottlenose dolphin in open sea. Since the necessary power increases as the third power of the speed, such discrepancy of the maximum speed of dolphins should be clarified. Since Gray's work (1936), many researchers (Fish 1993 and Nagai 2002) have tried to estimate the power generation capability of dolphins based on the maximum speed observed in the aquarium. In this approach, it is necessary to estimate the body drag. However, there is an uncertainty in the estimation of this parameter. Many studies have been made on the nature of the boundary layer around the body of a dolphin (see the extensive review by Fish and Rohr (1999)). For example, Fish (1993) found that the drag coefficient of the body is 3.2 times higher than the theoretical minimum assuming a turbulent boundary layer. His conclusion was derived from an analytical model of a dolphin based on the observed speeds of several trained dolphins, video analysis of the motion of the caudal fin and the 3D potential fluid dynamic theory of Chopra and Kambe (1977). However, the value of the drag coefficient thus derived shows considerable scatter depending on the data of individual dolphins used for the analysis. However, there is no such uncertainty for the

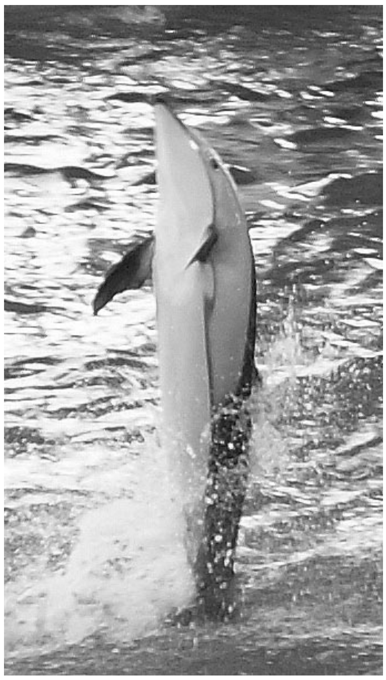


Fig. 1. Standing swimming of a dolphin.

standing swimming performance shown in aquariums where the body (in the air) is supported by the caudal fin in the water (see figure 1). It is clear that the thrust generated by the fanning motion of the caudal fin is equal to the body weight, which can be measured accurately. Therefore, an accurate estimate of the power generation capability could be possible without having to include the body drag if we can analyze the standing swimming. An analysis of standing swimming is only possible by using a numerical simulation technique which takes into account the effect of viscosity, since the flow around the caudal fin becomes an unsteady viscous flow with large scale flow separation. In this paper, as the first step, we determine the power necessary for standing swimming using a three-dimensional Navier–Stokes code (3D NS code). To the best of our knowledge, no analysis of standing swimming has been published to date. As the next step, we estimate the maximum speed (in water) based on the power generation capability thus determined. For the analysis of the second step, we employ a 3D MDLM (Isogai and Harino 2007) (modified doublet lattice method: the doublet lattice method (Albano and Rodden 1969) modified to take into account leading edge suction) coupled with an optimization technique. (As will be discussed later, the optimization method is used to find the optimum fin motion which attains the maximum propulsive efficiency.)

2. 3D NS SIMULATION OF STANDING SWIMMING

In the present paper, we consider one of the bottlenose dolphins (*Tursiops truncates*) studied by Nagai (2002) for the analytical model. The length (l), mass (M) and fineness ratio (F_r: 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 plan-form 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 of the fin is 4.96. The 3D NS code used in the present study is a RANS code (Reynolds averaged Navier–Stokes

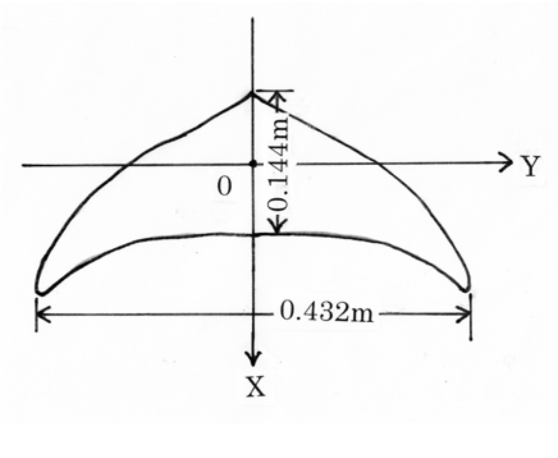


Fig. 2. Plan-form of the model dolphin.

code) originally developed by Isogai (2002). 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 wing and 9 points on the off-wing region) and 51 points normal to the wing surface. The code employs a TVD (total variation diminishing) scheme (Yee and Harten 1987) and the Baldwin and Lomax (1978) 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 ρ_∞. In figure 3, the definitions of the coordinate system and the motion of the caudal fin are shown, where H is the heaving displacement at the pitch axis, θ is the pitch angle and A is the location of the pitch axis. The fanning motion of the caudal fin is given by the following equations:

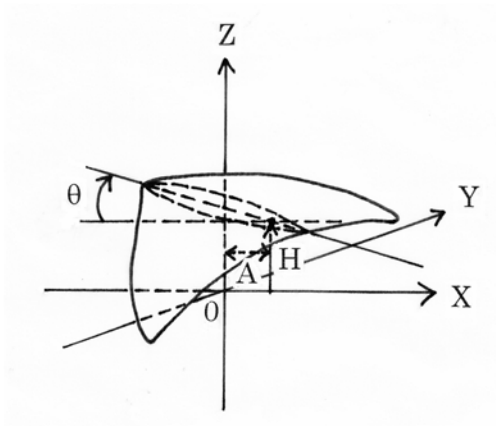


Fig. 3. Definitions of coordinates and fin motion.

$$H=H_0\sin(\omega t) \qquad (1)$$

$$\theta=\theta_0\sin(\omega t+\phi) \qquad (2)$$

where H_0 is the amplitude of the heaving oscillation, θ_0 is the amplitude of the pitching oscillation, ω is the circular oscillation frequency, t is time and ϕ is the phase advance angle of the pitching oscillation ahead of the heaving oscillation. 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. In the present computation, the caudal fin is assumed to be rigid as the first approximation since the major effect comes from the rigid wing motion defined by equations (1) and (2). The airfoil section is assumed to be a symmetrical NACA 0021 airfoil (Fish et al. 2007, Sun et al. 2010). As mentioned in Section 1, the thrust (the force generated in the negative direction of the X-axis (the adverse direction of gravity or the direction of the body axis) generated by the fanning motion of the fin should be equal to the body weight in the standing swimming condition. For this reason, we conducted several trial-and-error computations to find the fanning motion that exactly generates the thrust that sustains the body weight of the present dolphin model. The fanning motion thus found is as follows:

k_H=0.199, H_o/b_r=5.03, θ_o=58.9 deg., ϕ=75.8 deg. and a=-0.617

(V_H=8.95 m/s, f=3.93Hz)

where k_H is the reduced frequency defined by $k_H=\omega b_r/V_H$ and a is defined by ($a=A/b_r$).

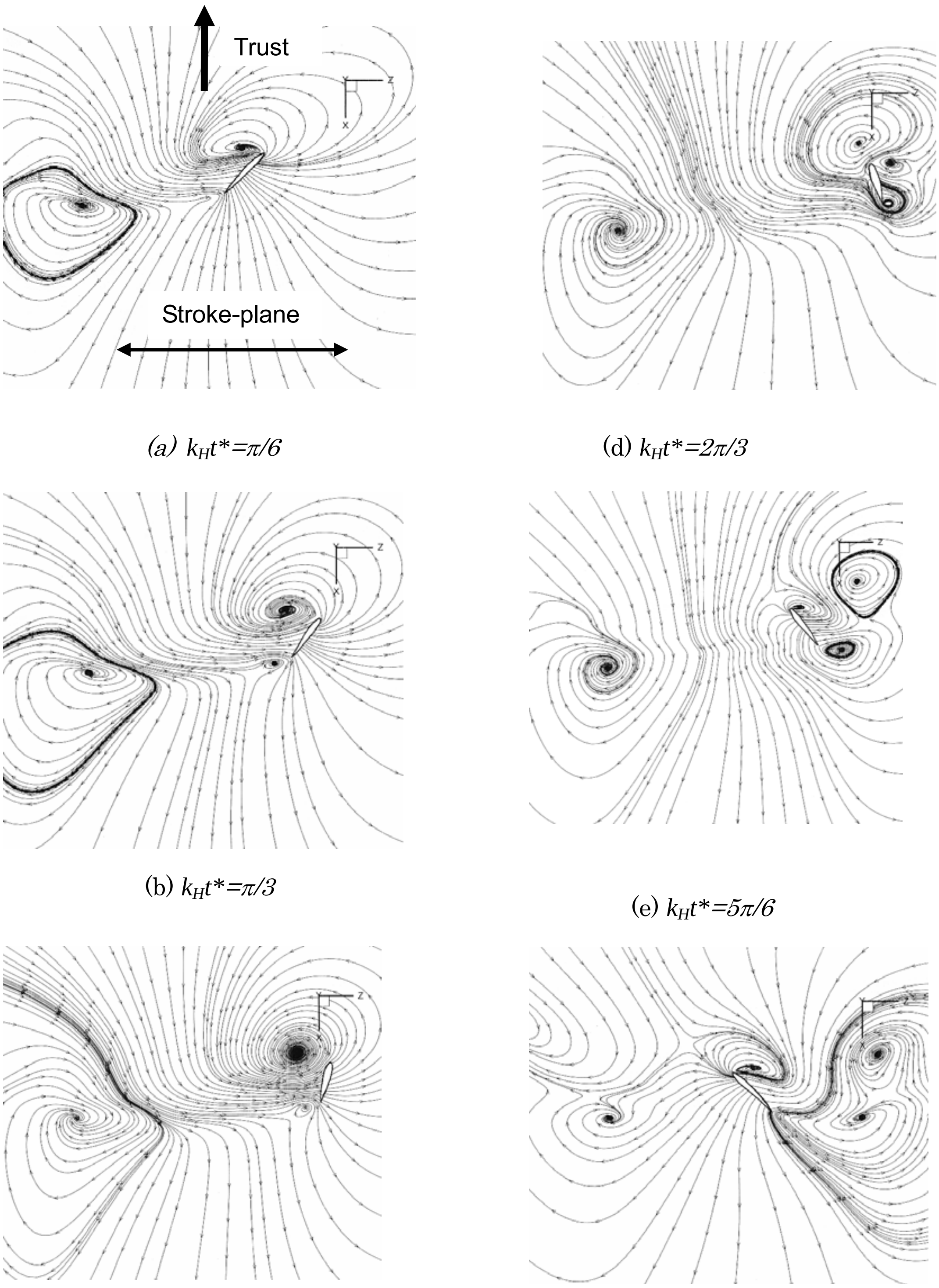
As results of the numerical simulation (we obtained the periodic solution at the third cycle of oscillation), we obtained a time averaged thrust of 1,356 N (138 kgf) and a time averaged power of 9,691 W. These results give a power-mass-ratio (PMR: necessary power per unit mass of body) of 70.2 W/kg. Note that the duration of standing swimming is about 6-10 seconds. According to Wilkie (1960) the power output of a human athlete corresponding to this duration is about 2 h.p. which is equivalent to 25 W/kg for 60 kg of body mass. Therefore, the PMR of dolphin is about 3 times larger than the human athlete. In figure 4, the flow patterns (stream lines) around the 54 percent semi-span during a half-cycle of oscillation are shown. (In figure 4, the dimensionless time t^* is defined by $t^*=t(V_H/b_r)$.) As seen in the figures, large-scale flow separation around the leading edge region is observed. In figure 5, the variations of thrust and power with respect to time during one cycle of oscillation are shown. As seen in the figure, the maximum value of thrust becomes about 270 kgf. It is interesting to see that the variations of thrust and power are almost sinusoidal despite the large-scale flow separation.

It is of great interest to determine the maximum swimming speed of the present model dolphin when the power predicted by the standing swimming is used for conventional swimming in water. This analysis is presented in the next section.

3. ESTIMATION OF PROPULSIVE PERFORMANCE OF A DOLPHIN

3.1 Method of analysis

In order to estimate the propulsive performance of the model dolphin in the water, predicting the body drag is essential. We take the following steps to predict the drag coefficient of the body and to estimate the cruising speed and necessary power:



(a) $k_H t^*=\pi/6$

(b) $k_H t^*=\pi/3$

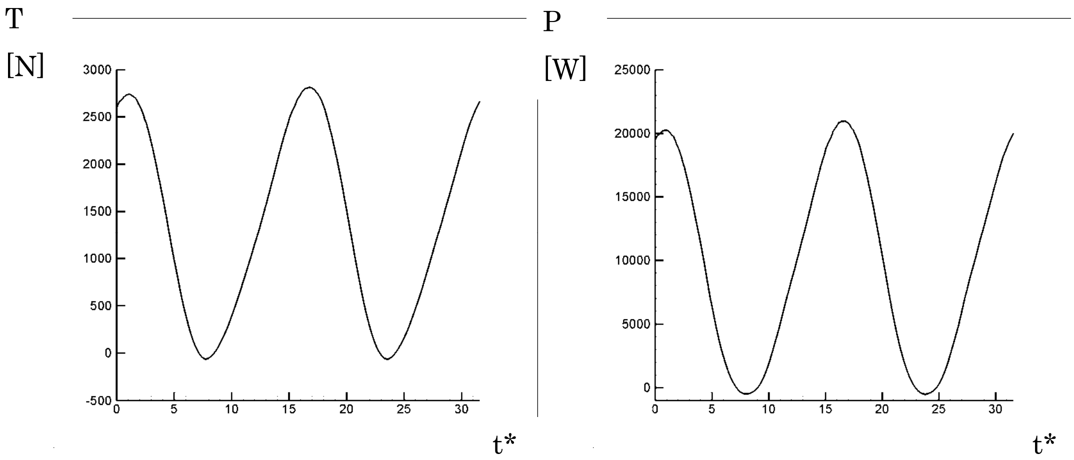
(c) $k_H t^*=\pi/2$

(d) $k_H t^*=2\pi/3$

(e) $k_H t^*=5\pi/6$

(f) $k_H t^*=\pi$

Fig. 4. Flow pattern around 45% semi-span.
($H=H_o\sin(k_H t^*)$, t^*: dimensionless time)



Thrust vs. time Power vs. time

Fig. 5. Variation of thrust and power during one cycle of oscillation for the standing swimming condition.

Step 1: We assume the forward velocity V (m/s), and determine the Reynolds number based on the body length $R_{e,l}$.

Step 2: Using $R_{e,l}$ thus determined and assuming the boundary layer around the body is fully turbulent (because $R_{e,l}$ is larger than 10^7 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 $R_{e,l} \leq 10^9$ (Schlichting 1968):

$$C_f = 0.455/(\log R_{e,l})^{2.58} - 1700/R_{e,l} \quad (3)$$

Step 3: Using C_f obtained in Step 2 and the following equation (Hoerner 1965), 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:

$$C_{D,w}=C_f\,(1+1.5(d/l)^{3/2}+7(d/l)^3) \quad (4)$$

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_t:

$$C_D = (S_w/S_t)C_{D,w} \quad (5)$$

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

Step 5: We determine the optimum fin motion, namely, the reduced frequency k ($k=b_r\omega/V$, note that the definition of k is different from the definition of k_H used in the computation of the standing swimming in Section 2),

H_o/b_r, θ_o, ϕ and *a,* and attain the maximum propulsive efficiency η_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 Harino 2007) coupled with an optimization algorithm of the complex method (Box 1965). The 3D MDLM code can compute the thrust and power of the oscillating wing of an arbitrary plan-form for a given flapping wing motion. The accuracy and reliability of the code is examined (see Isogai and Harino 2007) by comparing with the theory of Chopra and Kambe (1977). 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, θ_o, ϕ, a

Constraints: $C_T \geq C_D$, $H_0/b_r \leq 4.0$

where C_T is the thrust coefficient defined by $C_T=T/((1/2)\rho_\infty V^2 S_t)$

Further details of the optimization procedure using 3D MDLM coupled with the complex method are given in Isogai and Harino (2007). The number of iteration steps used to obtain the converged solution was about 200 -300.

3.2 Results

When we assume a swimming speed of 13 m/s, the computed results obtained at each step are as follows:

$R_{e,l}=2.29\times10^7$, $C_f=0.00257$, $C_{D,w}=0.00299$, $C_D=0.195$

As results of the optimization, we obtain

$\eta_p=0.880$, $C_T=0.195$, $C_W=0.221$

where C_W is the power coefficient defined by $C_W=P/((1/2)\rho_\infty V^3 S_t)$.

The optimum fin motion obtained is

$k=0.217$, $H_o/b_r=4.00$, $\theta_o=40.65$ deg., $\phi=79.7$ deg., $a=-0.506$.

C_T and C_W give a time averaged thrust of $T=619.9$ N and $P=9{,}161$ W, which is slightly less than the power necessary for standing swimming of 9,691 W. The PMR of this case is 66.4 W/kg. This means that this model dolphin can swim at a speed of 13 m/s with a propulsive efficiency of about 88%. The speed of 13 m/s is considerably higher than those observed in the aquariums.

The maximum effective angle of attack (Isogai 1999) of the present optimized fin motion is about 10 deg. Therefore, there may be no flow separation. In order to confirm this, a numerical simulation using the 3D NS code (Isogai 2002, Isogai and Harino 2007) has also been conducted since the existence of the flow separation degrades the propulsive efficiency and thrust considerably as pointed out by Isogai (1999, 2002). The flow condition and the caudal fin motion are the same as those of the optimum fin motion except that the amplitude of heaving oscillation is slightly modified to account for the viscous effect, namely, H_o/b_r=4.03. The results are as follows:

η_p=0.842, C_T=0.202, C_W=0.240, PMR=69.3 W/kg.

These values are very close to those obtained using MDLM, and it is also confirmed by examining the flow pattern that no flow separation occurs during the whole cycle of oscillation. As pointed out by Lang and Norris (1966) and Lockyer and Morris (1989), the swimming speed depends on the duration of the swim. The maximum speed of about 13 m/s predicted by the present analysis might be sustained only for several seconds. Following the same procedure (Steps 1–5), we also computed the power necessary to attain other speeds, namely, V=6.5–12 m/s. The results are summarized in Tables 1 and 2 including those obtained for V=13 m/s. As seen in Table 1, the optimum caudal fin motions determined by the present optimization technique are close agreement with those observed for the actual dolphins (the fluke amplitude A/L=0.23–0.25, Strouhal Number (fA/V)=0.275-0.314, where A is peak-to-peak fluke amplitude) (Rohr and Fish 2004). These numerical data are also plotted in Fig. 6 where the results obtained using 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 satisfies the condition $C_T \geq C_D$.) As seen in the figure, the results of MDLM and the NS code show close agreement. It is interesting that the PMR at speeds of 6.5–9.5 m/s is about 9–29 W/kg, far below the PMR of 70.2 W/kg predicted by the analysis of standing swimming. Note that the speeds of 6.5–9.5 m/s are those reported by Fish (1993), Nagai (2002) and Rohr et al. (2002) as the maximum speeds observed for captive and free ranging dolphins.

Table 1. Optimum caudal fin motion determined by optimization.

V (m/s)	$R_{e,l}$	$C_{D,W}$	C_D	*k*	*a*	H_o/b_r	θ_o *(deg)*	ϕ *(deg)*
6.50	1.14×10^7	0.00325	0.212	0.229	-0.64	3.99	42.4	77.2
9.43	1.66×10^7	0.00311	0.203	0.249	-0.58	3.96	47.0	76.0
12.00	2.11×10^7	0.00302	0.197	0.226	-0.50	4.00	42.7	78.4
13.00	2.29×10^7	0.00299	0.195	0.217	-0.51	4.00	40.7	79.7

Table 2. Results obtained by MDLM and the 3D NS code for the optimum fin motion.

Method	**V (m/s)**	**f (Hz)**	H_o/b_r	η_p	C_T	C_W	**PMR (W/kg)**
MDLM	6.50	3.12	3.99	0.877	0.212	0.242	9.08
	9.43	5.19	3.96	0.885	0.203	0.229	26.2
	12.00	5.99	4.00	0.883	0.197	0.223	52.7
	13.00	6.24	4.00	0.880	0.195	0.221	66.4
3D NS	6.50	3.12	4.02	0.850	0.222	0.261	9.33
	9.43	5.19	4.01	0.852	0.219	0.257	27.3
	12.00	5.99	4.03	0.847	0.203	0.240	54.8
	13.00	6.24	4.03	0.842	0.202	0.240	69.3

4. CONCLUDING REMARKS

In this paper, the standing swimming performance of a model dolphin (*Tursiops truncates*), for which the body in the air is sustained by the caudal-fin submerged in the water (the body weight is equal to the thrust generated by the fanning motion of the caudal-fin) is analyzed using 3D NS code as a first step, obtaining a power-mass-ratio of about 70 W/kg, which is about 3 times larger than that of human athlete. Based on this PMR, the maximum swimming speed of the model dolphin is estimated in the next step using the modified doublet lattice method coupled with an optimization technique which can find the optimum fin motion which attains the maximum propulsive efficiency. As our result, we obtained a maximum speed of about 13 m/s, which is considerably higher than those observed in aquariums. In addition, we estimated the PMR at

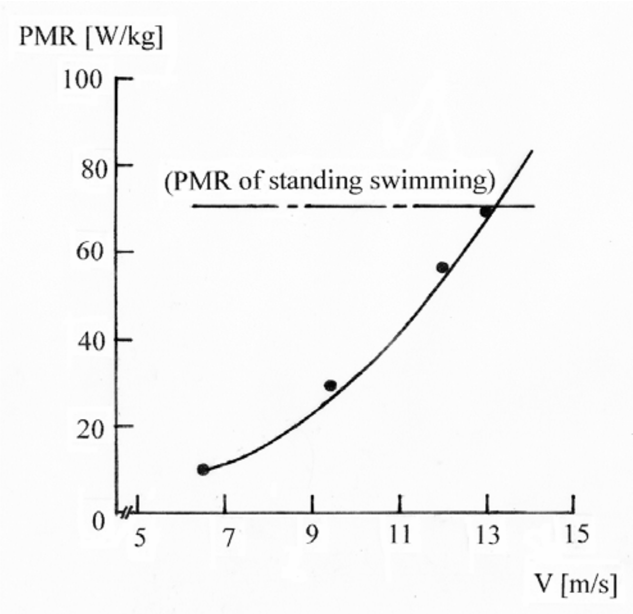


Fig. 6. Variation of power–mass-ratio with respect to swimming speed of the model dolphin (——: MDLM, ●: 3D NS).

other swimming speeds using the same technique, revealing that the PMR of the maximum speed of dolphins observed in the aquariums, namely 6.5–9.4 m/s, are in the range 9–29 W/kg, far below that estimated for the standing swimming condition. It is also shown that the analytical results obtained by the MDLM are in close agreement with those obtained using the 3D NS code.

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