Aerodynamic characteristics of flying fish in gliding flight

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Accepted 17 June 2010

SUMMARY

The flying fish (family Exocoetidae) is an exceptional marine flying vertebrate, utilizing the advantages of moving in two different media, i.e. swimming in water and flying in air. Despite some physical limitations by moving in both water and air, the flying fish has evolved to have good aerodynamic designs (such as the hypertrophied fins and cylindrical body with a ventrally flattened surface) for proficient gliding flight. Hence, the morphological and behavioral adaptations of flying fish to aerial locomotion have attracted great interest from various fields including biology and aerodynamics. Several aspects of the flight of flying fish have been determined or conjectured from previous field observations and measurements of morphometric parameters. However, the detailed measurement of wing performance associated with its morphometry for identifying the characteristics of flight in flying fish has not been performed yet. Therefore, in the present study, we directly measure the aerodynamic forces and moment on darkedged-wing flying fish (Cypselurus hiraii) models and correlated them with morphological characteristics of wing (fin). The model configurations considered are: (1) both the pectoral and pelvic fins spread out, (2) only the pectoral fins spread with the pelvic fins folded, and (3) both fins folded. The role of the pelvic fins was found to increase the lift force and lift-to-drag ratio, which is confirmed by the jet-like flow structure existing between the pectoral and pelvic fins. With both the pectoral and pelvic fins spread, the longitudinal static stability is also more enhanced than that with the pelvic fins folded. For cases 1 and 2, the lift-to-drag ratio was maximum at attack angles of around 0 deg, where the attack angle is the angle between the longitudinal body axis and the flying direction. The lift coefficient is largest at attack angles around 30–35 deg, at which the flying fish is observed to emerge from the sea surface. From glide polar, we find that the gliding performance of flying fish is comparable to those of bird wings such as the hawk, petrel and wood duck. However, the induced drag by strong wing-tip vortices is one of the dominant drag components. Finally, we examine ground effect on the aerodynamic forces of the gliding flying fish and find that the flying fish achieves the reduction of drag and increase of lift-to-drag ratio by flying close to the sea surface.

Key words: flying fish, gliding, wing morphology, lift, drag, stability, ground effect.

INTRODUCTION

The flying fish (family Exocoetidae) is an exceptional marine flying vertebrate showing successful gliding capabilities in air (Hertel, 1966; Rayner, 1986; Vogel, 1994). The flying fish glides over a total distance of as much as 400 m in 30 s by a successive sequence of taxiing and flight, and its maximum flight speed is in the region of 10–20 m s\(^{-1}\) (Hertel, 1966; Fish, 1990; Davenport, 1994). Morphologically, pairs of fins are physically modified to function as wings for flight and some genera such as Cypselurus have a body with flattened bottom to generate additional lift (Breder, 1930; Davenport, 1992; Davenport, 1994). The flying fish’s morphological and behavioral adaptations for its excellent gliding-flight capability have been examined, and several aspects (e.g. flight pattern of gliding and taxiing, the relationship between wing loading and aspect ratio of the pectoral fins, and possible importance of ground effect) of its flight have been determined or conjectured (Davenport, 1994).

Although reasons for the flight of flying fish have been suggested (i.e. escape from underwater predators or saving of transport cost) (Rayner, 1986; Davenport, 1994), the exact reason is still not clear. Nevertheless, their behavioral adaptation for flight is quite unique. When they emerge from the sea or the gliding speed decreases at the end of one glide, some flying fish dip the lower lobe of the caudal fin and beat the tail, which is called taxiing (Hertel, 1966; Fish, 1990; Davenport, 1992; Davenport, 1994). Supported by the wings (stretched pectoral fins), they use this taxiing to gain additional speed for successive gliding flights (Breder, 1930; Mills, 1936a; Mills, 1936b). The glide trajectory of flying fish has been observed to be almost straight (i.e. parallel to the sea surface) and its gliding height is an order of full span of the pectoral fins (Latimer-Needham, 1951; Hertel, 1966; Fish, 1991; Kawachi et al., 1993). Kawachi et al. (Kawachi et al., 1993) analyzed the gliding path of flying fish, using a simple analytical method based on the energy balance and an optimal control theory, to evaluate the gliding strategies for maximum gliding distance and time, respectively. They found that its straight gliding path is for maximum gliding distance, rather than for the longest gliding time.

As mentioned above, from the field observations and measurements of morphometric parameters, several features of flying-fish flight have been determined. However, detailed data on the wing performance are required to identify the flight capability of flying fish. Hence, in the present study, we investigated the wing performance of flying fish by directly measuring the aerodynamic forces, moment and conducting flow visualizations in a wind tunnel. We also examined how the flight performance is affected by the wing morphology and compared it with those of other flying animals. Finally, we examined the effect of water and solid surfaces underneath the flying fish model in a wind tunnel, and measured the aerodynamic forces and performed flow visualization to study the ground effect.
MATERIALS AND METHODS
Flying-fish models

About 40 darkedged-wing flying fish (Cypselurus hiraii, Abe) were caught in the East Sea of Korea in cooperation with the National Federation of Fisheries Cooperatives of Korea. The flying fish were then separately wrapped in a plastic bag in a fresh state and then all of them were put in an icebox, which were put down naturally. Five fish of similar sizes were selected and stuffed in the appropriate gliding positions (see below) at the Korea Research Center of Maritime Animals. These five models of flying fish are used in our experiment. The flying fish were stuffed within a day after they were captured. During the preparation of our fish models, they were neither frozen nor preserved in alcohol. Before stuffing the flying fish, the body mass, wing lengths and overall three-dimensional body geometry of each fish were measured, and these properties were conserved during the stuffing procedure as far as possible. To maintain the geometries of wings and body, the wings were fully spread and fixed, and urethane foam was injected inside the body.

The flying fish can be classified into two categories depending on the wing configuration. One is the ‘four-winger’ (Davenport, 1992; 1994) or ‘biplane-type’ (Breder, 1930; Fish, 1990), where both pectoral and pelvic fins are hypertrophied (e.g. Cypsilurus). The other is the ‘two-winger’ or ‘monoplane-type’, in which only the pectoral fins are enlarged (e.g. Exocoetus). Cypselurus hiraii belongs to the ‘four-winger’ or ‘biplane-type’ category.

To investigate the effect of wing morphology on the aerodynamic performance of flying fish, wing–body configurations of the five model fish were chosen as follows (Fig.1): (1) both the pectoral and pelvic fins spread (models L1–L3); (2) only pectoral fins spread with pelvic fins folded against the body (model M); (3) body only with both the pectoral and pelvic fins folded (model N). Furthermore, we varied the lateral dihedral angle of the pectoral fins for models L1–L3 to determine how it affects the aerodynamic performance. The wings of flying fish are composed of soft membrane supported by fin rays. Their leading edge is stiff but the trailing edge is flexible. All the fin rays are located on the lower wing surface, so the upper wing surface is smooth and the lower surface is ribbed. In the present study, the wing shape of each model was determined by fully spreading out the flying fish fin. Because the dried fin is weak and easily torn, we attached a very thin nylon cloth to the upper fin surface. For each model, we measured the morphometric parameters that are defined in Fig.2.

Force and moment measurements

Force and moment measurements were conducted in an open-circuit blowing-type wind tunnel. Fig.3 shows a schematic diagram of the flying-fish model in the wind tunnel. x, y and z denote the streamwise, vertical and spanwise directions, respectively, and the origin is located at the center of gravity of the flying-fish model (near the trailing edge of the pectoral fins in the streamwise direction). The test section was made of acrylic and measured 3 m × 0.3 m × 0.6 m in the streamwise, vertical and spanwise directions, respectively. The maximum wind speed at the test section was 30 m s⁻¹, and the uniformity of the mean velocity and background turbulence intensity were both within 0.5% at 12 m s⁻¹. The aerodynamic force and moment on the fish model were measured with a six-axis force/torque sensor (NANO17, ATI Industrial Automation, Inc., Apex, NC, USA). The resolutions of the sensor in measuring the force and moment are 1/1280 N and 1/256 Nm, respectively. From the weight test, we found that the sensor showed an excellent linearity (±1%) in the range of interest.

A slender strut was assembled on the lower surface of the fish model at a streamwise location near the trailing edge of the pectoral fins and was directly mounted on the force/torque sensor. To minimize the effect of strut, its cross-sectional shape was chosen to be a slender ellipse with a ratio of major to minor axis of 3.36. The height of the strut was adjusted to locate the flying-fish model at the center of the test section. Varying the attack angle (α; angle between the longitudinal body axis and the free-stream direction; Fig.2) from −15 deg to 45 deg by increments of 5 deg, we simultaneously measured the lift, drag and pitching moment. The angle of attack was controlled by an in-house device equipped with a revolving stage which had a resolution of 1 deg of rotation. The signals from the force/torque sensor were digitized by an A/D converter (PXI-6259, National Instruments Co., Austin, TX, USA) and sampled for 300 s at the rate of 10 kHz to obtain a fully converged mean value. The voltage outputs from the sensor were calibrated using the calibration matrix supplied with the sensor. The forces and moment were measured five times for each fish model and the averaged values are reported. The repeatability errors of force and moment measurements were within ±1.5%. The lift, drag and pitching moment on the struts alone were separately measured and used for the correction of those measured with each model. The measurements were performed at the free-stream velocity (u∞) of 12 m s⁻¹, the corresponding Reynolds number of which, based on
the average wing chord length \(c\) of pectoral fin, is \(Re = 1.9 \times 10^4\), depending on the model. This meets the typical condition of gliding flight of real flying fish (Hertel, 1966; Rayner, 1986; Fish, 1990; Davenport, 1994).

**Ground effect**

To examine the aerodynamic performance of flying-fish flight in ground effect, we considered two kinds of ground, i.e. solid and water surfaces. To provide a water surface beneath the flying-fish model, we eliminated a part of the bottom wall of the test section \([0.4 \, \text{m} \times 0.5 \, \text{m} \times \ell]\) and installed a tank in its place. This was filled with water to just below the bottom wall of the test section to avoid any overflow. For each ground condition, we measured the drag and lift forces on the models L3 and N at the attack angle \(\alpha\) of 0 deg by varying the flight height \(h\), i.e. the distance between the ground and the lower surface of the body. Owing to the slight inconsistency of the water surface, the non-dimensional height \(r = h/(S/2) = 0.33\) is the closest distance between the body and water surface \(r = 0.21\) for a solid surface.

**Flow visualization**

To investigate the flow structure around a gliding flying fish and identify the sources of its aerodynamic performance, we performed a smoke-wire flow visualization. For flow visualization, we focused on the model L3, which showed the best aerodynamic performance of the five flying-fish models considered (see below). The flow visualizations were performed at \(u_w = 6 \, \text{m} \, \text{s}^{-1}\) for a clear representation of flow structures and the corresponding \(Re\) was \(\approx 10^4\). We installed a smoke wire in front of the leading edge of the pectoral fins and observed the streamwise flow structure (side view) at \(z/S = 0, 0.1, 0.18\) and \(0.49\), respectively, where \(S\) is the full span of the pectoral fins (see Fig. 2). We varied the attack angle \(\alpha\) at 0 deg, 10 deg, 20 deg and 30 deg. The RP-1 fog fluid from Red Point Inc. (McAllen, TX, USA) and a 6 W argon laser (Stabilite 2017; Spectra-Physics, Santa Clara, CA, USA) with modulator (N30210) were used for the smoke-generating material and light source, respectively. The triggering of the smoke-line generation, digital camera (10D) and laser operation were synchronized via an A/D converter (PXI-6259; National Instruments Co.). We also used an array of smoke wires (14 vertical nichrome wires of the diameter of 0.2 mm connected to multiple 30 V DC power supplies and solid state relays) to observe the cross-plane flow structure (end view) in the wake behind a flying fish. We investigated the modification of the wake structure behind a flying fish in ground effect by varying the flight height \(r\) (=0.33, 0.67 and 1.12, respectively).

**RESULTS AND DISCUSSION**

**Morphometrics**

Table 1 shows the morphometric parameters measured for five flying-fish models. Definitions of these parameters are shown in Fig. 2. It is known that the adult flying fish are of variable size \((150–500 \, \text{mm} \, \text{maximum} \, \text{standard} \, \text{length})\) (Davenport, 1994) and the standard lengths \((SL)\) of the present models are about 200 mm. The pectoral fins are slightly swept back as shown in Fig. 1 and
Table 1. Morphometric parameters for the darkedged-wing flying fish (Cypselurus hiraii) models

<table>
<thead>
<tr>
<th>Model*</th>
<th>L₁</th>
<th>L₂</th>
<th>L₃</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard length, SL (mm)</td>
<td>205</td>
<td>209</td>
<td>203</td>
<td>199</td>
<td>202</td>
</tr>
<tr>
<td>Body mass, W (kg)</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Wing area of pectoral fins A₁ (mm²)</td>
<td>7069</td>
<td>6997</td>
<td>6937</td>
<td>5498</td>
<td>0</td>
</tr>
<tr>
<td>Wing area of pelvic fins A₂ (mm²)</td>
<td>1603</td>
<td>1745</td>
<td>1837</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Planform area of body A (mm²)</td>
<td>4377</td>
<td>4501</td>
<td>4474</td>
<td>4258</td>
<td>4640</td>
</tr>
<tr>
<td>Wing span†, S (mm)</td>
<td>252</td>
<td>260</td>
<td>261</td>
<td>233</td>
<td>–</td>
</tr>
<tr>
<td>Aspect ratio†, AR (S²/A₁)</td>
<td>9.0</td>
<td>9.7</td>
<td>10.7</td>
<td>9.9</td>
<td>–</td>
</tr>
<tr>
<td>Average wing chord length†, c (mm)</td>
<td>28</td>
<td>27</td>
<td>24</td>
<td>24</td>
<td>–</td>
</tr>
<tr>
<td>Dihedral angle of pectoral fin, β₁ (deg)</td>
<td>22</td>
<td>12</td>
<td>7</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>Incidence angle of pectoral fin, β₂ (deg)</td>
<td>12</td>
<td>15</td>
<td>12</td>
<td>8</td>
<td>–</td>
</tr>
<tr>
<td>Incidence angle of pelvic fin, β₃ (deg)</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Location of center of gravity, xcg/SL</td>
<td>0.39</td>
<td>0.43</td>
<td>0.42</td>
<td>0.44</td>
<td>0.47</td>
</tr>
</tbody>
</table>

*Graphical representation of each parameter is shown in Fig. 2.
†Aspect ratio, wing span and averaged chord length are based on the pectoral fins only.

have an aspect ratio of 9.0~10.7, which is comparable to those of birds (Withers, 1981; Fish, 1990; Vogel, 1994). In the process of stuffing the flying fish, the lateral dihedral angles (β₁) of the pectoral fins were artificially modified to be 22 deg, 12 deg and 7 deg for models L₁, L₂ and L₃, respectively, but other parameters were kept close to the natural state. Similar to the wings of modern aircraft that have the positive incidence angle of several degrees, the pectoral and pelvic fins of flying fish also have positive incidence angles (β₂ and β₃) from the longitudinal body axis (Fig. 2). In the present models, the incidence angles of pectoral and pelvic fins were 8~15 deg and 2~5 deg, respectively. It has been suggested that the flying fish controls these angles according to the flight conditions (Hubbs, 1933), but the ranges of the incidence angle during real gliding flight are not available in the literature. We found only one illustrative diagram (Breder, 1930) in which the incidence angles of pectoral and pelvic fins are shown to be 17 deg and 3 deg, respectively.

Fig. 4 shows the allometric relationship between the wing loading and standard length of our fish models (L₁, L₂ and L₃), together with those from Fish (Fish, 1990) and Davenport (Davenport, 1992). For this figure, our wing-loading data were obtained in two different ways: one is the fish body mass, measured directly before stuffing, and the other is the lift force measured directly from our wind tunnel experiment at the attack angle of 0 deg. The reason why the attack angle of 0 deg was chosen is given later in this paper. As shown in Fig. 4, the two data are nearly same for models L₁ and L₃, but shows about 30% deviation for model L₂. Overall, our data are close to those of Davenport (Davenport, 1992) and smaller than those of Fish (Fish, 1990). If the fish wing had shrunk after death and its shape significantly modified (Davenport, 1992), the lift force measured from the wind tunnel experiment would be remarkably different from the body mass. However, as shown in Fig. 4, the two data (the mass and lift force) agree very well with each other, indicating that our fish models (at least L₁ and much L₃) did not shrink much.

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**Force and moment measurements**

The lift (Cₜ) and pitching moment (Cₚ) coefficients are defined as Cₜ = L/(ρu²A₁), Cₚ = D/(ρu²A₁) and Cₚ = D/(ρu²A₂), respectively, where ρ is the air density, A is the reference area (A₁ + A₂ + Aₓ) for the flying-fish model, and L, D and M are the lift, drag and pitching moment, respectively. Since we measured total aerodynamic forces and moment exerted on the wings and body of flying fish, we defined the reference area as the sum of the planform areas of the pectoral (A₁) and pelvic (A₂) fins and body (A₃).

Fig. 5 shows the variations of lift (Cₜ) and drag (Cₚ) coefficients with the angle of attack (α) for models L₁–L₃, M and N. As shown in Fig. 5A, the lift coefficients for models L₁–L₃ and M are largest at α≈30–35 deg. In previous studies, the flying fish was observed to emerge from the sea at α≈30 deg from the horizontal surface and perform taxiing (Hertel, 1966; Davenport, 1994). Because the largest lift force is required for the flying fish to take off, the present result supports those observations assuming that the take-off angle is similar to the emerging angle of the fish from the sea. Interestingly, the lift coefficients of models L₁–L₃ and M do not fall off sharply and show broad peaks at high angles of attack with little loss of lift force even after stall. This observation agrees with the characteristics of the thin-airfoil stall suggested by McCullough and Gault (McCullough and Gault, 1951) who classified the characteristics of the airfoil stall at low Reynolds number as the trailing-edge stall, leading-edge stall and thin-airfoil stall, respectively. With the thin-airfoil stall occurring on a thin airfoil with a sharp leading edge, the lift coefficient curve is relatively flat even after stall. Since the wings of our fish models were thin and operated at low Reynolds...
number, they had the thin-airfoil stall characteristics. With smaller $\beta_1$ (from L1 to L3), the lift coefficient becomes larger at $\alpha>10$°, but the amount of its difference is quite small (less than 7%). However, the drag coefficients for models L1–L3 and M were minimum at $\alpha=-10$° to $-5$° and rapidly increased with increasing $\alpha$ (Fig. 5B). Without the enlarged pelvic fins (model M), the lift coefficient is smaller than those with pectoral and pelvic fins (models L1–L3) by more than 20% at $\alpha\geq0$°. The drag coefficient of model M is similar to or smaller than those of models L1–L3 by about 10% at $\alpha<0$°. Thus, the enlarged pelvic fins contribute to the generation of aerodynamic force, especially to the increase of lift force, which is attributed to the accelerated jet-like flow structure between the pectoral and pelvic fins (see below).

The variation of pitching moment coefficient ($C_m$) with $\alpha$ is shown in Fig. 6. For a glider to have a longitudinal static stability, the nose-down pitching moment should increase with increasing $\alpha$ (Thomas and Taylor, 2001). That is, a negative slope of the pitching moment curve ($\partial C_m/\partial \alpha<0$) is necessary for positive static stability: the more negative (steeper) the slope, the more stable the glider. In addition, a positive pitching moment (nose-up pitching moment) is necessary at the attack angle of zero lift for a balanced flight (Thomas and Taylor, 2001). As shown in Fig. 6, the slopes of the pitching moment curve were more negative for models L1–L3 than that for model M, indicating that the enlarged pelvic fins enhance the longitudinal static stability. Thus, the pelvic fins have a similar role to that of a tailplane. The pelvic fins of shark have also been shown to increase, to a small extent, the static stability for pitching movements (Harris, 1938). For models L1–L3, the slope of pitching moment coefficient curve of L1 (having largest $\beta_1$) becomes slightly more negative than the others, so model L1 showed slightly better longitudinal stability than models L2 and L3. In general, it is known that the lateral dihedral angle of the wing enhances the lateral static stability of the wing at the cost of lift (Thomas and Taylor, 2001). In our flying fish, the lateral dihedral angle also slightly enhanced the longitudinal static stability. Without both the pectoral and pelvic fins, a positive slope of the pitching moment curve was observed, indicating unstable static characteristics.

In Fig. 7, the variations of the lift-to-drag ratios ($L/D$) for models L1–L3, M and N with $\alpha$ are shown. For models L1–L3 and M, the $L/D$s are maximum at $\alpha=-5$ to 0°, indicating that the flying fish exhibits best gliding capabilities when it glides nearly parallel to the sea surface. This also agrees with previous observations that most trajectories of flying fish are observed to be nearly parallel to the sea surface (Latimer-Needham, 1951; Hertel, 1966; Fish, 1991; Kawachi et al., 1993). At $\alpha<5$°, the $L/D$s of models L1–L3 are larger than that of model M, indicating that the enlarged pelvic fins increase the glide distance of the flying fish. In previous studies, it was observed that the four-winger (biplane-typed) flying fish glides longer distances than the two-winger (monoplane-typed) flying fish.
To compare the gliding performance of the flying fish, the glide polar ($C_L$ vs $C_D$) of our flying fish (model $L_3$ showing the largest value of maximum $L/D$) is shown together with those of other animals’ wings (when they glide) and NACA2409. The morphometric and aerodynamic properties of various wings are listed in Table 2. Note that, for other insects and birds (Fig. 8), the lift and drag forces are measured only on the wings isolated from the body. The slope of the straight line, which is tangential to the polar curve and passes through the origin, represents the maximum lift-to-drag ratio of the relevant wing (see, for example, the dashed line in Fig. 8 for the $L_3$ model). In terms of maximum $L/D$, the gliding performance of flying fish is worse than that of NACA2409, wings of nighthawk and vulture having high aspect ratios (see Table 2), but is better than that of flying insect wings (note, however, that their operating Reynolds numbers are lower than our models), and comparable to those of wings of birds such as the hawk, petrel and wood duck.

As mentioned before, the data from other animals obtained by previous researchers (in Table 2 and Fig. 8) were obtained from the measurements on the wing only. During the gliding flight of birds or insects, the body generates additional lift and drag, so one should include them for the estimation of aerodynamic performance. For gliding birds, the planform area of a bird’s body is less than one-third of total planform area of wings and body (Tucker and Parrott, 1970). However, the body lift has been measured to support about 16% of the total lift force [zebra finch at gliding flight (Tobalske et al., 1999)], and the drag force on the body may not be negligible but smaller than that of the wings. Thus, we may estimate that the total $C_{L,\text{MAX}}$ and $C_{D,\text{MIN}}$ of the wings and body of gliding bird (based on the total planform area) would be slightly smaller than that of the wing only. In the case of a flying insect, the lift on the body is a small fraction (less than 10%) of the total lift, but the drag on the body is much larger than that of the wing only. It follows that the total $C_{L,\text{MAX}}$ and $C_{D,\text{MIN}}$ of the body and wings of a flying insect would be smaller and larger, respectively, than those of the wing only. Thus, we may conclude that the aerodynamic performance of our flying fish is comparable to those of certain species of bird and better than those of most flying insects, even after considering the drag and lift forces on the body.

**Flow structure around a gliding flying fish**

Fig. 9 shows the streamwise flow structures around a flying fish (model $L_3$ at four different angles of attack). At the spanwise location where pectoral and pelvic fins overlap (left column), we observed an interesting flow structure. Flow goes smoothly over the pectoral and pelvic fins without separation at $\alpha$=0 deg, at which the lift-to-drag ratio is maximum (Fig. 7). At $\alpha$=10 deg, the flow separates at the leading edge of the pectoral fin and re-attaches on the fin forming a separation bubble. When the attack angle is larger than 10 deg, full separation occurs at the leading edge of the pectoral fin and the drag force rapidly increases with increasing $\alpha$. As noted before, our flying fish model has a tandem wing configuration (bi-plane type), where the upper (pectoral fins) and lower (pelvic fins) wings were staggered and the incidence angles were 12 deg and 5 deg, respectively. Because of this configuration, at $\alpha$=10 deg, there was a jet-like accelerating flow (denoted by the circles in Fig. 9B,C) at which both the pectoral and pelvic fins exist. At the spanwise

![Graph of glide polars](image)

**Table 2. Morphometric and aerodynamic characteristics of various animal wings**

<table>
<thead>
<tr>
<th>AR</th>
<th>$L/D_{\text{MAX}}$</th>
<th>$C_{L,\text{MAX}}$</th>
<th>$C_{D,\text{MIN}}$</th>
<th>$Re$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flying fish (Cypselurus hiraii)</td>
<td>10.7</td>
<td>4.37 (0)</td>
<td>0.78 (35)</td>
<td>0.055 (−10)</td>
<td>2.0×10^4</td>
</tr>
<tr>
<td>Swallowtail butterfly (Graphium polices polices)</td>
<td>3.72</td>
<td>3.58 (5)</td>
<td>0.65 (40)</td>
<td>0.036 (0)</td>
<td>1.4×10^4</td>
</tr>
<tr>
<td>NACA 2409</td>
<td>12</td>
<td>19.1 (5)</td>
<td>1.51 (19.5)</td>
<td>0.01 (0)</td>
<td>5.0×10^4</td>
</tr>
<tr>
<td>Vulture wing (Coragyps atratus)</td>
<td>15.8</td>
<td>17 (5)</td>
<td>1.15 (12)</td>
<td>0.02 (0)</td>
<td>O(10^9)</td>
</tr>
<tr>
<td>Nighthawk wing (Chordeiles minor)</td>
<td>8.2</td>
<td>9 (6)</td>
<td>1.15 (15)</td>
<td>0.05 (3)</td>
<td>O(10^9)</td>
</tr>
<tr>
<td>Hawk wing (Buteo lineatus)</td>
<td>6.0</td>
<td>3.8 (6)</td>
<td>1.0 (25)</td>
<td>0.07 (2)</td>
<td>O(10^9)</td>
</tr>
<tr>
<td>Petrel wing (Oceanodroma leucorhoa)</td>
<td>8.2</td>
<td>4.0 (8)</td>
<td>0.88 (13)</td>
<td>0.07 (0)</td>
<td>O(10^9)</td>
</tr>
<tr>
<td>Fruit fly wing (Drosophila virilis)</td>
<td>5.5</td>
<td>1.8 (15)</td>
<td>0.87 (30)</td>
<td>0.33 (0)</td>
<td>2.0×10^9</td>
</tr>
<tr>
<td>Bumblebee wing (Bombus terrestris)</td>
<td>6.7</td>
<td>2.48 (15)</td>
<td>0.78 (30)</td>
<td>0.13 (0)</td>
<td>1.2×10^9</td>
</tr>
<tr>
<td>Wood duck wing (Aix sponsa)</td>
<td>6.2</td>
<td>3.8 (8)</td>
<td>0.9 (20)</td>
<td>0.1 (1)</td>
<td>O(10^9)</td>
</tr>
</tbody>
</table>

Note that data from previous studies are based on a wing only without the body.

1Numbers inside the parentheses denote the attack angles (in degrees) at which the $L/D_{\text{MAX}}$, $C_{L,\text{MAX}}$ and $C_{D,\text{MIN}}$ are measured for each wing.

2Model $L_3$. 
location of the middle of the pectoral fin (right column), however, the pelvic fin does not exist. Thus, the jet-like flow structure is not observed. This jet-like flow structure accelerates the flow above the pelvic fin and thus increases its lift force as we found from force measurement (Fig. 5). Comparing the wake widths behind the pectoral fin at $z/S=0.1$ and 0.18, we see that the jet-like flow also reduces the wake width behind the pectoral fin (denoted by the vertical bars in Fig. 9C,D) and thus is expected to reduce the drag force exerted on the pectoral fin.

As shown, the pectoral fin of flying fish has a positive incidence angle ($\beta_2$) from the horizontal, such that wing-tip vortices are readily generated even when the flying fish glides nearly parallel to the sea surface. In addition to this, the wing of flying fish is very thin and has a pointed wing-tip shape. Consequently, strong counter-rotating wing-tip vortices exist in the wake behind a gliding flying fish even at $\alpha=0^\circ$ deg (Fig. 10). This wing-tip vortex induces a downward flow in the wake, resulting in an induced drag in addition to the form and skin friction drag. For subsonic aircrafts or fighter planes operating at the Reynolds number of $10^7$−$10^8$, the skin friction (of the wings and body) and induced drag constitute more than 90% of total drag force (Filippone, 2000). However, the contribution of
induced drag to total drag increases and that of the skin friction decreases with decreasing Reynolds number (Blake, 1983). Therefore, it seems that the induced drag is one of the dominant drag components of the gliding flying fish (Re ~10⁴).

**Aerodynamic properties of flying-fish body**

Although the flying fish uses its hypertrophied pectoral and pelvic fins in gliding, the fins are usually folded against the body when the fish swims in the sea. In this section, we briefly investigate the aerodynamic properties of the body itself. The variations of lift, drag (Fig. 5) and pitching moment coefficients (Fig. 6) are shown for the model N (body only with both the pectoral and pelvic fins folded) with $\alpha$. The lift coefficient is nearly zero at $\alpha=-10$ deg and the drag coefficient is lowest at $\alpha=10$ deg. Both the drag and lift coefficients rapidly increase with increasing $\alpha$ at $\alpha>10$ deg (Fig. 5). Like almost all other fishes during swimming (Harris, 1938), the flying-fish body itself shows longitudinally unstable characteristics in the pitching direction: that is, $\partial C_M/\partial \alpha>0$ (Fig. 6). However, the flying fish with the pectoral and pelvic fins unfolded (models L₁–L₃ and M) shows statically stable characteristics.

To estimate the contribution of the flying-fish body to aerodynamic forces, we show the ratios of the drag and lift forces of model N to those of model L₃ with $\alpha$ in Fig. 11. Although the body shapes of two models are not exactly same, the size of the bodies are very similar to each other (see Table 1), so the contribution of the body to the aerodynamic force generation can be estimated. At $\alpha\leq10$ deg, the contribution of the body to total lift force is small (less than 7%), but increases with increasing angle of attack at $\alpha>10$ deg and reaches almost 20% of total lift force at $\alpha=40$ deg. However, the contribution of the body to total drag force decreases with the attack angle at $\alpha<10$ deg, becomes minimum at $\alpha=10$ deg, and slowly increases (from 10% to 15%) at $\alpha\geq10$ deg. Since the wing of flying fish is very thin and the incidence angle of pectoral fins of model L₃ is $\beta=12$ deg, the contribution of the body to total drag force is largest at $\alpha=-10$ deg (about 75%).

**Ground effect**

It has been shown in the literature that the ground effects are different for two- and three-dimensional bodies. For a two-dimensional body, the drag force decreases when the height between the body and the...
The drag by 14% was obtained at a certain angle of attack. Aerodynamic forces of a gliding flying fish (see Materials and Methods) were investigated by Davenport (1994; Vogel, 1994; Davenport, 2003). We installed a water surface at the bottom of the wall of the test section and performed experiments on the effect of the water surface (slip boundary) on the drag of a flying fish. Fish (1990; Kawachi et al., 1993; Barlow et al., 2001; Zhang et al., 2004). Here, the drag reduction comes from two sources; one is the reduction of induced drag as the ground affects the movement and diffusion rate of the counter-rotating tip vortices, and the other is the reduction of form drag as the blockage effect by the ground hinders the generation of the wake vortices. By contrast, in previous studies based on a potential flow lifting-line theory (Blake, 1983; Rayner, 1991), it has been suggested that the reduction of induced drag is obtained when the ratio of the flight height (h) to the half wing span (b) is smaller than 0.5 (e.g. about 20% reduction of the induced drag at r=0.3). Since our flying-fish model has both wing and body, the ground effect should be complicated.

When they fly nearer the ground, the flyers can obtain considerable advantages in the aerodynamic performance as noted above (Blake, 1983; Rayner, 1991). It has been suggested that the flying fish takes advantage of the ground effect to prolong the gliding distance by increasing the lift-to-drag ratio, especially during take-off and end phase of the flight (Fish, 1990; Kawachi et al., 1993; Davenport, 1994; Vogel, 1994; Davenport, 2003). We installed a water surface at the bottom of the wall of the test section and investigated the effect of water surface (slip boundary) on the aerodynamic forces of a gliding flying fish (see Materials and methods). Furthermore, we considered two fish models (L3 and N) in ground effect, i.e. with and without the fins (wing).

Fig. 12 shows the variations of drag force and lift-to-drag ratio with the ratio of the flight height (h) to the half wing span (b=5/2, r=h/b). The lift force was almost unaffected by the ground for all r values considered in this study (not shown here). The amount of drag reduction due to ground effect is larger for a water surface than for a solid surface. For model L3, the drag force was nearly constant at r>0.35 but decreased by 9% at r=0.21 in the case of solid surface. However, the drag force with a water surface started to decrease with decreasing r from r=0.97 and maximum reduction of the drag by 14% was obtained at r=0.33. Consequently, the lift-to-drag ratios for both solid and water surfaces increased with decreasing r from r=0.35 and 0.97, respectively (Fig. 12B). For model N (body only), drag reductions of 4% (at r=0.21) and 7% (at r=0.33) were from its body only for solid and water surfaces, respectively, whereas the of 9% and 14% were from the body and wing for model L3. Therefore, the drag reduction by ground effect comes almost equally from the body and wing.

Since it is assumed that a significant amount of induced drag is exerted on the flying fish, we visualized the wake behind the flying fish to examine the wing-tip vortices with varying flight height. Fig. 13 shows the flow visualizations at three y–z planes for r=1.12 and 0.33 in the case of water surface. When r was small (r=0.33), the wing-tip vortex interacted with the water surface and lost its strength faster than that when r=1.12 (Zerihan and Zhang, 2003; Barber, 2007), resulting in the reduction of the induced drag. Therefore, the drag reduction on a gliding flying fish in ground effect comes from (1) the direct blockage effect between the whole body and the ground, and (2) modification of the wing-tip vortices. Considering the real situation of gliding flying fish, the slip velocity of the water surface should be $u_{wind}=u_{ind}$, where $u_{wind}$ is the flying speed of the fish and $u_{ind}$ is the wind-induced surface velocity; $u_{ind}=0.03u_{w}$ (Wu, 1975; Tsanis, 1989). The experimental setup satisfying this requirement is not possible with the wind tunnel used, but we expect bigger drag reduction in the real situation than that shown in Fig. 12A.
Concluding remarks

For the first time, we have performed a direct wind-tunnel experiment to investigate the aerodynamic properties of flying-fish flight and provided qualitative and quantitative data for the flying fish flight. Force measurements were performed for the real flying-fish models with different wing morphologies. The aerodynamic performance of flying fish is comparable to those of various bird wings, and the flying fish has some morphological characteristics in common with the aerodynamically designed modern aircrafts. The maximum lift coefficient of flying fish is measured at $\alpha=30$–$35^\circ$ where the flying fish is observed to emerge from the sea. The lift-to-drag ratio is largest at $\alpha=-5$–$0^\circ$, indicating that the best gliding performance can be achieved when the flying fish glides nearly parallel to the sea surface. As the lateral dihedral angle of the pectoral fins decreases, the lift coefficient slightly increases. In addition to the enlarged pectoral fins, the large pelvic fins have an important role in enhancing the lift-to-drag ratio and longitudinal static stability. The enhancement of the lift-to-drag ratio from the pelvic fin is attributed to the jet-like flow existing between the pectoral and pelvic fins. For both solid and water surfaces, the drag coefficient decreases and thus the lift-to-drag ratio increases as a result of the ground effect, indicating that the flying fish obtains substantial advantages by gliding close to the sea surface. The ground effect is more pronounced for the water surface having a slip boundary condition.

In the present study, as shown above, we examined the variations of aerodynamic force with the changes in the wing morphology, such as the angle of attack and lateral dihedral angle. The gliding performance (i.e. maximum lift-to-drag ratio) was enhanced as the lateral dihedral angle of pectoral fins decreased. However, in a few previous studies, it was observed that the flying fish glides with pronounced lateral dihedral angle of the pectoral fins (Hubbs, 1933; Fish, 1990; Davenport, 1994). Hubbs (Hubbs, 1933) argued that the flying fish controls the aerodynamic forces by varying the dihedral and attack angles of the pectoral fins. It is known that the positive wing dihedral angle provides rolling stability to restore the glider to the level flight (Thomas and Taylor, 2001). This positive lateral dihedral angle reduces the effective span of the wing, thus reducing the lift force. Thus, in the future it would be interesting to investigate the trade-off between the rolling stability and the lift-to-drag ratio with the lateral dihedral angle.

Finally, it has been argued that the flying fish has the ability to change the camber as well as the angle of attack and dihedral angle of the wings, although the specific variation of the camber during

Fig. 13. Flow visualizations: end views for the case of water surface at $r=1.12$ (middle column) and $r=0.33$ (right column). The schematic diagram on the left illustrates the location of the laser sheet for each visualization.
its flight is not known (Breden, 1930; Hubbs, 1933). Similar to a previous study (Davenport, 1994), the present flying fish models have slightly cambered pectoral fins and flat pelvic fins. In general, the camber is known to increase the lift force at least for low angles of attack. Therefore, the role of camber on the forces on the wing during the flight of flying fish should be another interesting topic to pursue in the future.

ACKNOWLEDGEMENTS

Preliminary results of this work were presented at the IUTAM Symposium on Unsteady Separated Flows and Their Control, Corfu Island, Greece, June 18-22, 2007, and published in the Proceedings of this symposium (Park and Choi, 2009). We appreciate the cooperation from the National Federation of Fisheries Cooperatives of Korea and the Korea Research Center of Maritime Animals for preparing the flying-fish models. We also thank Dr Woo-Pyung Jeon for the help in the initial setup of our experiment. This work was supported by a National Research Laboratory Program (ROA-2006-000-10180-0), a World Class University Program (R31-2008-000-10083-0), and a Converging Research Center Program (2009-0082824) through the National Research Foundation of Korea funded by the Ministry of Education, Science, and Technology, Korea.

LIST OF SYMBOLS

- \( A \): total planform area (\(=A_1 + A_2 + A_3 \))
- \( A_1 \): planform area of pectoral fins
- \( A_2 \): planform area of pelvic fins
- \( A_3 \): planform area of body
- \( AR \): aspect ratio (\(=S^2/A_1 \))
- \( b \): half wing span (\(=b/2 \))
- \( c \): average chord length of pectoral fins (\(=A_1/S \))
- \( C_D \): drag coefficient
- \( C_L \): lift coefficient
- \( C_M \): pitching moment coefficient
- \( D \): drag force
- \( h \): flight height (distance between the ground and the lower surface of the body)
- \( L \): lift force
- \( L/D \): lift-to-drag ratio
- \( M \): pitching moment
- \( r \): ratio of flight height to half wing span (\(=h/b \))
- \( Re \): Reynolds number (\(=\nu c_s/v \))
- \( S \): wing span of pectoral fins
- \( SL \): standard length
- \( u_{ind} \): wind-induced water velocity
- \( u_s \): freestream velocity
- \( x_c \): location of the center of gravity
- \( \alpha \): angle of attack
- \( \beta_1 \): lateral dihedral angle of pectoral fins
- \( \beta_2 \): incidence angle of pectoral fins
- \( \beta_3 \): incidence angle of pelvic fins
- \( \nu \): kinematic viscosity

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