Diving Simulation concerning
Adélie Penguin

Shinichiro ITO** and Masanori HARADA**

Penguins are sea birds that swim using lift and drag forces by flapping their wings like other birds. Although diving data can be obtained using a micro-data logger which has improved in recent years, all the necessary diving conditions for analysis cannot be acquired. In order to determine all these hard-to-get conditions, the posture and lift and drag forces of penguins were theoretically calculated by the technique used in the analysis of the optimal flight path of aircrafts. In this calculation, the actual depth and speed of the dive of an Adélie penguin (*Pygoscelis adeliae*) were utilized. Then, the calculation result and experimental data were compared, and found to be in good agreement. Thus, it is fully possible to determine the actual conditions of dive by this calculation, even those that cannot be acquired using a data logger.

**Key Words**: Optimal Control, Aircraft, Penguin, Diving Simulation, Flight Path

1. Introduction

Dive depth loggers tell us how deep penguins dive. This information, coupled with elapsed time, velocity and two-dimensional acceleration, gives us the time series data of penguins’ diving behavior. According to Williams[1], Adélie penguins can dive for up to three minutes and reach depths of 90 meters. Most dives are approximately one minute in duration and reach depths of approximately 20 meters. How diving depth changes with time is defined here as the diving path. Based on the field experimental data taken using a PD2G data logger (for pressure, depth, surging and swaying acceleration data) developed by NIPR (National Institute of Polar Research, Japan), a typical deep-diving paths was found as shown in Fig. 1, which has a curvature point where ascending rate changes. It has not been clearly explained why such a diving path is formed. Sato et al.[2] investigated a penguin’s dive on the basis of the effect of inhaled-air volume on buoyancy and maximal diving depth. Their results showed that penguins regulate their inhaled-air volume to optimize the costs and benefits of buoyancy. If diving is considered as one of the optimal control problems, it would be either the shortest time problem or the minimum energy problem. Before resolving this issue, we simulated in this study the diving state and the posture of a penguin during a dive. An optimal control theory of an aircraft flight is

![Fig. 1 Typical aspects of deep diving observed in Adélie penguin. A small propeller for speed measurement is installed in the logger. Propeller rotation number (RPS) is proportional to body speed described as velocity (m/s) = 0.05 x rotation per second. Sato[3] assumed that during prolonged ascent, taking an oblique ascent angle shown as two elliptic circles and slowing down near the surface may represent a way of avoiding the potential risk of decompression sickness.](image-url)
adopted for analyzing the diving path of a penguin assuming its inhaled air volume to be constant. The theory used adopted in calculation is that used for the analysis of optimal flight paths of aircrafts. The equations used include the effect of induced drag by a penguin's wings and that of added mass, which has a same order of body mass in the body affected by buoyancy. The calculation data is compared with the field experimental data.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ARₐ</td>
<td>Aspect ratio</td>
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<tr>
<td>Cₜ</td>
<td>Thrust coefficient</td>
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<tr>
<td>a</td>
<td>Ellipse body length</td>
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<tr>
<td>m</td>
<td>Mass of penguin</td>
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<td>S</td>
<td>Wing area</td>
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<tr>
<td>V</td>
<td>Velocity</td>
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<tr>
<td>ρₛ</td>
<td>Penguin density</td>
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<tr>
<td>Cₐ</td>
<td>Lift coefficient</td>
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<tr>
<td>k</td>
<td>Induced drag coefficient</td>
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<tr>
<td>b</td>
<td>Ellipse body radius</td>
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<tr>
<td>mₑ</td>
<td>Mass from floating</td>
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<tr>
<td>t</td>
<td>Time</td>
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<tr>
<td>z</td>
<td>Depth</td>
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<tr>
<td>ρₑ</td>
<td>Seawater density</td>
</tr>
<tr>
<td>Cₑ₀</td>
<td>Zero lift drag coefficient</td>
</tr>
<tr>
<td>kᵢ, kₑ</td>
<td>Added mass coefficients</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
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<tr>
<td>mₜ</td>
<td>Total mass</td>
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<tr>
<td>T</td>
<td>Thrust force</td>
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<tr>
<td>γ</td>
<td>Pitch angle</td>
</tr>
<tr>
<td>Vᵢ</td>
<td>Air volume of lungs</td>
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2. **Materials and Method**

2.1 **Formulation of the penguin motion**

The forces that affect swimming penguins are gravity, buoyancy, lift and drag by beating wings, and induced drag from shedding vortices. Moreover, the mass of seawater surrounding a penguin's body is affected by locomotion and it is so close to the mass of the body that the inertia force of the fluid mass cannot be negligible. This mass is called added mass. The added masses expressed as Aₑ and Aₑ in Eqs. (1) and (2) are important factors for analyzing the object affected by buoyancy. Induced drag acts on an object and generates lift force. It is described as kₑ in Eq. (1) due to blowdown which is proportional to \( Cₐ/\pi ARₑ \), caused by the wing. The penguin is modeled to resemble an object like a rugby ball with a pair of small wings shown in Fig. 2. It is expressed as a simple mass point model including the added mass term. Thus, the equations of motion for a swimming penguin are

\[
(m + Aₑ) \frac{dV}{dt} = T - \frac{1}{2} \rhoₛ V^2 S(Cₑ₀ + kₑ) \sin \gamma - mₑg \sin \gamma
\]

\[
(m + Aₑ) \frac{dγ}{dt} = \frac{1}{2} \rhoₛ V^2 SCₑ₀ - mₑg \cos \gamma
\]

\[
\frac{dx}{dt} = V \cos \gamma
\]

\[
\frac{dz}{dt} = V \sin \gamma
\]

where

\[
k = \frac{1}{2} \pi ARₑ
\]

\[
mₑ = m - mₜ
\]

\[
mₜ = \left( L + \frac{m}{\rhoₛ} \right) \rhoₛ
\]

The added masses are defined by

\[
Aₑ = kₑ \left( \frac{4}{3} \rhoₑ \pi a b^2 \right)
\]

\[
Aₑ = kₑ \left( \frac{4}{3} \rhoₑ \pi a b^2 \right)
\]

Each parameter is taken using an Adélie penguin whose \( m = 5 \) kg, \( k = 0.05 \), \( L = 1.3 \) litre, \( \rhoₚ = 1.012 \times 10^6 \) kg m⁻³, \( \rhoₛ = 1.028 \times 10^4 \) kg m⁻³, \( 2aₑ = 0.05 \) m, \( 2bₑ = 0.40 \) m, \( Cₑ₀ = 0.0236 \), \( kᵢ = 0.209 \) and \( kₑ = 0.702 \). The air volume of the penguin's lung is assumed to be constant.

3. **Results and Discussion**

Numerical calculations to solve the optimal trajectory of a penguin's dive are performed in a shallow diving section using a modified GA (genetic algorithm) for optimal control problems. The experimental data shown in Fig. 3 are part of data 97GA4715s, with elapsed times from 5984 to 5980 seconds obtained at JARE 37 (Japan Antarctic Research Expedition 37th, 1997). They are shown as a dash line in each figure. The following equation is also defined as a performance index \( J \) to solve the Eqs. (1), (2), (3) and (4).
Fig. 3 Transition of diving depth. The duration of a dive was 46 seconds with a maximum depth of 17 meters. It shows that a penguin dives steeply at first and ascends gradually.

\[ J = \int_{0}^{t_{\text{dive}}} ((V - V_{\text{experiment}})^2 + (z - z_{\text{experiment}})^2) \, dt \]

The parameter \( J \) evaluates the difference between the calculated velocity and depth and the experimental results. It is used for adjusting the calculated velocity and depth by minimizing \( J \) during the dive. Namely, the calculation results are almost the same as the experimental results.

Figure 3 shows diving depth against elapsed time. The penguin reaches a depth of almost 20 meters in approximately 10 seconds. The solid line indicates the theoretical calculation result and the other dash line shows the experimental result. The calculation data have a relatively good agreement with the experimental data. Figure 4 shows the transition of advance velocity in a dive. The penguin keeps swimming at almost the same advance speed \( V \) of 2.3 m/s except during the descent and ascent phases. During ascent phase, the velocity reaches up to 4 m/s. The advance speed, 4 m/s, is approximately 1.6 times larger than that of the cruising speed. This velocity may be the upper limit of Adélie penguins determined by the physiological constraints of diving such as decompression sickness\(^9\).

The observed surging accelerations obtained using the PD2G logger changed when the posture of the diving penguins changed. Thus, the actual observed surging acceleration is obtained by differentiating the actual advance velocity. The observed surging acceleration is compared with the calculated ones in Fig. 5. Both results show good agreement with each other. The observed spike pattern in the last stage of the ascent phase seems to indicate that the penguin decelerates near the sea surface.

Let us consider the state of an aircraft in flight. Usually, lift force is proportional to the square of speed \( (\text{Lift force} = C_l \frac{1}{2} \rho v^2 S) \). Therefore, an aircraft needs a large lift coefficient \( C_l \) to be able to take off at a low speed. Thrust force is also required to accelerate for takeoff. Until an aircraft reaches its target altitude, a large lift or large lift coefficient \( C_l \) is required. In its cruising state at a constant speed at horizontal level flight, an aircraft flies when the lift/thrust ratio is maximum so that a larger lift can be obtained by the lower thrust. However, thrust is not required during descent because aircrafts use gravity to descend. Lift force is maintained during gradual descent. During landing, a large lift coefficient is required when the speed has dropped. When the dive of penguins is divided into phases similarly to those of aircraft flight with a starting phase, descent phase, cruising phase, ascent phase and ending phase, the same transitions of lift and drag forces can be considered.

Lift coefficient \( C_l \), which cannot be actually observed, is shown in Fig. 6. The \( x \)-axis also indicates the elapsed times. A negative lift coefficient means that a downward lift force is exerted on a body. That is, the negative lift force opposes the buoyancy force. Similarly, a large positive lift force is necessary during takeoff. It has a large negative value in the dive section from the start up to the time the target depth is reached. After reaching the target depth, \( C_l \) increases again and is maintained constant in the horizontal level phase and ascent phase section. This over-shooting of \( C_l \) can be observed very often for control parameters. Actually, the calculation in this
study uses lift force as a control parameter and penguins manage their lift forces by controlled beating of their wings. It is quite natural that a minimum lift force that cancels buoyancy should be sufficient for cruise diving. $C_i$ in the ascent phase should have a high negative value compared with that in the descent phase for penguins not to exceed maximum speed, 4 m/s, as mentioned previously. To control ascent velocity, penguins seem to generate a high negative lift or downward force by changing the angle of attack on their wings or by changing the diving path without beating their wings.

Thrust coefficient $C_t$ against elapsed time is shown in Fig. 7. Thrust coefficient is a nondimensional number, which represents the magnitude of the driving force or of the force to advance. At the starting point, the thrust coefficient is large, as aircrafts require the maximum thrust force during takeoff. With increasing diving depth, thrust coefficient decreases gradually even during level swimming. It becomes almost zero during the ascent phase. This is because buoyancy force is transferred to the thrust force produced by beating wings. According to Sato, penguins stop beating their flippers during the final stages of the ascent. This fact coincides with the calculation result of passive ascent without thrust force.

Figure 8 represents the pitch angle $\gamma$ of the body. The calculated pitch angle is negative when the body moves downward. The pitch angle $\gamma$ starts from $-30^\circ$. The angle $\gamma$ increases to zero and then decreases gradually. It reaches its minimum of about $-50^\circ$ at approximately the depth of the medium point between the starting point and the target depth. This means that the pitch angle is quite large. From this point to the target depth, the pitch angle $\gamma$ increases up to zero as the head is raised. In a horizontal level swimming movement, the pitch angle of the body $\gamma$ becomes almost zero or the body becomes approximately horizontal. In the ascent phase, the posture turns to head up or the angle $\gamma$ becomes positive. Just before reaching the sea surface in the floating movement, the calculated pitch angle is positive similar to that in the descent phase. This figure shows the comparison between the pitch angle of a penguin calculated from its actual movement, and the pitch angle obtained by this calculation. Most of the experimental data in Fig. 8 are negative. It is considered that these phenomena are due to the offset angle of the position of the logger fixed on the penguin. As we take only the increase and decrease in pitch angle into consideration, calculation clearly shows the tendency of the body to go upward first, then go downward at the start of dive.

Although the actual fine change of pitch angle is
not expressed at the end of the dive, the tendency of the body to go upward and then downward is simulated. Figure 9 shows the total diving distance from the start of the dive and it is found that a penguin swims a distance of nearly 100 meters when it swims straight forward. Although the trajectory of the diving path is not straight, the total diving distance is approximately proportional to the elapsed dive time. Such a factor as total diving distance cannot be obtained from the experimental data, but it is possible to estimate it by calculations.

4. Conclusions

The diving conditions for an Adélie penguin in an experimental dive are solved by the optimal control method. The numerical results expressed the diving parameters, such as surging acceleration, lift coefficient $C_l$, thrust coefficient $C_T$, body pitch angle $\gamma$ and total diving distance. It is found that numerical calculation is very effective in determining diving parameters which cannot be obtained using data loggers.

An on-going research would be able to solve problems relating to energy consumption during diving.

References


