Polar Biosci., 13, 95–100, 2000

Analysis of diving behavior of Adélie penguins using acceleration data logger

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Abstract: Acceleration data loggers were attached to five adult Adélie penguins at Hukuro Cove, Lützow-Holm Bay in austral summer 1997/1998. The loggers recorded time series data of speed, depth, surging acceleration and swaying acceleration in flush memories inside. From time series analyses, the frequency of 2- to 3-Hz was found in the surging acceleration during descent in a straight line. The cycle seemed to correspond to wingbeat frequency of the Adélie penguin. The relation between wingbeat frequency and diving depth was that the frequency ranged from 1.5-Hz to 3.0-Hz when the penguins dive in water shallower than 30-m and was over 2.5-Hz in water deeper than 50-m. The acceleration data logger is a powerful tool to estimate kinematic parameters of free-range marine animals.

key words: Adélie penguin, acceleration data logger, power spectrum density, wingbeat frequency, diving

Introduction

To understand foraging behavior of Adélie penguins, it is necessary to know kinematic parameters such as swimming speed and wingbeat frequency, since the parameters are fundamental to evaluate the swimming abilities of the penguins. Clark and Bemis (1979) examined kinematic parameters in a study of swimming abilities of several species of penguins including the Adélie penguin. They measured the parameters at a zoo using film and videotape sequences. However, the parameters obtained at small and shallow aquariums were open to question. We therefore adopted brand-new micro data loggers to measure these kinematic parameters. In this study, we were able to determine the wingbeat frequency from the acceleration data of the free-range Adélie penguin.

Materials and methods

Acceleration data loggers, UWE-PD2GA (Little Leonardo Co. Ltd., Tokyo) were designed for the Adélie penguin. The loggers weighed 17.7 g in water, were 20 mm in

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diameter with 122 mm length, and had 32-Mbit flush memories to store four channel data including surging and swaying acceleration ($\pm$4G), swimming speed (0–200 m/s), and depth (0–200 m). These acceleration data represented longitudinal and lateral oscillations, respectively. These data were converted into 12-bit digital data and archived by a micro processor inside. The sampling rate was variable ranging from 0.0078 s to 2.0 s according to the purpose of the experiment. We adopted 0.0938 s for sampling rate of acceleration to investigate wingbeat frequency, and every one second as the sampling rate for depth and speed.

All experiments were performed at the Hukuro Cove colony, Lützow-Holm Bay (69° 12′S, 39° 39′E) in the 39th Japanese Antarctic Research Expedition (JARE-39) in austral summer 1997/1998.

The loggers were attached to feathers, centered on the backs of Adélie penguins, with epoxy adhesive. When the penguins returned back to the colony, we recaptured the bird, retrieved the loggers and downloaded archived data in the memories into a hand-held computer. We applied spectrum analysis to investigate the cyclical fluctuation in the acceleration data. Especially to determine the wingbeat frequency, power spectrum density (PSD) was calculated using a Fast Fourier Transformation (FFT) with a computer program package, Igor Pro (WaveMetric, Inc.).

Results

We attached the loggers to five adult Adélie penguins, of which body weights ranged from 4.2 kg to 5.1 kg (Table 1). Maximum diving depths ranged from 28.8 m to 73.0 m, maximum speeds ranged from 1.8 m/s to 3.7 m/s (Table 1).

As a first step to analyze the diving behavior, we focused on surging acceleration data, since the surging acceleration was powered by wingbeat of the penguins. Figure 1 shows time series data of the surging acceleration and depth in one dive of an Adélie penguin, no. 471. The data, 0826:40–0829:20 on 27 December 1997 shown in Fig. 1, show the deepest dive in the whole 20-h long record. We simply divided the surging acceleration data into a descending phase and an ascending phase. The descending phase started from 0826:40–0827:20 and the ascending phase started from 0827:40–0828:25. The penguin descended in a straight line in the descending phase and *vice*

Table 1. Body mass, time of release, data length, maximum depth and maximum speed for Adélie penguins which were released with data logger, PD2GA, in 1997/1998.

Penguin no.	Body mass (kg)	Release time		Data length (h)	Max. depth (m)	Max. speed (m/s)
424	4.2	2215	2 Jan. 98	15.8	41.7	1.8
471	5.1	1414	26 Dec. 97*	19.5	71.8	3.5
487	4.9	1118	2 Jan. 98	13.8	73.0	3.7
489	4.3	1311	2 Jan. 98	28.4	28.8	2.3
491	4.9	2315	3 Jan. 98	40.9	51.5	2.0

* The data logger was set to start five hours later.

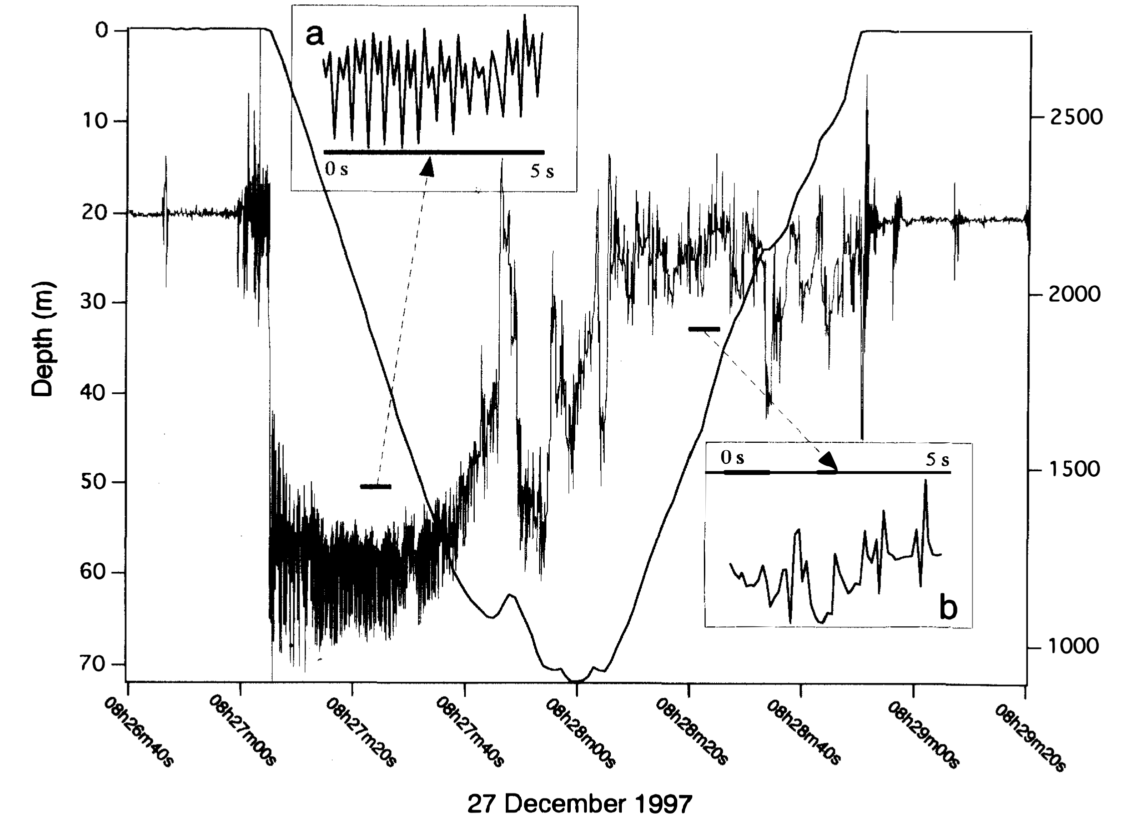

Fig. 1. Surging acceleration and depth in one dive of Adélie penguin no. 471. Five second periods are enlarged for the descending phase (a) and ascending phase (b).

versa in the ascending phase. To examine the difference between the two phases, the acceleration data were re-plotted as Fig. 1a, b. Figure 1a shows a clearly cyclical fluctuation of 12–3 times for 5 s.

Figure 2 shows the typical results of the PSD analyses. Figure 2(A) is the PSD in the descending phase and Fig. 2(B) is that in the ascending phase. A peak at 2.65 Hz in the descending phase was found but there was no peak in the ascending phase. This 2.65-Hz cycle generally agrees with the result in Fig. 1a. The 2.65-Hz cycle also agrees with maximum wingbeat frequency described by Clark and Bemis (1979). They measures maximum speed and wingbeat frequency of several species of penguin in the Detroit Zoo with a videotape recorder. In addition, diving propulsion of the penguins was powered by only their wingbeat in the descending phase. On the other hand, propulsion in the ascending phase was driven by their own buoyancy (K. Sato, unpubl. data). Therefore, as the 2.65-Hz cycle seemed to be the wingbeat frequency, we investigated the relation between the wingbeat frequency in the descending phase and diving depth. Figure 3 shows the relation between diving depth and wingbeat frequency in the descending phases of five individuals. In this analysis, we adopted surging acceleration data deeper than 10-m depth in descending phase at one bout of dive events including the deepest record since the PSD was not accurate in a small number of data above 10-m depth. The data of nos. 471, 487, and 489 were from one bout including the deepest dive, the data of no. 424 were from two bouts including the deepest dive, and

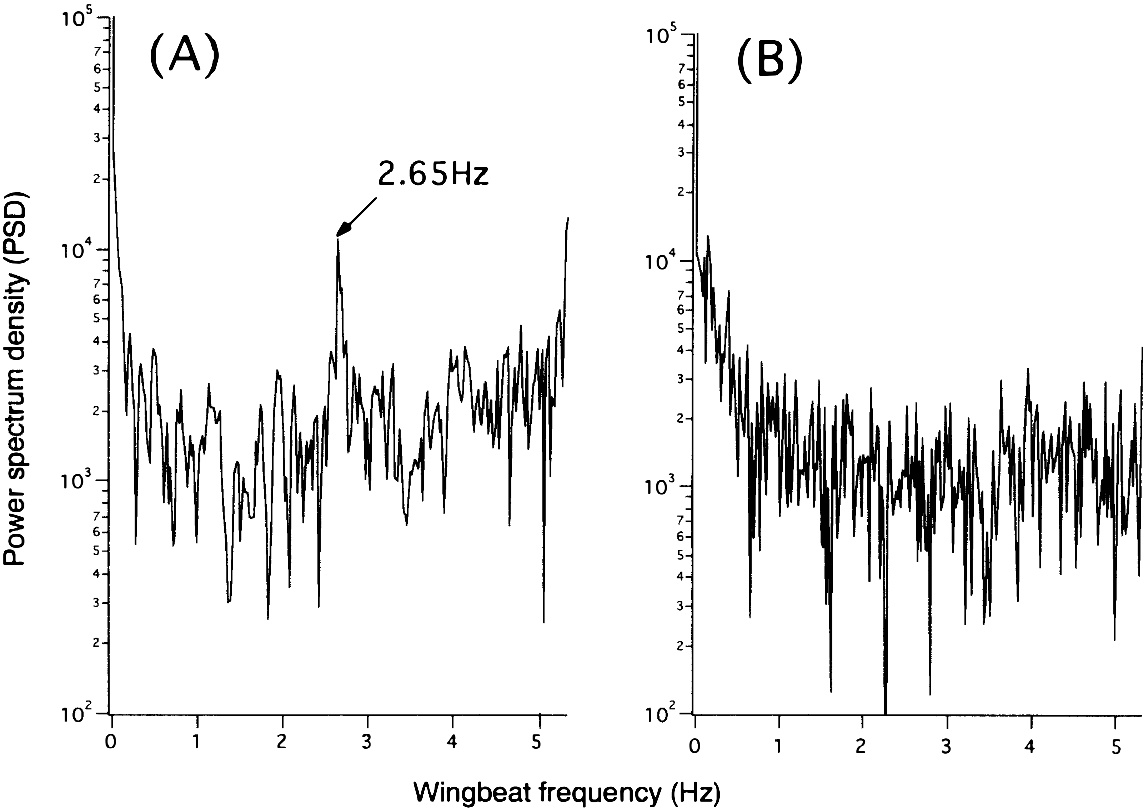

Fig. 2. Typical power spectrum density (PSD) for surging acceleration from PD2GA attached to Adélie penguin no. 471. (A) is the PSD of the descending phase and (B) is that of the ascending phase in Fig. 1.

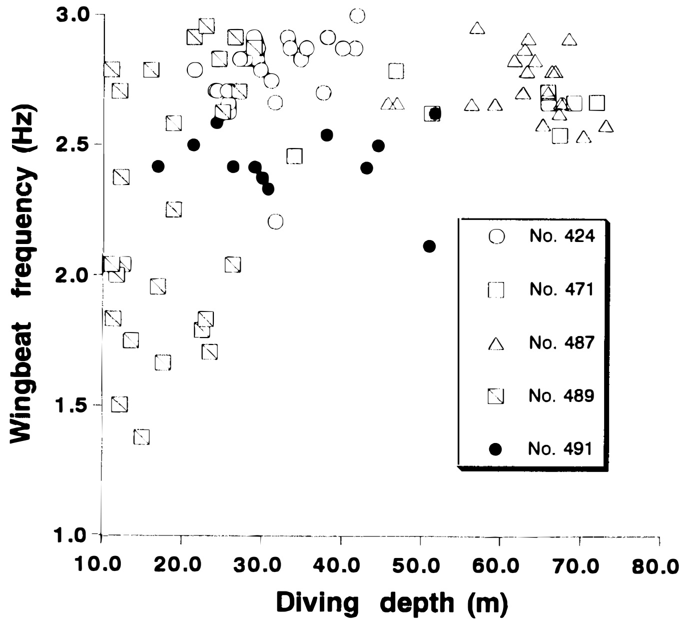

Fig. 3. Relation between diving depth and wingbeat frequency in the descending phase. The frequency was determined by the peaks of the power spectrum density (PSD) of the surging acceleration data deeper than 10-m depth. The data of Nos. 471, 487, and 489 are from one bout of dive events including the deepest dive, the data of No. 424 are from two bouts including the deepest dive, and the data of No. 491 are from all bouts.

the data of no. 491 were from all bouts. The deeper the penguins dived over around 50 m depth, the more frequently they stroke to obtain more propulsive force to dive against buoyancy. In contrary, when the penguins dived into relatively shallower depth, they stroke flippers at various frequencies.

Discussion

Recently various types of micro data logger have been developed (Naito, 1997). Miniaturization and enlargement of memory size in the logger make it possible to design a multi-channel logger for utility. The PD2GA adopted in this study had four channels including speed, depth and two directional accelerations. Those accelerations were measured every 0.0078 s for several hours in the finest data-acquisition mode (every 0.0938 s for several tens of hours in this study). These acceleration data at very high frequency (VHF) can reproduce momentary locomotion of penguins that we have never seen in the deep sea. The finer scale data have extremely large length, eg. the 40.9-h data of no. 491 were over 20-Mbytes (Table 1). The large data lengths may be a practical limitation to analysis with personal computers in the near future.

The power spectrum density (PSD) is a standard method to investigate a cycle in time series data such as the acceleration data. The Igor Pro is convenient to calculate the PSD with the Fast Fourier Transformation (FFT). Since this technique may be an important method to analyze kinematics data in VHF, evaluation of the technique is necessary in various species of marine organisms. Preliminary experiments were successfully performed in free-range red sea bream *Pagrus major* with the PD2GA to estimate tailbeat frequency (N. Arai, unpubl. data).

Time precision of the acceleration data was enough to describe the wingbeat frequency, which ranged from 2-Hz to 3-Hz. A dominant frequency which seemed to correspond to the wingbeat was found in the descending phase. On the contrary, no cyclical frequency was found in the ascending phase. This indicates that the penguins ascended to the sea surface mainly by their buoyancy, without their own power (K. Sato, unpubl. data). The relation between diving depth and wingbeat frequency is not so clear in this study. The penguins control wingbeat frequency ranging from 1.5-Hz to 3.0-Hz in water shallower than 30-m depth to look for prey or whatever purpose, but they dive into water deeper than 50-m depth using maximum power produced by maximum wingbeat frequency to feed. In this study, the analyses were focused on the simplest diving pattern to compare the typical wingbeat frequencies between in the descending and ascending phases. To analyze complex diving patterns, we have to analyze the swaying acceleration as well as the change of swimming speed. Especially, the swaying acceleration was expected to widely fluctuate when the penguins decided to change their swimming direction in search of prey. Moreover, the propulsive magnitude of the wingbeat, which can be estimated from the amplitude of surging acceleration, was neccesarry to clarify whether the penguins controlled their wingbeat power as well as the wingbeat frequency in shallow waters or not.

The speed and moving distance can be calculated by integration of the acceleration. Therefore, we can position an individual using the acceleration logger if direction and three-dimensional acceleration are simultaneously determined by any sensor. The direction is usually determined by a gyro-compass in navigation. But, the gyro-compass is too large to be installed in the micro data logger. Therefore, we are now developing a new type of direction sensor featuring a magneto-impedance (MI) effect. The MI effect is a highly sensitive change in the impedance in response to the application of an external field (Mohri, 1995). The MI effect makes it possible to create a micro-sized and highly sensitive field sensor to be installed in the micro data logger in the near future.

Acknowledgments

We thank all the members of the 39th Japanese Antarctic Research Expedition and the crew of the icebreaker Shirase for their support and cooperation in the field work. This study was partly supported by a Grant-in-Aid for Scientific Research (10660179), the Ministry of Education, Science, Sports, and Culture.

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(Received March 1, 1999; Revised manuscript accepted September 8, 1999)