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New model of flap-gliding flight

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HIGHLIGHTS

- A new modelling approch for flap-gliding flight is presented.
- Flap-gliding flight is shown to be superior to continuous flapping flight.
- This holds in the entire speed region.
- The minimum energy cost is considerably smaller and the associated speed is lower.
- With non-dimensionalization and scaling, generally valid results are derived.

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ABSTRACT

A new modelling approach is presented for describing flap-gliding flight in birds and the associated mechanical energy cost of travelling. The new approach is based on the difference in the drag characteristics between flapping and non-flapping due to the drag increase caused by flapping. Thus, the possibility of a gliding flight phase, as it exists in flap-gliding flight, yields a performance advantage resulting from the decrease in the drag when compared with continuous flapping flight. Introducing an appropriate non-dimensionalization for the mathematical relations describing flap-gliding flight, results and findings of generally valid nature are derived. It is shown that there is an energy saving of flap-gliding flight in the entire speed range compared to continuous flapping flight. The energy saving reaches the highest level in the lower speed region. The travelling speed of flap-gliding flight is composed of the weighted average of the differing speeds in the flapping and gliding phases. Furthermore, the maximum range performance achievable with flap-gliding flight and the associated optimal travelling speed are determined.

1. Introduction

Flap-gliding flight in birds is an intermittent flight mode in which periods of flapping are followed by gliding periods (Rayner et al., 2001; Tobalske and Dial, 1994; Norberg, 1990; Ward-Smith, 1984). An illustration adopted from Rayner et al. (2001) is given in Fig. 1 which shows one cycle of flap-gliding flight. A cycle which forms the basic element of flap-gliding flight and which is continually repeated consists of two phases of which one is active flapping flight and the other passive, non-flapping flight with the wings extended. In the flapping phase, the potential energy state of the bird is increased due to climbing to a higher altitude, while in the non-flapping phase the bird glides to reach the altitude at the beginning of the cycle. The energy built up in the climbing phase is used to compensate for the drag work in the gliding phase (Rayner et al., 2001; Norberg, 1990).

Flap-gliding flight is subject of continuous interest (Pennycuick, 2008; Biewener, 2003; Muijres et al., 2012; Tobalske, 2007; Tobalske, 2010).

An issue of the research concerned with flap-gliding flight is the economy and performance achievable with this flight mode (Rayner et al., 2001; Tobalske and Dial, 1994; Norberg, 1990; Ward-Smith, 1984; Pennycuick, 2008; Biewener, 2003; Muijres et al., 2012; Tobalske, 2007, 2010, 2001; Rayner, 1985). Generally, results and conclusions from existing models and treatments vary and show differences as regards possible economy and performance advantages of flap-gliding flight when compared with continuous flapping flight. There are conclusions according to which flap-gliding does not save energy (Ward-Smith, 1984; Pennycuick, 2008). The minimum external work done in flap-gliding flight for travelling a certain distance is regarded the same as in continuous flapping flight. A reason why birds perform flap-gliding flight is related to wingbeat frequency level and fuel energy conversion into work. According to other investigations, flap-gliding is thought to be less costly than continuous flapping during flight at most speeds (Tobalske, 2010; Rayner, 1985). A further

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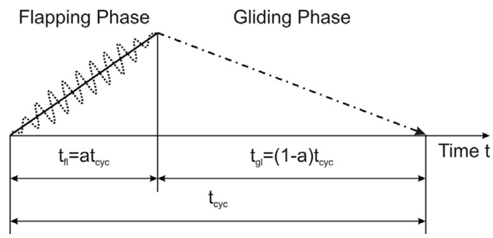

Fig. 1. Flap-gliding flight (according to Ref. Rayner et al. (2001)). A flap-gliding flight cycle consists of 2 phases, yielding (1) a flapping phase of duration $t_{fl} = at_{cyc}$ and (2) a gliding phase of duration $t_{gl} = (1-a)t_{cyc}$ where t_{cyc} is the total cycle time and a is the flapping ratio.

model for describing the energetic economy of flap-gliding flight is based on empirical estimates of the lift-to-drag ratio for continuous flapping and for continuous gliding flight (Muijres et al., 2012). According to this model, an energy saving can be achieved with flap-gliding flight. There are hypotheses and mechanisms that consider other aspects of intermittent flight than those concerned with mechanical energy (Rayner et al., 2001). Such aspects are beyond the scope of this paper.

A particular aspect in this context is that there are species which show flap-gliding flight as well as bounding flight (Tobalske, 2007, 2010, 2001; Tobalske et al., 1999). Compared with continuous flapping at all speeds, average mechanical power output should be lower in flap-gliding flight at slower speeds and in bounding flight at faster speeds (Tobalske, 2001; Rayner, 1985). The point is why flap-gliding flight is performed in the low speed range and what is the reason for a possible energetic advantage in this speed range.

Central point for the aerodynamic modelling of flap-gliding flight is the drag characteristics and the mechanical power output. For the required mechanical power output, the drag characteristics of the flapping and the gliding phases are determinative. In many investigations on flap-gliding flight until now, a difference in the drag between the phases of flapping and non-flapping is not made (Rayner et al., 2001; Norberg, 1990; Ward-Smith, 1984; Pennycuick, 2008; Tobalske, 2007, 2010, 2001; Rayner, 1985; Tobalske et al., 1999). The drag can be considered to consist of the zero-lift drag and the induced drag (Rayner, 1999). The induced drag is regarded to be basically the same when modelling the flapping and the gliding phases.

The purpose of this paper is to develop a new approach for modelling flap-gliding flight. Focus is on the central point addressed above, concerning the drag characteristics of the flapping and the gliding phases as well as the mechanical power output. The goal is to derive mathematical relations for the drag characteristics adequate for the flapping phase and for the gliding phase. It will be shown that there is an aerodynamic cost of flapping in terms of a drag increase when compared with non-flapping. This means for flap-gliding flight that the gliding phase yields a performance improvement because of the associated decrease in the drag. Results are derived which show that there is an energy saving of flap-gliding flight when compared with continuous flapping flight. Furthermore, the minimum energy cost per range as well as the associated, optimal flight condition in terms of the maximum range speed are determined. Introducing an appropriate non-dimensionalization, results and findings of generally valid nature are derived.

2. Material and methods: mathematical model of flap-gliding flight

Flap-gliding flight consists of a sequence of individual cycles which are periodically repeated (Rayner et al., 2001). A cycle which can be regarded as the basic element of flap-gliding flight and which is schematically shown in Fig. 1 comprises 2 phases of total length t_{cyc}, yielding

1) Flapping phase.
2) Gliding phase with extended wings.

2.1. Aerodynamic modelling of drag characteristics in gliding phase

The drag in non-flapping, gliding flight is generally given by the relation (Norberg, 1990; Rayner, 1999)

$$D = C_D \frac{\rho}{2} V^2 S \tag{1}$$

where C_D is the drag coefficient, ρ is the air density, V is the speed and S is the wing reference area. The drag coefficient consists of the zero-lift drag and the induced drag (Rayner et al., 2001; Ward-Smith, 1984; Rayner, 1999), yielding

$$C_D = C_{D0} + \frac{k}{\pi A} C_L^2 \tag{2}$$

where C_{D0} is the zero-lift drag coefficient, k is the induced drag factor, A is the aspect ratio of the wing ($A = b^2/S$, with wing span b) and C_L is the lift coefficient. The zero-lift drag coefficient can be expressed as

$$C_{D0} = \frac{S_b}{S} C_{D,par} + C_{D,pro} \tag{3}$$

where S_b is the cross-sectional area of the body, $C_{D,par}$ is the parasite drag coefficient and $C_{D,pro}$ is the profile drag coefficient.

2.2. Aerodynamic modelling of drag Characteristics in flapping phase

Concerning flapping flight, reference is made to recent research (Sachs, 2015) which shows that there is an increase in the induced drag due to flapping when compared with non-flapping flight. There are two effects of flapping that cause the induced drag increase.

One effect is due to tilting of the lift vectors at the left and right wings because of flapping. Basically, the lift vectors are perpendicular to the wings, as graphically shown in Fig. 2a for non-flapping flight and in Fig. 2b for flapping flight. The lift vectors are tilted when the wings are flapping, and the tilt angle is equal to the flapping angle, Fig. 2b. Tilting of the lift vectors means that the lift vectors no longer act in the vertical direction, but in a slanted direction corresponding to the tilt angle. As a consequence, only the lift vector components which act in the vertical direction are effective for the vertical force balance in forward flight (i.e., only the vertical lift components yield the aerodynamic force that is effective in balancing the weight). The presentation in Fig. 2b shows that the vertical lift components are smaller than the magnitude of the lift vectors for all flapping angles $\nu \neq 0$, yielding

$$L_{vert} < L \tag{4a}$$

where L is the resultant lift vector magnitude in terms of the sum of the lift vectors at both wings and L_{vert} is the corresponding resultant lift component in the vertical direction. The relation given in Eq. (4a) shows that it is necessary to generate more lift than is available for the vertical force balance. In terms of the associated lift coefficients, Eq. (4a) can be rewritten as

$$C_{L,vert} < C_L \tag{4b}$$

where

$$C_L = \frac{L}{(\rho/2)V^2 S}$$

$$C_{L,vert} = \frac{L_{vert}}{(\rho/2)V^2 S} \tag{5}$$