Dynamics and Kinematics Analysis During Take-Off and Landing in Birds

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Abstract

Take-off and landing in birds are an important subject of study in Advanced Systems of Aeronautical Propulsion, since it is possible to analyze the transition from wing to leg forces and vice-versa. From the studies carried out to date, it is important to note that the flight in most birds starts with an initial impulse followed by a high-angled wing movement to ensure the minimum lift for successful take-off. However there are other birds, such as hummingbirds and albatrosses that have morphological restrictions that will change the way the bird takes off. In the landing phase, high aerodynamic work performed by the wings is expected to provide controlled deceleration. After the touch, some birds still flap their wings to counteract inertia. The studies performed in this field contribute for the primordial goal of representing the natural flight with the technological means available nowadays. Therefore, an overall comprehension in this area will allow to create new aeronautical systems with an operating mode similar to those found in nature.

Introduction

As is well known, the efficiency of birds is quite superior since they can adapt to any flight condition. For this reason, birds are a reference in aeronautics and therefore, to better understand the flight mechanisms, we must study and search for systems that viable represent the natural flight. Birds and today’s aircraft have three distinct phases, although performed in different ways. The main reason for this discrepancy is that the birds have a perfect combination of the lift generation mechanism with the propulsion system, which has not been achieved so far on aircraft.

When initiating or ending a flight, the bird uses its hind limbs as the main source of energy. Thus, the study of muscular structure has a great importance because it allows the calculation of forces associated with a certain movement (Hill, 1953).

The flight in the majority of birds, initiates with the forward motion of the center of mass followed by a small jump accompanied with a wing movement to the vertical position which indicates that the bird starts its own flight without any lift production (Barata et al., 2017).

An example of a species that does not perform the gravity center movement is Coturnix Coturnix and due to this fact it needs to apply a larger force on the ground in order to have a successful take-off. (Earls, 2000).

During take-off phase, the ground reaction force is approximately vertical and depends of the body mass as well as the absence of gravity center motion. Independently of these factors, in general, birds generate about 80% to 90% of their initial take-off velocity with hindlimbs (Heppner e Anderson, 1985; Provini et al, 2012).

After losing contact with the ground, birds will have to start the lift generation process that must be intense and efficient.

In 1987, James H. Marden studied this last phase of take-off using a large variety of flying animals, including birds, insects and bats and posteriorly related their morphological characteristics with the lift production. From this study, Marden concluded that the maximum lift production shows a positive correlation with body mass, muscular mass, wing surface area and wingspan.

In the approach to a perch, birds tend to decelerate, losing kinetic energy up to the landing point. During this process, birds may choose one of two types of approach. It can be either slow and metabolically expensive or fast and energetically economic. The first form of landing consists in a slow and smooth descent as well as a controlled
deceleration which increases the precision of touchdown with a reduction of injury risk. In the second case, the bird opts for a high speed approach, suffering horizontal deceleration peak moments before landing (Green e Cheng, 1998).

The second type of landing is typical from birds familiar with the contact point and presents a high kinetic energy, describing a straight trajectory tangent to the ground. The other kind of approach, shows a low kinetic energy due to the intensive use of wings in landing, which results in a curvilinear path. Both descents are accompanied with a leg extension in a certain instant and head movements that allow birds to recognize visually the environment. (Dial, 1993; Green et al, 1994).

In 1993, D. N. Lee concluded that birds controllably decelerate keeping the dimensionless parameter $\dot{\tau}$, defined as being the temporal variation of the ratio between position and velocity, approximately constant in this phase. This indicator has as physical meaning the time that it takes to reach a certain position with constant speed. This is a powerful indicator of when the bird can extend its legs before landing.

During touchdown, it is expected an increase in the ground reaction force imposed by deceleration (Bonser e Rayner, 1996). The intensity of the ground force is significantly less when compared with take-off because the work done by wings is way higher during landing than in the initial phase of take-off (Provini et al, 2012).

All investigations in this area are based in several laws and equations that represent the dynamics and kinematics of take-off and landing. In the beginning of flight, the bird has two forces, one conservative, its own weight, and a non-conservative force, the drag that can be neglected in this phase.

The elastic potential energy needed to jump is stored in the hind limbs and then converted in kinetic energy. This energy is now transformed in potential energy until the bird reaches its maximum jump height. Associated with this process is the conservation of mechanical energy expressed by Equation (1) wherein this variation is approximately null since there are no non-conservative forces applied.

$$\Delta E_M = \Delta E_C + \Delta E_P$$ (1)

After jumping, the variation of mechanical energy will be different from zero because an aerodynamic force comes up with non-conservative characteristics due to the flapping motion created by the bird. Therefore,

$$\Delta E_M = W_{FNC}$$ (2)

Relatively to the final stage of flight, the variation in mechanical energy takes a value not null corresponding to the work performed by wings, when landing as shown in the Equation (2).

Next section presents two of the most used methods in the analysis of dynamics and kinematics of natural flight as well as the associated formulas with each method. It is also illustrated an image of the installation of the acquisition data system relative to the first method and a scheme of a mass-spring-damper system that is used to obtain forces applied in the ground.

Posteriorly we indicate some of the obtained results by several investigators in this area, where it is shown graphs and images gathered over this bibliography revision and authors’ interpretations about these results.

Finally, the results are discussed and is presented a summary that includes the majority of the conclusions until nowadays and also what should be studied in order to apply these concepts in artificial flight.

**Methods**

In this area, researchers have been using several methods to measure forces and analyze the kinematics in the take-off and landing moments.

One of the most used methods is based on the determination of the forces using the Newton’s Second Law from the velocity field. The flow is measured using PIV (Particle Image Velocimetry) which allows the instantaneous measurements of the velocity vectors in a whole plane. This technique consists in capturing images of regions of the fluid flow, using a high speed video camera in several time intervals. From the images gathered it is possible to calculate the velocities through the analysis of the particles’ displacements during a time period.

After finding the velocities in various points, it is possible to estimate the acceleration taking into account that:
$$\vec{a} = \frac{d\vec{v}}{dt} \approx \frac{\vec{v}_{i+1} - \vec{v}_i}{\Delta t} \quad (3)$$

With the estimated acceleration the resultant force is obtained using Newton’s Second Law:

$$\vec{F} = m \vec{a} \quad (4)$$

In the following figure there is a representation of the PIV method.

Together with this procedure recording systems are used for post-processing to determine the birds’ velocity and estimate the acting forces. Usually the bird’s eye is used as reference even if it is blocked by the wing, because it is possible to interpolate the birds’ current position (Green e Cheng, 1998).

Another method that is also very common is the use of a mass-spring-damper system, that allows the attainment of forces from the equilibrium in this kind of system. Considering now the system in the Figure (2) as a generic assembly scheme to obtain forces when birds are taking off or landing.

From the force balance it comes that:

$$\vec{F} = \vec{F}_{ext}(t) - k \vec{x} - c \frac{d\vec{x}}{dt} \quad (5)$$

The resultant force, which is the ground reaction force is then obtained using sensors that measure the displacements of the spring.

This method should be subjected to some corrections due to the fact that the used masses are very small which makes them susceptible to oscillations (Green and Cheng, 1998).

Thus, it is recommended to use an operational amplifier to amplify the signal and an active filter to filtrate it in order to reduce the associated noise and consequently the error (Provini et al., 2014).

**Results**

In this section, we have some of the most relevant results in this area. In the two following figures we have the results of Provini et al. 2014 in the landing process of two two species, *Diamond Doves* and *Zebra Finches*.

Figure (3) and (4) shows that species *Zebra Finches* presents a wing beat intensity and a perch reaction force smaller in relation to the species *Diamond Dove*. This last species executes the last wing beat after landing while species *Zebra Finches* performs its last wing beat in the moment of landing. The work made by aerodynamic forces in both species decreases, whereby the latest wing beats are mostly for control and stability.

![Figure 3: Forces produced in the last four wing beats by Zebra Finch. Pink line - Perch data; Blue line - PIV data; Yellow bars - Mean aerodynamic force during a wing beat.](image)
Figure 4: Forces produced in the last four wing beats by Diamond Dove. Pink line - Perch data; Blue line - PIV data; Yellow bars - Mean aerodynamic force during a wing beat.

Figure (5) shows that the species Zebra Finches exhibits a high landing angle when comparing to Diamond Doves, probably due to its aerodynamic characteristics. Besides that, the leg extension in Diamond Doves occurs before than in the species Zebra Finches.

The next four images are referred to a study performed by Green and Cheng in 1998 where it is possible to see the novelty effect of a perch or unfamiliarity to it during approach and landing.

The graphs of Figure (6) are characteristic from a low kinetic energy landing because it shows a significant reduction in horizontal velocity during approach and a trajectory with a gradual increase of the body angle that favors a precise landing.

Figure 6: High energy landing. The horizontal components are represented by filled circles and vertical components by white circles.

Figure (7) reveals that in high kinetic energy landings the horizontal velocity suffers a severe decrease due to a negative horizontal acceleration generated by the wings. In contrast, vertical velocity is slightly affected and the trajectory tends to be a straight horizontal line which is characteristic from this kind of landing.

Figure 7: High energy landing. The horizontal components are represented by filled circles and vertical components by white circles.
In Figure (8) it is possible to see a positive correlation between kinetic energy and horizontal velocity. This relation was not verified with the vertical component of velocity, revealing that a high kinetic energy is mostly due to the horizontal component of velocity.

![Figure 8: Relation between final kinetic energy and final horizontal velocity.](image)

As shown in Figure (9), the maximum force is also positively correlated although less noticeable. So, a high kinetic approach will probably produce a bigger reaction force on the ground.

![Figure 9: Relation between final kinetic energy and maximum force applied in a perch.](image)

In the next figure, it is shown a study done by Tobalske et al. 2004 where they analyzed the take-off of a hummingbird.

The results show that the applied force on the perch by the hummingbird does not reach a considerable peak or changes significantly during the initial phase of flight. This fact can be explained by the relatively small hind limbs when compared to other birds which limits significantly the impulse generated by them. For this reason, the wings’ role is crucial for the beginning of flight. After the first upstroke, the vertical forces on the perch diminish due to lift generation and a small impulse is executed in the horizontal direction. It is important to say that hummingbirds have a typical wing beat style pretty similar to insects although it is energetically expensive.

![Figure 10: Take-off of Selasphorus Rufus and its kinematics. (A) Beginning of the counter movement, (B) Beginning of leg impulse, (C) Wing unfolding, (D) First upstroke, (E) End of leg impulse, (F) End of take-off.](image)

Another important study performed by Richard Bonser and Jeremy Rayner was the analysis of ground reaction forces of a starling.

These researchers identified four phases of take-off in the starling that are represented in Figure (11) with a, b, c and d. The first phase corresponds to when the bird is resting on the perch and therefore the reaction force has the same value as its own weight. At phase b, there is a fast reduction of the reaction force justified by the rapid flexing of the hind limbs moments before the jump. In c it reaches the maximum force corresponding to the maximum in both components. These two components different from zero imply that there is an angle of take-off that can be calculated using the arctan function. The last phase represents the end
of take-off when there is already no contact with the perch.

From this experience, resulted two linear equations based on empirical values where we can calculate the force using the birds’ mass since Bonser and Rayner concluded that in this species there is a proportionality relation between mass and force.

**Conclusion**

Starting firstly by take-off, birds, in their vast majority, begin their flight jumping into the air with their wings vertically extended, using elastic potential energy stored by their hind limbs. Therefore, there is no lift production immediately after loosing contact with the ground.

Usually this procedure is done with a forward movement of the center of mass together with a leg flexing, which allows the bird to maximize his initial velocity and optimize his take-off performance. After take-off, the angle of attack varies substantially in order to ensure a high lift production and propulsion to the bird, typical of a flapping wing.

Among the various birds studied, the hummingbird stands out for being a bird which, in contrast to the majority of birds, has a very peculiar wing beat, similar to an insect, although this wing beat style turns out to be energetically expensive. Hummingbirds relatively to other birds, have hind limbs proportionally smaller in relation to its body, which considerably lowers its elastic energy storage capability. Thus, hummingbirds do use the wings as the main source of acceleration at the beginning of flight.

Another interesting example is the albatross, which does not follow the standard parameters of initial flight since it starts his flight with a run identical to current aircrafts.

Considering the landing phase, it is expectable a peak in the reaction force applied in the ground by hind limbs, because these and the surface will have to absorb the kinetic energy associated with the approach.

Generally the aerodynamic forces produced by wings are way higher during landing than takeoff. Therefore, the reaction forces on the ground must be lower in landing when comparing to take-off according to energy conservation law.

It is important to say that the energy absorbed by legs is less than the work done per wing beat, which helps us conclude that wings have a great impact in the final phase of flight.
The studies analyzed in the present work revealed and systematized the peculiar aspects of take-off and landing as well as the transition to free flight of some birds. More research should be extended to a wide variety of species in order to improve the knowledge of these phases of the flight. The analysis of more complete and general set of results would allow the establishment of laws representing the relation between the absorbed forces and aerodynamic characteristics to assist new design procedures.

References