A Review on Aerodynamics of Non-Flapping Bird Wings

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ABSTRACT: Birds are known for their agility, manoeuvrability, and flexibility during flight. These features allow their ability to fly under a large range of flight conditions. Bio flyers and bio aerodynamic/fluid surfaces have inspired many to perform experiments and simulations as well as to relate their results to engineering applications. Wings specifically have been the most inspirational element. Aerodynamic forces, structure, unsteady flow, fluid-structure interaction, flow control, flow adaptive elements and mechanisms, flow vortices, flapping mechanisms, and hovering flight of birds are examples of research interests. This paper presents an overview of prior analyses and experiments on the aerodynamic performance and mechanical properties of birds in steady non-flapping flight.

KEYWORDS: Flexibility, Porosity, Aerodynamics, Birds, Feather.

INTRODUCTION

Recently, the need for micro air vehicles has resulted in an increase in the attention to bird flight and in the study of their performance as they fly at low Reynolds numbers (Carruthers *et al.* 2010). It is very important to seek the viable aspects in studying natural flyers that can be implemented in practical applications such as wing aerodynamics, structure and control, as noted by Jacob (1998).

Aerodynamics of bird airfoils and wings is classified into three categories. First, the analysis of airfoils/wings of birds as a fixed rigid body; second, birds airfoils/wings in flapping phase; and third, flexible airfoils/wings in non-flapping flight. Bird wing structure is another focus found in some studies in which the feathers bend and twist under aerodynamic forces. Therefore, establishing their mechanical properties leads to an understanding of their influence on aerodynamic performance as studied by Bachmann (2010), Bonser and Purslow (1995), Jacob (1998), Macleod (1980), Purslow and Vincent (1978). Also, movement and vibration of feathers play a role in flight control as mentioned by Brown and Fedde (1993) and Jacob (1998), influencing aerodynamic performance. Adaptive wings improve efficiency, manoeuvrability, control, weight and cost (Jacob 1998).

Natural flyers are difficult to study experimentally due to the complexity in their structural surface, control and agility in manoeuvring (Shyy *et al.* 2008). The wing structure, surface flexibility, flexibility of feathers, vane and surface hair are a huge challenge to mimic. Another challenge is that the fluid motion is unsteady and has many different phases as the birds' flap bend and wings move based on the flight conditions. A challenge is that the scaling of both fluid dynamics and structural dynamics

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between smaller natural flyer and practical flying hardware/lab experiment (larger dimension) is fundamentally difficult (Shyy *et al.* 2008). A study of wings with flexible and porous surfaces has not been performed yet. Figure 1 shows a dorsal view of a bird wing planform with its nomenclature that highlights the complex geometry of the multilayer planforms with different functionalities for each layer and sublayer components. Figure 2 describes the sublayer component structure that exposes the nature of the non-prismatic, flexible slender beam structure with flexible connections.

MECHANISM/MORPHOLOGY

A feather consists of a shaft and vanes (Fig. 3). The inclination of the barbs makes the vane more resistant to aerodynamic forces from its lower side than upper side (Fig. 4). Vanes of a feather are not equally distributed on the shaft. One vane is larger than the other side of the feather's shaft, which creates moment on a single feather about its shaft. However, multiple feathers overlap resulting in zero moment (a small tilting moment occurs due to the flexibly of the feather) (Muller and Patone 1998).

Mechanical behaviour of wings is affected by differences in morphology and function of feathers. The outer primaries are more resistant to forces than inner primaries, especially at the tip, and the outermost primary acts as a reversible airfoil during take-off (Ennos *et al.* 1995). Tip feathers of a bird's wing reduce the drag by allowing air to pass thorough and use tip reversal upstroke (Crandell and Tobalske 2011).

Mechanoreceptors — alula receptors, convert feather receptors and secondary feathers receptors — (Fig. 1), associated with feathers, function as flow sensors. The discharge frequency of mechanoreceptors is produced by dorsal elevation of coverts, which is related to the elevation of the angle of attack. They detect flow separation point, predict the upcoming flow stall point and measure the airspeed on surface using frequency vibration as noted by Brown and Fedde (1993).

Wing alula makes the underwing coverts deployment closed with wing sweep during pitch-up manoeuver and is protected by passive peeling coming off from its tip (Carruthers *et al.* 2007). The aeroelastic devices were also examined in the Eagle wing using a video camera at a high speed of 500 frames per second placed on the upper wing to analyse the deflection of underwing coverts in outdoor and indoor perching sequences. Carruthers *et al.* (2007) concluded that underwing coverts operate as a high lift device and the alula functions, as strakes.
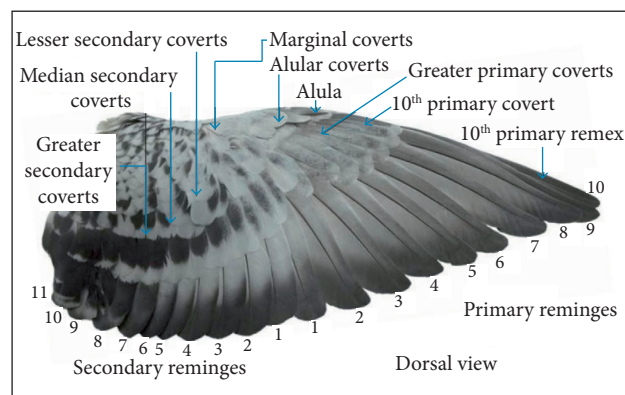
Figure 1. Topography of a Pigeon wing (dorsal view on a separated Pigeon wing; Bachmann, 2010). The numbers represent location of feathers in the wing.
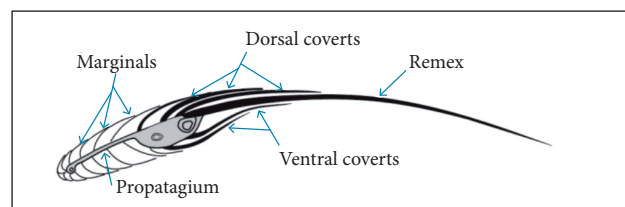

Figure 2. Diagrammatic section of a bird wing at the lower arm level. The shaded area indicates the impervious parts of the extremity (Muller and Patone 1998).
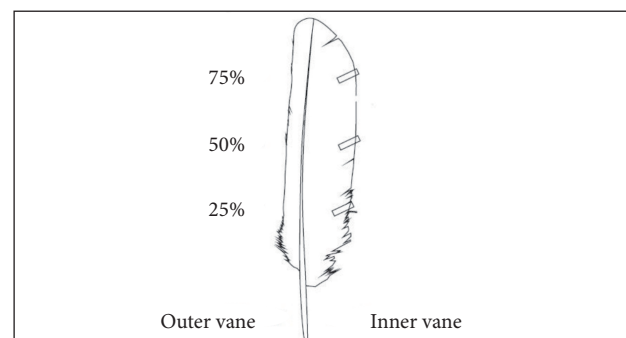

Figure 3. Inner and outer vane of feather (Bachmann 2010).
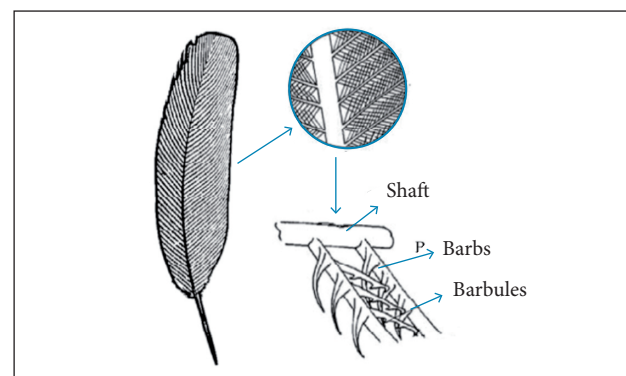

Figure 4. Characteristic of bird feather (Chen *et al.* 2013).

These aeroelastic devices seem to be used for flow control to enhance unsteady manoeuvres. However, these suggestions are based on visualization of a flying bird and were not determined through experiments.

AERODYNAMICS OF BIO WINGS/AIRFOILS

Extensive research on airfoil shape, unsteady flow analysis, structure and control is required for adaptive wing development where such applications are feasible in practical applications such as micro air vehicles (MAVs) (Jacob 1998).

The drag on bird airfoils is almost constant over a range of lift coefficients, as found by Carruthers *et al.* (2010), where the aerodynamic performance of reshaped 2-D airfoil of Eagle wing was analysed at Reynolds number of $1 \times 10^5 < Re < 2 \times 10^5$. However, Withers (1981) found that bird wings have high drag coefficient (0.03 – 0.13), which results in low minimum lift-to-drag (L/D) ratio as experimented on a dried bird wing at $Re = 1 \times 10^5 – 5 \times 10^5$. Bird wings do not perform as good as conventional airfoils and have low efficiency (Carruthers *et al.* 2010; Withers 1981). However, this comparison has been made between high Reynolds number airfoils and low Reynolds number bird wing airfoils, which makes this comparison questionable. On the other hand, bird wings have the advantage of performing at a wide range of angles of attack. (Carruthers *et al.* 2010) used a 2-D airfoil reconstructed from a 3-D scanned wing of a free flying Eagle. However, the 3-D scanning was performed at a single instant of pitching manoeuvre and it represents a single flight phase of the bird. Birds have high lift devices that increase the lift at a high angle of attack (Usherwood 2009), and bird wings with low lift coefficients have low drag coefficient and vice versa (Withers 1981).

Barn Owls and Pigeon wings were experimentally studied by Bachmann (2010) who found that Owls have thicker airfoils than Pigeons, which allows Owls to fly at low speed. On the other hand, Pigeons need to beat their wings faster, which leads to a higher speed, but they are noisier compared to Owls (Bachmann 2010). Owl's feathers absorb the sound that makes them less noisy compared to other birds and they fly almost silently (Chen *et al.* 2012; Geyer *et al.* 2014). Pressure distribution on bird's wing shows that they can be treated using conventional airfoil theory at low Reynolds number as determined by Withers (1981). Thin airfoils with Gottingen-like wing camber are more suitable for

MAVs compared to dragon fly wing camber as they produce high L/D ratio, and swept-back leading edge wing increases the performance of MAVs (Lin *et al.* 2007).

Usherwood (2009) estimated lift coefficients of dried and replica Pigeon wing using direct measurement of forces and mapped forces of pressure distribution. The lift coefficient was found to be 1.64 and 1.44 for dried and replica surfaces, respectively (these values do not represent the actual live bird's wing as its shape changes based on aerodynamic forces).

Bechert *et al.* (2000) described techniques of reducing wall shear stress to control boundary layer separation using different surface riblets consisting of biological surfaces such as shark skin replica, plastic model scales, hairy surfaces and surfaces where no-slip condition can be controlled.

Chen *et al.* (2013, 2014) studied the effect of bird wing herringbone riblets on drag and compared them to conventional micro-grooves (riblets). The result shows a drag reduction 16 – 20% higher than in the traditional riblets; moreover, optimal angle between herringbone riblets is about 60°.

The drag on a bird's body is proportional to its mass; as the mass increases, the drag increases as studied by Pennycuick *et al.* (1988) on frozen waterfowl bird. The body drag coefficients were estimated to be 0.25 to 0.39 at Re = 145,000 – 462,000. Lift and drag coefficients decrease with increase in flight velocity in bound flight as experimented by Tobalske *et al.* (2009) on Zebra Finch. The lift and drag coefficients decrease from 1.19 and 0.95 to 0.7 and 0.54 as the velocity increases from 6 to 10 m/s. The lift coefficient decreases significantly as the dihedral angle increases, drag and side forces change significantly by the large dihedral angle that leads to change in the rolling and yawing moments and results in unstable changes of aerodynamics parameters as studied by Sachs and Moelyadi (2010).

POROUS WINGS

Porosity is present in bird wings where the flow can penetrate between/through feathers. Air transmissivity of feathers was studied by Muller and Patone (1998) from the ventral to dorsal direction and vice versa. It was found that both directions have a small difference in air transmissivity that is about 10%. However, significant difference occurs in air transmissivity between inner and outer feather vanes.

Mazellier *et al.* (2012) experimented free-motion flexible-porous flaps mounted on a bluff body and found a reduction in drag by 22%. These flexible flaps move and vibrate through the aerodynamic forces. The displacement and vibration frequency

of the flaps is a function of Reynolds number. However, the properties of flexibility and porosity was not specified, and the study aimed to analyse drag reduction based on changing Reynolds number and the frequency produced by the flap flexibility regardless of its elasticity value. Yang and Spedding (2013) made 180 small cavities using holes of 0.5 mm diameter on the upper surface of an Eppler 387 wing to use acoustic resonance which changed the aerodynamic performance; the lift coefficients increased from 0.7 to 1, and the drag reduced by 10% at Re = 60,000. At a transitional phase, where Re = 40,000 and the angle of attack ranged from 0 to 9, the L/D ratio was higher compared to the same wing without holes. The improvement in lift coefficient occurs due to the flow turbulence inside the hole cavities. However, the study was concerned about resonance effect and not the effect of porosity.

Iosilevskii (2011) analytically studied thin wing membranes segmented into forward solid and aft porous parts. The aerodynamic centre moves non-uniformly to the quarter chord position of the forward section with increase in permeability and leads to a decrease in lift slope. The permeability depends on wing construction and on the flight conditions (it increases with velocity). This analytical model needs to be experimentally verified: an experiment with different permeability values, from low to high, and also at different Reynolds numbers, would prove this analytical model. The seepage flow through the wing reduces the lift slope and creates drag, which can be limited if the aft part width is less than the chord length (Iosilevskii 2013).

Bae *et al.* (2012) used CFD to study the effect of porosity on a trailing edge of a 2-D flat plate at Re = 1,000. They applied numerical penalization method with different porosities and predicted the relationship between pressure drop and flow velocity compared to numerical flow simulation of a non-porous 2-D flat plate. The results showed a reduction in drag and lift due to passive flow suction and blowing on the surface. Porosity has a significant impact on aerodynamic performance if the proper value of permeability is selected. Study on a 3-D model is yet to be performed, and the criteria for the correct selection of surface porosity are unknown.

FLUID-STRUCTURE INTERACTION

Any change in the structure, such as vibration, deformation or movement due to aerodynamic forces, falls under fluid-structure interaction (FSI) analysis. There are two types of FSI: one-way FSI and two-way FSI. One-way FSI changes the fluid's behaviour due to change in structure by controlled deformation, displacement or vibration. Two-way FSI is defined as changes in the structure because of aerodynamic forces and, then, a change in the aerodynamic behaviour due to the changes in the surface structure caused by the flow itself.

Bird wings are flexible, and the airfoil profile changes with aerodynamic forces and flight conditions. Therefore, the study of FSI is significant to understand its impact on flight performance (Gursul *et al.* 2014; Klän *et al.* 2009; Rojratsirikul *et al.* 2009).

PASSIVE CONTROL OF FLOW

Elasticity of feathers, wing coverts, surface velvets and feather mechanoreceptors are passive devices for flow control and aerodynamic force adjustment to the flight conditions as discussed by Brücker and Weidner (2014). The elasticity of the feather shaft helps the flow to stabilize and allows the bird to control the flow during different phases of flight (Bostandzhiyan *et al.* 2008).

Velvet-like surfaces on bird wing force the flow to reattach and delay the stall for a longer period at high angle of attack (Brücker and Weidner 2014; Klän *et al.* 2009; Winzen *et al.* 2013). A significant difference is present in the shear-layer roll up process, where it remains almost normal and locked for a longer period in the case of airfoils with adaptive hairy flaps while there is a rapid increase in the separation region in clean airfoil (Brücker and Weidner 2014).

Flaps and slats of airfoils are other devices used to improve the aerodynamic performance. There are two types of flaps: controlled flaps, used in aircraft, and passive flaps, as in bird wings. Flaps improve the aerodynamic performance and delay the stall at high angle of attack (Schatz *et al.* 2001; Schluter 2010). Numerical study on moveable flaps to control the flow separation shows a reduction in drag by 10% and an increase in lift by 10% at high angle of attack (Schatz *et al.* 2001). However, Schluter (2010) used a water tunnel at Re = 300,000 – 40,000 to analyze the effect of self-activated movable flaps of a 2-D wing mounted on the top surface near the trailing edge. When the flap is of 0.2c length at x/c = 0.6, the lift increased by 50%. When another flap is added at x/c = 0.8c, with length of 0.2c, there is no improvement in the lift. On the other hand, when the flap size length increased to 0.4c at the same location, the lift increased by 15% only. However, number of flaps, size and location still need to be analysed comprehensively in a wide range to arrive carefully at an optimum solution. Wang and Schlüter (2012) performed experiments on a 3-D wing with self-activated flaps using wind tunnel at Re = 4×10^4. The study

compared a set of flaps (1 to 4), at different positions along the chord and span. Authors claimed that a single flap performs best. Also, downwash force can be reduced by shortening the span of the flap. It was also determined that self-movable flaps perform best when they cover 80% of the wing span with width of 0.3 of chord and are located at 0.7 of chord measured from the leading edge. More studies have to be undertaken to obtain an optimum solution.

Another device in bird wings is the leading edge slat (Alula) which acts as a spoiler; it increases lift and stall angle of attack as simulated by Ge et al. (2013) on a 2-D section of a bird wing. However, the leading edge slat in birds (Alula) does not cover all the leading edge but a portion of it. In the mentioned study, natural flaps were replaced by artificial flaps to represent high lift systems, enhancing the maximum lift by 20%.

Unsteady flow structure and oscillating airfoil were simultaneously measured and compared to a fixed airfoil by Gursul et al. (2014) and Rojratsirikul et al. (2009). The fluctuation of airfoil was investigated as a function of the angle of attack, and it was found that flow generates rolling vortices on the top surface in case of a vibrating structure that delays the stall at a higher angle of attack (Rojratsirikul et al. 2009). The lift coefficients for a flexible wing were found to be higher than the coefficients for a rigid wing at sweep angle of 40 – 55°. If the sweep angle is more than 55°, the lift coefficient for a flexible wing becomes less than the coefficient for a rigid wing (Gursul et al. 2014).

The influence of aerodynamic forces on the large flexibility of a wing was examined experimentally in a wind tunnel using an elasto-flexible wing of a pre-stressed membrane by Béguin and Breitsamter (2014), who found that the aerodynamic forces deform the wing surface and adjust camber based on the aerodynamic conditions when experimented in a large flexible wing. However, the question that remains unanswered is the modulus of elasticity selection criteria or the range/criteria of the aeroelastic non-dimensional parameter. Numerical simulations on segmented airfoil show an increase in the lift of up to 39% near the stall angle (Hefeng et al. 2015). Three-segmented flexible airfoils produce better results than other segmented configurations. However, further studies on segmented airfoils are needed to find out if equal segments on airfoil surface result in optimal performance or not. Furthermore, experimental data could lead to validated simulation results.

The ability of a flow to vibrate flexible membranes was tested by Genç (2013) on 2-D and 3-D low aspect ratio wings;

2-D membrane wings vibrate more than 3-D wings because of the absence of tip vortex in 2-D wings that allows the shear layer to get closer to the surface. The largest deformation of the flexible membrane occurs near the tip due to the tip vortices.

Flexible surfaces perform aerodynamically better than rigid surfaces; they delay the separation at a high angle of attack and can be used as passive control (Du and Sun 2010; Genç 2013; Gursul et al. 2014; Hefeng et al. 2015; Rojratsirikul et al. 2009).

BIRD WING TIP/WINGLET

Winglets are devices to reduce the induced drag, and, in birds, they are flexible. Wing tip feathers of birds are considered to be winglets and they are flexible with spiral multi-feather elements. Bird wings are considered as non-planar, and a basic theory of non-planar systems is given by Cone Jr (1962) to determine the minimum induced drag and lift that can be expressed regarding aspect ratio and vortices distribution. A spiroid winglet was introduced by Guerrero et al. (2012) and was found to increase the lift and its slope by 9% .The L/D ratio improved by approximately 7%. However, it increased the parasite drag due to increase in surface area as well as interference drag. On the other hand, the spiroid winglet used by Guerrero et al. (2012) does not represent the bird winglet in terms of shape and flexibility.

Eder et al. (2015) estimated the induced drag factor of free-flying White Storks by calculating bird speed versus wing loading and aspect ratio. The induced drag factor ranges from 0.7 to 0.96 at lift coefficients of 1.2 – 1.6.

Tucker (1993) compared three types of wingtips: feathers of Harris' Hawk, slotted tip made of balsa wood and shaped as Clark Y airfoils and unslotted Clark Y wingtip mounted on a base wing. Feathers on the tip of bird wings reduce the drag ratio by 105% as the angle of attack increases from 4° to 14°. On the other hand, the L/D ratio of slotted balsa wing tips increased by 49% whereas the L/D ratio of unslotted Clark Y increased by 5% only. As the angle of attack increases from 0° to 15°, the drag increased by 25% in unslotted Clark Y and decreased by 6% in wing with feathers tip. The total drag of wing with feathers decreased by 12% compared to other wings. However, the bird feathers are flexible and bend at airspeed — these affect even the shape of the feather. Flexibility and shape of the wing tip feather under aerodynamic forces cause difference in L/D ratio and drag reduction.

Tucker (1995) investigated the effects of Harris' Hawk wing tip feathers (Fig. 5) on induced drag factor and compared

them to the same wing tip but with clipping of the feather tip. The tests were performed in a wind tunnel for a free gliding Hawk at speeds from 7.3 to 15 m/s. The induced drag factor of unclipped feathers is about 0.56 and increased to 1.1 in clipped feathers. Thus, it has been verified that bird wing tip feathers cause a reduction in drag.
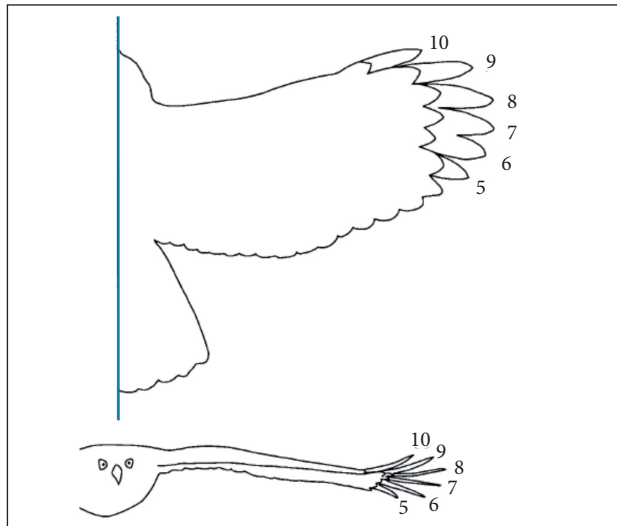

Figure 5. Tip of Harris' Hawk in flight (Tucker 1995).

ACTIVE CONTROL

Changes in wing/airfoil shape affect the flow behaviour. Pinkerton and Moses (1997) evaluated the capabilities of a piezoelectric actuator called THUNDER to vary the upper surface geometry of subscale airfoil, improving the performance. Venkataraman *et al*. (2014) derived a model for a poroelastic actuator on the upper surface to study FSI and its effect on the wake. They confirmed that the flow region behind an airfoil depends on the flexibility characteristics of the upper surface. Bilgen *et al*. (2010) used an actuator of microfiber composite to morph an airfoil (NACA 009 and NACA 0013). The airfoil with a chord of 127 mm was tested in wind tunnel at Re = 127,000, and the voltage ranged from 100 to 1,700 V. The results show an increase in lift by 1.67 with maximum actuation, and a maximum L/D ratio of 26.7 can be achieved. Further analytical studies for variable twist and variable camber using the same airfoil and actuators have been presented by Bilgen *et al*. (2011) to study the response of a morphing structure to achieve optimal lift and L/D ratio. A panel method software XFOIL has been used. The maximum lift achieved is 1.67 at a certain shape, and the maximum L/D ratio obtained was 40.3 at another specific morphed shape. However, even if this study

was done using active control, it shows the effect of surface shape on aerodynamic performance, which is similar to the case of birds, since their wing surfaces are flexible and can be morphed to accommodate the varying flight conditions during different flight phases, producing maximum aerodynamic performance.

AERODYNAMICS OF GLIDING FLIGHT

Gliding is flying without flapping the wings, and birds use gliding mode to save energy (Videler and Groenewold 1991). Birds adjust their wing span in gliding to have enough lift and fly at a certain glide angle to keep them aloft (Tucker and Parrott 1970; Zahedi and Khan 2007). Gliding is described as the relationship between bird wing speed and airspeed. There are two types of gliding: static, in which birds depend on the upward wind velocity, and dynamic, where the birds use the changing axial airspeed to stay aloft (Tucker and Parrott 1970). Zahedi and Khan (2007) studied theoretically the wing taper factors for birds. The model was developed from three birds (Jackdaw, Harris' Hawk and Laggar Falcon) to estimate the taper factor of their wings which are 1.8, 1.5 and 1.8, respectively. Also, an equation was derived to estimate the minimum wing span ratio during glide flight. Tucker (1987) analytically studied the effect of variable wing span on gliding and defined the gliding maximum performance curve as the minimum sinking speed at each air speed.

Experiments on bird glide show that L/D ratio of Pigeon in gliding is 10, and the maximum vertical diving speed of Laggar Falcon is 100 m/s. Tucker and Parrott (1970) used a trained Pigeon in a wind tunnel to glide at different speeds, investigating the gliding performance in a more accurate sense. However, the L/D ratio of Kestrel gliding is 10.9 at a speed of 14.9 m/s, and the angle of attack is 5.5° (Videler and Groenewold 1991). Extended wings are great for both gliding and turning. Swept wings are better for fast glide but less active in generating lift while turning at high speeds, sink speed and turning rate are hugely affected by selecting the right sweep (Lentink *et al*. 2007).

Field experiments by Videler and Groenewold (1991) suggest that birds use three methods to adjust lift and drag in gliding: wing span variation, pitching angle of bird's longitudinal axis (which is independent from wind speed) and spreading the tail to adjust the lift and drag. Bird tail has effect on L/D ratio; if the tail is trimmed, it reduces the L/D ratio and, if extended, it increases the L/D ratio (Tobalske *et al*. 2009). However, in wind tunnel, the birds only use wing span to control lift and

drag (Tucker 1987). Glide angle increases with the increase in dihedral angle of bird wing (Sachs and Moelyadi 2010).

STRUCTURE

An understanding of the mechanical properties of feathers is essential as they directly affect the aerodynamic properties due to their elasticity. A general review of feather on bird's feather biomechanics and structure was done by Zahedi and Khan (2007). The structure and shape of rachis allow them to withstand high forces and prevent them from cracking. Studies on feather microstructure show that the fiber matrix of keratin is arranged in such a way that it provides stiffness and strength; at the same time, it is flexible and elastic.

Bonser and Purslow (1995) examined the properties of feather keratin to find the Young's modulus (E) through tensile tests for eight different bird feathers. Modulus of elasticity for feathers was $E = 2.5$ GPa for all birds except for Grey Heron — $E = 1.78$ GPa. However, Purslow and Vincent (1978) found an E for the feather shaft of Pigeon equal to $7.8 \pm 2\%$ GPa. Bachmann *et al.* (2012) found the Young's modulus values of Pigeon and Barn Owl feathers between 4.14 and 6.93 GPa. On the other hand, Macleod (1980) examined the Young's modulus of contour feather for Brown Chicken, Turkey, Pheasant and Herring Gull in tension and bending tests and for distal and proximal regions. The results from the tension tests show that E ranges from 0.045 to 0.181 GPa and from 0.21 to 0.682 GPa for proximal and distal regions, respectively. In bending tests, E ranges from 0.005 to 0.024 GPa and from 0.457 to 1.85 GPa for proximal and distal regions, respectively. There is a difference in range of magnitude for the stiffness values due to different methods or tests used (Bonser and Purslow 1995). Rachis cross-section geometry controls the flexural stiffness rather than keratin material properties according to Bachmann *et al.* (2012), Bonser and Purslow (1995) as well as Purslow and Vincent (1978). The geometry and the second moment of area of the feather shaft increase as the body weight increases and vice versa. Second moment of area gradually decreases along the shaft from feather base to its tip, which results in higher rigidity in feather shaft at its root and greater elasticity at the tip (Bostandzhiyan *et al.* 2008; Macleod 1980; Purslow and Vincent 1978).

Bird wings can withstand higher forces than the forces they are normally exposed to. Normal stress applied on birds feather is 8.3 up to 15.7 MPa while the ultimate stress point at the bending is 137 MPa, which gives a safety factor between 6 and 12 (Corning and Biewener 1998). This feature of safety allows them to fly under extreme conditions. Flexural stiffness is more critical than strength in feather shaft.

However, all the studies mentioned above focused on the feather structure properties, especially feather shaft properties, which gives strength for the bird wing to withstand the forces. Investigation of the elasticity modulus of the coverts (hairs) is still required. The coverts pop-up when birds fly at a high angle of attack. To make a flexible surface similar to a bird's surface or to study the effect of coverts on aerodynamic performance, the properties of the coverts need to be known.

EXPERIMENTS/SIMULATION METHODS

In Aerodynamics, there are three ways of predicting or calculating the aerodynamic performance of wings/airfoil, which are: analytical/mathematical model, numerical simulation and experimental test. Analytical/mathematical model is used to represent a specific problem, but in general it is derived for simple geometries/airfoils. Numerical simulation is widely used to solve complicated problems as it reduces the cost of experiments, although it is costly in terms of time. Experimental test is considered the most robust method if done correctly, because it gives more realistic results. It is also used to verify the results of simulations.

One of the experimental methods is the particle image velocimetry (PIV), which has been used to measure the influence of hairy surfaces on aerodynamic performance and separation control by Brücker and Weidner (2014), Klän *et al.* (2009) and Winzen *et al.* (2013). Pressure distribution measurements and oil pattern method were used by Klän *et al.* (2009) to verify the results obtained from PIV, and the results show agreement among the three methods. In their experiments, the airfoil profile used was obtained form an average reconstructed artificial wing obtained by scanning an Owl's wing. Rojratsirikul *et al.* (2009) used high speed PIV to study the fluid structure interaction of a 2-D airfoil at a Reynolds number range of 53,100 – 106,000. The measurements were taken for the unsteady flow and structural changes simultaneously, and the oscillation in structure behaviour was investigated as a function of angle of attack and velocity.

Tobalske *et al.* (2009) studied Zebra finch wing aerodynamics in intermittent bound phases using PIV and force transducer.

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The measurements were performed at different speeds from 2 to 12 m/s and different angles of attack ranging from −5° to 50°. A uniform structure of the wake was observed, and the forces derived from both measurements of PIV and force transducer have a close agreement.

The dual-plane PIV has been used by Waldman and Breuer (2012) to increase the dynamic range of PIV measurements on a fixed wing and has been compared to PIV. Both measurements indicate the same position of vortex downstream but dual-plane PIV covers a more dynamic range by an order of magnitude. Dual-plane PIV captures the velocity of outer flow more accurately, which leads to more accurate results. It is also able to capture the strength of the wake downstream qualitatively and quantitatively.

Another development of PIV, called digital PIV (DPIV), has been used by Spedding *et al.* (2003) in low-turbulence wind tunnel to study the free-flying bird wake. DPIV measurement uses two cameras and allows a moving object to wake so that it can be measured more accurately and with more reliability. The shortcoming of the method is the difficulty in matching the optical axis of the two cameras. However, mismatches can be removed to quite high accuracy, by careful mapping of the apparent displacements of stationary control objects imaged by both cameras. It removes the disturbances of lens/camera and examines only the effect of moving object disturbances. Spedding *et al.* (2009) confirmed the ability of DPIV to measure the background structure of small turbulences in a low turbulence wind tunnel, which can be used to measure the aerodynamics of small flyers. Genç (2013) also used DPIV in a closed loop open-jet wind tunnel to calculate the average and instantaneous velocity field on a membrane wing at Re = 48,700. They also used digital image correlation system to measure membrane deformation and load cell, calculating forces on the wing. Waldman and Breuer (2012) used a fixed model with load cell direct measurement of aerodynamic forces to explore the challenges of selecting appropriate experimental parameters to have more accurate dynamic measurements. Isaac *et al.* (2006) used hydrogen bubbles and dyes as traces to visualize the flow over a moving and pitching flat blade.

Visualization of flow on flying birds is another method for examining the flight mechanism or flow separations. Carruthers *et al.* (2007) used a high-speed camera carried by an Eagle to examine the function of coverts in perching modes. Eder *et al.* (2015) performed field measurements using infrared laser tracking to estimate the induced drag of souring and gliding flight of White Storks. The test was carried for 100 adult White Storks and it was found that the speed ranges of these birds at soaring, gliding and fast speed are 7.5 – 10, 10 – 14 and 14 – 19 m/s, respectively. The wrist angle (angle between the frontal edge of the cascade and the propatagium sinew — see Fig. 6) ranges of soaring, gliding and fast flight are 15° – 19°, 20° – 24° and 25° – 50°, respectively.

Chen *et al.* (2013, 2014) used SEM and CFD to investigate the effects of herringbone-type riblets on drag reduction using a microstructure of secondary feathers of Pigeon and then used a 3-D plane with herringbone riblets to compare them to traditional riblets.

Sachs and Moelyadi (2010) used CFD to study the effect of large dihedral angle of Pigeon-like wings on aerodynamic performance. A CAD model for Pigeon wing at different dihedral angles was used. The airfoil section is the same for all dihedral angles. However, the shape of airfoil in real birds changes during each flight phase; thus, this simulation is simplified to a minimum complexity of bird wing geometry.

On the other hand, analytical aerodynamic analysis of flexible and bird-like wing/airfoils was attempted by Iosilevskii (2013), who derived a closed-form mathematical model for the lift and pitching-moment coefficients of a thin wing membrane by sectioning the surface into two parts: a solid forward part that is impermeable and the aft part, which is porous. Another closed-form solution is obtained to study the seepage drag for the same model using Darcy's law. Venkataraman *et al.* (2014) developed a linear mathematical model by combining vortex-shedding minimal-order model with oscillator mode to study FSI and its effects on the flow region. Both minimal model proelastic coating and FSI coupling are assumed to be linear.

Biomimetics of a bird wing is defined as the replication and development of a wing/airfoil similar to those of the birds regarding
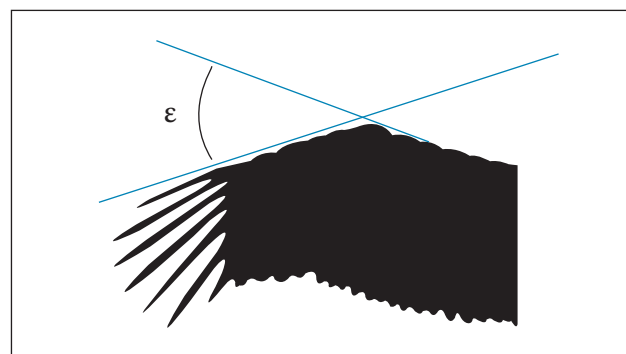

Figure 6. The wrist angle (ε) between the frontal edge of the cascade and the propatagium sinew (Eder *et al.* 2015).

shape and properties in mathematical, simulation or experimental form. Mazellier *et al.* (2012) implemented a biomimetic approach and used a squared cylinder geometry with free-rotating elastic self-deformable (made of a rigid material coated with plastic skeleton) porous (fabric) flaps to replicate the feather vane to study its effects on aerodynamic performance. Lin *et al.* (2007) developed aluminum plates with Gottingen wing — a wing span of 15 cm, thickness to chord ratio of 1.3 and camber of 6% — and compared their aerodynamic performance to other airfoils that have a half-forward part similar to a dragonfly wing. Corning and Biewener (1998) used a metal foil strain gauge to evaluate the safety factor in feather shaft of a free-flying Pigeon. Strain was recorded at both compression (down stroke) and tension (up stroke). Photogrammetric reconstruction technique was used by Carruthers *et al.* (2010) to reconstruct the wing section of a free-flying Eagle. A mathematical model was used to reshape 2-D airfoil, analyzing the aerodynamic performance. Klän *et al.* (2009) also used Owl airfoil extracted from a 3-D scanned wing and experimented it in a wind tunnel at Re = 2,000 – 4,000 with and without velvet to study the effect of velvet on delaying stall angle. However, the 3-D shape was smoothed and the twist was removed. The effect of smoothing Owl wing and removing the twist might have significant impact on aerodynamic performances.

The aerodynamic performance of real birds was studied by Pennycuick *et al.* (1988), who used a frozen waterfowl in a wind tunnel to estimate the drag coefficient at Reynolds number of 145,000 - 462,000, and Usherwood (2009), who used a dried Pigeon wing and a replica flat plate to measure and compare aerodynamic forces on both revolving surfaces at a Reynolds number of 108,000 using a propeller rig. The direct measurement of forces was taken, and the mapped forces of pressure distribution were calculated. Withers (1981) also used dried wings of different types of birds and experimented them at Re = $1 - 5 \times 10^5$. Dried wings, however, differ from live bird wings, which might affect the aerodynamic performance.

MAVs, wind turbines, tidal wave turbines and other devices perform at low Reynolds numbers similar to birds. Thus, lessons learnt from aerodynamics of bird wings in steady flight could be implemented in such applications to enhance their performance.

CONCLUSION

This paper focuses on the past research carried out on fixed bird wings (non-flapping wing), in terms of analysis, simulation and experiments which have been performed by researches for a wide range of bird wing aerodynamics. However, some areas in bird aerodynamics can be studied more thoroughly as the bird wings consist of highly complex representation of flexible (not flapping) and porous surfaces. Many of these problems are mentioned throughout this article.

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