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Investigation of Wing Forms Through Mass and Wing Area Chart

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Abstract: The wing loading parameter depending on the wing area and weight and the aspect ratio parameter, which is the wing shape factor, are the main parameters that determine the fixed-wing flight mechanics. In this study, the relationship between wing forms and flight style of 195 bird species was evaluated using wing area and mass scatter plot. The slope of the mass and wing area chart is proportional to the 1/wing loading. The results showed that birds with more wing area per unit mass tended to perform unpowered flight styles such as soaring and gliding; and birds with less wing area per unit mass tended to have powered flight styles, such as flapping and hovering. In general, it has been found that the slope of the trendline curve is more inclined tended to expend more energy in flight. Unlike the fixed-wing flight mechanics, hand-wings and arm-wings should also be examined to understand the flight mechanics of flapping wings as different effects occur during flapping flight in terms of the lift and thrust forces. In addition, scythe-shaped wings differ from high-speed wings in terms of the ratio of hand wing length/arm wing length according to their wing structure.

Kütle ve Kanat Alanı Grafiğinden Kanat Formlarının İncelenmesi

Anahtar Kelimeler
Kanat yüklemesi, Kanat formları, Tırpan şeklindeki kanatlar, Kanat yapısı, Kanat morfolojisi

Öz: Kanat alanı ve ağırlığa bağlı olan kanat yükleme parametresi ve şekil faktörü olan en boy oranı parametresi, sabit kanatlı uçuşun mekaniğini belirleyen ana parametrelerdir. Bu çalışmada, 195 kuş türünün kanat formları ile uçuş tarzları arasındaki ilişki, kanat alanı ve kütle dağılım grafiği kullanılarak değerlendirilmiştir. Kütle ve kanat alanı grafiğinin eğimi 1/kanat yüklemesiyle orantılıdır. Sonuçlar, birim kütle başına daha fazla kanat alanına sahip kuşların, süzülme ve süzülme gibi enerji gerektirmeyen uçuş stillerine sahip olma eğiliminde olduğunu göstermiştir; ve birim kütle başına daha az kanat alanına sahip kuşlar, kanat çırpma ve havada asılı kalma gibi enerji gerektiren uçuş stillerine sahip olma eğilimindedir. Genel olarak, daha düşük eğri eğimli kuşların kural olarak uçarken daha fazla enerji harcadıkları belirtilmelidir. Çırparak uçuş sırasında kaldırma ve itme kuvvetlerinin oluşumu açısından farklı etkiler meydana geldiğinden, çırpma kanatlarının uçuş mekaniğini anlamak için sabit kanatlı uçuş mekaniğinin aksine el kanatları ve kol kanatları da incelenmelidir. Ayrıca kanat yapılarına göre tırpan kanatlar, el kanadı uzunluğu/kol kanat uzunluğu oranı bakımından yüksek hızlı kanatlardan farklılık gösterir.

1. INTRODUCTION

Size, shape, and structure are the main factors that determine the wing morphology. The first studies in the literature of bird wing morphology were made by German schools [1,2]. Savile [3] proposed wing forms that are still widely used today: elliptical wings, high speed wings, high aspect ratio (AR) wings, and slotted high lift wings. Savile classified the wing forms according to their shape and flight behavior and ignored the wing structure. Elliptical wings and high aspect ratio wings are shape-based designations. Although the designation of slotted high lift wings is related to flight, it is related to wing size, as high lift can only be achieved with long and wide arm wings. On the other hand, high-speed wings are a designation based solely on flight characteristics, regardless of size, shape, and structure. There is a strong relationship between wing forms and flight styles. For example, wings with a high aspect ratio provide high lift and thrust, and these wings are suitable for dynamic soaring and flap-gliding. Birds with slotted high lift wings have long-wide arm wings, and a large wing area, which is advantageous in thermal soaring. Fast take-offs, tight maneuvers, short bursts of high-speed are the main flight characteristics provided by elliptical wings. The birds with high-speed wing forms do not have a specific flight style, although most forms of wings have their own unique flight style.

Rayner [4] did a correlation study between wing area and bird mass, showing that the general curve corresponds to square cube law (2/3) and hummingbirds shows a different curve slope from the general bird curve slope, again Corvidae shows a different curve slope from Passerines. Rayner has also attempted to decipher bird wing morphology using principal component analysis (PCA) via the AR and wing loading axes. Contrary to Rayner, Norberg [5] proposed the term relative wing loading (RWL) instead of wing loading. Norberg claimed that AR-RWL charts gave a more effective result in the distribution of wing morphology and flight styles, and classified groups of birds in terms of wing characteristics and flight patterns. Lockwood et al. [6] used convexity and pointedness parameters to investigate the effect of wingtip shape on detecting morphological adaptations to migration. They found that the migrants have relatively more pointed and more convex with larger AR. Videler [7] was the first to describe the unique wings of the common swift as a “scythe-shaped wing”. Videler [7] suggested that the swifts' slender and pointed hand-wing forms leading edge vortices (LEVS), that produce aerodynamic flow system that generates lift over a wide range of angles of attack.

The wing loading and aspect ratio are the main parameters studied to examine the effects of mass, wing size and shape factor on the fixed-wing bird flight. Unlike fixed-wing bird flight, hand-wings and arm-wings should be examined to understand the flight mechanics of wing flapping as different effects occur during flapping in terms of the lift and thrust forces flight. The wing loading parameter (the ratio of weight to wing area) is an aerodynamic parameter that allows us to understand the effect of both size and mass on flight characteristics. The second important parameter in fixed wing flight mechanics is the wing aspect ratio, which has an impact on gliding ability [8]. The wing aspect ratio parameter (ratio of wingspan squared to wing area) is a shape dependent aerodynamic parameter. The best glide rate is proportional to the square root of the aspect ratio, so a high aspect ratio is an indicator of the ability to glide [9]. Keast [10] suggested that short and low aspect ratio wings, which are usually found in resident species, are advantageous for rapid take-off.

As mentioned earlier, the flight mechanics of the flapping wing are different from the fixed wing bird flight. The arm wing is a part of wing close to the body, consisting of humerus, ulna, and radius bones with secondary and tertiary feathers. The hand wing is a part of wing close to the wingtip, consisting of the metacarpals and phalanges bones with the alula and primary feathers. The ratio of arm wing to hand wing affects the flight behavior and eco-morphology of birds, since during flapping the arm-wing determines lift ability of the wings, while the hand-wing determines thrust ability of the wings. Kruyt et al. [11] argued that the effect of aspect ratio is changed according to whether birds were flapping their wings or being in a fixed position. Again, Henningsson et al. [12] suggested that the efficiency of lift production during wing flapping is higher than that of gliding. Also, Muijres et al. [13] claimed that energy is more conserved in flap-gliding flight than in continuous flapping flight. Lilienthal [14] claimed that, during flapping, arm-wings (inner wings) create a lift force, hand-wings (outer wings) create thrust force and contribute to control and maneuverability. The mechanism of formation of the lift force and the thrust force in ornithopters supported this claim. Harmon [15] and Dvorak [16] corroborated this claim with tests conducted on flapping aerial vehicles, namely ornithopters.

In this study, it is aimed to investigate the effects of wing loading, shape, and size factors on bird flight styles in the mass wing area distribution chart of 195 bird species classified according to the 6 types of wing forms proposed in the method section.

2. MATERIAL and METHOD

Within the scope of the study, data on the body mass, wing area, aspect ratio, wingspan, and average wing chord length of 195 birds were collected. Biometry of bird data compiled from previous studies [8, 17, 18, 19, 20]. The wing size in birds is related to mass, and the study of scaling between mass and size is based on the idea that the unit length scale is proportional to mass to the power of 1/3. Therefore, the wing area is proportional to the mass the power of 2/3. The equation of correlation between wing area (S) and mass (m) can be written as in Eq. 1 where a is about 2/3, and c is a constant coefficient that varies according to bird groups [19, 21, 22]. The power of mass, denoted by a, determines the tendency of the wing size to grow relative to the mass and differs in groups of birds. Power correlation is used to decipher the relationship between bird mass and wing area in the charts provided in the result section of paper.

$$S = c.m^{2/3} \qquad (1)$$

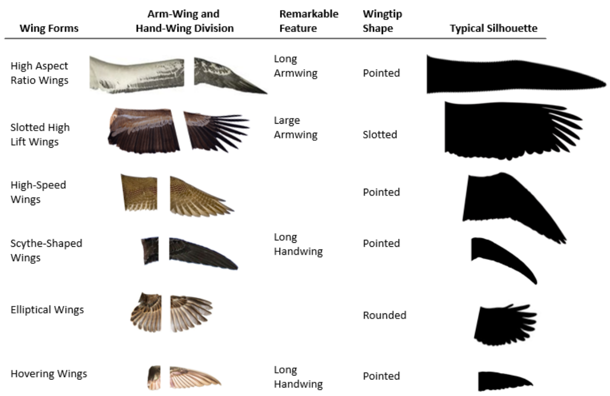

Figure 1. Structure properties of studied wing forms

To understand the criteria by which the wing forms are separated, the split wing structures and the wing silhouettes used in the result charts are given in Fig.1. Photoshop tool was used to separate and scale the hand and arm wings.

The scythe-shaped wings and hovering wings of hummingbirds have a high ratio of length of hand-wing to length of arm-wing compared to typical high-speed wings. Therefore, in this study, these wing forms were not considered as a high-speed wing form as Saville did, but as separate wing forms. Swift and Hummingbirds are agile birds because their long hand-wings provide high thrust. The wings of hummingbirds are like the wings of swifts; however, the arm-wings are slightly thinner than those of the swifts, and their hand wings are slenderer than those the swifts. Swallows and Martins belong to the Hirundae family of the order Passeriformes, but their wing structure is more like the SSW (arm wings are short, hand wings are long). In scythe-shaped wings, the ratio of hand wing length/arm wing length is greater than that of typical high-speed wings, as shown in the Eq. 2.

$$\left(\frac{\text{Handwing Length}}{\text{Armwing Length}}\right)_{SSW} > \left(\frac{\text{Handwing Length}}{\text{Armwing Length}}\right)_{HSW} \qquad (2)$$

The representation of the aerodynamic effects by wing position is shown in Table 1. The wing loading and aspect ratio are the main parameters examined to study the effects of mass, wing size and shape factor on the fixed-wing bird flight. Unlike fixed-wing bird flight, hand-wings and arm-wings must be examined to understand the flight mechanics of wing flapping.

Table 1. Aerodynamic factors according to avian wing position

Wing Position	Parameter	Aerodynamic Factor
Fixed Wing	Weight	Wing loading
	Wing size	
	Wing shape	Aspect ratio
Flapping Wing	Wing structure	Arm-wings generate lift Hand-wings generate thrust

3. RESULTS

Wing area and mass distribution charts are useful in describing the effect of wing loading on flight behavior. The slope of the trendline in the mass and wing area graph is proportional to 1/(wing loading). In this study, regression analysis was performed between the bird mass and the wing area based on the wing forms. Fig. 2 shows the trend line curves of the bird mass relative to the wing area on a logarithmic scale for birds with 6 different wing forms.

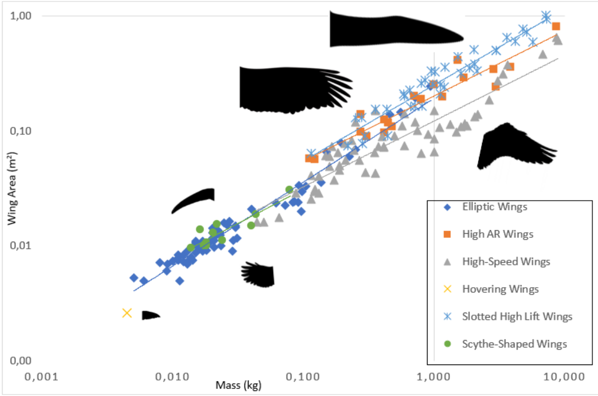

Figure 2. Distribution of wing size and mass according to wing forms. A base-10 log scale is used for all axes.

The power of the given mass that is “a” at Eq.1 differs in groups of birds. The trendline in all birds follows the 2/3 (0.66) rule, which has also been found in the literature, and the power of the mass calculated for 195 bird species in this study is 0.69. The trendline on the mass and wing area chart gives very consistent results in distinguishing between unpowered flight styles and powered flight styles. These results show how important the wing loading parameter is in flight mechanics. As can be seen from the Fig. 2, there is a relationship between low wing loading and unpowered flight strategies. In addition, it can be said that birds with the slope of the trendline curve is more inclined, as a rule, expend more energy when flying. Birds falling below the general trendline in Fig. 2 (Waterfowls, Galliformes and Anna's Hummingbird) often use powerful flight strategies, such as hovering or continuous flapping. In contrast, the birds that remain above the trendline are shown in Fig. 2 (Birds of prey, Falconiformes, high aspect ratio winged birds) often use unpowered flight strategies such as dynamic soaring, thermal soaring, or gliding.

The increase in wing area along with the increase in bird mass can be understood from the curve slopes of mass and wing area chart. The power equation of the trendlines gives the unit increase in wing area proportional to the bird mass. Fig. 3 shows the trendline equation of Corvidae wings, elliptical wings (EW) and slotted high-lift wings (SHLW). The curve-trend-line-equations show that the large members of Corvidae behaves like Accipitriformes, not Passeriformes. Large members of the Corvidae have transitional wing forms between the typical passerines with EW and the Accipitriformes with SHLW. Even though the family Corvidae belongs to the order Passeriformes, the wing forms of Ravens, Rooks and large Crows are similar to SHLW, that is the wings of Accipitriformes. Large members of Corvidae are capable of thermal soaring and gliding flight [23-25].

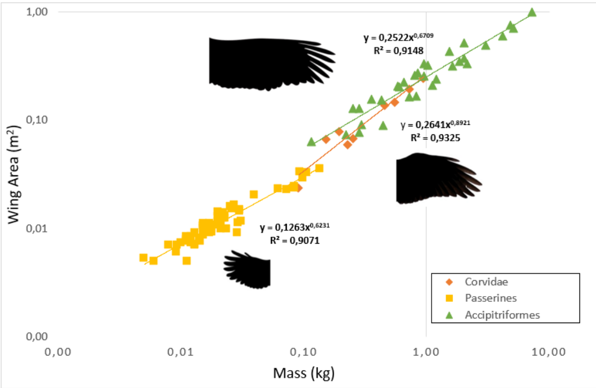

Figure 3. Distribution of wing size and mass of elliptical wings (EW) and slotted high lift wings (SHLW). A base-10 log scale is used for all axes.

Fig. 4 shows the wing area and the mass distribution curve of birds weighing more than 1 kg. The difference in curve slope between SHLW (birds of prey) and high-speed winged birds (HSW, waterfowls) is clearly visible. The most advantageous bird group in terms of wing area is SHLW, while the most disadvantaged bird group is HSW-waterfowls. Wing aspect ratio (AR) is important for gliding flight, while a large wing is important for soaring flight. For example, frigate birds with high aspect ratio wings (HARW) can use both thermal soaring because they have a large wing area, like SHLW, and dynamic soaring because their wing AR is high. The efficiency of lift production in the flapping flight is higher than in the gliding flight. This fact may explain why waterfowl (with a low wing loading) do not glide or flap continuously during migration. In addition, the wing aspect ratio (AR) is a decisive parameter on the ability to glide. For example, large birds with similar wing loading, albatrosses use dynamic soaring and ducks use continuous flapping.

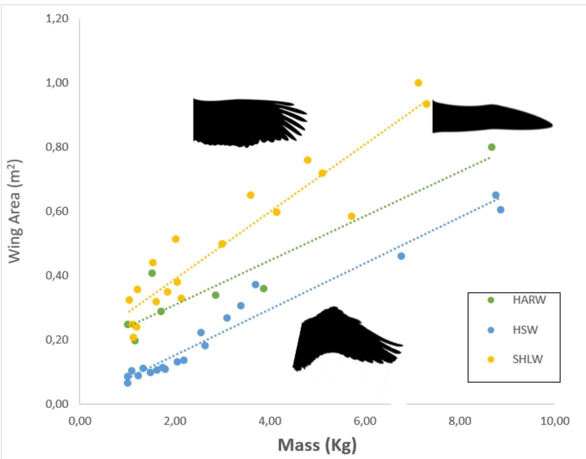

Figure 4. Distribution of wing size and mass of birds weighing more than 1 kg, where HARW is High Aspect Ratio Wings, HSW is High-Speed Wings, and SHLW is Slotted High Lift Wings.

High-speed wings (HSW) are the wing forms of the most heterogeneous groups of birds have. The Dunlin (*Calidris Alpina*) weighing 50 grams and the Whooper Swan (*Cygnus cygnus)* weighing 9 kg have the HSW form. Even though most wing forms have their own unique style of flight, this generalization is invalid in HSW forms. That is, birds with the HSW form may have one of several different flight styles, such as thermal soaring, gliding, or continuous flapping. Fig. 5 shows the distribution between mass and wing area for HSW type wing forms. The slope of the curve shown in Fig. 5 gives an idea of the flight styles: Falcons with the low slope trendline curve can perform gliding and thermal soaring flights. Medium-curve slope; the Shorebirds, Sandgrouse, and Columbiformes use short-term gliding and long-term flapping, while lowest-curve slope, divers and waterfowls need to flap continuously during migration. A striking result here is that large waterfowl, that is, geese and swans, have different curved slopes than small waterfowl, that is, ducks. Swans and geese have a relatively larger wing area per unit mass than ducks.

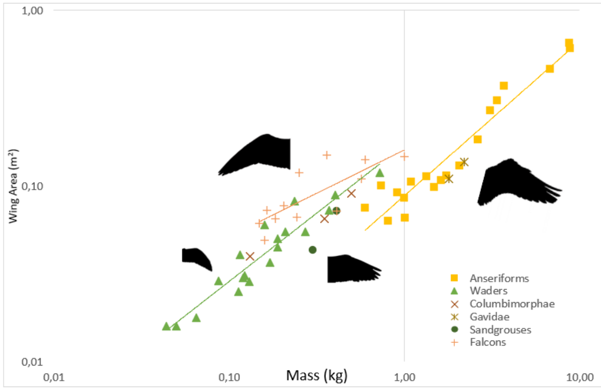

Figure 5. Distribution of wing size and mass of high-speed wing forms. A base-10 log scale is used for all axes

The difference between SSW and EW with similar wing area is due to the wing structure and shape rather than size, while the decisive difference between SSW and HSW depends on the wing size and wing structure. This is because the wingtips of the SSW are more pointed than the HSW, and the ratio of the (hand-wing length)/(arm-wing length) is larger than the typical HSW. As can be seen from Fig. 6, the SSW has a similar wing area as the EW; however, the SSW has a higher AR, that is, the ability to glide(flap-gliding). Swifts have a smaller wing area than Falcons but have a relatively higher AR value. Falcons can sweep their wing shape in diving flight conditions, while Swifts can sweep their wing shape up to 60 degrees in cruising flight conditions [26,27].

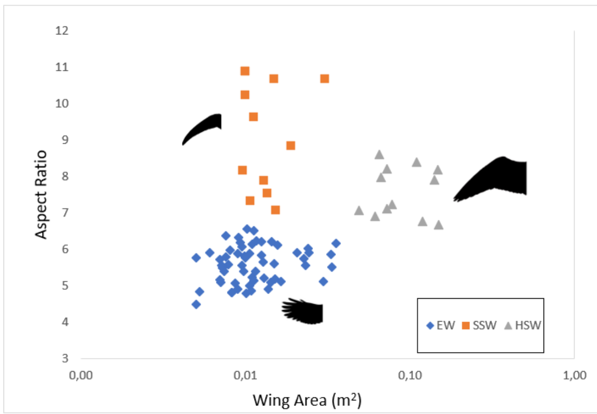

Figure 6. Distribution of aspect ratio and wing area of Elliptical Wings (EW), Scythe-Shaped Wings (SSW), and high-speed wings (HSW, only Falconiformes). A base-10 log scale is used for X axis.

Swifts are the fastest birds in cruising flight (non-diving flight), as the long-armed wings generate high thrust and the pointed wing tips reduce drag. On the other hand, wings with small arm-wings provide less lift, but they create extra lift by using leading edge vortices to compensate for this. These results indicate that the effects of wing structure on the flight form should be examined more, except for wing loading and AR, because features of the arm-wing and hand-wing have very significant effects on all flight styles except gliding and soaring. In addition, Passerines and swifts with similar wing loading but different AR have different flight styles. This is a phenomenon related to both the AR (gliding) and the wing structure (flapping).

4. DISCUSSION

The study, which claims that Savile's [3] bird wing forms are inadequate, suggested scythe-shaped wing form and hovering wing forms in addition to Savile's classification. The study examined the effects of wing loading in fixed-wing flight mechanics to explain the effect of wing structure on flight styles. The study examined the effects of wing loading on flight, as stated by Pennyquick [8]'s fixed wing flight mechanics, on the trendline slopes and showed the difference between gliding and non-gliding birds in charts. As a result of this study, birds with lower slope curves flapped their wings more often, it coincides with the proposal of lift production during wing flapping is higher than that of gliding of Henningsson et al. [12]. The study examined the effects of wing loading in fixed-wing flight mechanics to explain the effect of wing structure on flight styles. While the wing loading parameter is mainly taken into account in the mass wing area distribution charts given in the results. The most interesting result of this current study is that the groups of birds remain below the trendline curve given in Fig. 2 use powered (flapping, hovering) flight styles and the groups of birds remain above the trendline curve have unpowered flight styles (soaring, gliding). In fact, when Rayner's (1988) study is examined, this result is evident in the wing area-mass chart, but it was not expressed by Rayner [4]. It can also be seen in the results that birds with a lower curve inclination (due to the high wing load), as a rule, expend more energy in flight. Among the unpowered flight styles, the large wing area for soaring and the high aspect ratio for gliding stand out as prerequisites. Although most wing forms have distinctive flight style, the reason why birds with high-speed wing forms do not have a specific flight style has been questioned (see Fig. 5).

Lilienthal [14]'s arm-wings create a lift force, hand-wings create thrust force claim coincides with claim that the Swift's long arm wing plays a key role in reaching the highest speed in level flight. Since the effect of wing structure is more dominant in flapping wing flight, it is necessary to examine the arm-wings and hand-wings in detail. There are many studies on the flight style of swifts [26-29] however, there is no studies in the literature on the difference of swifts' hand-wings and arm-wings from the typical high-speed wings. In this study, based on the difference in wing structure, the wing form difference between scythe-shaped wing (SSW) and high-speed wings (HSW) was shown descriptively using photoshop, not quantitatively due to absence of experimental data.

This study supports the study of Videler [7] and suggests that the wings of Swift should be described as a scythe-shaped wing form, not a high-speed wing form. The distinction between the scythe-shaped wing form and the High-speed wing could be a potential research topic for future experimental research. Wang et al. [30] suggested that the ratio of feather length to total arm length could be used to evaluate the flight modes of Mesozoic birds. In that study, they suggested a high correlation between flight styles and the ratio of feather length to total arm length. Similarly, it is a very strong claim that the difference in flight style between scythe-shaped winged Swifts and high-speed winged Falcons is due to the ratio of the length of the hand-wing to the length of the arm-wing.

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