Dynamic Parameters of Flight Surface (Wing) and Induced Air of Hovering Birds

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Abstract: *The 'Flight Apparatus' consists of flight muscles and 'Flight surface' and its main function is to induce air in downward direction due to wing beat so as to execute flight. The flight 'System' comprises of 'Air' and 'flier' and constitutes 'Action - Reaction pair'. The action of wing is on air around the flier and in turn reaction on the flier in opposite direction which balances 'Gravitational force' ie weight of the flier. In view of this, dynamic parameters of flight surface (wing) and induced air of the flier for 25 species of small, medium and large size birds are studied in order to understand flight, when the birds are in their states of hovering flight. The relations are drawn between the different dynamic parameters of wing and induced air, which explain avian flight adequately.*

Key words: *Dynamic parameters; Flight surface (wing); induced air; flying birds; hovering state.*

1. INTRODUCTION:

When a flier is in the state of hovering, it is said to be in the dynamical equilibrium which is achieved by the flier by generating the air induced downwards due to wing beat in turn develops a reacting force, just to balance its body weight. The flier and induced air put together is considered as a "system".

Pennycuick [1] reported that apart from the wing beat frequency, the induced velocity of air is also a function of the body mass and wingspan of the flier. According to this theory the induced velocity of air should increase under transverse wing mutilation and should be independent of longitudinal wing mutilation.

Puranik and Adeel Ahmad [2] studied the flight sound in *T. Javanica* and subjected the complex tone to Fourier analysis. They described the pressure pattern developed by the wings around the insect in tethered state.

Puranik, et. al [3] proposed that the wing beat frequency of any flier in the hovering state of flight could be determined from the knowledge of the rate of mass flow of air induced downward by the wing disc. This shows that the wing beat frequency is a function of the body mass, wing span and wing breadth. Hence any variation in these parameters produced by the wing mutilation should introduce corresponding variations in the wing beat rate of the flier.

Adeel Ahmad and Gopala Krishna [4] reviewed the work, both theoretical and experimental, on the wing beat frequency of various myogenic and neurogenic fliers.

Sanjay Sane [5] developed a theoretical model based in rotor theory to estimate the mean induced flow over the body of flapping insects, which is able to capture some key characteristics of mean induced flow over the body of a flying insect. Specially, it predicts that induced flow is directly proportional to wing beat frequency and stroke amplitude and is also affected by a wing shape dependent parameter. The derivation of induced flow includes the determination of spanwise variation of circulation on flapping wings. These predictions were tested against the available data on the spanwise distribution of aerodynamic circulation along finite *Drosophila melanogaster* wings and mean flows over the body of *Manduca sexta*. The model described by Sanjay Sane allows to estimate how far field flows are influenced by near-field events in flapping flight.

Nasiha Saher Bano, et al [6] presented a comparative study on wing beat frequency of various species of birds. Frequency of wing beat of avian fliers was calculated using different theories and the data was compared and discussed. They suggested that Mass flow theory is superior to any other theory proposed for the computation of wing beat frequency.

Nasiha Saher Bano, et al [7] reported data on induced power, inertial power and dynamical efficiency of 25 species of wide variety of birds, when they fly in the state of hovering. Also, presented body parameters such as body mass, length, span, effective breadth, area, moment of inertia and frequency of wing beat of birds. The study on flight of small, medium and large size birds revealed that induced power was directly proportional to mass or weight of the flier. Further, suggested that inertial power was not a function of any one parameter of flight surface (wing) of a flier. But it comprised wing dimensions, moment of inertia, stroke angle and frequency of wing beat. Finally, they concluded that dynamic efficiency (η) of flight surface (wing) of birds was a function of body parameters as such it could not be related to a single parameter and was independent of size (small, medium and large) of a flier.

Burrows et al [8] analysed kinematics of take-off in *Proutista moesta* from high speed videos and reported individual insects used two distinct mechanisms involving different appendages. Firstly, fast take-off propelled by synchronized movement of hind legs without the use of wings. Secondly, slow take-off powered by beating of wings alone, having no involvement of hind legs.

A search of literature reveals that investigations of flight adaptation of natural fliers such as birds were made using experimental procedures and theoretical models. Theories of bio-aerodynamics have not been examined to utmost satisfaction.

Hence, in the present investigation, dynamic parameters of the system (flier + air) of small, medium and large size birds are studied. The moment of inertia of the wing is computed, considering wing design and geometry. The details of measurement of basic body parameters of the birds are mentioned elsewhere [6, 7].

For the understanding of the flight system it is necessary to study the following flight parameters:

1. Dynamic parameters of the wing such as frequency of wing beat (υ), angular velocity (ω_w), angular acceleration (α_w), linear velocity (v_w), angular momentum (L_θ) and kinetic energy (K_w) of the wing.
2. Dynamic parameters of induced air such as rate of mass flow (dm/dt), mass (M_a), velocity (v_i), acceleration (a_i), momentum (P_a) and kinetic energy (K_a) of the air induced due to the wing beat.

All these parameters are calculated using basic measured parameters of the flier, like mass of the flier (M_f); length (l_w), span (L_w), effective breadth (B_{eff}), area (A), mass (M_w) of the flight surface (wing).

2. DYNAMIC PARAMETERS OF THE WING:

A theory is developed for the computation of dynamic parameters of the wing. The wings of any natural flier (insect or bird or bat) have length '1' and effective breadth 'B_{eff}' and at a time 't' make an angle θ_t with the transverse axis zz' with respect to the body axis. They oscillate to maximum angle θ ie stroke angle in front of and behind zz' according to equation

$$\theta_t = \theta_0 \sin\ (2\pi\upsilon t) \qquad (1)$$

where υ is the frequency of wing beat and θ_t is the angle of wing stroke at an instant of time 't'. θ_0 is the amplitude of the wing stroke ie θ/2. Differentiating we get the angular velocity of the wing, ω_t at an instant of time t as

$$\omega_t = \frac{d\theta_t}{dt} = 2\pi\upsilon\theta_0 \cos\ (2\pi\upsilon t) \qquad (2)$$

Maximum angular velocity of the wing,

$$\omega = \pi\upsilon\theta$$

Squaring both the sides of the equation (2),

$$\omega_t^2 = 4\pi^2\upsilon^2\theta_0^2 \cos^2(2\pi\upsilon t)$$

The mean value of $\cos^2(2\pi\upsilon t)$ over a cycle is ½ hence, the mean value of ω^2 is

$$\overline{\omega}^2 = 2\pi^2\upsilon^2\theta_0^2$$

Differentiating equation (2), we get angular acceleration at the time t,

$$\alpha_t = \frac{d^2\theta_t}{dt^2} = -\ 4\pi^2\upsilon^2\theta_0 \sin(2\pi\upsilon t)$$

Maximum angular acceleration of the wing,

$$\alpha = 2\pi^2\upsilon^2\theta \qquad (3)$$

Angular momentum of the wing,

$$L_\theta = I\omega \qquad (4)$$

Kinetic energy of the wing,

$$K_w = ½\ I\omega^2 \qquad (5)$$

3. DYNAMIC PARAMETERS OF THE INDUCED AIR:

The important dynamic parameters of induced air to be considered for the flight of natural fliers are mass flow, induced velocity, momentum and kinetic energy of the air induced in downward direction due to the wing beat.

Consider a wing of span 'L_w' moving in the horizontal plane with velocity 'v'. A circle of diameter 'L_w' can be drawn through it, the area of which is $\pi L^2/4$.

Wing swept area or wing disc area,

$$S_d = \pi(L/2)^2 = \pi L^2/4$$

Wing disc volume = Wing disc area x effective wing breadth,

$$V_d = S_d\, B_{eff}$$

Mass of induced air passing through wing disc,

$$M_a = S_d\, B_{eff}\, \rho \qquad (6)$$

The rate of mass flow of air pushed in downward direction through the disc due to wing motion is

$$\frac{dm}{dt} = (S_d B_{eff}\, \rho\upsilon)/2 \qquad (7)$$

Here, υ is taken as υ/2, because down stroke alone is effective in pushing the air in the downward direction. The upstroke is considered to be the recovery stroke. Here, the rate of mass flow of induced air ($\frac{dm}{dt}$) is calculated based on the important parameter of the flight surface (wing) – the wing beat frequency (υ).

3.1. Derivation of velocity of induced air

An expression is deduced for the velocity of air induced downwards due to the wing beat by calculating reacting force (R) which balances gravitational force ie weight of the flier.

Reacting force (R) = Rate of mass flow of the air + Change in induced velocity of air (Δv_i)

$$R = dm/dt \times \Delta v_i$$

Rate of mass flow ($\frac{dm}{dt}$) in terms of induced velocity (v_i) can be written as

$$\frac{dm}{dt} = S_d \rho v_i \qquad (8)$$

The change in induced velocity (Δv_i) is calculated by considering the velocity of induced air above the wing disc is zero and below the wing disc is $2v_i$.

Therefore $\Delta v_i = 2v_i - 0 = 2v_i$

∴ $R = S_d \rho v_i (2v_i)$

But $R = M_f g$

∴ $2S_d \rho v_i^2 = M_f g$

$$v_i = \left[\frac{M_f.g}{2S_d.\rho}\right]^{1/2} \qquad (9)$$

It is assumed that only this air is affected by the passage of the wing and that all of this air given a downward velocity v_i. If so, air is given momentum,

$$P_a = M_a v_i$$

Kinetic energy of air induced downward direction due to wing beat,

$$K_a = ½ M_a v_i^2$$

4. RESULTS AND DISCUSSION

Table1 and Table 2 give average values of dynamic parameters of flight surface and induced air respectively of 25 species of different size birds taking 5 birds of each species. The parameters selected for the study are angular velocity, linear velocity, angular acceleration, angular momentum and kinetic energy of the wing; and rate of mass flow, mass, velocity, acceleration, momentum and kinetic energy of air induced due to the wing beat.

Figs. 1 to 6 are plots which depict relations between mass of induced air (M_a) and mass of the flier (M_f); rate of mass flow of air (dm/dt) and mass of the flier (M_f); velocity of induced air (v_i) and velocity of wing (v_w); Angular acceleration of wing (α) and acceleration of induced air (a_i); angular momentum of the wing (L_θ) and momentum of induced air (P_a); kinetic energy of the wing (K_w) and kinetic energy of induced air (K_a) for 25 species of birds. The equations of best fit graphs along with R^2 are as following:

$M_a = 0.224\ M_f - 1.6153$ $R^2 = 0.95$
$dm/dt = 1.8831\ M_f - 4.7124$ $R^2 = 0.96$
$v_i = 0.0248\ v_w + 101.87$ $R^2 = 0.39$
$a_i = 14.909\ \alpha^{0.534}$ $R^2 = 0.95$
$P_a = 0.15\ L_\theta + 113.85$ $R^2 = 0.57$
$K_a = 0.3191 K_w + 6003.3$ $R^2 = 0.56$

Dynamic parameters of wing and induced air bear linear relationships, except accelerations irrespective of the size of the birds (small, medium and large) when they are in the state of hovering.

Finally, the present study suggests that the flight is a basic requirement of a natural flier, whether it may be an insect or bird or bat. It is to be noted that the flight mechanism of a natural flier is entirely different to the mechanism and design of man-made flight machines. Basically, flight performance or adaptation of a flier depends upon its morphology and body dimensions and as well as dynamic parameters of flight surface and air induced due to wing beat. It is interesting to note that in natural fliers, there exists single mechanism alone ie wing beat to execute different styles of flight unlike man - made flying machines.

Table 1 - Dynamic parameters of flight surface (wing)

S. No.	Flier	υ (Hz)	ω_{max} (rad/sec)	v_w (cm.sec^{-1})	α_w (rad.sec^{-2})	L_θ (rad.gm.cm^2.sec^{-1})	K_w (erg)
Passeriformes							
1	*Nactorinia asiatica*	10	77	538	4828	201	7729
2	*Estrilda amandava*	40	307	1985	77250	332	50974
3	*Loncura malabarica*	45	346	2468	97769	366	63319
4	*Loncure punculata*	40	307	2310	77250	449	68909
5	*Loncura malacca*	30	230	1733	43453	346	39823

6	*Passer domesticus*	17	131	1293	13953	340	22165
7	*Dicrurus adsimilis*	5	38	714	1207	2612	50148
8	*Turdoides striatus*	15	115	1486	10863	11406	657088
9	*Acridotherus tristis*	10	77	1524	4828	15347	589388
10	*Corvus splendens*	5	38	2327	1207	26254	504136
Psittaciformes							
11	*Melosittacus undulatus*	20	154	1783	19312	7739	594461
12	*Psittacula cathorpae*	8	61	1100	3090	5911	181619
13	*Psittacula krameri*	10	77	1736	4828	24933	957534
Pelecaniformes							
14	*Egeretta garzetta*	6	46	1558	1738	28002	645247
15	*Ardeola gravii*	10	77	2673	4828	47668	1830701
16	*Bubulaus ibis*	6	46	1908	1738	29928	689637
Coraciformes							
17	*Merops orientalis*	8	61	777	3090	1369	42063
18	*Upupa apops*	6	46	802	1738	3512	80921
19	*Coracias indica*	5	38	1025	1207	8365	160621
Apodiformes							
20	*Apus affinus*	12	92	1263	6952	2393	110274
Galliformes							
21	*Peridicula astatica*	20	154	2000	19312	11399	875527
Strigiformes							
22	*Bubo bengalensis*	10	77	1874	4828	20800	798830
Falconiformes							
23	*Falco peregrinus*	8	61	1499	3090	17967	552030
Gruiformes							
24	*Grus grus*	9	69	1548	3911	22467	776558
Columbiformes							
25	*Columba livia*	11	84	2011	5842	46048	1945304

Table 2 - Dynamic parameters of Induced air

S. No.	Flier	dm/dt (gm.sec^{-1})	M_a (gm)	v_i (cm.sec^{-1})	a_i (cm.sec^{-2})	P_a (gm.cm.sec^{-1})	K_a (erg)
Passeriformes							
1	*Nactorinia asiatica*	6.82	0.68	110	1099	75	4118
2	*Estrilda amandava*	24.26	0.61	135	5413	82	5554
3	*Loncura malabarica*	36.42	0.81	142	6388	115	8154
4	*Loncure punculata*	36.55	0.91	141	5646	129	9101
5	*Loncura malacca*	24.98	0.83	170	5099	142	12024
6	*Passer domesticus*	32.61	1.92	151	2560	289	21757
7	*Dicrurus adsimilis*	63.52	12.70	111	553	1404	77625
8	*Turdoides striatus*	82.06	5.47	161	2417	882	71032
9	*Acridotherus tristis*	139.41	13.94	149	1485	2071	153776
10	*Corvus splendens*	451.18	90.24	149	743	13418	997607
Psittaciformes							
11	*Melosittacus undulatus*	42.54	2.13	144	2882	306	22082
12	*Psittacula cathorpae*	57.42	7.18	129	1035	929	60178
13	*Psittacula krameri*	204.35	20.43	145	1450	2962	214671
Pelecaniformes							
14	*Egeretta garzetta*	366.12	61.02	148	890	9056	672001
15	*Ardeola gravii*	610.96	61.10	160	1599	9771	781317
16	*Bubulaus ibis*	545.19	90.86	136	815	12345	838538
Coraciformes							
17	*Merops orientalis*	34.08	4.26	100	802	427	21414
18	*Upupa apops*	65.18	10.86	110	661	1197	65908
19	*Coracias indica*	142.17	28.43	124	620	3528	218883

Apodiformes							
20	*Apus affinus*	34.35	2.86	100	1203	287	14384
Galliformes							
21	*Peridicula astatica*	67.30	3.37	156	3120	525	40945
Strigiformes							
22	*Bubo bengalensis*	250.75	25.07	154	1543	3869	298431
Falconiformes							
23	*Falco peregrinus*	246.64	30.83	148	1187	4573	339176
Gruiformes							
24	*Grus grus*	212.71	23.63	185	1663	4367	403463
Columbiformes							
25	*Columba livia*	390.44	35.49	177	1948	6287	556836

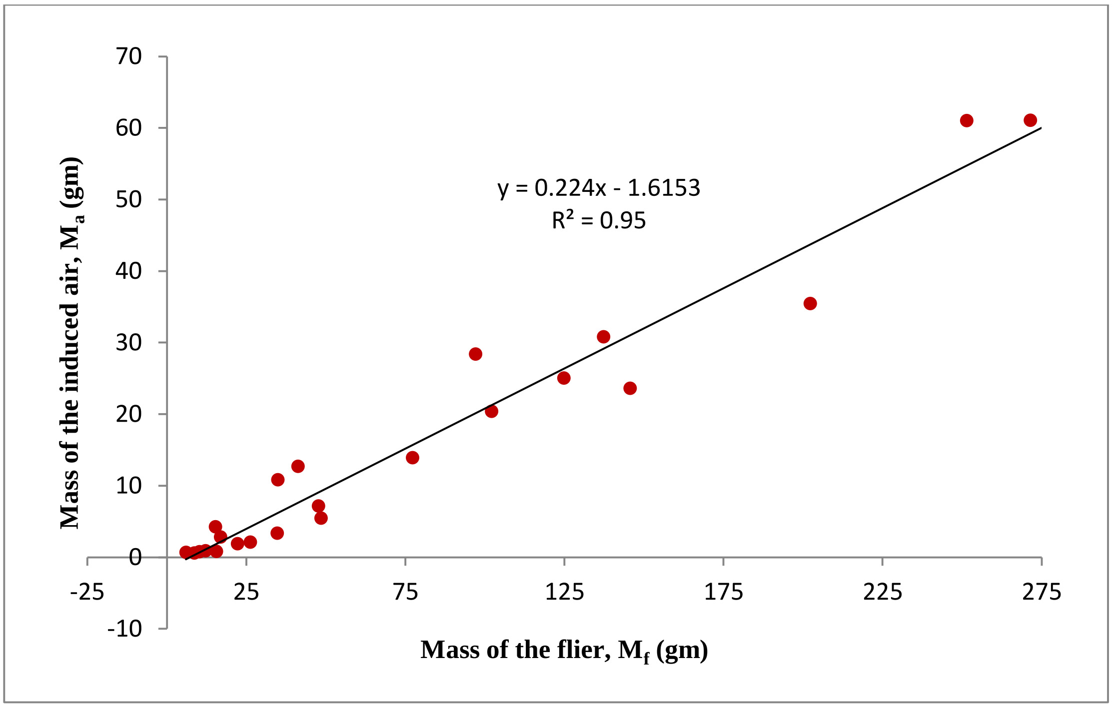

Fig. 1. A plot between Mass of induced air and Mass of the birds

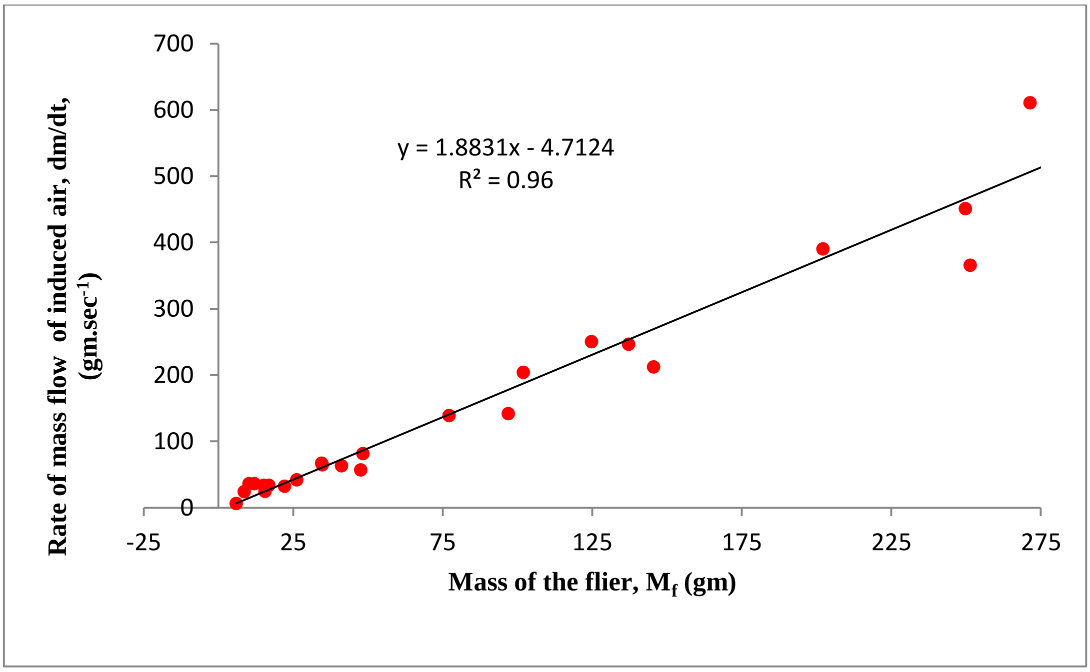

Fig. 2. A plot between Rate of mass flow of induced air and Mass of the birds

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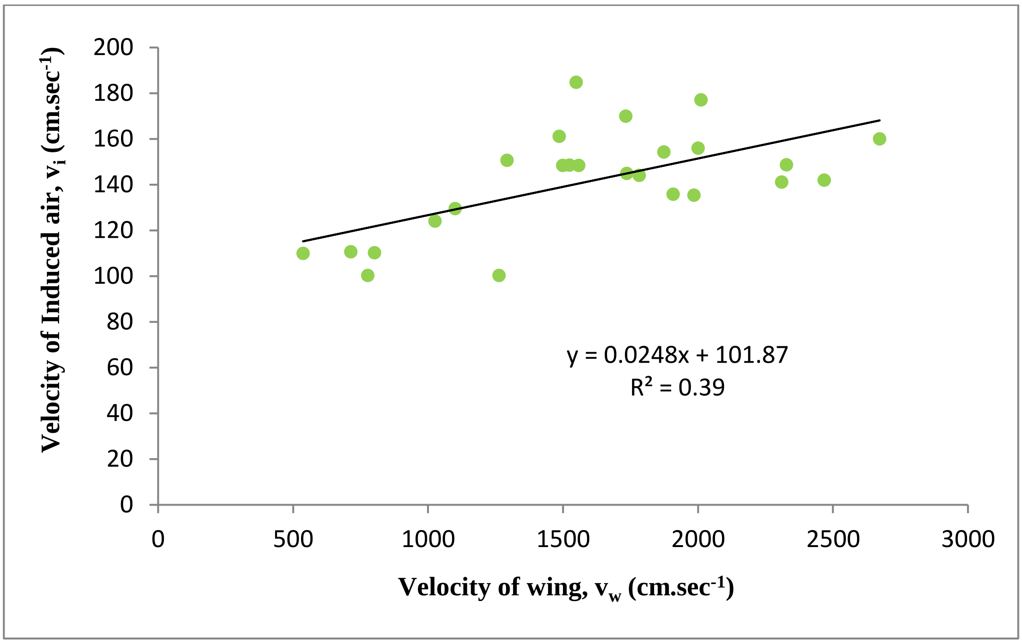

Fig. 3. A plot between Velocity of induced air and Velocity of wing of the birds

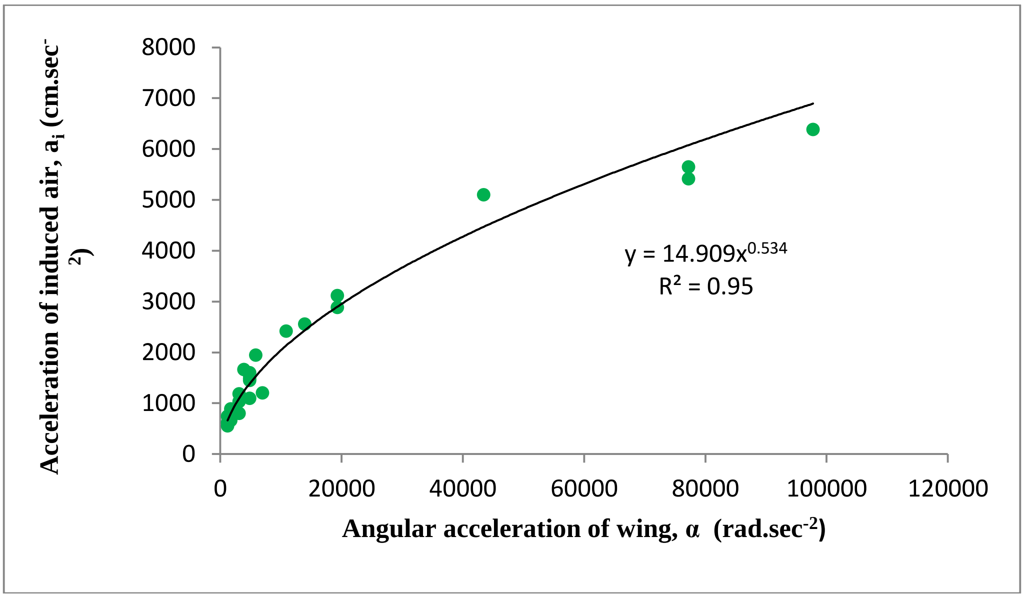

Fig. 4. A plot between Angular acceleration of wing and Acceleration of induced air of the birds

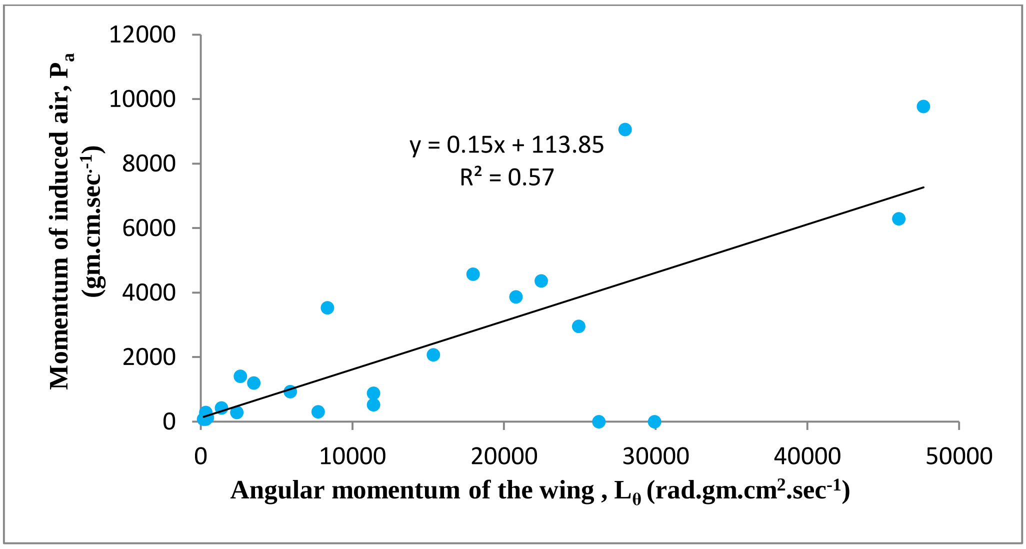

Fig. 5. A plot between Angular acceleration of wing and Acceleration of induced air of the birds

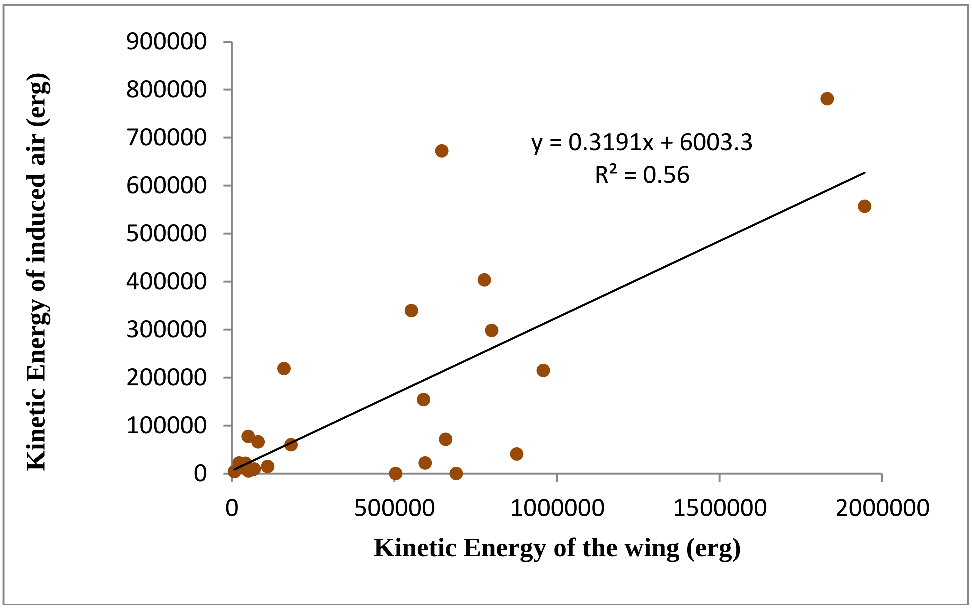

Fig. 6. A plot between Angular acceleration of wing and Acceleration of induced air of the birds

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