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POWER REQUIREMENTS OF AVIAN FLIGHT IN HOVERING STATE

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Abstract: The study reports 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, presents body parameters such as body mass; length, span, effective breadth, area, moment of inertia and frequency of wing beat of flight surface birds. The present study on flight of small, medium and large size birds reveals that induced power is directly proportional to mass or weight of the flier. Further, suggests that inertial power is not a function of any one parameter of flight surface (wing) of a flier. But it comprises wing dimensions, moment of inertia, stroke angle and frequency of wing beat. Dynamic efficiency (η) of flight surface (wing) of birds is a function of body parameters as such it can not be related to a single parameter and is independent of size (small, medium and large) of a flier.

Keywords: Birds, Basal metabolism, Inertial power, Induced power, Specific power, Hovering flight.

1. Introduction

Several attempts have been made since a long time to estimate the energy consumed during flight by insects, birds and bats. Several lines of attack are possible to estimate the energy so consumed. Among them, two are very important. One is the measurement of the aerodynamic properties of fliers under the controlled conditions in a wind tunnel. Other is the estimation of the metabolic rate, oxygen and food consumption. Literature gives many values of oxygen consumption [1-4] and food consumption [5-9] by various fliers. Sotavalta [10-11] performed a series of experiments on honey bees and drone flies to measure the oxygen consumption and food consumption and reported that in insects of different size and also in two species of humming bird, the values of oxygen consumption vary from $W^{1.15}$ to $W^{1.20}$, where W is the weight of the flier. Maynard – Smith [12] stated that for geometrically similar fliers of different size, in general the power required for flight is about $(\text{weight})^{1.12}$.

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In case of mammals and birds, the rate of energy metabolism, when the animal in the resting condition, is known as Basal metabolic rate (BMR). As the metabolic rate of poikilotherms is temperature–dependent, they have no Basal metabolic rate. But for these animals (insects, some bats), the metabolic rate can be measured at a given environmental temperature, which is referred to as the "standard metabolic rate". In any group of organism the logarithms of the BMR have a linear relationship to the logarithms of body weight. This is shown in the Benedict's [13] mouse to elephant curve for mammals and birds. Several equations have been given by various workers to predict metabolic rate on the basis of body weight for passerines, non-passerines and mammals [14]. But the Basal metabolic rate of bats seems to have escaped the attention at the hands of researchers. Weis Fogh [15-18] studied a large number of insects and made the comparisons between metabolic rate, aerodynamic power and dynamic efficiency and reported that the majority of insects depend upon an effective elastic system in the thorax. Sotavalta [19] studied input power, i.e., metabolic rate and output power, i.e., inertial power, of several insects by mutilating their wings in steps and reported that the power input and power output remain constant in spite of the change in the wing loading. Pennycuick [20] studied the power requirements for horizontal flight of *Columba livia* on the basis of mass flow. Tucker [21-22] modified Pennycuick's theory for the power requirements of flight, and worked out the analysis of induced power for various fliers [23].

In the present investigation, inertial power, induced power, dynamic efficiency of flight surface is calculated for some species of birds when they are in their state of hovering.

2. Materials and Methods

The large, medium and small size birds of Indian origin were collected in and around Hyderabad. Length (l) and span (tip to tip distance, L) were measured using measuring tape. Area of the wing was measured taking its contour of the wing on white paper and using plani meter. Mass of the flieris determined using electronic weighing machine. Based on the observation on wing kinematics, the stroke angle was approximated to 120^0 irrespective of size of the flier. Wing beat frequency of small size birds was evaluated using electronic stroboscope, while for some of the medium and large size birds noted from available at a in literature [24]. Moment of inertia of wings was determined by 'strip method'. The details were mentioned elsewhere [25].

3. Induced Power

The induced power is defined as the power required by a flier to support its weight in air which is different for a flier at different states of flight. In hovering flight, the weight of the flier must be supported by the upward reaction on the wings. It means the rate at which the downward momentum is imparted to the air is equal to the body weight. The rate of change of momentum is the product of the downward velocity (V_i) and the mass of air to which this velocity is imparted in unit time. The flier flaps its wings and sweeps out a wing disk, whose diameter is equal to the wing span (L) and area S_d, given by

$$S_d = \frac{\pi L^2}{4} \tag{1}$$

It is assumed that air is accelerated equally at all points throughout the wing disk along the axial direction (Z-axis). The mass of the air within the disk is induced downwards with a velocity V_i. Due to the presence of a region of increased pressure below and behind the disk, the air after leaving the disk continues to accelerate downwards and reaches a velocity $2V_i$ far below the bird. Therefore, the volume of air accelerated downward per unit time is $2S_d V_{iz}$. Let f_m be the mass of air passing through the wing disk per unit time, then

$$f_m = 2S_d V_{iz}\,\rho \tag{2}$$

where ρ is the air density

$$f_m V_{iz} = 2S_d {V^2}_{iz}\,\rho \tag{3}$$

By Newton's third law of motion

$$W = 2S_d {V^2}_{iz}\,\rho \tag{4}$$

where W is the weight of the bird

$$V_{iz} = \frac{W^{\frac{1}{2}}}{(2S_d\rho)^{\frac{1}{2}}} \tag{5}$$

Let P_i be the induced power in hovering state, then

$$P_i = WV_{iz} \tag{6}$$

$$P_i = \frac{W^{\frac{3}{2}}}{(2S_d\rho)^{\frac{1}{2}}} \tag{7}$$

Since the air is assumed to be accelerated equally at all parts of the disk, any deviation from this situation requires more power to support the weight. Hence a correction factor K is introduced for such deviations. Hence we have

$$P_i = K\frac{W^{\frac{3}{2}}}{(2S_d\rho)^{\frac{1}{2}}} \tag{8}$$

In the case of wings of an airplane and the helicopter rotors, the value of K ranges from 1.1 and 1.2 [4], but there is no information about this factor in the case of wings of natural fliers. Pennycuick [20] considered the value of K to be unity in his earlier theories and investigations. But Tucker [21-23], contradicted this value and chose a value 1.43 for K which is rather high. Weis-fogh [15] assigned a value of 2 in analyzing the hovering flight of a humming bird. But Adeel Ahmad [25] on the basis of experimental data, reported a value for K as 1 which is the most suitable for the wings of insects, birds and bats.

4. Inertial Power

This is defined as the power needed to accelerate the wings at each stroke. Considering the wing motion of a flier to be approximately simple harmonic, a relation for P_w can be given as

$$P_w = 4\pi^2 I\theta^2\nu^3 \quad (9)$$

where I is the moment of inertia of wings, θ is the wing stoke angle in radians, ν is the wing beat frequency. In case of insects θ is measured by keeping a circular scale marked in degrees behind the insect and by viewing the wing movements through a telescope under the synchronized stroboscopic flash [25]. In case of birds and bats the reported values of θ are considered. Moments of inertia was computed by the strip method and is given by the formula

$$I = \sum_{i=1}^{n} m_i r_i^2 \quad (10)$$

where n is the number of strips and r_1 is the distance of the strip from the wing joint and m_1 is the mass of the strip.

5. Dynamic Efficiency

It is an important aerodynamic parameter of a flight surface of a flier and can be defined as the ratio of induced power P_i to the sum of the of the induced power and the inertial power

P_w. This is denoted by η. thus

$$\eta = \frac{P_i}{P_i + P_w}$$

6. Results and Discussion

Table 1 presents basic data on mass of 25 species of birds. The data includes mass of the fliers; length, span, area, effective breadth, moment of inertia and frequency of wing beat of the flight surface (wing) of the birds. All these parameters lie in a large range, when a variety of birds are considered. The body mass of the birds of the study varies from 6–306gm.

The wing length is in the range of 7 to 42cm. The wings pan is approximately double, if body breadth is neglected. The values of effective wing breadth lie in the range of 3 to17cm. The wing area ranges from 40 to 1311cm^2. These basic parameters are used for the calculation of P_i, P_w and η.

Table 1 - Basic Body Parameters of birds

Flier	M_f (gm)	L (cm)	B_{eff} (cm)	l (cm)	A (cm^2)	I (gm.cm^2)	υ (Hz)
Corvussplendence	306	78	17	39	1311	684	3
Psittaculakrameri	106	52	9	26	446	323	6
Columba livia	258	63	12	31	741	540	4
Falco sp.	135	56	10	28	567	293	6
Grus sp.	149	50	11	25	567	325	6
Bubo sp.	124	53	10	26	517	267	5
Passer domesticus	22	22	5	11	118	2.6	15
Loncuramalacca	16	18	3	9	54	1.5	20
Estrildaamandava	9	16	3	8	40	1.1	24
Loncuramalabarica	13	17	3	8	47	1.13	21
Loncurepunculata	14	18	3	9	51	1.4	20
Egerettagarzetta	272	81	13	38	927	606	4
Bubulaus ibis	292	91	14	42	1143	652	3
Ardeolagravii	276	76	13	35	904	615	4
Acridotherustristis	95	46	9	21	372	201	7
Psittaculacathorpae	49	50	6	19	207	96	8
Peridiculaastatica	38	29	5	13	131	71	12
Dicrurusadsimilis	37	43	9	19	329	68	9
Turdoidesstriatus	51	32	7	13	184	100	13
Nactoriniaasiatica	6	16	5	7	49	2.7	25
Haropsorientalis	17	29	6	13	161	22.4	13
Coraciasindica	103	59	13	28	551	219	6
Upupaapops	39	39	10	18	323	73	9
Apusaffinis	18	30	5	14	105	24.8	12
Malasittacusundulatus	29	28	5	12	89	49.9	15

M_f: Mass of the flier; L: Wing span; l: wing length; B_{eff} Effective wing breadth; A: Total wing area (pair);
I: Moment of Inertia of the wing; υ: Frequency of wing beat

Table 2 shows data on induced power of the flier, and inertial power and dynamic efficiency of its flight surface (wing). Induced power ranges from 0.1 to 5 watt. Inertial power is in the range of 0.1 to 4. Dynamic efficiency of wings lies in the wide range of about 10 to 90 %.

Flight of a flier (whether theflier is natural flier or man-made), constitutes a *system* comprising *Flier* + *Induced air,* when the flier is in the state of hovering. Hence, Induced power (P_i), the power required to accelerate the air in the downward direction, is the essential requirement of the flight of a flier to keep it in air. Induced power executes the flight. The present study on flight of small, medium and large size birds reveals that induced power is directly proportional to mass or weight of the flier (Fig. 1.) as it should be.

Inertial power (P_w), the power required to keep the wings of a flier beating, is the basic requirement of a flier to execute its flight. The flight of a natural flier can not be imagined without wing beat. The present study suggests that inertial power is not a function of any one parameter of flight surface (wing) of a flier. But it comprises wing dimensions, moment of inertia, stroke angle and frequency of wing beat. Dynamic efficiency (η) of flight surface (wing) of birds is a function of body parameters as such it can not be related to a single parameter and is independent of size (small, medium and large) of a flier.

Table 2 - Power requirements of birds in hovering state of flight

Flier	P_i (watt)	P_w (watt)	η (%)
Corvussplendence	5.06	0.32	94
Psittaculakrameri	1.55	1.20	56
Columba livia	4.85	0.60	89
Falco sp.	2.07	1.09	65
Grus sp.	2.68	1.21	69
Bubo sp.	1.92	0.58	77
Passer domesticus	0.35	0.15	70
Loncuramalacca	0.26	0.22	56
Estrildaamandava	0.12	0.26	32
Loncuramalabarica	0.20	0.18	53
Loncurepunculata	0.21	0.19	53
Egerettagarzetta	4.09	0.67	86
Bubulaus ibis	4.05	0.30	93
Ardeolagravii	4.45	0.60	87
Acridotherustristis	1.49	1.19	56
Psittaculacathorpae	0.51	0.85	37
Peridiculaastatica	0.60	2.12	22
Dicrurusadsimilis	0.39	0.86	31
Turdoidesstriatus	0.84	3.79	18
Nactoriniaasiatica	0.07	0.73	9
Haropsorientalis	0.18	0.85	17
Coraciasindica	1.31	0.82	62
Upupaapops	0.46	0.92	33
Apusaffinis	0.19	0.74	20
Malasittacusundulatus	0.41	2.91	12

P_i: Induced power; P_w: Inertial power; η: Dynamic efficiency

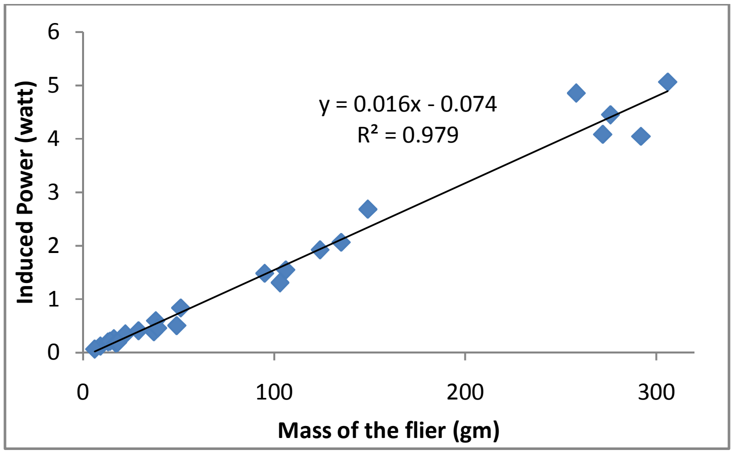

Fig. 1. A plot between Mass and Induced power of the fliers

References

[1] B. Hocking, Trans. R. Ent. Soc., London, Vol. 104(1953), pp. 223 - 345.

[2] T. Weis Fogh, Phil. Trans. B. Vol. 237(1952), pp. 1-36.

[3] H. Kalmus, Z. Vergl. Physiol., Vol. 10(1929), pp. 445-455.

[4] R.A. Davis, G. and Fraenkel, J. Expt. Biol., Vol. 17(1940), pp. 402-407.

[5] L.E. Chadwick, and D. Gilmour, Physiol. Zool., Vol.12 (1940), pp. 151-160.

[6] V.B. Wigglesworth, J. Expt. Biol., Vol. 26(1949), pp.150-163.

[7] E. Zebe, Z. Vergl. Physiol., Vol. 36 (1954), pp. 290-317.

[8] O.P. Pearson, Condor, Vol. 52(1950), pp. 145-152.

[9] O. Sotavalta, Ann. Zool. Soc. Vanamo, Vol. 16, No. 5(1954), pp. 1-27.

[10] J. Maynard-Smith, New Biology, Vol. 14(1953), pp. 64-81.

[11] O. Sotavalta, and E. Laulajainen, Ann. Acad. Scient. Feni. A IV. Vol. 53(1961), pp. 5-25.

[12] F. G. Benedict, Vital Energetic, Carnegie Institute of Washington Publications, 503, Washington, D.C. (1938).

[13] A. George. Energy Metabolism, Animal Function: Principles and adaptations, Bartholomew ed. by Malcolun S. Gordon, Amerind Publishing Co. Pvt. Ltd., New York (1971).

[14] C. J. Pennycuick, Mechanics of Flight, Avian Biology, ed. by Farner, D. S. and King, J. R., Vol. 5, Academic Press, N.Y. (1957).

[15] T. Weis Fogh, Phil. Trans. R. Soc., London, Vol. 327 (1952), pp. 1-36.

[16] T. Weis Fogh, J. Expt. Biol., Vol. 41(1964), pp. 257-71.

[17] T. Weis Fogh, J. Expt. Biol., Vol. 56 (1972), pp. 79-104.

[18] T. Weis Fogh, J. Expt. Biol., Vol. 59 (1973), pp. 169-230.

[19] O. Sotavalta, Ann. Zool. Soc. Vanamo, Vol. 15(1952), pp. 1-67.

[20] C.J. Pennycuick, J. Expt. Biol., Vol. 49(1968), pp. 527-555.

[21] V.A. Tucker, Amer. Zool., Vol. 11(1971), pp. 115-124.

[22] V.A. Tucker, J. Expt. Biol., Vol. 58(1973), pp. 689-709.

[23] V.A. Tucker, American Scientist, Vol. 63(1975), pp. 413-419.

[24] J.R. King and D.S. Farner, Biology and comparative physiology of birds, ed. A.J. Marshall, Academic press, Inc., New York,(1961), pp. 215-288.

[25] Adeel Ahmad, A comparative study on flight surface and aerodynamic parameters of insects, birds and bats, Ind. J. Expt. Biol., Vol. 22(1984), pp. 270.