On speed and aerodynamic forces of mosquito

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Received 29 April 1999; revised 23 March 2000

In the present investigation, speed of mosquitoes *A. aegyptii* (Linne) and *Culex quinquefasciatus* (Say) is measured by designing and constructing a low speed wind tunnel in the laboratory. The velocity of mosquitoes is less than the other myogenic and neurogenic insects. Lift, one of the important aerodynamic forces that a flier has to develop for its efficient flight, is studied in mosquitoes by developing a simple technique using digital single pan balance. Lift, drag and their coefficients of hovering mosquito are calculated from the knowledge of body parameters by considering the wings of mosquito as harmonic oscillator. The calculated value of lift is verified with the experimental. The study throws light on morphophysiological adaptation of mosquitoes for the generation of aerodynamic forces in hovering, tethered and forward flights.

The speed of flight of a number of insects, as recorded in the literature, is reported by Wigglesworth. Speeds reported for bee vary from 2.5 to 6.0 m/sec and for diptera from 2.0 (Musca) to 14.0 (Tabanus) m/sec. In many cases such estimates of speeds have been arrived at by observation alone. Observations based on experimental conditions have been given by Kennedy. In the present investigation, a low speed wind tunnel is designed and constructed in the laboratory for measuring the speed of mosquito.

The wings in level flight produce a mean aerodynamic force that balances two force vectors: weight, which is in vertical direction, and body drag in the horizontal direction. This mean force is conventionally resolved into the orthogonal components, lift and thrust. The beating wings generate these forces by changing the momentum of the air in the vicinity. Thrust is generated as the wings accelerate air backwards and lift is generated as air is accelerated downward. Weis-Fogh reported that the forces necessary to support the animals' weight could be explained in terms of the classical lift generation mechanism. Adeel Ahmad did extensive work on aerodynamic parameters of different fliers and reported that a flier is conditioned by the basic aerodynamic problems. Brodski, on the basis of wing kinematics data, analysed the flight of may fly. Norberg used steady state aerodynamics and momentum theories to calculate lift and drag coefficients. Dickinson Michael and Goetz measured lift and drag of small insects on a two dimensional model with simultaneous flow visualisation. Worthmann measured lift and thrust of locusta, fastened to a force transducer in front of a wind tunnel during tethered flight. Esch Harald measured lift, wind speed, wing beat frequency of honey bees in a servo-mechanically controlled wind tunnel. Cloupeall et al. measured instantaneous lift produced in locust, flying in a wind tunnel by means of piezoelectric probe.

In the present investigation, lift of the smallest insect, mosquito is measured by developing a simple technique using digital single pan electrical balance and calculated the aerodynamic forces - lift, drag and their coefficients by developing a theory by considering the wings of a flier as harmonic oscillator. The calculated value of lift is verified with the experimental.

**Materials and Methods**

Experiments were performed on laboratory reared mosquitoes *Aedes aegyptii* (Linne) and *Culex quinquefasciatus* (Say). The dimensions of body and that of wings were measured under the suitable magnification of dissecting microscope, using camera lucida. An analytical balance of least count 0.01 mg was used to determine mass of the flier. Knowing body parameters (mass) and wing parameters (span, length and effective wing breadth), aerodynamic parameters were calculated. The wing stroke angle observed under the stroboscopic flash is about 60°. The reported values of body parameters of *A. stephensi* (Liston) were taken to calculate lift, drag and their coefficients.
Speed of mosquito flight

In order to study the flight performance of insects under well defined aerodynamic conditions, a wind tunnel was designed and constructed in the laboratory. The forward velocity of mosquitoes, *A. aegyptii* and *C. quinquefasciatus* was studied under the wind tunnel.

Figure 1 shows a horizontal section of wind tunnel, constructed with plywood of thickness 5 mm. The cross section of the tunnel is hexagonal. The working section is a free jet of air with circular cross section. At the outlet, the diameter is 12 cm, but the smooth part of the jet has a decreasing diameter because of mixing up with surrounding still air. The origin of coordinate system is at 15 cm from the outlet of the wind tunnel. F is the table fan (without mesh), which fits exactly into the inlet and blades of the fan can move freely. The wind speed can be regulated between 0 and 10 m/sec by connecting a dimmerstat to the fan. The honey comb (HC) at the inlet side serves to reduce the turbulence of air. Beyond the honey comb, cross section of the tunnel is continuously decreases so as to reduce turbulence further. Wind speed was measured by using wind mill type commercial anemometer, at different voltages of the fan. A plot is drawn between voltage and wind speed (Fig. 2), from which wind speed can be determined directly, knowing the voltage applied to the fan.

Mosquito under study was suspended to a stand by means of a very thin metal wire. The mosquito was free to fly along the axis of the wind tunnel. The mosquito, when flying, moves in the forward direction (towards wind tunnel), making certain angle with the horizontal. The thin wire carrying mosquito makes an angle with the vertical. Then the speed of the wind was so adjusted that the wire carrying mosquito comes back to the initial position. Then the speed of the mosquito is equal to that of the wind.

Lift of mosquito under tethered flight

To determine lift of mosquitoes *A. aegyptii* and *C. quinquefasciatus* in tethered flight, the sample was freely suspended in a digital single pan electrical balance. The thin metallic wire carrying the mosquito was attached to the hook provided in the balance.

The initial reading of the balance was taken, when the mosquito was at rest and again the balance was read when it was flying in still air. The difference between the two readings multiplied by the acceleration due to gravity (g) is the upward force—the lift, acting on the mosquito.

Coefficients of lift and drag

A theory is presented for the calculation of lift, drag and their coefficients of hovering mosquito by considering its wings as harmonic oscillator.

The wings oscillate with the transverse axis $zz'$ with respect to the body axis, according to the equation

$$\phi = \phi_0 \sin(2\pi v t) \quad \ldots \quad (1)$$

where $v$ is the frequency of wing beat, $\phi$ is the angle of wing stroke.

The angular velocity of the wing,

$$\omega = 2\pi v \phi_0 \cos 2\pi v t \quad \ldots \quad (2)$$

The mean value of $\omega^2$ is

$$\omega^2 = 2\pi^2 v^2 \phi_0^2 \quad \ldots \quad (3)$$

Fig. 1—(a) Horizontal section of wind tunnel. (b) Honey Comb (HC)
since mean value of $\cos^2 2\pi vt$ over a cycle is $1/2$.

The basic equation for lift in aerodynamics is

$$L=\frac{1}{2}pA\overline{v}^2C_L$$  \hspace{1cm} (4)

Here, $p$ is density of air; $A$ is the wing area; $\overline{v}$ is velocity of wing; $C_L$ is the coefficient of lift.

Consider a narrow strip of wing, $\delta x$ wide at a distance $x$ from the base of the wing, its velocity is $\omega x$ and the lift is $\delta L$ which acts on it. Since the body is supported by two wings, the mean lift on the whole wing must be equal to half of the body weight, the equation for coefficient of lift, $C_L$, can be derived as

$$C_L=\frac{3}{2}\frac{(M_f/g)}{(\pi^2 \rho \overline{v}^2 A^2)}$$  \hspace{1cm} (5)

where $M_f$ is mass of the flier, $g$ is the acceleration due to gravity and $I$ is the wing length.

Consider a wing of length $l$ moving in the horizontal plane with velocity $v$. A circle of diameter $l$ can be drawn through it. The rate of mass flow of air pushed in downward direction through the disc due to wing motion is

$$\frac{dm}{dt} = \frac{\pi l^2 v}{4}$$  \hspace{1cm} (6)

It is assumed that only this air is affected by the passage of the wings and that all of this air is given a downward velocity $v_i$. Lift, the rate at which the air is given momentum ($p$) is

$$L=\frac{dp}{dt} = \frac{dm}{dt} v_i$$  \hspace{1cm} (7)

The rate at which the air is given kinetic energy ($K$) is

$$\frac{dK}{dt} = \frac{1}{2} \frac{dm}{dt} v_i^2$$  \hspace{1cm} (8)

A part of the work done against drag in moving the wings must be used to give kinetic energy to air. This drag concerned is called induced drag.

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**Table 1—Data on speed of A. aegyptii and C. quinquefasciatus**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sex</th>
<th>Mass of flier ($\times 10^{-3}$ g)</th>
<th>Speed (m/sec)</th>
<th>Mass of flier ($\times 10^{-3}$ g)</th>
<th>Speed (m/sec)</th>
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Mean: 0.93±0.047

Mean: 1.18±0.18
### Table 2—Data on lift of *A. aegypti* in tethered flight

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<th>Sample</th>
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<th>In flight</th>
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<th>Lift (dyne)</th>
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### Table 3—Data on lift of *C. quinquefasciatus* in tethered flight

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<th>In flight</th>
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### Table 4—Comparison of aerodynamic forces—lift and drag and their coefficients of *A. aegypti*, *C. quinquefasciatus* and *A. stephensi*

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<th>Flier</th>
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<th>Lift, L (dyne)</th>
<th>Drag, D</th>
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<td>Experimental</td>
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</table>
Since \( \frac{dk}{dt} = D \cdot v \); drag, \( D = \frac{2L^2}{\rho td^2v^2} \) \ldots (9)

Since \( \frac{L}{D} = \frac{C_L}{C_D} \); \( D = (1/2)\rho Av^2C_D \) \ldots (10)

Comparing equations (9) and (10) and substituting \( L^2 \) from equation (4), we get

\[ C_D = \frac{A}{\pi d^2} C_L \] \ldots (11)

Knowing \( C_L \) and \( C_D \), \( D \) can be calculated. Hence, coefficients of lift and drag are the functions of body parameters of the flier.

The average values of \( C_L \), \( C_D \), \( L \) and \( D \) have been calculated for mosquitoes, \( A. aegyptii \), \( C. quinquefasciatus \) and \( A. stephensi \), taking the mean values of body parameters of 10 female and 10 male mosquitoes.

**Results and Discussion**

Table 1 presents the data on speed of 3 female and 8 male \( A. aegyptii \). The average value of speed is 0.93 m/sec. in female and 1.18 m/sec. in male mosquitoes, suggesting that male \( A. aegyptii \) flies more faster than females. Also table 1 shows that the data on speed of 10 female and 10 male \( C. quinquefasciatus \). The mean values of speed is 1.01 m/sec. in females and 0.96 m/sec. in males. The mosquito flies with, more or less, the same speed irrespective of sex. However, the velocity of mosquitoes of the present investigation is less than myogenic and neurogenic insects, reported in literature.

Table 2 gives the data on lift of 10 female and 6 male \( A. aegyptii \), when it is in the state of tethered flight. The requisite measured parameters for the calculation of lift are also shown in the table. The average value of lift is 5.9 dyne in females and 2.04 dyne in males. It is evident from the table that female \( A. aegyptii \) generates considerably more lift when compared with male. Similar data for \( C. quinquefasciatus \) is presented in Table 3. The average value of lift is 4.57 dyne in females and 1.77 dyne in males. It can be noticed from table that the lift generated in females is significantly more than that of male mosquitoes.

Table 4 compares the aerodynamic forces such as lift (L) and drag (D) and their coefficients, \( C_L \) and \( C_D \), in the case of \( A. aegyptii \), \( C. quinquefasciatus \) and \( A. stephensi \). The theoretical and experimental values of lift are also compared in the case of \( A. aegyptii \) and \( C. quinquefasciatus \). There exists a good agreement between the theoretical and experimental values. The aerodynamic forces and their coefficients of \( A. aegyptii \) and \( C. quinquefasciatus \) have been calculated by considering the body parameters measured in the present investigation. Similarly, lift is calculated for \( A. stephensi \), considering its body parameters reported in the literature. From the knowledge of lift, the other aerodynamic force, drag is calculated. It is interesting to note that lift is significantly more than induced drag. Similarly, \( C_L \) is also more than \( C_D \) in the case of mosquitoes of the present investigation. Hence the values of \( C_L/C_D \) are found to be considerably high. The non-dimensional parameters \( C_L \) and \( C_D \) are very important in characterising the fliers aerodynamically, when they are in the state of hovering. These coefficients mainly depend upon morphology, design and texture of the wing; the mechanism of flight machinery (wing-muscle system). The study reveals that \( C_L \) is less than other myogenic and neurogenic insects. But, to some extent, this parameter is in the range of birds and bats. However induced drag is less than 1, similar to other insects, birds and bats. It can be concluded that the coefficients of lift and drag can be considered as species specific parameters. Thus, the study throws light on morpho-physiological adaptation of mosquitoes for the generation of aerodynamic forces in hovering, tethered and forward flights.

**Acknowledgement**

One of the Authors (VRR) is thankful to Sri Y B Satyanarayana, Principal, Dharmavant College of Science and Commerce, Yakutpura, Hyderabad, for his permission to carry out this research work.

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