Available online at www.sciencedirect.com
ScienceDirect
Journal of Bionic Engineering 12 (2015) 418–431

Mechanism of Locust Air Posture Adjustment

Diansheng Chen, Kewei Chen, Ziqiang Zhang, Benguang Zhang
Robotic Institute in School of Mechanical Engineering and Automation, *Beihang University*, *Beijing* 100191, *China*

Abstract

Stimulated locusts often tumble during the jumping process. Locusts can also recover their bodies in the air for flight or landing stability. To increase jumping distance and avoid landing collision of bio-inspired jumping robots, the mechanism of air posture adjustment of locusts is examined in this research. This mechanism can be used to improve the stability of robot. The abdomen swings, wing motions, and the variations in body angle are recorded by a high-speed camera when locusts free fall in air with normal or upside-down initial posture. Results indicate that the wings and abdomen are mainly utilized for air posture adjustment. Moreover, abdomen swing and forewing rotation have positive effects on body pitch. However, locusts have difficulty in recovering their bodies from the upside-down posture without wings, although the body pitch caused by unpredictable perturbation in air can be compensated through abdomen swing. Consequently, body roll is attributed to the wing motion, which is related to two factors, namely, the different flapping amplitudes of the wings on both sides, and the different flapping velocities of wings during the upstroke and downstroke periods. This research may provide reference for the design of jumping robots.

Keywords: locusts, air posture adjustment, abdomen swing, asymmetric flapping wings

doi: 10.1016/S1672-6529(14)60133-5

Nomenclatures

x_i, x_j, x_l (i, j, l = 1, 2, 3)	The cartesian coordinates
α	The angle of the head-thorax referenced to horizontal
β	The angle of abdomen referenced to horizontal
φ	The angle of head-thorax referenced to abdomen
θ	Wings stroke angle
ϕ	Wings deviation angle
ψ	Wings pitch angle
α_A	Wings attack angle
L_w	Length of wings from root to tip
H_a	The angular momenta for the head-thorax
H_b	The angular momenta for the abdomen
J_A	The head-thorax Moment of Inertia (MOI)
J_B	The abdomen moment of inertia
$\dot{\alpha}$	The angular velocity of head-thorax
$\dot{\beta}$	The angular velocity of abdomen
ψ_S	The stroke plane angle
C_L	The wings lift force coefficient
ρ_{air}	The air density
S_w	The area of wing
u	The air flow velocity
c_w	The length of wing chord

1 Introduction

Locusts, which are capable of jumping and flight, can expertly control jumping trajectories[1,2] and change the flight direction to reach the desired targets or avoid collision in air[3–5]. Locusts often tumble rapidly during the jump when stimulated and can recover in air to fly or land stably[6]. The mechanism of locust air posture adjustment can improve the air stabilization of bio-inspired jumping robots to increase jumping distance and avoid collision when landing.

The abdomen of locusts can swing around the thoracic-abdominal joint and effectively affect jumping trajectory and flight control. Locusts swing their abdomens upward by contracting the dorsal muscles to produce torque, which may counter the pitching torque produced by jumping thrust[1]. Further studies indicate

Corresponding author: Diansheng Chen
E-mail: chends@163.com

that the simulated jumps with dorsiflexion are more stable than those without dorsiflexion. Moreover, the movements of locust abdomens have been observed during flight control and presumably used as rudders in yaw correction[7,8]. Studies on other tethered insects, such as hawkmoth, moths, fruit flies, and honeybees, also indicate that abdomen may have a positive effect on flight control[9–11]. The abdomen movements of insects have been recorded in tethered flight with the stimulation of visual[9,10,12] or mechanical rotations[13] or wind jet[7–8,14]. Three possible mechanisms of the abdomen for flight stability have been proposed. (I) The abdomen deflection, acting as a rudder, will change the streamlining of the body[7]. Given that abdomen swing, similar to the spanning tails of birds[15], increases air resistance, torque is then generated to make the body pitch and yaw. Thus, the abdomen would act as a rotational brake. (II) The abdominal movements shift the center of body mass and redirect the average lift force provided by the wings to control flight[9,10,13,16]. When lift force and gravity act on the different lines of the body, the generated torque finally results in body posture change. Therefore, the abdomen serves as a driver of flight path change. (III) The abdomen can redirect the lift forces via the conservation of angular momentum[11]. However, no further studies have been done to validate these hypotheses because insects are confined (most are tethered), except those in the experiments of Cofer[1]. Although, the stimuli that facilitate abdomen movement are revealed, the relationship between body posture change and abdomen movement remains unknown.

Wings, which are another factor affecting flight control, have been discussed in two hypothetic mechanisms. (I) The angular asymmetry of the left and right wings is regarded as a factor affecting air posture. Locusts avoid colliding with objects in their flight path with the forewing on the inside of the turn more depressed than the opposite one during the downstroke[3,4,17,18]. (II) The variable pronation of the forewings is regarded as another contributor to turning during flight[19–21]. The increased forewing pronation on the inside of the turn reduces the wing angle of attack, thereby resulting in reduced thrust. Meanwhile, Zarnack and Möhl suggested that increasing the steepness of the downstroke on the outside of the turn increases the angle of attack, thus resulting in increased thrust[20]. The asymmetric aerodynamic force acting on the wings finally causes the turn. Furthermore, substantial deformations of the wings have been discovered during the flapping cycle of locusts[22,23] and are assumed to be a factor for collision avoidance in air[5]. However, the influence of tether in most experiments cannot be ignored.

Minimally restrained flying insects have been recently used to investigate the flight control mechanism[24,25]. Shindo *et al*. studied the attitude control mechanism of free flying butterfly by focusing on the pitch and roll rotations[26]. Analyses of the air flow around wings suggest that pitch and roll rotations are induced by different pressure distributions on wings. These distributions are caused by wing rotation and the flapping of one side wing preceded that of the other side wing resulted in the body roll. Our previous experimental studies with the locust-inspired robots have also indicated that asymmetric wing motion and abdomen swing can change posture[27]. However, a theoretical analysis is not conducted in that work.

Clearly, locusts can control their jumping trajectories during the jumping period, meanwhile adjusting their air postures to recover from the perturbation. This mechanism can inspire engineers to enhance the stable air posture of jumping robots to increase the jumping height and distance. One method is to equip the robots with tails or abdomens, which have been used in the falling vehicles[28], jumping robots[29,30] and running robots[31,32]. Moreover, wings are regarded as another method to enhance the jumping performance. The fixed wings[33–35] or foldable wings[36,37] are used for glide to enhance the jumping distance. However, all these robots need stable initial posture and can hardly recover from the rolling bodies. Locusts have sometimes been found to make several complete revolutions throughout the jumping trajectories and can adjust their air posture to fly or land stably[6]. However, the mechanism of their air posture adjustment is still unclear.

Our studies may help reveal the mechanisms of air posture adjustment of locust. First, the locust is dropped in air without any restrictions, and the directing influences of the abdomen and wing motion on air posture are recorded. Second, a two-rigid-body model is developed to investigate the relationship of posture change and abdomen swing with the moment of momentum theory. Finally, wing motions are studied when the locust is dropped in normal or upside-down posture. The effects of wing flapping on body pitch and roll are discussed.