REVIEW

New Developments in the Unsteady Viscous External Biofluiddynamics for Miniaturized-Insect Flight *†

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Abstract The tentative ideas on frontier problems of the external biofluiddynamics for miniaturized-insect flight are given. The emphasis of investigations is put on the unsteady and viscous features of complex interactions between motile animals and their surrounding fluid media. A description of current situations on this research topic is outlined and some ideas on its future developments are mentioned.

Key words insect flight, external biofluiddynamics, unsteady viscous flow

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1 Introduction

Winged insects and fishes have experienced a billions-year process of evolution with natural selection for their survival and have developed their superior and complete performance of flying and swimming, which any modern man-made air and underwater vehicles cannot possess. They may be regarded as living machines, which act under their neural control with their muscle contraction as a motor to transform the biochemical energy to the mechanical energy and then implement their wing-flapping or body-undulating propulsion. We are interested in understanding the design concepts of these living machines, which include the neural science, muscle mechanics, morphology diversity and locomotion patterns (kinematics), propulsion and its control studies (dynamics), energy costs and efficiency (energetics), biological material properties, etc. All these are involved in a discipline of flying and swimming biomechanics.

James Lighthill published in 1975 his classic book《Mathematical Biofluiddynamics》[1], which is distinguished from the rest of fluiddynamics in that the fluid movements are energized by the working of an animal s motile external or internal surfaces, mostly flexible. He mentioned that the characteristic motility means ability to make actively controlled movements in response to stimuli. The main goal of the **external biofluiddynamics** involves investigation of animal′s propulsion and its control.

One fourth century has passed since the publication of Lighthill′s book which mainly contains nonviscous and quasi-steady flow approximations for fish swimming and bird flying. The present lecture is intended to give some descriptions and personal ideas on the unsteady viscous external biofluiddynamics for miniaturized-insect flight.

The purposes of this biomechanical research are both biological and technological. Firstly, for compara-

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tive biology studies of motile animals, biologists are interested in the consequences of mechanical effects of flying and swimming on the physiology, behavior, ecology, microevolution, macroevolution and neural science. They should understand not only the functioning, but also the evolution, of the various systems for locomotion of animals within external fluids. Secondly, for bionic studies, engineers are interested in seeking the secret of superior performance of animal′s locomotion and suggesting new engineering possibilities for improvement of man-made air and marine vehicles. Recently, based on the big progress of high technology achieved, the **biomimetics** has attracted people′s great attention. The robotic fish and the robotic fly have appeared or will appear soon, which is a matter of significance in practical applications.

2 Fluiddynamic Research on Flight of Miniaturized Insect

2.1 Background

Insects are a most abundant feature of life on Earth with approximately 5 ~10 millions species, among which pterygota (the subclass of winged insects) has a proportion of 99%. The average body length for insects is 3 ~5 mm, due to that the smaller the body size, the larger the number of species. Miniaturization of the body size is the tendency of evolution process occurring among winged insects and yielding a profusion of diverse miniaturized forms for the majority of insects.

From the earlier time of 20th century, people began and continued to investigate the morphology diversity and the flight kinematics of birds, bats and large insects, and in the mean while, conducted aerodynamic and energetic research for them. Just recently, due to great achievements made in the experimental techniques and the theoretical fluiddynamics, the interest of research scientists was gradually shifted from centimeter-sized locusts, moths, dragonflies, butterflies, bumblebees, etc. to millimeter-sized and even smaller insects, for example, fruit fly.

Flight of miniaturized insects uses wing-beat frequencies in excess of 100 Hz, which can be attained only by the asynchronous flight muscle found mainly in the orders Coleoptera (like beetles), Diptera (like flies, mosquitoes), and Hymenoptera (like wasps, ants), as well as Hemiptera (like bugs), Thysanoptera (like thrips), etc. Higher wingbeat frequencies are further associated with greater force production that in turn enables a reduction in wing area relative to body mass. So flight of miniaturized insects makes the surrounding flow field highly unsteady and highly viscous with the Reynolds number ranged $Re = O(10^2 \sim 10^0)$.

As to wing morphology and flapping modes of small insects, it is found that insects usually use very thin, membrane-type wings, which are corrugated by wing venation, providing trough-distributed, coarse (unstreamlined) surfaces. These wings are highly flexible, making torsional shape flexion around their longitudinal axes. Wing shape flexion includes both active deformation controlled motilely by the insect and also passive deformation induced by aerodynamic forces. It is very remarkable that a quite unusual "hair-type" wing shape has been observed for some tiny insects, e. g. thrips. The fundamental wing-flapping mode for most insects consists of : upstroke + pronation + downstroke + supination, which may be regarded as a combination of the up-and-down rotational oscillation of the longitudinal axis of the wing around an origin (elytrum) on the body and the torsional oscillation of the flexible wing around its longitudinal axis, accompanied by remarkable shape flexion. Besides this, Weis-Fogh (1973) found that a few small insects (e.g. wasp with its mass of 25 μg and beat frequency about 400 Hz) use a special wing-beating mode called clap-fling in which contralateral wings close together dorsally and then separate by rotation about the adjacent trailing wing edges prior to the translational motion of the downstroke. Some insects use the fundamental wing-flapping mode combined with some clap-fling mechanism, which occurs in damselflies and occasionally in free-flying fruit flies. The insect wing morphology and its kinematics are diverse for different insect species and even for individuals within a species.

The study of unsteady aerodynamics for miniaturized-insect flight is a very challenging problem on which attention has been taken mainly from this decade. It should be noted that, parallel to developments of aeronautics and astronautics in 20th century, the discipline Aerodynamics was born and developed to a complete steady aerodynamic theory and then to the unsteady aerodynamics (even for viscous flows), which is applicable to large moving objects of high or moderately high Reynolds numbers. Available understanding of unsteady aerodynamic mechanism would not be completely applicable to the high unsteady and high viscous ($Re = O(10^2 \sim 10^0)$) flow case of insect flight. Research results of Kawachi Millibioflight Project (1992 ~ 1997) showed that for small objects (cm-mm size) of $Re < 1000$, very thin wings, such as membrane wings even with corrugation, are superior for producing lift than streamlined fine shape wings with a 10% ~15% thickness, which are appropriate to large objects of higher Reynolds numbers[2]. Therefore, it should be an exciting task to establish a new branch of unsteady aerodynamics for insect flight, especially for highly unsteady and highly viscous flow case in tiny insect flight.

An abundant database has been cumulated for morphology diversity of winged insects, especially relatively large insects. As to kinematic and aerodynamic investigations and measurements for insect wing-flapping, mostly, the feasible experimental approach is to make a flapping insect tethered in a special apparatus, so that there is no way to get completely the exact natural flight performance. Free-flight investigation should be a very necessary way to implement, even though tremendous difficulties exist. Experimental tracking of free-flying insects in a confined instrumented room has partly succeeded, but reliable kinematic and particularly aerodynamic data obtained is very short. Effective and successful free-flight investigations of kinematic and aerodynamic performance for insect flight in nature are rarely reported. In comparison with experimental biomechanical results for flight of relatively large insects, studies of tethered and free-flight kinematics and aerodynamics in small insects are very limited in number.

Ellington (1995)[3] and Dudley (1999)[4] have given some descriptions of unsteady aerodynamics for the insect propulsion study. In order to understand unsteady high-lift mechanisms of insect flight, Ellington, et al. (1996)[5] have visualized the airflow around the wings of a tethered hawkmoth (cm. size level) and furthermore made high-resolution flow visualizations on a mechanical flapper model that closely mimics wing-flapping of a hovering hawkmoth, where an intense stable leading-edge delayed-stall vortex was found on the downstroke, of sufficient strength to explain the high-lift forces. As for aerodynamic measurements for small insects, Dickinson, et al. (1999)[6] built a dynamically scaled robotic model of a hovering fruit fly ($Re = 136$, $f = 145$ Hz), equipped with sensors at the base of one wing capable of directly measuring the time course of aerodynamic forces, in addition to quantified flow visualizations during pronation and supination processes. They supposed that enhanced unsteady aerodynamic effects for the fruit fly may result from three mechanisms: delayed stall, rotational circulation, and wake capture; the latter two factors come from the pronation and the supination and generate aerodynamic forces during stroke reversals. These two rotational effects not only contribute to the required lift for insect hovering, but also provide a potent means by which the insect can modulate the direction and magnitude of flight forces during steering maneuvers. Besides, in earlier time Dickinson, et al. (1996)[7] have tried to take flow visualizations and instantaneous force measurements of tethered real fruit flies, but the measured forces lagged in time in excess of expected inaccuracies.

Insect flight is characterized by its excellent performance of keeping dynamic stability in steady flight and making agile maneuverability in takeoff and landing, in patrolling, pursuit, and evasion, in tracking odor plumes and making the nuptial performance, etc. We are interested in understanding how insects control the dynamic stability and maneuverability of their flight. The flight control organs of insects act as an ideal active close-loop controlling system, which involves continuous sensing of flight and environmental information based on visual systems and other mechanoreceptors, the central processing of multiple sensory inputs and finally generation of locomotor output appropriate to changing aerodynamic demands via the nervous and muscle systems. The controlling actuation is implemented by bilaterally asymmetric wing motions and supplemented by asymmetric abdominal and leg motions, disrupting transient excursions from intentional motions or changing abruptly the nominal equilibrium of steady flight. Extensive work on observing the response of asymmetric wing kinematics of tethered insects is available, but still primarily in descriptive stage, using steady-state aerodynamic interpretations. A great deal of new investigations for fluiddynamists should be done on mechanism studies of unsteady controlling of stability and maneuverability of insect flight, e.g. the aerodynamic responses to unsteady excitations, the maneuver time-course of 3-D flight trajectory combined with 3 degree-of-freedom body orientations, etc.

With respect to bioenergetics of insect flight, it is required to estimate total power consumption in flying, i. e. metabolic power input to muscle contraction, in contrast to mechanical power required for propulsion. Due to some confusion in defining the mechanical forward propulsion efficiency caused by the aerodynamic thrust (e. g. what means $\eta_{mech}=0$ for insect hovering?), only the overall efficiency of flight muscle is concerned, which is very low, typically between 5% and 10%. Estimates of mechanical power expenditure are necessary for comparative studies of biomechanical design and performance. So power curve is defined as the variation in mechanical power expenditure with the forward propulsion velocity. Up to now, little has been done in working with the power curve for insects, particularly small insects.

In brief, the unsteady viscous external biofluiddynamics for miniaturized-insect flight is a less exploited research field and much work is need to do on observations of morphology diversity, on investigations of free-flight kinematic and aerodynamic characteristics, on understanding mechanisms of propulsion and particularly control in maneuvers, on estimations of energy expenditure, etc. for various insect species. This will lead to the combined biological analyses of physical flight mechanisms, locomotor performance in nature, and phylogenetic associations, giving a better functional and evolutional understanding of insect diversity for different insect species. Also, this will provide a prerequisite biofluiddynamic foundation for developments of robotic insects.

2.2 Some remarks on future directions

(1) Morphology, kinematic, and aerodynamic measurements and investigations

Morphological, kinematic, and aerodynamic data for small insects are extremely deficient. Even for the tethered-insect case, current instrumentation and experimental methodology are poorly suitable to the case of high beating-frequency and very limited observation space. Mechanical intelligent flapping models, keeping partial dynamical similarities with real organism, are recommended for high-resolution quantified flow-field visualizations and precise unsteady force measurements, even though such an approach may be biologically incomplete in explicit applications to specific life forms. Aerodynamic consequences of wing shape flexion and deformation can also be studied by simulated flapping models. It is a very urgent and very challenging task to develop free-flight measuring techniques for insects, especially for the small body-size ones to give the detailed quantitative descriptions of 3-D flight kinematics of flapping insects and 3-D induced flow-field patterns, especially vortex wakes, which are necessary for analyses of unsteady force production and mechanical power expenditure.

(2) Numerical predictions of flow field patterns and aerodynamic performance of insect flight

Several topics require using the means of numerical computations, e.g.:

①Direct problem

In case of given wing-body morphology, wing flapping kinematics, and flight speed, we can get details of numerical flow visualizations and time variation course of unsteady aerodynamic forces by solving N-S equations. Computational techniques have to be developed for the troublesome unsteady problems.

②Inverse problem

In case of given detailed free-flight kinematics (including the flight trajectory and velocities as well as accelerations in the flight history), it is possible to solve an inverse problem for the equation of flight mechanics to identify the time course of global aerodynamic characteristics of insect flight, as it has been made for the free-flight test of aero-vehicles.

③Mathematical modeling of coupled fluid / solid mechanics problem for active and passive wing flexion

Active and passive wing shape flexion and deformation of membrane-type wings have unknown influences on the propulsion and control performance of insect flight. A coupled fluid / solid mechanical interaction model has to be established, for which a prediction method of aerodynamic load on the flexed 3-D wing and a visco-elastic model of wing tissue material for predicting passive deformation of the loaded wing are needed to be given. So this is also a very challenging problem.

(3) Propulsion mechanisms of wing flapping

①Unsteady high-lift mechanism study

More work is required to focus on finding and identifying distinct mechanisms of unsteady high-lift performance on the basis of present understanding[5,6].

②Mechanism study on membrane-type corrugated wing and hair-type wing configuration

What is the mechanism for usage of the membrane-type and hair-type wing? Are they beneficial to better aerodynamic effects in moderately low Reynolds numbers, or just for the structural preference?

③Mechanism study on wing shape flexion

What are the aerodynamic consequences of wing shape flexion? Is its effect very considerable on propulsion, or merely for maneuvering control?

④Mechanism study on optimal mechanical energy expenditure

A new approach for estimations of mechanical energy expenditures of unsteady flapping flight and then the prediction of power curve for different forward speeds is required. It would be possible to make any optimal analysis of mechanical energy expenditures for exploring the mechanism of efficient energy availability.

(4) Aerodynamic mechanisms on unsteady control of stability and maneuverability of insect flight

①Aerodynamic response study of asymmetric wing kinematics

More experimental and computational work is required to obtain unsteady aerodynamic forces and moments as well as flow visualizations, induced by various asymmetric-wing-kinematics cases and to give unsteady aerodynamic interpretations.

②Mathematical modeling of maneuver courses based on coupled models of aerodynamics and flight mechanics

In order to know the time history of 3-D trajectories and body orientations of insect flight due to changing aerodynamic characteristics in maneuvering cases, similar to the available approach for solving the coupled model of aerodynamics and flight mechanics in aeronautics, mathematical modeling of insect maneuvering flight is capable to be developed.

③Numerical simulations of various insect-flight behaviors

On the basis of preceding studies, it is possible to achieve simulations of flight courses for various insect-flight behaviors, e.g. quick turn, quick 100° reversal, backward flight, sideways flight without roll, ascend and descend, etc.

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研究小型昆虫飞行的非定常黏性外部生物流动力学的新进展

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摘 要 介绍了关于小型昆虫飞行的外部生物流体力学的前沿科学问题, 旨在揭示昆虫振翅飞行与周围空气介质之间相互作用的非定常、黏性复杂流动特性. 说明了这一新领域的研究概况, 并指出了若干研究方向.

关键词 昆虫飞行, 生物外部流体力学, 非定常黏性流