AN INSECT’S ROLE IN THE DEVELOPMENT OF MICRO AIR VEHICLES

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ABSTRACT

Winged insects are nature’s answer to the perfect small-scale flying machine. These insects have evolved complex flight controls and power sources that are the essence of form and function as far as micro flight is concerned. As such, they have played an important role in the development of flight mechanisms and body designs for micro-air vehicles (MAVs). Scientists from around the globe have been racing to develop a tiny unmanned aircraft that can be used in situations where humans dare not tread. Studying insect flight seems to be at the very core of this research. New studies have advanced our understanding of insect mechanics and aerodynamics bringing the goal of a small-scale MAV within reach. By all conventional means insects should not be able to fly. To support an insect’s body weight, the wings must produce two to three times more lift than has been shown in conventional fixed wing flight studies. Insects accomplish this in two ways. Some insects use a fling mechanism of clapping their wings together on the upstroke and then flinging them apart during the downstroke, causing a vortex around each wing that helps to create lift. However, most insects rely on a leading edge vortex (LEV) that is created by a wing stall during flight. This type of stall creates a very strong spanwise flow across the wing causing a LEV to corkscrew to the wing tip producing lift. To this end, most scientists have focused their energy on recreating the stability that the LEV gives to insect lift in their experimental MAVs. However, there is still some

interest in looking at the two-winged fling mechanism as an alternative. The purpose of this paper is to discuss these two design strategies that find their basis in insect flight focusing, in particularly, on the LEV flight mechanism. Further, it will discuss in detail and give examples of how scientists are using their growing knowledge of the LEV to help advance research on MAVs.

INTRODUCTION

Insect flight has captivated humans for many centuries. There are nearly a million species of flying insects and of the living 13,000 warm-blooded vertebrate species (i.e., birds and mammals), 10,000 (9000 bird and 1000 bats) have taken to the sky (Shyy, Berg, & Ljungqvist, 1999). The first appearance of winged insects is shrouded in the past, but they probably took to the air almost 350 million years ago (Ellington, 1999). The insect fossil record lends a few clues to the origins of flight. It has shown that early flying insects, also known as protopterygotes, had wingspans that ranged from as small as 10 mm to as large as 710 mm. The Protodonata, which were the ancestors of the dragonflies, were among the early fliers; their wings were similar enough to modern forms to suggest comparable flight capabilities, although perhaps with less refinement (Ellington, 1999). Aviation and aeronautical advances have moved rapidly forward since the Wright brother's momentous flight nearly a century ago. While it has taken nature's flying machines, which have been evolving over the last 350 million years, a little longer it is still is impressive. Shyy et al. (1999) keenly observed that insects have been experimenting successfully with wing design, aerodynamics, control, and sensory systems for millions of years.

Fairly recently, interest has been growing in finding a way of harnessing the power of insect flight and applying it to the development of micro-air vehicles (MAVs). These MAVs would be able to operate inside buildings and confined spaces. Industry, commerce, and the military have all identified potential roles for such MAVs (Ellington, 1999). Much of the research has focused on downscaling fixed wing models to fit the desired specifications of MAVs. There is however a design for these MAVs that has been 350 million years in the making: the insects. Van den Berg & Ellington (1997) indicated that insect flight could be a very successful design for MAVs because they have much better aerodynamic performance than conventional wings and rotors.

MAV design based on insect flight has advanced in many directions. Two strategies have emerged and one in particular holds much promise. The first strategy is based on what is known as the fling mechanism of insect flight. This mechanism creates a vortex around each wing that enhances lift. The second design strategy revolves around a leading edge vortex (LEV). The LEV is created by dynamic stall during flapping; a strong spanwise flow is also generated by the pressure gradients on the flapping wing, causing the LEV to spiral out to the wingtip (Ellington, 1999). This area of insect flight is being studied more because it offers stability in flight and less mechanical damage than the fling mechanism. The purpose of this paper is to discuss these two design strategies that find their basis in insect flight focusing, in particularly, on the LEV flight mechanism. Further, it will discuss in detail and give examples of how scientists are using their growing knowledge of the LEV to help advance research on MAVs.

DEFINING MICRO-AIR VEHICLES

Before going into detail on the strategies that underlie the flight of micro-air vehicles (MAVs) it is useful to define and describe just what a MAV is. MAVs are defined as flying vehicles of approximately six inches in size (hand held) and are developed to provide reconnaissance in confined spaces (inside buildings, tunnels, etc.) (Zbikowski, 2002). The definition employed in the Defense Advanced Research Projects Agency's (DARPA) program limits these craft to a size less than 15 cm (about 6 inches) in length, width, or height (McMichael & Francis, 1997). The feasibility of MAVs has been made possible by current advances in micro-technologies. This puts to rest some flight control concerns that have arisen. For instance, the weight and relative complexity of motors, sensors, and other equipment controlling the flight of full-sized aircraft render them unlikely to be shrunk for use in MAVs. To that end research into micro-electrical-mechanical systems are under way. These tiny three-dimensional machines with moving parts will ultimately be used to direct flight controls, power sources, propulsion systems, and avionics. Cameras and sensors are also being made smaller and smaller. For example, McMichael & Francis (1997) concluded that maturing microsystems such as tiny CCD-array cameras, equally small infrared sensors, and chip-sized hazardous substance detectors have been catalytic in providing the motivation for like-sized delivery platforms. As such, MAVs have nearly unlimited possibilities for use. With current advances in micro-technology MAVs could be used in military or law enforcement surveillance, biological warfare detection, civilian air quality assessment, or even search and rescue. MAVs can be used to fly into collapsed buildings, for instance, to locate survivors, into Chernobyl-like nuclear power plant wreckage to assess conditions, and potentially into any structure or container to locate illegal drugs or weapons (Page, 1998). It must be noted that MAVs are not smaller versions of larger aircraft. They should be thought of as aerial robots, as six-degree-of-freedom-machines whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location where it may perform any of a variety of missions, including (as stated above) reconnaissance and surveillance, targeting, tagging, and bio-chemical sensing (McMichael & Francis, 1997).

One of the most formidable tasks being undertaken by MAV designers lies in finding a way to achieve stable controlled flight. The environment acts much differently upon a MAV than on more conventional aircraft. Unsteady flow effects arising from atmospheric gusting or even vehicle maneuvering are far more pronounced on small scale MAVs where inertia is almost nonexistence, that is, where wing loading is very light (Shyy et. al. 1999). These effects are further highlighted by Woods et al. (2001) who observed that MAVs will be significantly affected by environmental and building-induced airflow, and weather. These problems are starting to be answered by studying insects and how they masterfully control the sky in even the most sinister conditions.

THE INSECT’S ROLE IN MICRO-AIR VEHICLE DESIGN

A main concern in building MAVs is to find a flight system that is stable, quiet, and maneuverable in tight spaces. These requirements lead to problems in overcoming the lift needed to fly, hover, and maneuver. Many wing designs have been looked at to overcome these problems. For instance, Dornheim (1999) mentioned that under the DARPA program there are three designs currently being tested: a fixed wing (like an airplane), a flexible wing (like a helicopter), and a flapping wing (like that of a bird or an insect). The following focus will be directed to the latter model of a flapping wing.

One of the main roles that insects play in the design of MAVs can be found in their ability to produce incredible amounts of lift. MAVs encounter Reynolds numbers (steady-state characterizations of the flow regime represented as a measure of size multiplied by speed) much lower than conventional aircraft. Calculations of environmental factors on small-scale machines become very important because they affect these entities differently than their large-scale counterparts. An efficient wing design for an MAV must provide enough lift and sufficiently low amounts of drag for a vehicle where aerodynamic behavior is different than that of a larger aircraft (Woods et al., 2001). Researchers began to see that they would not be able to model MAV wings after conventional aircraft designs. Interest soon turned toward taking a closer look at natures answer to getting high amounts of lift while keeping drag at a minimum. They noticed that insect wings exhibited rounded leading edges and sharp trailing edges. Woods et al. (2001) pointed out that the rounded leading edge is crucial to maintain attached flow around the aerofoil over a reasonable range of angle of attack, which, as a consequence, minimizes drag. To support their body weight, the wings of insects typically produce 2-3 times more lift than can be accounted for by conventional aerodynamics (Ellington, 1999). Without this lift insects and for that matter all flying machines, biological or manmade, would not make it of the ground. Some two winged insects are able to do this by employing a specialized fling mechanism. This novel lift mechanism was first proposed and described by Weis-Fogh (1973) to explain the high lift produced by the wings of the parasitic wasp *Encarsia formosa*. Ellington (1999) concisely described the fling mechanism as wings that are clapped together and then flung open before the start of the downstroke, creating a lift-enhancing vortex around each wing. In other words, the flinging motion creates a large amount of circulation around the wings during the rotating phase of the wing beat. This in turn determines the amount of lift on the next half-stroke. It was also reported by Ellington (1999) that technical applications of the fling are limited by the mechanical damage that accompanies repeated clapping of the wings. The fling mechanism, while important in explaining the great lifting capabilities of some insects, has given way to some new findings that explain the source of extra lift.

The finding of a leading edge vortex (LEV) produced by many insects during flight has gained much of the current focus in insect flight studies and MAV design strategies. The LEV is a region of low pressure above the wing and thus will augment the lift force (Ellington et al., 1996). This finding is important because when coupled with other MAV components such as body design and propellant technologies it could dramatically increase lift needed for MAV flight.

THE LEADING EDGE VORTEX

To appreciate a discussion about the leading edge vortex it is important to first understand a little bit about insect flight. Insects fly by oscillating and rotating their wings through large angles, while sweeping them forwards and backwards (Zbikowski, 2002). This mode of flying relies on unsteady aerodynamics, producing high lift coefficients and excellent maneuverability. The beating of the insect wing can be broken down to the downstroke and the upstroke. Szmelter & Zbikowski (2002) indicate that at the beginning of the wing downstroke, the wing is in the uppermost and rearmost position with the leading edge of the wing pointed forward. The wing is then pushed downwards and forwards and is continuously rotated, so that the angle of attack changes considerably during this downward push. At the end of the downstroke, the wing is twisted swiftly, so that the leading edge now points in the opposite direction and the upstroke begins. During the upstroke the wing is pushed upwards and backwards and rotated continuously yet again, which again changes the angle of attack throughout the motion. At the highest point, the wing is twisted a final time, and the leading edge again points forward and the next downstroke can begin. These phases become important when trying to determine exactly when the LEV is formed.

Two decades of research, much of it by Ellington and his colleagues, have shown how insects make wide use of unconventional aerodynamic mechanisms which exploit the unsteady airflow resulting from the flapping motion to obtain far more lift than conventional, steady-state aerodynamics would allow (Wootton, 2000). One of the most important findings was that many insects produce a LEV to obtain the extra lift needed for flight.

The leading edge vortex (LEV) is created by dynamic stall during flapping; a strong spanwise flow is also generated by the pressure gradients on the flapping wing, causing the LEV to spiral out to the wingtip (Ellington, 1999). This definition was a long time in the making. Many studies were done to try to figure out what happens during insect flight to create a LEV. Most utilized a model wing to simulate different flapping paradigms produced by insects. Usherwood & Ellington (2002) indicated that experiments based on flapping models are the best way at present to investigate the unsteady and three-dimensional aspects of flapping flight. Willmott & Ellington (1997) discovered a leading edge vortex on the wings of the hawkmoth, *Manduca Sexta*, which increased in size from wing base to tip. The vortex was small at low flight speeds, but increased in size with speed until it extended across the whole wing. The flapper was also used to try to tease out exactly what forms the LEV.

There have been two theories postulated as to what creates the LEV during insect flight: rotational lift and dynamic stall. Van den Berg & Ellington’s (1997) study attempted to answer the question of which of the two mechanisms was causing the LEV. The study utilized a model flapping insect wing, dubbed the ‘flapper’, and a smoke flow chamber: the combination of which could show when and where vortices were produced. If rotational lift were responsible for the production of a LEV it would be generated during the upstroke and the recaptured during the downstroke. In other words, the vortex would be already be sweeping across the wingspan at the beginning of the downstroke. On the other hand, if dynamic stall were responsible the LEV would be generated during the downstroke itself. A dynamic stall occurs when a wing is able to operate above the stall angle, which thereby temporarily increases the lift capability of the wing. Van den Berg & Ellington (1997) did not observe any LEV before the beginning of the downstroke. This finding made them lean toward a dynamic stall as being the causative agent of the LEV. Further, they found that the core of the vortex broke down as it moved out toward the tip of the wing and soon after mid-downstroke the vortex broke away from the wing surface. This by itself is not important. However, a secondary vortex formed immediately where the initial one broke away, which once again confirms that the mechanism is dynamic stall (Van den Berg & Ellington, 1997).

LEVs IMPORTANCE IN MAV DESIGN

The above discussion has shown how insects have made use of several unconventional aerodynamic mechanisms that are able to take advantage of the unsteady airflow resulting from the flapping motion of the wing to acquire a considerable amount of lift that cannot be explained by steady-state aerodynamics. One of these has proven to be highly applicable to the design of MAVs

The primary mission for MAVs is surveillance. This type of mission calls for slow forward speeds, superb maneuverability in tight places, and the ability to carry and perhaps even deliver a considerable payload. As discussed earlier, the leading edge vortex produces a high amount of lift by producing a dynamic stall. This allows the wing to operate at high angles of attack at which it would otherwise stall and gain a substantial amount of extra lift. The high angle of attack that is made possible by an LEV wing design could give an MAV the maneuverability it needs to fly into tight spaces such as buildings and containers. The lift created by the dynamic stall could by utilized to help carry heavy loads of sensors into places that are unsafe for humans. To put it succinctly, the LEV would allow a MAV the maneuverability that is needed at slow speeds while producing the lift required to carry a heavy payload.

It is important to note that new research is being conducted that may advance MAV flight design even further. While studying the flight patterns of *Vanessa atalanta*, Srygley & Thomas (2002) reported that visualizations of airflow in free flying butterflies show that butterfly flight is not random, but instead results from the mastery of an array of aerodynamic mechanisms. This is indeed important to MAV designers because with this information they will be able to find and utilize multiple flight mechanisms that work in symbiosis to achieve the aerodynamics needed for MAVs to maneuver in a way that will rival their insect counterparts.

CONCLUSIONS

Most of the wing motions produced during insect flight are fairly similar to conventional aerodynamics. However, flapping winged insects have other wing motions that offer special advantages that might prove useful in the design of MAVs. Much research has been completed to try to answer the question of how to generate high amounts of lift while producing only small amounts of drag. This has been shown to be important due to the differing effects of the environment on micro-scale machines as well as the energy and maneuverability requirements of the MAVs main function. These requirements along with the small size of MAVs cause conventional aerodynamics to fall short and have lead researchers to lean toward unsteady explanations of flight to further their design strategies. The main focus has been on the dynamic stall produced by the leading edge vortex. The leading edge vortex opened many doors for MAV researchers because it provides an explanation for flight not before possible. It allows for the production of more lift during flapping flight and during steady motion at the same velocities and angles of attack.

350 million years of “research and development” have given them the model. It is now up to the researchers to find a way to harness the ingenuity of one of nature’s greatest accomplishments and truly make micro-air vehicles take off.

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