Experimental Studies of Flapping-wing Aerodynamics

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Abstract

There is great interest in developing micro air vehicles (MAVs) that can operate indoors as currently there is no practical autonomous or remote-controlled airborne system capable of operating in this environment. Such a system would be useful for search and rescue, high-risk inspection or reconnaissance in buildings or other confined spaces. The most suitable type of MAV for this application appears to be a flapping-wing micro air vehicle (FMAV) based on insect-like flapping-wing flight. This mode of flight offers the abilities to sustain hover, operate at low flying speeds and perform rapid and complex manoeuvres in confined spaces, which is seen in nature with two-winged insects (Diptera). To deepen the understanding of flapping-wing aerodynamics, necessary for the development of FMAVs, there is a need for high-quality experimental data on the subject as it is currently lacking. The aim of this PhD research project is to address this need by performing experimental studies on insect-like flapping wings.

For this research, a first-of-its-kind mechanical flapping-wing apparatus that mimics insect-like flapping-wing motion has been designed and developed by the author. This apparatus features a novel flapping mechanism (a patent-pending three degree-of-freedom 3-RRR parallel spherical mechanism) which gives the wing three controllable degrees of freedom required to produce the three separate motions necessary for mimicking an insect-like flapping-wing trajectory: sweeping (side-to-side), plunging (up and down) and pitching (angle-of-attack variation). In this mechanism these three motions are independently controllable. A typical trajectory of an insect wing is one in which the wingtip traces the path of a figure-of-eight on a spherical surface with pitch reversal (supination and pronation) at either end of the stroke as illustrated in Figure 1. The present mechanism not only enables this but also a very wide range of other insect-like flapping kinematics to be achieved, up to a flapping frequency of 20Hz, as pictured in Figure 2. In contrast, past mechanical flappers typically have had fixed kinematics, wings with only two degrees-of-freedom, and maximum frequencies well below 20Hz. This new apparatus, therefore, enables flapping-wing experiments which have never hitherto been performed.

Experiments with the apparatus focused on observing and understanding the effects of varying flapping kinematics on the flows and aerodynamic forces produced by the wing. For example, how does changing the angle-of-attack, or stroke amplitude (number of degrees swept by the wing in a flap), affect the lift and the flow structures? Such questions are of interest in FMAV development because it is essential to know what type of flapping kinematics are appropriate to produce high lift. Experiments conducted by the author utilised stereoscopic particle image velocimetry (PIV) to measure the flow velocities around the flapping-wing driven by the apparatus. PIV employs a laser light sheet, smoke seeding and two high-speed cameras to measure instantaneously all three flow velocity components over a grid of points within the light sheet (measurement plane). Lift measurements were accomplished with a strain-gauge force balance fitted to the apparatus. These techniques enabled a parametric study in which various flapping kinematic parameters (angle-of-attack, stroke amplitude, flapping frequency etc.) were varied, and the resulting changes in the mean lift and flows produced were measured.
Results confirmed the presence of a leading-edge vortex (LEV) over the wing, which feeds into the tip vortex, as illustrated in Figure 3. This is similar to the LEVs formed on delta wings, and its existence on flapping wings has been well established by previous researchers. The LEV is responsible for the high lift generated by insect-like flapping wings. Results have revealed details of how the LEV and other flow structures develop and interact over a flapping-cycle, pictured in Figure 5. The flow development is mainly characterised by the formation of a LEV which develops a strong axial velocity through its core and remains present on the upper wing surface, even until the end of the half-stroke when the wing stops. Investigations by the author of the effects of changing various kinematic parameters have revealed that, in the Reynolds number (Re) range relevant to FMAVs (Re on the order of $10^4$), the LEV exhibits breakdown. This work has shown breakdown to be a function of stroke amplitude, since with lower stroke amplitudes LEV breakdown was suppressed. However, despite the presence of breakdown, the LEV remains attached to the wing surface throughout a half-stroke and continues to augment lift as Re is increased, as shown in Figure 4. Additional key results have revealed appropriate values for kinematic parameters (e.g. flapping frequency, stroke amplitude and angle of attack schedule) to produce optimal mean lift.

![Figure 1: Flapping Cycle](image1)

![Figure 2: Close up of flapping mechanism (left) and frames from high speed photography of flapping-wing executing a figure-of-eight wing trajectory at 20Hz (right)](image2)
Figure 3: Instantaneous streamlines coloured with axial velocity highlighting LEV and tip vortex over wing at a 20Hz flapping frequency.

Figure 4: Effect of increasing flapping frequency (and, therefore, Reynolds number) on mean lift and mean lift coefficient.
Figure 5: Top views of wing revealing flow formation throughout one half of the flapping period ‘T’, starting when the wing accelerates from rest, followed by translation, and ending with pitch reversal and simultaneous deceleration of the wing to rest; flapping frequency is 20Hz (Re = 15400); left column shows vortex core diameter (dark grey surfaces) and vortex axes coloured with axial vorticity; right column shows instantaneous streamlines released from vortex axes coloured with axial velocity normalised with respect to the mean wingtip speed (8.4m/s), black streamlines released along the wing edge, and transparent grey isosurfaces of $Q = 6 \times 10^6$ from the vortex identification ‘Q criterion’; positive axial direction points along an axis towards the end without a white dot; LEV = leading edge vortex; TPV = tip vortex; RTV = root vortex; STRV = starting vortex.
Author’s Date of Birth
1983

Submission Statement
The author confirms that this submission is entirely the work of the author, and is based on a PhD research project conducted at Cranfield University, Shrivenham.