Vortex flows on UAVs: Issues and challenges

I. Gursul
Department of Mechanical Engineering
University of Bath
Bath, UK

ABSTRACT

Separated and vortical flows are dominant over various unmanned air vehicles (UAVs). In this article, issues and challenges of vortical flows for future UAVs are reviewed. These include shear layer instabilities, vortex breakdown and wing stall, vortex interactions, nonslender vortices, multiple vortices, and manoeuvring wing vortices. There are also issues relating to vortical flows in certain flow/structure interactions, as well as in aerodynamics/propulsion interactions. Separated and vortical flows are even more dominant at low Reynolds number flows. The main features of vortical flows, unsteady aerodynamics, and propulsion related vortical flow isssues relevant to mini- and micro air vehicles, are discussed.

NOMENCLATURE

a	amplitude of plunging motion
AR	aspect ratio
c	chord length
C_μ	momentum coefficient
C_D	drag coefficient
C_L	lift coefficient
f	frequency
h	displacement
Re	Reynolds number
s	semispan; displacement for plunging motion
St	Strouhal number, fc/U_∞
t	time; thickness
T	thrust; period
u	velocity
U_∞	free stream velocity
x	streamwise distance
X	breakdown location
y	cross stream distance or spanwise distance
z	vertical distance above wing surface
α	angle-of-attack
Λ	sweep angle
Λ_v	vortex angle
δ	flap angle
ω	vorticity

1.0 INTRODUCTION

Although UAVs have various forms, such as high altitude long endurance (HALE) aircraft, unmanned combat air vehicles (UCAVs), mini-UAVs and micro air vehicles (MAVs), there are common issues. In most cases, laminar-transitional flows are dominant, and separation, transition and vortical flows play important roles. In particular, UCAVs and MAVs have dominant vortical flows (see Fig. 1). Current and future UCAVs usually have low sweep angles (35° to 55°) and look like flying delta wings. Some configurations are similar to double delta wings, with multiple strake and wing vortices. Future UCAVs will be highly manoeuvrable and highly flexible.

Paper 2877. Manuscript received 12 February 2004, revised version received 3 November 2004, accepted 12 November 2004.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

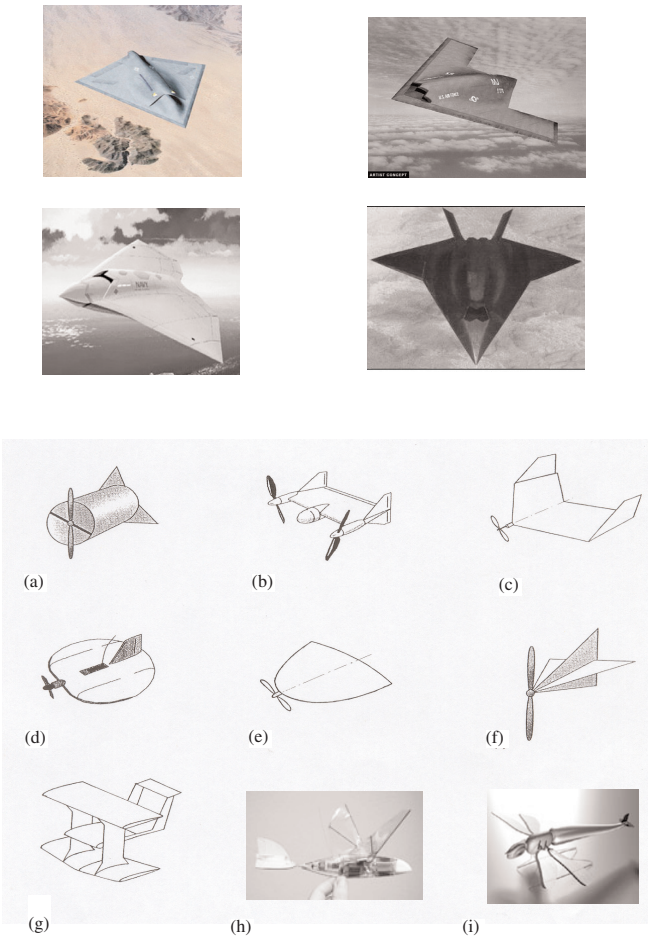


Figure 1. Current and future unmanned combat air vehicles (top) and micro air vehicles (bottom).

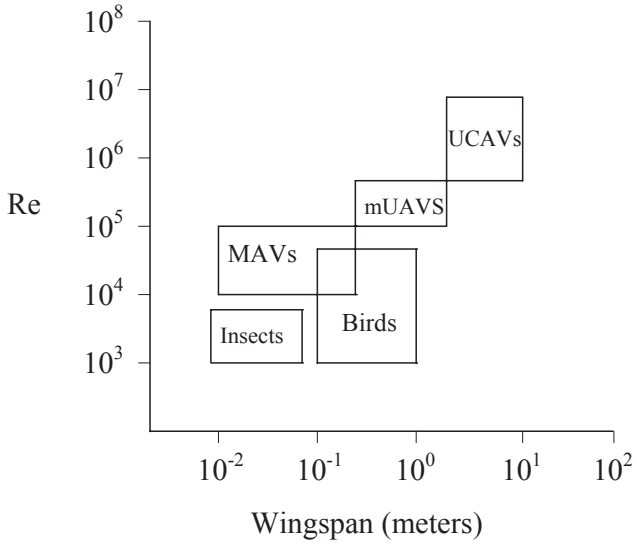


Figure 2. Reynolds number range for unmanned air vehicles.

Figure 1 also shows several micro air vehicles that have been built and flown: (a) ring wing, (b) rectangular wing, (c) swept wing, (d) disc-wing, (e) trochoidal wing, (f) cruciform delta, (g) biplane MAV, (h) and (i) flapping wing MAVs. Current and future fixed-wing micro air vehicles exhibit a variety of separated and vortex-dominated flow fields, including tip vortices, leading-edge vortices, vortex shedding, and vortex breakdown. Some aspects of these vortical flows show great sensitivity to the Reynolds number. Such flows are even more important when the unsteady aerodynamics of MAVs in gusts is considered. The objective of this paper is to highlight issues and challenges of vortical flows on UCAVs and MAVs.

Figure 2 shows the range of Reynolds number and characteristic length for UCAVs, mini-UAVs, MAVs, as well as birds and insects. It is seen that unmanned air vehicles cover a range of Reynolds numbers from 10^4 to 10^7. Corresponding Mach numbers are very small for small vehicles (with the exception of space/Mars exploration applications), but can be significant for UCAVs. Vortical flow issues discussed in this paper fall into three categories: vortex formation, vortex instabilities and interactions, and vortex/wing interactions as shown in Table 1. Their relevance to specific type of unmanned air vehicles is also indicated. Almost all of these topics are unsteady aerodynamics problems, in addition some exhibit strong flow/structure interactions. Characteristic ranges of dimensionless frequency, fc/U_∞, and displacement normalised by the chord length, h/c, are also given in Table 1.

2.0 VORTICAL FLOW ISSUES ON UCAVS

The flow over a slender delta wing at moderate angles of attack is dominated by two large, counter-rotating leading-edge vortices that are formed by the roll-up of vortex sheets. The flow separates from the leading edge of the wing to form a curved free shear layer above the suction side of the wing, which rolls up into a core. The time-averaged axial velocity of the vortex is roughly axisymmetric and its maximum can be as large as four or five times the free stream velocity. These large axial velocities are due to very low pressures in the vortex core, which generate additional suction and lift force on the delta wings.

2.1 Shear layer instabilities

The separated shear layers roll up periodically into discrete vortical substructures, as visualised by Gad-el-Hak and Blackwelder[1], over a delta wing. This phenomenon was attributed to a Kelvin-Helmholtz type instability of the shear layer. The origin of these structures was subject to some controversy as several researchers[2,3] revealed the existence of stationary small-scale vortices around the primary vortex. The spatially fixed substructures were measured by velocity probes at fixed locations, and were identified as a result of time-averaging the flow. Their relationship to the temporal substructures was recently demonstrated by direct numerical simulations[4]. Instantaneous flow shows the temporal substructures and the transition process with increasing Reynolds number (see Fig. 3). More interestingly, the time-averaged flow shows isosurfaces of the time-averaged axial vorticity and mean vortical substructures. These results indicate that 'steady' and 'unsteady' substructures are not necessarily two separate phenomena. There is also experimental evidence[5] that these substructures can persist even after vortex breakdown occurs in the core. Details of shear layer structure and transition need to be investigated further.

2.2 Vortex breakdown and wing stall

At a sufficiently high angle-of-attack, the vortices undergo a sudden expansion known as vortex breakdown, which was first observed by Werle in 1954 in a water tunnel facility. Different explanations of the vortex breakdown phenomenon based on hydrodynamic

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

Table 1
Aspects of vortical flows, key flow mechanisms, and characteristic range of important parameters for unsteady aerodynamics and flow/structure interactions

	Aspects of vortical flows	Relevance	Important features	
			Unsteady aerodynamics Frequency O(fc/U_∞)	Flow/structure interaction Displacement O(h/c)
Vortex Formation	Flow separation and reattachment	All	0·1 1	
	Shear layer instabilities	All	10	
	Transition	All		
	Nonslender vortices	All		
	Flapping wing propulsion	MAV	1	0·1 1
	Synthetic jet propulsion	MAV	1-10	
Vortex interactions/ instabilities	Vortex breakdown	All	1	
	Stall	All	1	
	Vortex pair interactions	All	0·01-0·1	
	Multiple vortices	UCAV	?	
	Vortex/jet interaction	UCAV	?	
Vortex/wing interactions	Manoeuvring wing vortices	UCAV	0·01-0·1	0·1-1
	Nonslender wing rock	UCAV, mUAV	0·01-0·1	0·1-1
	Vortex/flexible wing interaction	UCAV	1	0·01-0·1
	Gust response	MAV	0·1	

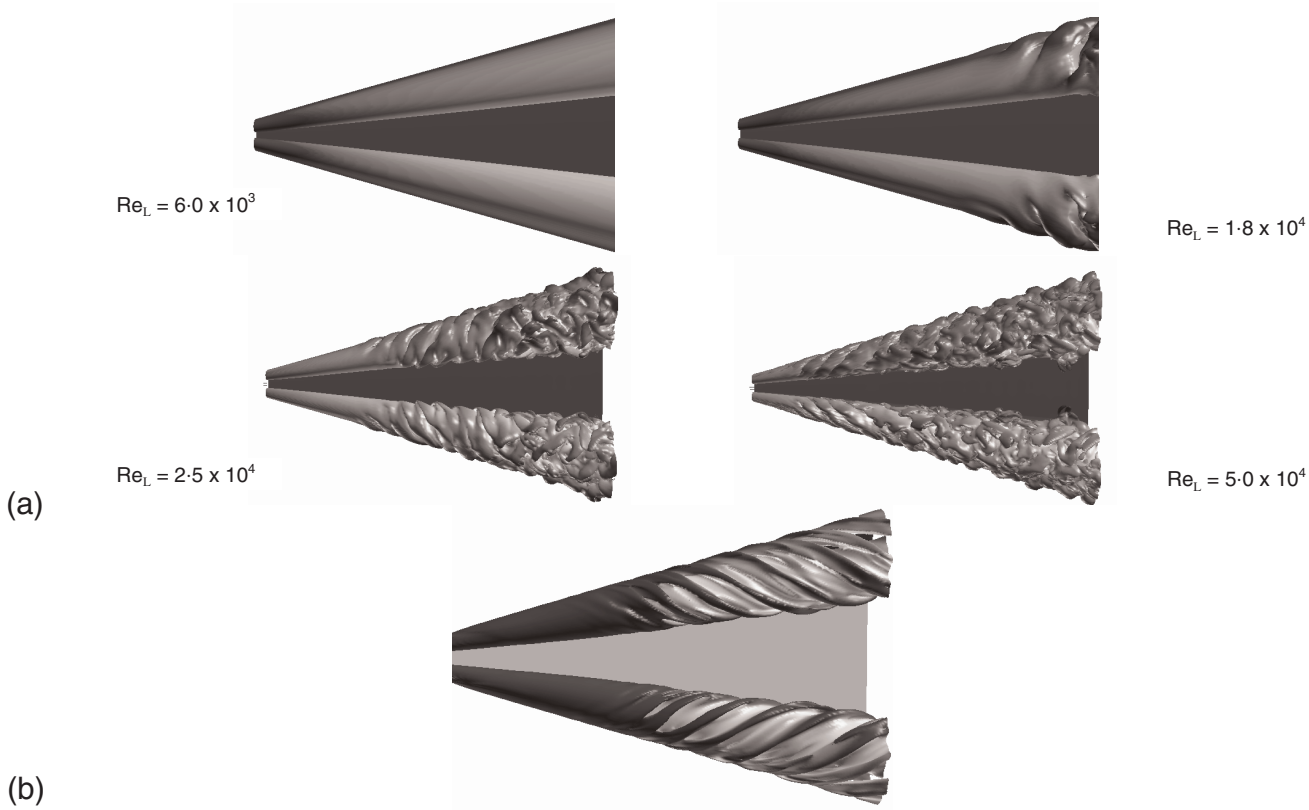


Figure 3. (a) Iso-surface of axial vorticity for instantaneous flow, showing the transition process with increasing Reynolds number, $\Lambda = 75°$, $\alpha = 25°$; (b) time-averaged flow showing mean vortical substructures for $Re_L = 5 \times 10^4$[4].

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

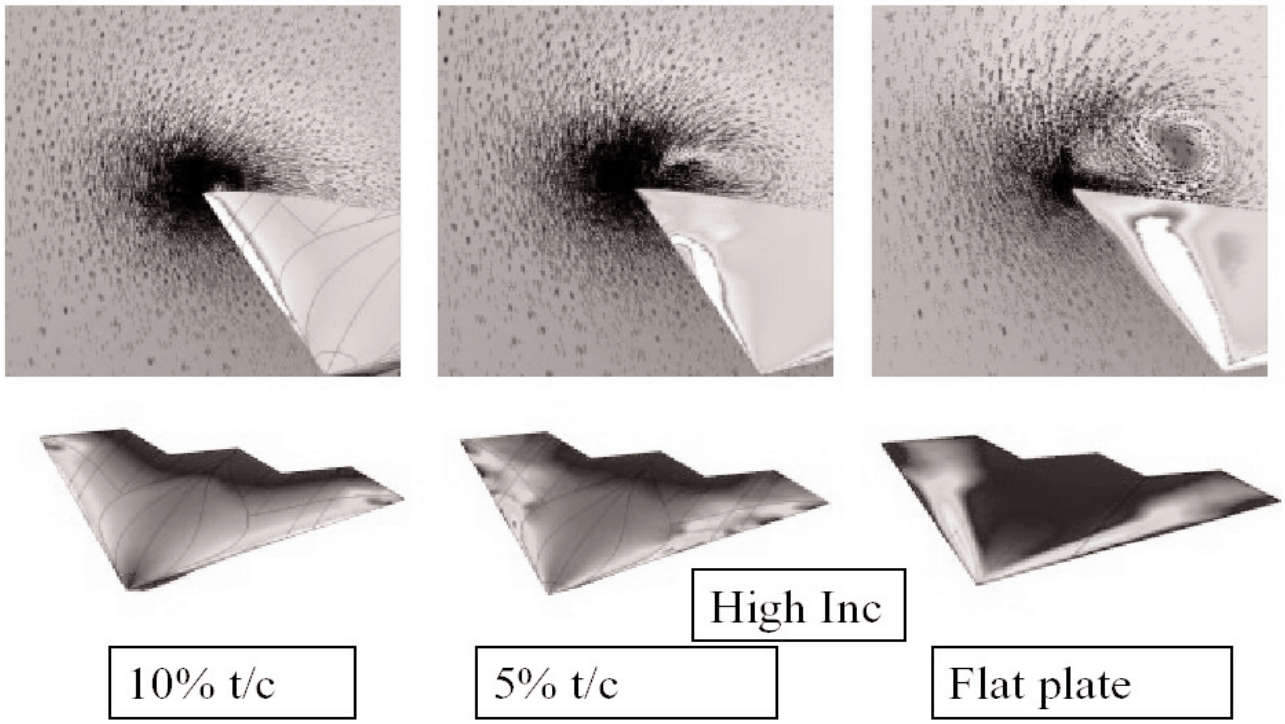


Figure 4. Effect of wing thickness and leading-edge shape on vortex flow for a generic UCAV configuration[10].

instability, wave propagation, and flow stagnation are summarised in several review articles[5,6,7]. It is now generally agreed that this phenomenon is a wave propagation phenomenon, and there is a strong analogy to shocks in gas dynamics. Concepts of supercritical and subcritical flows based on the wave propagation characteristics seem to play an important role in the understanding of vortex breakdown. Although a great deal of effort has been focused on the study of the vortex breakdown phenomenon, its accurate prediction for a generic UCAV configuration at high Reynolds numbers remains challenging[8].

Vortex breakdown has adverse effects on time-averaged performance. For example, the magnitude of the lift and nose down pitching moment decreases after vortex breakdown for slender wings. However, the effects of vortex breakdown are more modest for low sweep angle delta wings[9]. For typical UCAV configurations with low sweep angles, wing stall has more dramatic effects on pitching moment[9,10] than vortex breakdown. Also, the wing thickness and leading-edge shape are more important for the development of the vortical flow and wing stall, as shown in Fig. 4. Relative to the slender delta wings that have been the subject of much past research, the aerodynamics of moderate sweep UCAV wings with rounded leading edges remains less understood.

There has been less emphasis on the unsteady aspects of vortex breakdown, which have an impact on aircraft stability and control and wing/fin buffeting. It is well known that the flow downstream of vortex breakdown exhibits a well-documented hydrodynamic instability, called helical mode instability[11]. Experimentally observed periodic velocity/pressure oscillations correspond to the most unstable normal modes of the time-averaged velocity profiles of the vortex (downstream of breakdown) based on the linearised, inviscid stability analysis. Unsteady flow phenomena relevant to vortex flows over delta wings have been studied in several previous investigations[11,12,13]. It should be noted that current knowledge of the unsteady aspects of breakdown is limited to slender wings[14].

2.3 Vortex interactions

It was observed in several experiments that the vortex breakdown location over stationary delta wings is not steady and exhibits fluctuations along the axis of the vortices. Subsequently it was discovered that these oscillations are in the form of an antisymmetric motion of breakdown locations for left and right vortices[15]. This is demonstrated by plotting the difference and average of left and right vortex breakdowns in Fig. 5. The two breakdowns, which are almost mirror images, oscillate in an antisymmetric motion. The amplitude of these fluctuations can be a significant fraction of the chord length. These oscillations may be very important for the stability and control of highly manoeuvrable aircraft, and also have important consequences for wing and tail buffeting. As typical UCAV configurations look like delta wings without fuselage, vortex interactions might be important.

It was also reported that the oscillations of breakdown locations are quasi-periodic. Both flow visualisation and pressure measurements at high Reynolds numbers confirmed the existence of vortex interactions. The exact mechanism of this interaction and whether vortex breakdown is an essential part of it remains little understood. It was found that the oscillations become larger and more coherent as the time-averaged breakdown locations get closer to each other when the angle-of-attack or sweep angle is increased. Although this kind of vortex interaction is more of a concern for slender wings, evidence of such interactions at a relatively low sweep angle of $\Lambda = 60°$ was reported[16] recently (see Fig. 6). Wing tip accelerations occurred in an antisymmetric structural mode for a slightly flexible delta wing when vortex breakdown occurred on the wing. Again, this finding highlights the potential concerns for typical UCAV configurations.

2.4 Nonslender vortices

Much of our knowledge of vortex flows is related to slender vortices. There is very little known about the structure of vortices and unsteady flow phenomena over nonslender delta wings ($\Lambda \geq 55°$). Figure 7 shows an example of flow visualisation for a $\Lambda = 50°$ delta wing, where

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

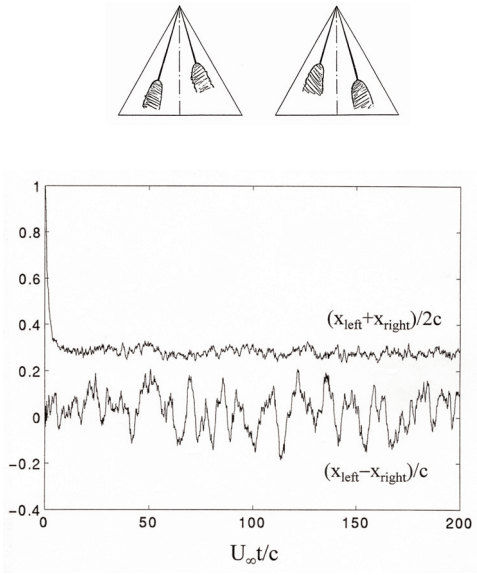


Figure 5. Time history of average and difference of breakdown locations showing antisymmetric oscillations.

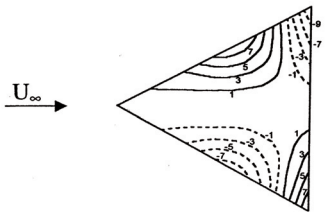


Figure 6. Antisymmetric structural mode for a slightly flexible delta wing when vortex breakdown occurred on the wing.

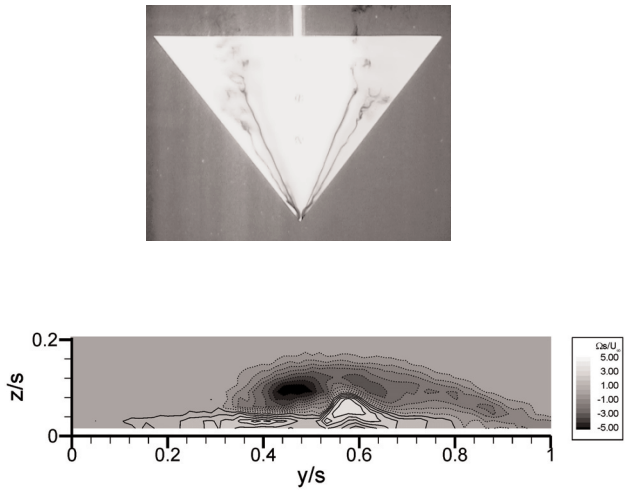


Figure 7. Flow visualisation of vortices over a nonslender delta wing with a sweep angle of $\Lambda = 50$ (top). Vorticity is shown in a cross-flow plane upstream of breakdown, revealing dual vortex structure (of the same sign of vorticity) (bottom).

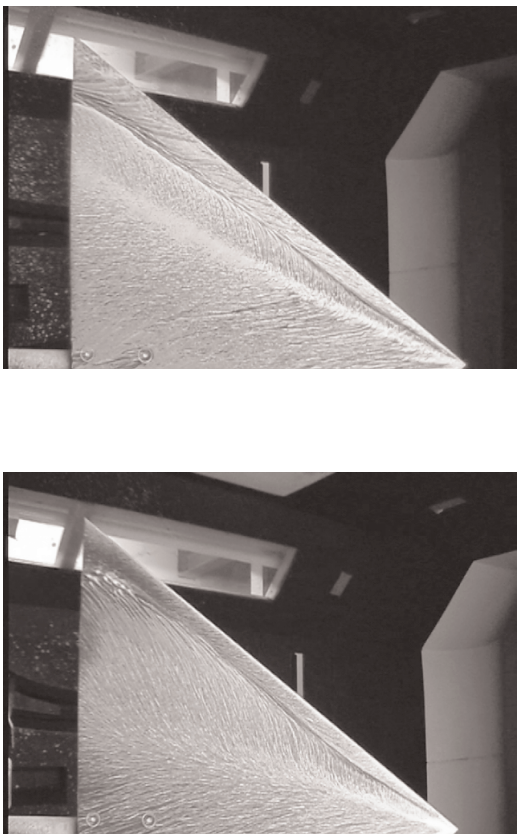
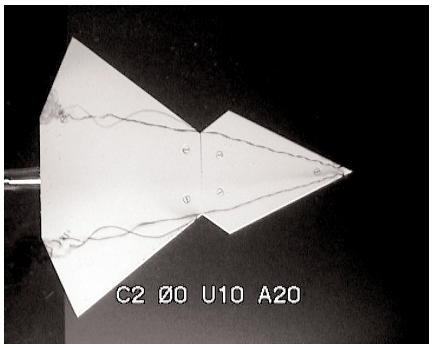


Figure 8. Surface flow visualisation for $\Lambda = 50°$ for $\alpha = 2{\cdot}5°$ (top) and $\alpha = 15°$ (bottom).



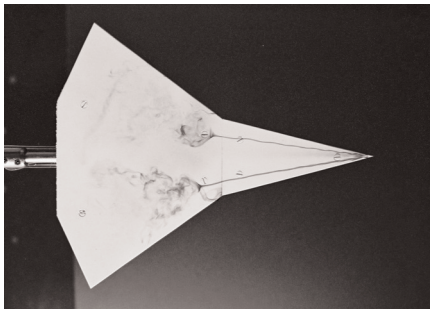


Figure 9. Interaction of multiple vortices originating from strake and wing, showing coiling-up and vortex breakdown.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

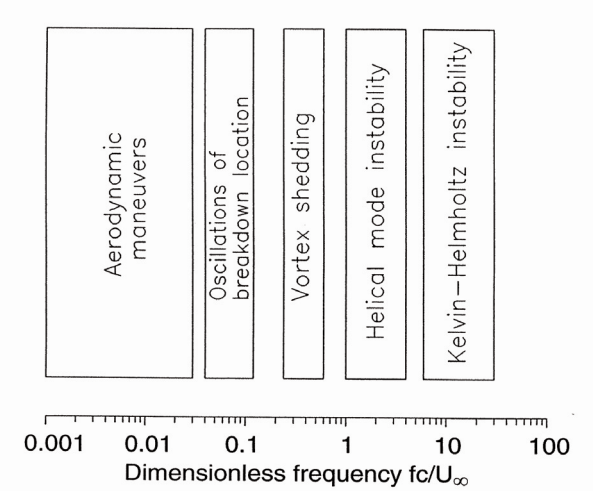


Figure 10. Spectrum of unsteady flow phenomena over delta wings as a function of dimensionless frequency[15].

a dual vortex structure is identified. Both particle image velocimetry (PIV) measurements[17] and direct numerical simulations[18] confirmed that both vortices have the same sign of vorticity as shown in Fig. 7. This dual vortex structure is a result of the primary vortex being split into two by boundary layer vorticity. This phenomenon is unique to nonslender wings where the vortical flow is very close to the wing surface, and vanishes as angle-of-attack or sweep angle is increased.

It has been found that wings with sweep angles as low as 40° at angles-of-attack as low as a few degrees can produce strong vortical flows. An example of surface flow visualisation for $\alpha = 2{\cdot}5°$ is shown in Fig. 8 for $\Lambda = 50°$ delta wing, where the secondary separation and reattachment lines are visible. For both incidences shown in Fig. 8, there is a change in the curvature of the secondary separation line around the quarter-chord, which is presumably due to the vortex breakdown. Features of vortex cores, types of axial flow (jetlike or wakelike) and characteristics of vortex breakdown exhibit considerable differences[17,18] from those of slender wings. In general, vortex breakdown is much milder and sometimes difficult to identify based on the velocity field (i.e. axial flow deceleration is small). Also, unlike for slender wings, the shear layer reattachment on the wing surface is possible even after vortex breakdown reaches the apex.

There is a need to understand separated and vortical flows at nonzero roll angles for nonslender wings. Recently, it was discovered that nonslender delta wings can exhibit wing rock phenomenon[19]. Unlike slender wings, this phenomenon occurs around a nonzero mean roll angle. It is believed that coupling between flow separation from rounded leading-edges and reattachment on the wing surface is the main source of large roll oscillations. This type of roll instability is a concern for typical UCAV configurations, and needs to be investigated further.

2.5 Multiple vortices

Another area that has received little attention is the interaction of multiple vortices such as found on double delta wings (see Fig. 9). Interactions of multiple vortices, complex vortex patterns, coiling-up and merging, vortex breakdown, and unsteady interactions are highly challenging vortical flows. These aspects are even more complex and challenging for manoeuvring aircraft.

There might be potential benefits in investigating optimum sweep angles for strake and wing in order to avoid premature breakdown and adverse interactions. There is very little known about the unsteady aspects of such interactions of multiple vortices. Previously discussed interactions of a vortex pair might induce unsteady interactions of four vortices (two vortex pairs).

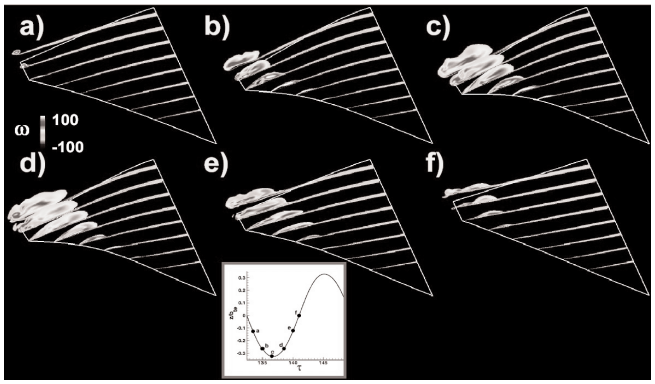


Figure 11. Interaction of leading-edge vortex with a flexible delta wing[24]. The inset shows the tip deflection as a function of time.

2.6 Manoeuvring wing vortices

The spectrum of unsteady flow phenomena over stationary delta wings is shown in Fig. 10 as a function of dimensionless frequency[15]. Also shown is the frequency range of aerodynamic manoeuvres for current fighter aircraft. Future unmanned aircraft will be highly manoeuvrable and highly flexible, with the capability of performing extreme manoeuvres at high g (30g vehicle envisioned). At such high reduced frequencies, there is the possibility that the coupling of aerodynamic manoeuvres with vortex instabilities may occur. Prediction of such flows remains a challenge for future UCAV configurations[8]. For highly manoeuvrable UCAV configurations, highly nonlinear unsteady aerodynamics presents major challenges for the development of flight control laws.

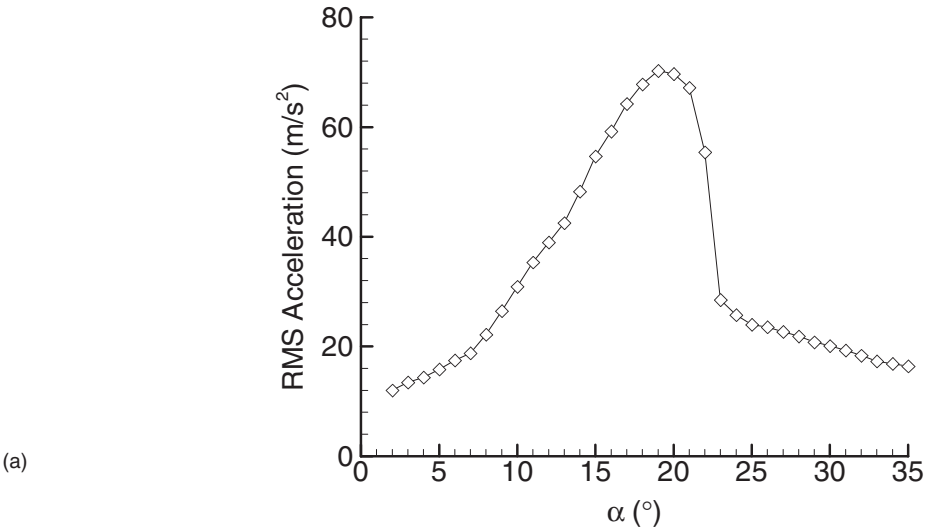
The dynamic response of leading edge vortices and breakdown is important for the flight of unmanned aircraft. For a pitching delta wing, both the formation of leading-edge vortices[20] and vortex breakdown[21,22] show hysteresis and time lag with respect to the quasi-steady case. This time lag, which is important for the stability and control of aircraft, has also been observed for other types of wing motion, such as plunging and rolling. The time lag of vortex breakdown is much larger than that of vortex formation. Although it is common to all unsteady flows, regardless of the type of unsteady motion[23], the mechanism of hysteresis and time lag is not well understood.

3.0 VORTEX/FLEXIBLE WING INTERACTION

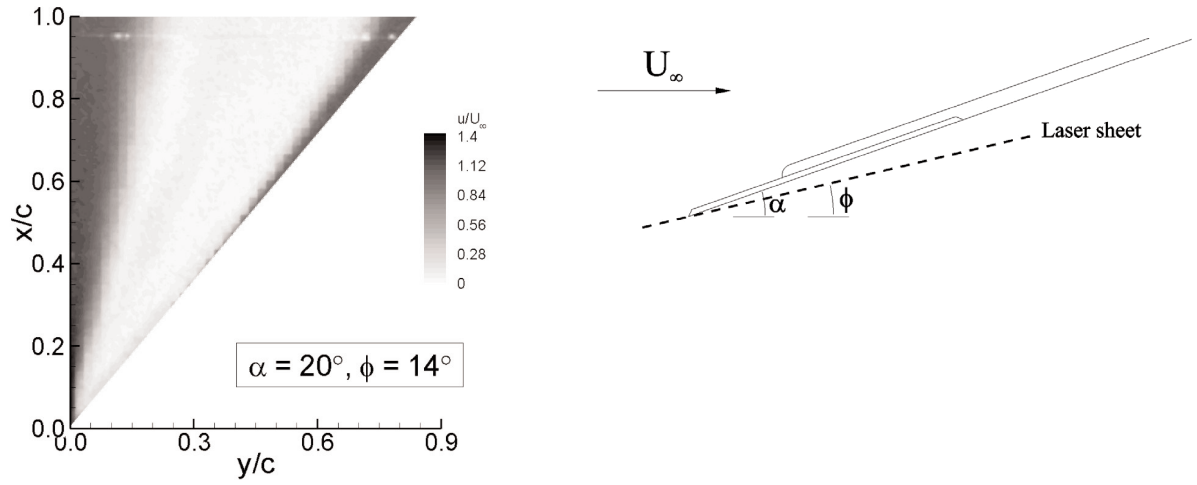
Because of unusual designs and high rate motions, wing flexibility becomes an issue. The coupling of unsteady, separated and vortical flows with flexible wings may result in limit-cycle-oscillations or control problems. For flexible delta wings, vortex–wing interaction (see Fig. 11) may lead to limit cycle oscillations, where the vortex acts like an aerodynamic spring[24]. Unsteady flow phenomena may interact and couple with structural vibrations.

It was shown for a slightly flexible delta wing[16] with a sweep angle of $\Lambda = 60°$ that the buffeting level depends on the vortex regime, and vortex breakdown is the most important source of unsteadiness. However, the main source of buffeting becomes different for nonslender wings[25]. It was shown that, for $\Lambda = 50°$ wing, the maximum buffeting occurs around = $\alpha = 20°$,as shown in Fig. 12(a). The time-averaged flow in the plane shown in the inset of Fig. 12(b) indicates that vortex breakdown occurs at the apex and there is no streamwise vortex. However, velocity measurements near the wing surface reveal that the shear layer reattachment occurs as shown on the left side of Fig. 12(c), and generates large unsteadiness as shown by the rms velocity levels on the right side of Fig. 12(c).

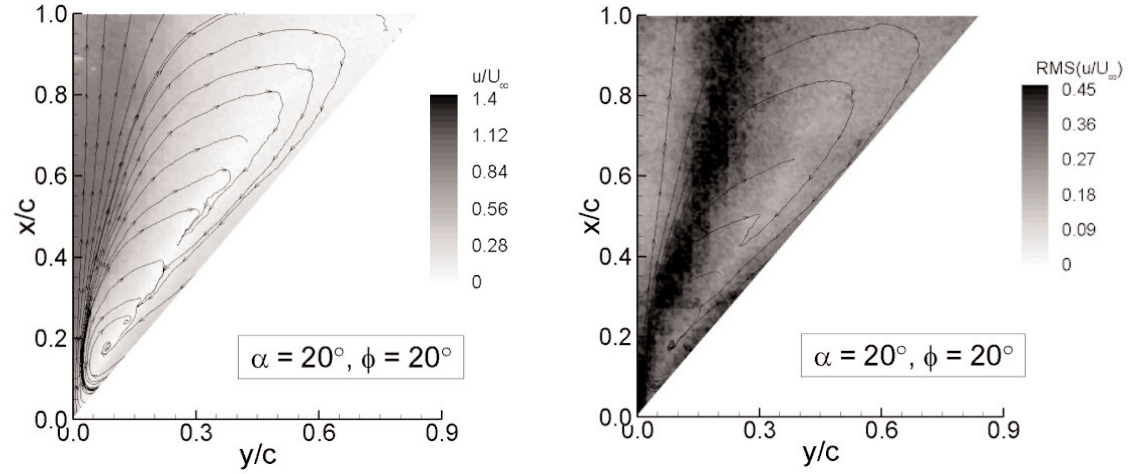
https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press



(a)



(b)



(c)

Figure 12. (a) Buffeting response for a slightly flexible delta wing, $\Lambda = 50°$ (b) time-averaged flow in the plane shown in the inset; (c) time-averaged (left) and rms (right) velocity near wing surface.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

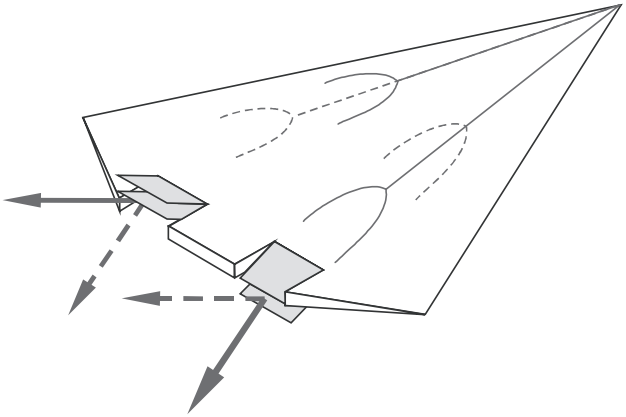


Figure 13. Schematic of thrust vectoring and its effect on vortex flow and breakdown.

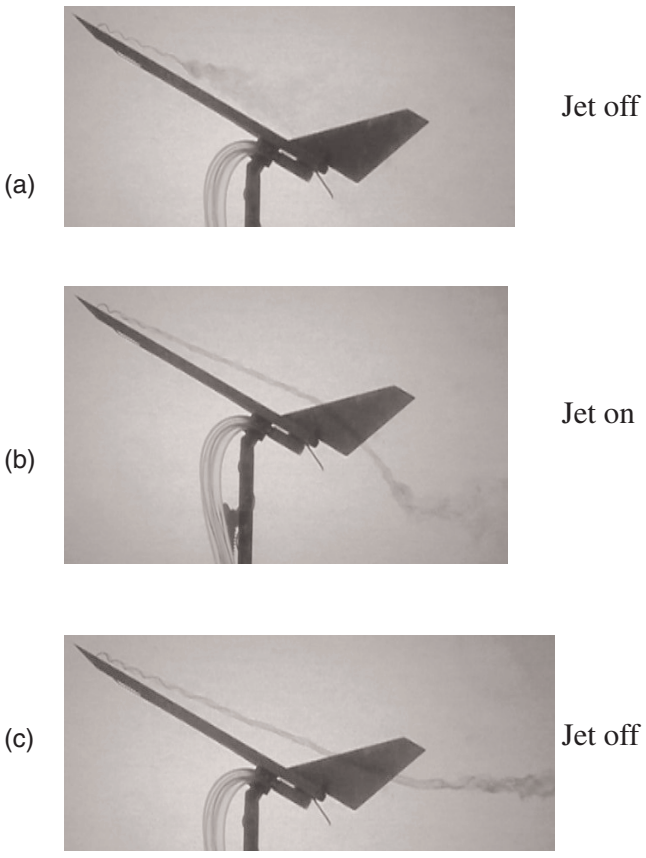


Figure 14. Flow visualisation of leading-edge vortex for (a) jet off, (b) jet on, (c) just after the jet is turned off[27], jet deflection angle $\beta = 30°$.

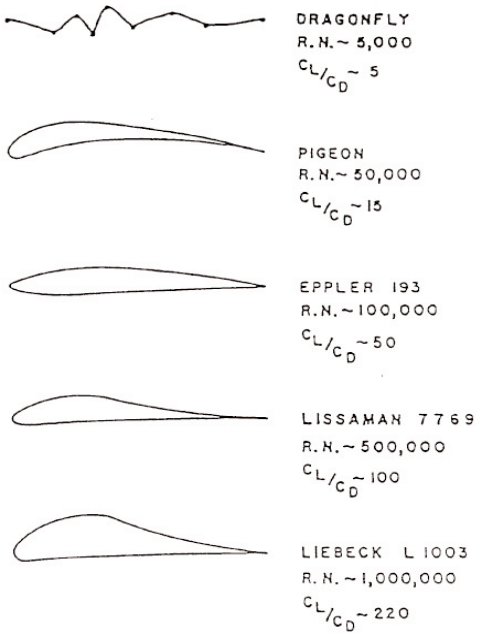


Figure 15. Representative low-Reynolds number aerofoils as a function of Reynolds number (taken from Ref. 28).

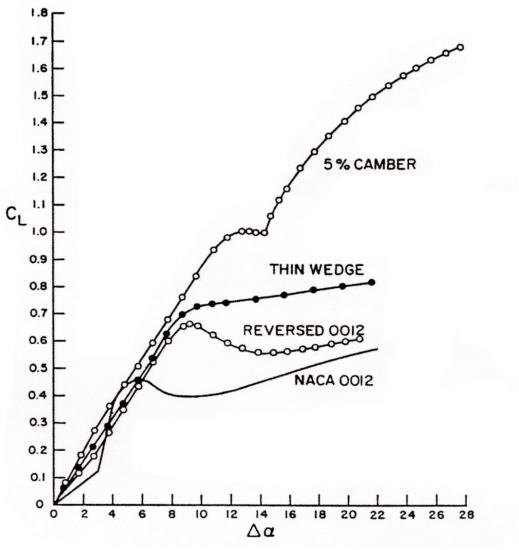


Figure 16. Variation of lift coefficient with angle-of-attack for various aerofoils for Re = 20,700[29].

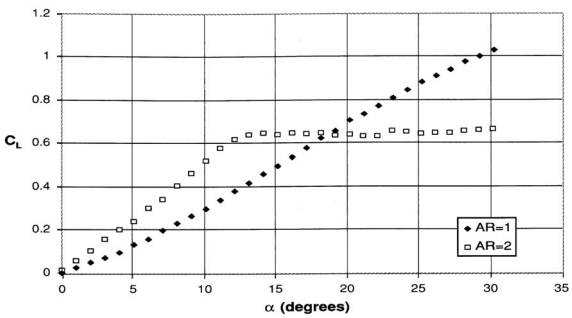


Figure 17. Variation of lift coefficient with angle-of-attack for flat-plate wings with elliptical planform[31].

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

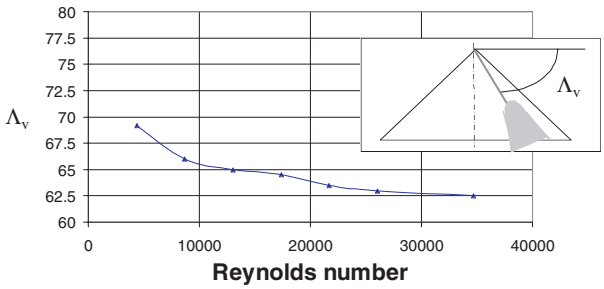


Figure 18. Variation of vortex angle with Reynolds number, $\alpha = 15°$, $\Lambda = 50°$.

Hence, the shear layer reattachment, rather than the vortex breakdown phenomenon, is the most important source of buffeting for nonslender wings. Vortex shedding produces surprisingly small levels of buffeting.

The coupling of structural modes with flow instabilities (see Fig. 6) presents challenges for aeroelastic simulation of such flows. As the oscillating leading edge is an unsteady source of vorticity, the effect of wing flexibility on vortical flows needs to be investigated. Recently[26], it was shown that substantial lift enhancement (up to 45%) can be achieved on a flexible delta wing.

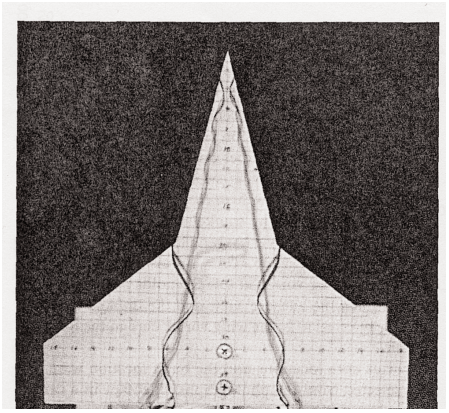
4.0 VORTEX/PROPULSION INTERACTION

The effect of thrust vectoring on wing vortex flows is a typical example of aerodynamics/propulsion interaction, as sketched in Fig. 13. The effect of trailing-edge jets on the vortical flow over delta wings has been examined by several investigators. In each case, trailing-edge jets were shown to exert a significant influence on dominant flow features, such as the breakdown location of leading-edge vortices. Figure 14 shows flow visualisation images[27] for (a) jet off, (b) jet on (in a 'steady-state case'), and (c) just after the jet is turned off. It is seen that the leading-edge vortex is drawn towards, and parallel to, the jet in the steady-state case. When the jet is turned off, the wing vortex realigns itself to become almost parallel to the free stream. Vortex breakdown then slowly propagates upstream, and eventually reaches a steady-state location similar to that shown in Fig. 14(a). The role of jet entrainment and the effect of jet vortices on the wing vortex are worthy of further study.

Figure 14(c) also illustrates the hysteresis and lag associated with the wing vortical flow. The presence of large time-constants associated with this complex jet-vortex interaction is important for the dynamic aspects of thrust vectoring. In particular, the consequences of this behaviour are serious for the stability and control of the vehicle, if the control system is based on static characteristics. An adequate description of the non-linear and unsteady aerodynamics, including vortical interactions and aerodynamic hysteresis, is therefore of importance to flight control system designers.

5.0 VORTICAL FLOW ISSUES ON MAVS

Micro air vehicles (MAVs) are defined as unmanned aircraft with no physical dimension greater than 150mm. MAVs can take the form of fixed, rotary or flapping wings, of which the fixed wing configurations have been shown to require the least amount of energy over a range of windspeed and unsteady flight conditions, provided hovering flight is not required in the mission profile. Both fixed-wing and flapping wing MAVs exhibit vortex-dominated flows.



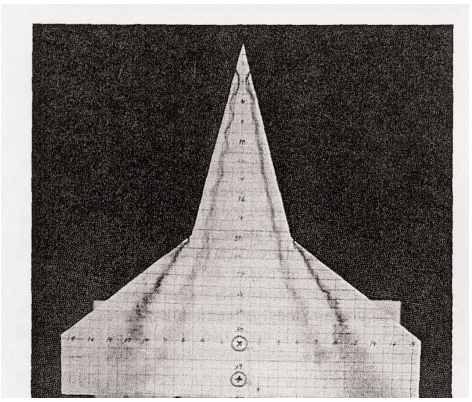


Figure 19. Effect of Reynolds number on vortex merging: Re = 15,000 (top) and Re = 75,000 (bottom)[32].

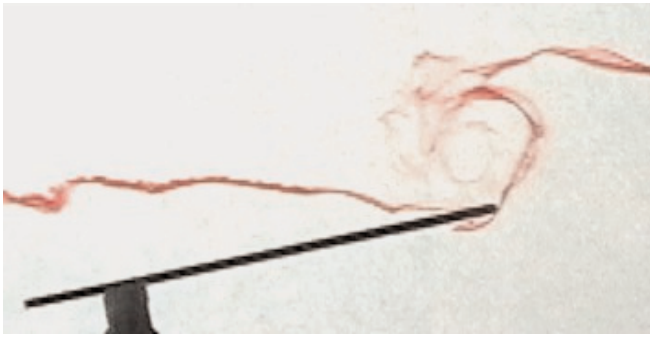


Figure 20. Experimental simulation of transient and periodic gust encounter with a micro air vehicle. In this picture, an example of transient gust is shown. Flow is from right to left and flat-plate wing is also seen in the picture. Transient gusts, representing eddies in the atmosphere were simulated using oscillating aerofoil/flap combinations upstream (not shown in the figure).

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

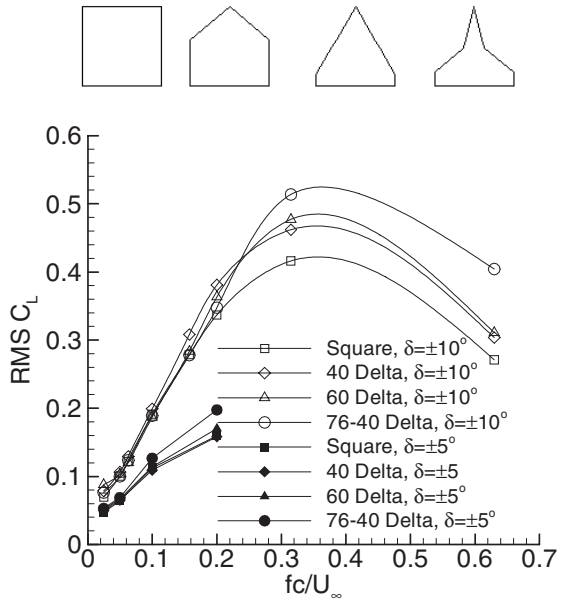


Figure 21. Variation of RMS lift coefficient with non-dimensional frequency for two gust amplitudes corresponding to flap angles of $\delta = \pm 5°$ and $\delta = \pm 10°$ of the gust generator. Low aspect ratio wings tested are shown in the inset.

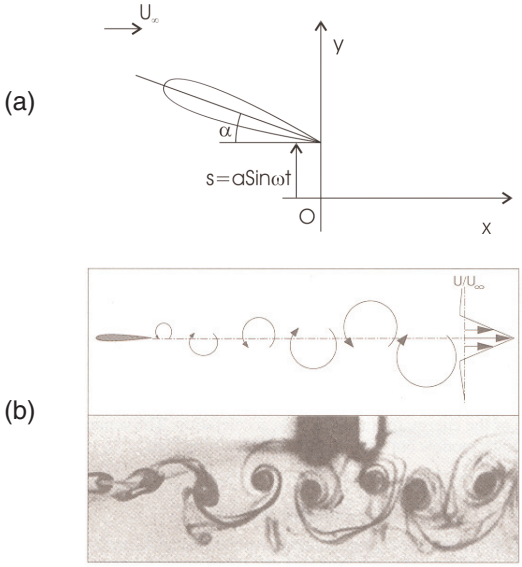


Figure 22. (a) Schematic of pitching and plunging aerofoil; (b) thrust-indicative vortex street[40].

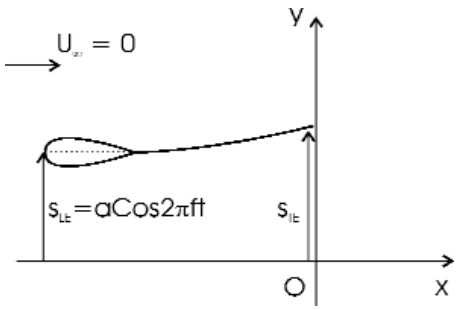


Figure 23. Schematic of a flexible aerofoil plunging periodically in the vertical direction.

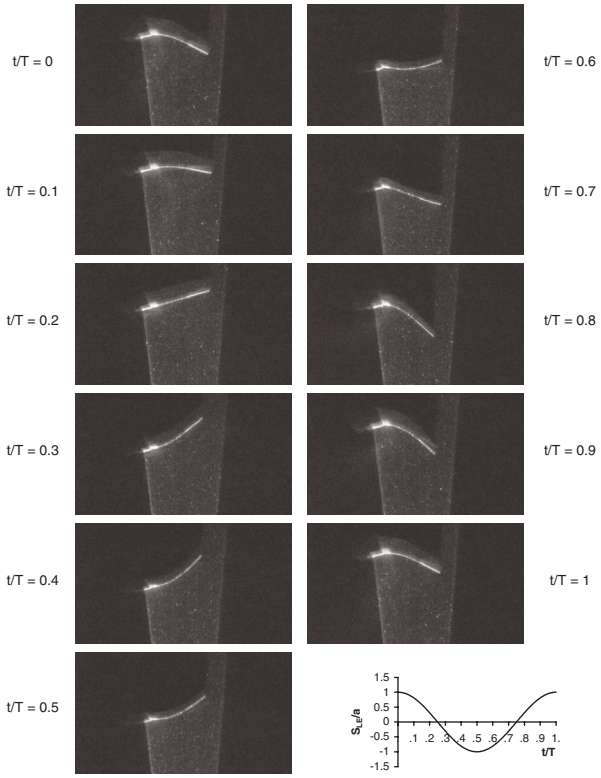


Figure 24. The shape of the very flexible aerofoil over one period; Re = 20,250, *a/c* = 0·194.

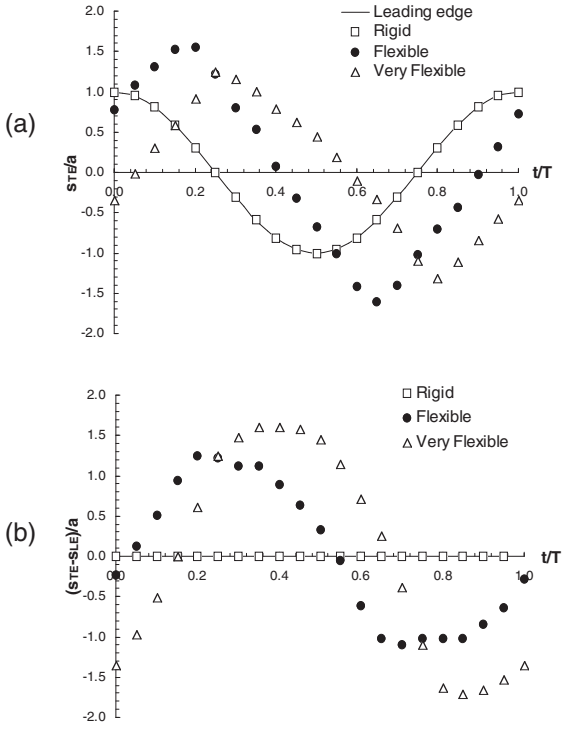


Figure 25. (a) Displacement of the trailing edge and (b) displacement of the trailing edge relative to the leading edge; Re = 20,250, *a/c* = 0·194.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

5.1 Low Reynolds number aerodynamics

Typically, the Reynolds number based on wing chord length will be 10^4 to 10^5 for a MAV. Most aerofoil shapes, even those designed specifically for low Reynolds number flight, exhibit considerable sensitivity to the Reynolds number as it drops below 10^5. Thick aerofoils (i.e. 6% and above) show very poor lift performance. In contrast, thin aerofoil sections (i.e. less than 6% thick) can exhibit superior performance. Figure 15 shows representative low-Reynolds-number airfoils[28] in the range of Re = 5,000 to 1,000,000. It is seen that aerofoils become thinner with decreasing Reynolds number.

Recent experiments[29] have shown that thin, flat and cambered plates perform well at low Reynolds numbers as shown in Fig. 16. This is particularly interesting, because the flow separates at the leading-edge even at low incidences. Hence, at this scale, separated flows are dominant. The performance of thin plates seems insensitive to changes in Reynolds number and wind tunnel turbulence. Furthermore, Laitone[29] showed, by reversing a NACA 0012, that the lift coefficient was actually improved. This work showed that in low Reynolds number aerodynamics, lift is not as dependent on a sharp trailing edge as it is at higher Reynolds number flows. This suggests the possibility of using trailing-edge blowing for propulsion and flow control.

5.2 Vortices at low Reynolds numbers

Due to the span restrictions, coupled with the likely weight of MAVs, very low-aspect-ratio wings are likely to be utilised. A very limited amount of research has been published concerning aerodynamics of low-aspect-ratio wings[30] in the past. Basic experimental data (lift and drag curves) for low-aspect-ratio wings at low Reynolds numbers have been presented by Torres and Mueller[31]. Figure 17 shows the variation of lift coefficient with angle-of-attack for flat-plate wings with an elliptical planform for two aspect ratios. It is seen that the AR =1 wing produces monotonically increasing lift coefficient with incidence, very much like a thin delta wing. Tip vortices contribute to lift, and affect the majority of the wing surface.

Current and future fixed-wing micro air vehicles exhibit a variety of separated and vortex-dominated flow fields, including tip vortices, leading-edge vortices, vortex shedding, and vortex breakdown[30]. Some aspects of these vortical flows show great sensitivity to the Reynolds number. Although primary slender vortices are not sensitive to the Reynolds number, nonslender vortices on wings with low sweep angles are more sensitive as the vortices form closer to the wing surface, and viscous interactions become important. For example, Fig. 18 shows that the spanwise location of the vortex axis varies considerably with Reynolds number (in the range of Re ≤ 20,000) for a 50° sweep delta wing. Also, in the presence of multiple vortices, such as those found on double delta wings, vortex merging is very sensitive to the Reynolds number. Strake and wing vortices are coiled-up at low Reynolds numbers[32], but are not separated at high Reynolds numbers as shown in Fig. 19. In spite of the diversity of the existing MAV planforms, there is very little information on the vortical flows and aerodynamic force data at this scale.

5.3 Gust response

Due to their operation in the atmospheric boundary layer, MAVs will be extremely susceptible to gust loads. This is particularly important in an urban environment, where local architecturally induced gusts may be present. It is common to observe atmospheric turbulence having root mean square levels of the order of $1ms^{-1}$ near the ground. Typically, this means up to 20% variation in flight speed when streamwise turbulence is considered (assuming a flight speed of $5ms^{-1}$). Cross-stream turbulence will cause the effective angle-of-attack to vary by up to 10°. Membrane wings capable of adjusting the aerofoil shape in response to freestream variations is discussed in Ref. 33.

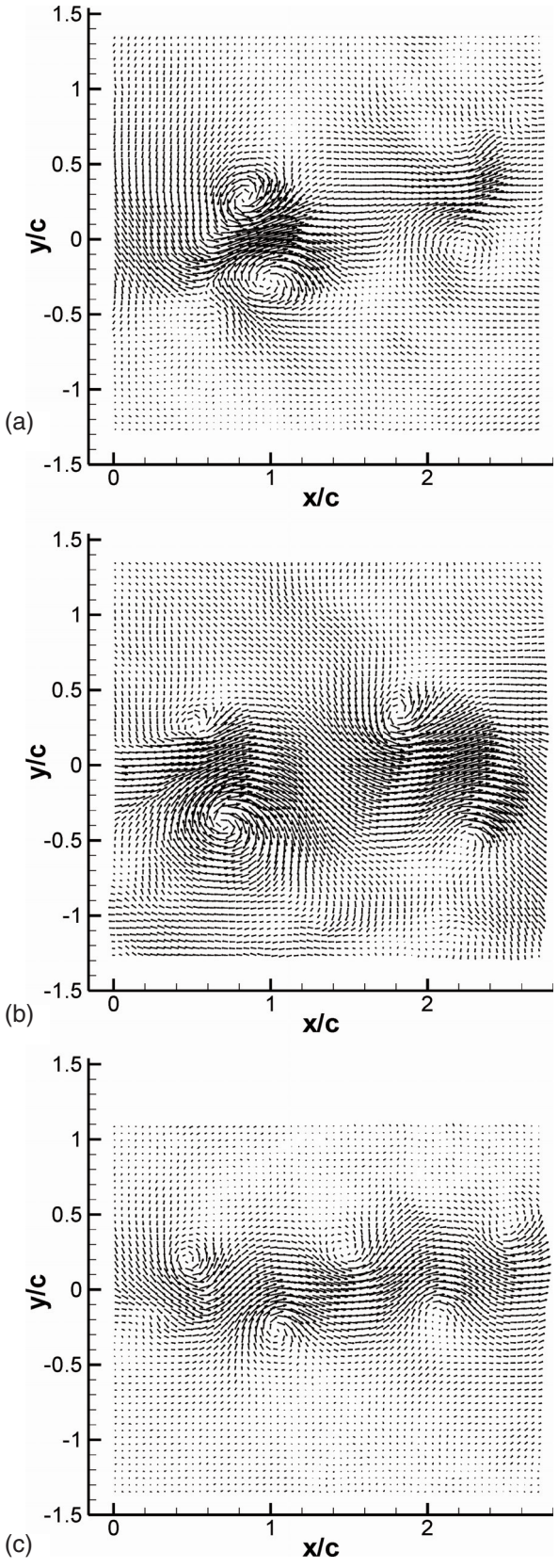


Figure 26. Instantaneous velocity field for (a) the rigid airfoil, (b) the flexible airfoil and (c) the very flexible airfoil; Re = 20,250, a/c = 0·194.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

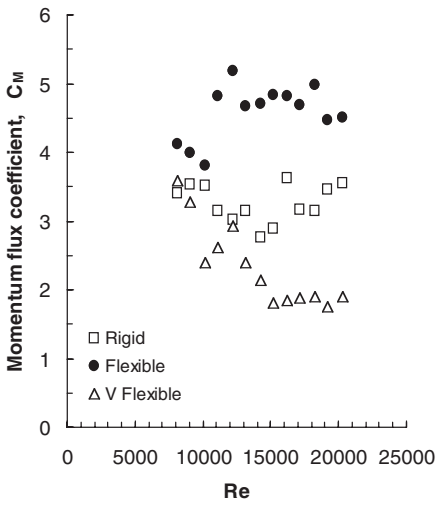


Figure 27. Momentum flux coefficient as a function of Reynolds number Re = fc^2/υ for a/c = 0·194.

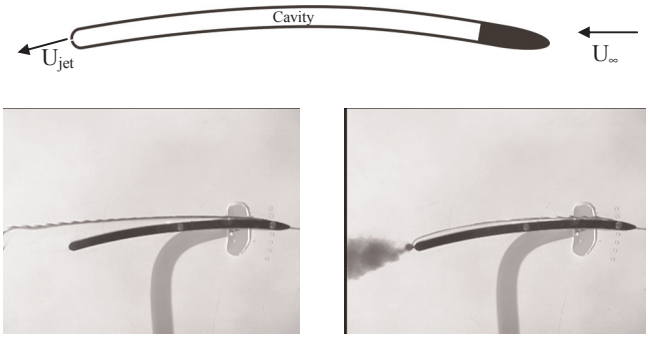


Figure 28. Flow visualisation for Re = 10,000 and $\alpha = 5°$ for no blowing (left) and $St = fc/U_\infty$ =16 (right).

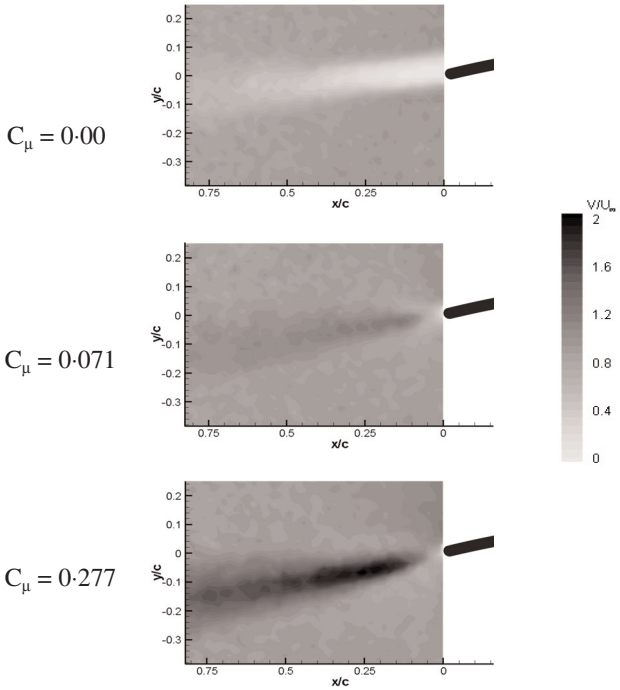


Figure 29. Contours of velocity magnitude measured by PIV for Re = 10,000, St = 5·7, $\alpha = 5°$.

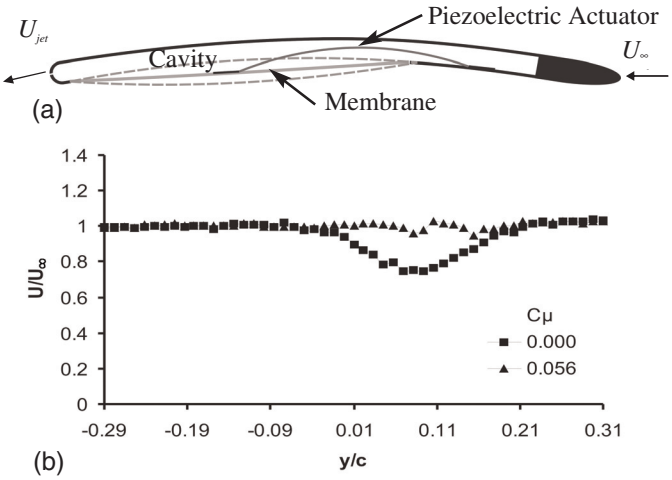


Figure 30. (a) Schematic layout of internally actuated aerofoil; (b) time-averaged streamwise velocity profile in the wake for Re = 20,000, St = 5, $\alpha = 5°$.

It is well known that different types of vortical flows respond to unsteady free stream perturbations in very different ways. Detailed study of gust response, and deeper understanding of unsteady aerodynamics of MAVs are very much needed. In a recent study, both periodic gusts and transient gusts[34] as shown in Fig. 20 (representing eddies in the atmosphere) were simulated using oscillating aerofoil/flap combinations upstream of wings.

Figure 21 shows the variation of the root-mean-square (RMS) value of the fluctuations of lift coefficient as a function of dimensionless frequency of periodic gusts for two gust amplitudes[34]. For low dimensionless frequencies, the rms value of lift fluctuations is nearly the same for all wings for a given flap angle amplitude, but there are significant differences at higher frequencies (corresponding to small eddies with the size of micro air vehicle). Large hysteresis and phase lag of the development of vortical flows and resulting phase lag of lift force depend on the leading-edge sweep angle.

6.0 MAV PROPULSION ISSUES

The conventional propulsion method for current micro air vehicles is propellers, which are very inefficient at low Reynolds numbers. In particular, efficiency drops very rapidly with decreasing Reynolds number for small MAVs. In addition, the influence of the propeller flow field on lift and drag of MAVs is always a concern. Further research is needed to develop more efficient, and perhaps unconventional, propulsion systems for low Reynolds number flows and MAV applications. The fact that birds, insects and many sea creatures use flapping-wing propulsion[35] successfully has encouraged recent interest[36] in the development of MAVs. In particular, insect flight has been considered as a model for small MAVs with high agility and hovering capability in enclosed environments[37,38]. Hybrid MAVs with a fixed-wing for lift generation and oscillating surfaces for thrust generation have been considered[39].

Plunging (periodic motion in the vertical direction to the freestream) and pitching aerofoils are known to produce thrust, if the oscillation frequency or amplitude is large enough. The mechanism of thrust generation is related to the production of a pair of opposite sign vortices[40] at the trailing-edge of the wing during the oscillation cycle, as shown in Fig. 22, where the aerofoil, at incidence α, moves up and down at frequency ω. Hence, flapping wing propulsion is one of the best examples of vortex-dominated flows relevant to micro air vehicles. It was noted[41] that examples of flapping wings in nature combine both pitching and plunging, although this is not a

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

requirement for thrust generation. The thrust and propulsive efficiency depends on the phase angle between pitching and plunging as well as the amplitudes. High efficiencies are possible for a properly tuned system of the two-degree-of-freedom motion. In general, when flow separation occurs at low Reynolds numbers, the propulsive efficiency is rapidly degraded. The limiting case of low Reynolds number aerodynamics is the thrust generation at zero freestream velocity. This particular case is relevant to the thrust generation by many insects and birds for hovering in still air.

There is growing evidence that wing flexibility[33] may be exploited for better performance for low Reynolds number flows. In order to understand the effect of wing flexibility on thrust generation, experiments with flexible aerofoils[42] plunging periodically (see Fig. 23) were conducted. An aerofoil with a flexible plate attached at its trailing-edge has been studied as a simple model of 'flexible aerofoil'. The rigid leading-edge is subject to a sinusoidal plunging motion. Figure 24 shows the deformation of the flexible aerofoil over one oscillation cycle. It is seen that the displacement of the trailing-edge has a large phase lag. This is also shown in Fig. 25 by plotting the time history of the position of the trailing-edge (Fig. 25(a)) and the displacement of the trailing-edge relative to the leading-edge (Fig. 25(b)), which shows the deformation. The latter can be viewed as instantaneous geometric incidence due to deformation, and has a phase angle with respect to plunging. This phase delay appears to play a major role on the flow field as shown in Fig. 26. Almost symmetrical vortical flow consisting of vortex pairs or antisymmetric vortical flow consisting of alternating structures is possible. The calculated momentum flux shown in Fig. 27 reveals that it is largest for the flexible aerofoil, but the very flexible aerofoil does not perform as well as the rigid one, implying that there is an optimum flexibility.

The use of synthetic (zero net mass flux) jets for the propulsion of fixed-wing MAVs is investigated[43] as a possible alternative. The formation of a time-averaged jet resulting from periodic excitation of a cavity (which can be modelled as a train of counter-rotating vortex pairs) and its interaction with wing aerodynamics[44] have been studied. As a thick trailing edge does not have an adverse effect on lift generation at low Reynolds numbers, a synthetic jet was placed at the trailing-edge of the wing (see Fig. 28). It was shown that when the synthetic jet is activated, the separated shear layer reattaches near the trailing-edge for a cambered wing for momentum coefficients larger than a critical value. It is expected that lift will be enhanced while sufficient thrust is generated. The PIV measurements shown in Fig. 29 indicate that the separation region disappears when the synthetic jet is activated, resulting in nearly zero net drag. Above the critical value of the momentum coefficient, the jet produces net thrust, which strongly depends on excitation frequency. There are challenges for realistic configurations operating on this principle: optimum excitation frequencies, for a typical MAV, are around 50Hz, which is much smaller than the resonance frequencies of most commercially available actuators, and there is very little space for the actuators inside thin aerofoil cross-sections. A generic aerofoil with an internal actuator is shown in Fig. 30(a). This design was made of a hollow aerofoil with a membrane in the lower surface and an internal piezoelectric actuator. Figure 30(b) shows that zero net drag can be achieved when the synthetic jet is activated.

7.0 CONCLUSIONS

Separated and vortical flows are dominant over various unmanned air vehicles (UAVs). In this article, vortical flow issues and challenges for future UAVs are reviewed. A better understanding and prediction of the transition process, vortex breakdown and wing stall on typical UCAV configurations with low sweep angles and rounded leading-edge are needed. Since the flow separation process is more complicated and Reynolds number sensitive for rounded leading-edges, vortex formation and vortex instabilities are more difficult to predict. Most of the available experimental and computational simulations have been carried out for sharp leading edges for which the separation line is fixed. There is an urgent need to understand the effect of rounded leading edges and, in particular, Reynolds number. Recently discovered self-excited roll oscillations of nonslender wings might originate from the flow separation characteristics on the rounded leading-edges.

The unsteady aspects of these flows and vortex interactions remain little understood. Vortex pair interactions and interaction of multiple vortices (of the same sign) should be investigated in detail for nonslender configurations. In order to develop highly manoeuvrable aircraft, further investigations are needed to understand the unsteady aerodynamics of both nonslender vortices and multiple vortices, hysteresis, and time-lag effects. This has obvious importance for flight control of unmanned air vehicles. In the case of thrust vectoring, transient effects due to vortex/jet interaction might be important. The frequency range of relevant unsteady flow phenomena is so wide that time-accurate numerical simulations of these flows are difficult. A combination of comprehensive experimental data, accurate time-dependent simulations, and simple theoretical models can be useful for better physical understanding of time-lag and hysteresis effects.

As future unmanned aircraft will be highly manoeuvrable and highly flexible, vortex/flexible wing interactions may result in limit-cycle-oscillations. While accurate prediction of flow/structure interactions for large deflections and highly unsteady flows is challenging, experimental simulation of the aeroelastic phenomena is also difficult due to model scaling requirements. Fortunately, for UAVs, this problem is not as severe.

Separated and vortical flows are more dominant at low Reynolds number flows. Some aspects of these vortical flows show great sensitivity to the Reynolds number. The unsteady aerodynamics of low-aspect ratio wings in gusts is important for MAVs. There is also need to investigate more efficient propulsion systems for MAV applications. These unusual propulsion systems rely on vortex formation, and involve highly unsteady flows and sometimes highly flexible surfaces. Experimental studies are often leading the computational simulations in this area due to the obvious challenges in computational modelling. However, at least for relatively low Reynolds number flows, direct numerical simulations (DNS) should be possible.

ACKNOWLEDGEMENTS

Research programmes funded by the US Air Force Office of Scientific Research, the European Office of Aerospace Research and Development, the Engineering and Physical Sciences Research Council, Ministry of Defence, QinetiQ and BAE Systems contributed to this review article.

REFERENCES

1. GAD-EL-HAK, M. and BLACKWELDER, R.F. The discrete vortices from a delta wing, *AIAA J*, 1985, **23**, pp 961-962.
2. RILEY, A.J. and LOWSON, M.V. Development of a three-dimensional free shear layer, *J Fluid Mechanics*, 1998, **369**, pp 49-89.
3. MITCHELL, A.M. and MOLTON, P. Vortical substructures in the shear layers forming leading-edge vortices, *AIAA J*, 2002, **40**, (8), pp 1689-1692.
4. VISBAL, M.R. Computational and physical aspects of UAV vortical flows, Workshop on aerodynamic issues of unmanned air vehicles, 4-5 November 2002, University of Bath, UK. See also, VISBAL, M.R. and GORDNIER, R.E., On the structure of the shear layer emanating from a swept leading edge at angle-of-attack, AIAA-2003-4016, 33rd Fluid dynamics conference and exhibit, 23-26 June 2003, Orlando, FL, USA.
5. HALL, M.G. Vortex breakdown, *Annual review of fluid mechanics*, 1972, **4**, pp 195-218.
6. LEIBOVICH, S. Vortex stability and breakdown: survey and extension, *AIAA J*, 1984, **22**, (9), pp 1192-1206.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press

7. DELERY, J.M. Aspects of vortex breakdown, *Progress in Aerospace Sciences*, 1994, **30**, pp 1-59.
8. MORTON, S. High resolution computational unsteady aerodynamic techniques applied to maneuvering unmanned combat aircraft, workshop on aerodynamic issues of unmanned air vehicles, 4-5 November 2002, University of Bath, UK. See also, CEAS Aerospace Aerodynamics Research Conference, 10-12 June 2003, London, UK.
9. EARNSHAW, P.B. and LAWFORD, J.A. Low speed wind tunnel experiments on a series of sharp-edged delta wings, R&M 3424, August 1964.
10. PEMBERTON, T. Aspects of use of CFD for configuration design of UAV concepts, Workshop on aerodynamic issues of unmanned air vehicles, 4-5 November 2002, University of Bath, UK.
11. GURSUL, I. Unsteady flow phenomena over delta wings at high angle-of-attack, *AIAA J*, February 1994, **32**, (2), pp 225-231.
12. GURSUL, I. and XIE, W. Buffeting flows over delta wings, *AIAA J*, 1999, **37**, (1), pp 58-65.
13. MENKE, M. and GURSUL, I. Unsteady nature of leading edge vortices, *Physics of Fluids*, 1997, **9**, (10), pp 1-7.
14. GURSUL, I. Review of unsteady vortex flows over slender delta wings, *J Aircr*, in print. See also, AIAA-2003-3942, AIAA Applied Aerodynamics Conference, 23-26 June, 2003, Orlando, FL, USA.
15. MENKE, M., YANG, H. and GURSUL, I. Experiments on the unsteady nature of vortex breakdown over delta wings, *Experiments in Fluids*, 1999, **27**, (3), pp 262-272.
16. GRAY, J.M., GURSUL, I. and BUTLER, R. Aeroelastic response of a flexible delta wing due to unsteady vortex flows, AIAA-2003-1106, 41st Aerospace Sciences Meeting and Exhibit, 6-9 January 2003, Reno, NV, USA.
17. TAYLOR, G., SCHNORBUS, T. and GURSUL, I. An investigation of vortex flows over low sweep delta wings, AIAA-2003-4021, AIAA Fluid Dynamics Conference, 23-26 June 2003, Orlando, FL, USA.
18. GORDNIER, R.E. and Visbal, M.R. Higher-order compact difference scheme applied to the simulation of a low sweep delta wing flow, AIAA-2003-0620, 41st Aerospace Sciences Meeting and Exhibit, 6-9 January 2003, Reno, NV, USA.
19. MATSUNO, T. and NAKAMURA, Y. Self-induced roll oscillation of 45-degree delta wing, AIAA-2000-0655, 38th AIAA Aerospace Sciences Meeting and Exhibit, 10-13 January 2000, Reno, NV, USA.
20. GAD-EL-HAK, M. and HO, C.M. The pitching delta wing, *AIAA J*, 1985, **23**, (11), pp 1660-1665.
21. ROCKWELL, D. Three-dimensional flow structure on delta wings at high angle-of-attack: experimental concepts and issues, AIAA Paper 93-0550, January 1993.
22. VISBAL, M.R. Computational and physical aspects of vortex breakdown on delta wings, AIAA Paper 95-0585, January 1995.
23. GURSUL, I. Proposed mechanism for time lag of vortex breakdown location in unsteady flows, *J Aircr*, 2000, **37**, (4), pp 733-736.
24. GORDNIER, R. High-fidelity computational simulation of nonlinear fluid-structure interaction problems, workshop on aerodynamic issues of unmanned air vehicles, 4-5 November 2002, University of Bath, UK. See also, GORDNIER, R. and MELVILLE, R., Numerical simulation of limit-cycle oscillations of a cropped delta wing using the full navier-stokes equations, *Int J Computational Fluid Dynamics*, 2001, **14**, (3), pp 211-224.
25. TAYLOR, G.S. and GURSUL, I. Buffeting flows over a low sweep delta wing, *AIAA J*, September 2004, **42**, (9), pp 1737-1745. See also, Unsteady vortex flows and buffeting of a low sweep delta wing, AIAA-2004-106, 42nd Aerospace Sciences Meeting and Exhibit, 5-8 January 2004, Reno, NV.
26. TAYLOR, G.S. and GURSUL, I. Lift enhancement over a flexible delta wing, AIAA-2004-2618, 2nd AIAA Flow Control Conference, June 2004, Portland, Oregon.
27. PHILLIPS, S., LAMBERT, C. and GURSUL, I. Effect of a trailing-edge jet on fin buffeting, *J Aircr*, 2003, **40**, (3), pp 590-599.
28. SHYY, W. Membrane wing aerodynamics for MAV applications, workshop on aerodynamic issues of unmanned air vehicles, 4-5 November 2002, University of Bath, UK.
29. LAITONE, E.V. Aerodynamic lift at Reynolds numbers below 7×10^4, *AIAA J*, September 1996, **34**, (9), pp 1941-1942.
30. GURSUL, I., TAYLOR, G. and WOODING, C.L. Vortex flows over fixed-wing micro air vehicles, AIAA-2002-0698, 40th AIAA Aerospace Meeting and Exhibit, 14-17 January 2002, Reno, NV, USA.
31. TORRES, G.E. and MUELLER, T.J. Aerodynamic characteristics of low aspect ratio wings at low reynolds numbers, Proceedings of the conference: Fixed, flapping and rotary wing vehicles at very low Reynolds Numbers, Univ of Notre Dame, Notre Dame, IN, 5-7 June 2000, pp 228-305.
32. HEBBAR, S.K., PLATZER, M.F. and FRITZELAS, A.E. Reynolds number effects on the vortical-flow structure generated by a double-delta wing, *Experiments in fluids*, 2000, **28**, pp 206-216.
33. SHYY, W., BERG, M. and LJUNGQVIST, D. Flapping and flexible wings for biological and micro air vehicles, *Progress in Aerospace Sciences*, 1999, **35**, pp 455-505.
34. WOODING, C.L. and GURSUL, I. Unsteady aerodynamics of low aspect ratio wings at low reynolds numbers, Royal Aeronautical Society Aerospace Aerodynamics Research Conference, 10-12 June, 2003, London.
35. LIGHTHILL, M.J. *Aerodynamic Aspects of Animal Flight, in Swimming and Flying in Nature*, **2**, ed. WU, Y-T, BROKAW, C.J. and BRENNEN, C. pp 423-491. New York/London:Plenum, 1975.
36. MUELLER, T.J. and DELAURIER, J.D. Aerodynamics of small vehicles, *Annual Review of Fluid Mechanics*, 2003, **35**, pp 89-111.
37. MAXWORTHY, T. The fluid dynamics of insect flight, *Annual Review of Fluid Mechanics*, 1981, **13**, pp 329-350.
38. ELLINGTON, C. Insect flight and MAVs, Workshop on aerodynamic issues of unmanned air vehicles, 4-5 November 2002, University of Bath, UK.
39. JONES, K.D. and PLATZER, M.F. Flapping wing propulsion for a micro air vehicle, AIAA-2000-0897, 38th Aerospace Sciences Meeting and Exhibit, 10-13 January 2000, Reno, NV.
40. JONES, K.D., DOHRING, C.M. and PLATZER, M.F. Experimental and Computational Investigation of the Knoller-Betz Effect, *AIAA J*, May 1998, **36**, (7), pp 1240-1246.
41. JONES, K.D., LUND, T.C. and PLATZER, M.F. Experimental and computational investigation of flapping wing propulsion for micro air vehicles, Chapter 16 in *Fixed and Flapping Wing Aerodynamics for Micro air Vehicle Applications*, MUELLER, T.J. (Ed) pp 307-339, published by AIAA, 2001.
42. HEATHCOTE, S., MARTIN, D. and GURSUL, I., flexible flapping airfoil propulsion at zero freestream velocity, *AIAA J*, November 2004, **42**, (11), pp 2196-2204. See also, AIAA-2003-3446, AIAA Fluid Dynamics Conference, 23-26 June 2003, Orlando, FL.
43. WHITEHEAD, J. and GURSUL, I. Aerodynamics and propulsion of synthetic jet based micro air vehicles, AIAA-2003-4004, AIAA Fluid Dynamics Conference, 23-26 June, 2003, Orlando, FL.
44. WHITEHEAD, J. and GURSUL, I. Interaction of synthetic jet propulsion with wing aerodynamics at low reynolds numbers, AIAA-2004-0093, 42nd Aeropsace Sciences Meeting and Exhibit 3-8 January 2004, Reno, Nevada.

https://doi.org/10.1017/S0001924000000439 Published online by Cambridge University Press