AERODYNAMICS & CONTROL of a ROTATING DISC WING

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Abstract

A spin-stabilised axi-symmetric disc-wing has potential application as an unmanned air vehicle (UAV) or guided projectile. The aim of this research is to investigate the aerodynamics of a disc-wing configuration and assess the feasibility of various aerodynamic control methodologies, for UAV applications. Wind tunnel tests of both non-spinning and spinning disc models provided information for a description of disc-wing aerodynamics, the effect of spin was found to be small. The feasibility of the disc-wing configuration for UAV applications is discussed. Passive flow control methods such as variable rim height devices and low aspect ratio rotor blades were tested in the wind tunnel and found to provide promising control moments of useful magnitude. For simplicity, a wind tunnel based feasibility study was devised to demonstrate the effectiveness of various passive flow control methodologies, which are analogous to the proposed active solutions. A summary of the proposed capabilities for the disc-wing UAV concept is given.

Nomenclature

AdvR	Advance ratio ($\Omega\pi c$ / V)
AoA	Angle of attack (°)
*A*R	Aspect ratio
cg	Centre of gravity
cp	Centre of pressure
C_L	Lift coefficient
C_D	Drag coefficient
C_{Do}	Profile drag coefficient
C_Y	Side force coefficient
C_M	Pitching moment coefficient, about c/2
C_R	Rolling moment coefficient
c	Disc-wing chord & diameter (m)
c_b	Rotor blade chord (m)
g	Acceleration due to gravity (ms^{-2})
h	Rim height extension (m)
L	Lift (N)
Re	Reynolds number
t	Disc thickness (m)
V	Wind velocity (ms^{-1})
x,y,z	Roll, pitch, yaw axes
p,q,r	Rates of roll, pitch, yaw (rad s^{-1})
R,M,N	Rolling, pitching, yawing moments (Nm)
β	Blade attitude (°)
Ω	Spin rate (Hz)

[i] 'Frisbee-like' is used to define the aerodynamic shape of the generic flying disc-wing model tested in this study, for ease of description and understanding. Frisbee™ is a registered trademark of Wham-O Inc.

Introduction

The authors are conducting an experimental investigation into the aerodynamics and control of a spin stabilised axi-symmetric disc-wing as part of an ongoing research program to develop a disc-wing UAV (unmanned air vehicle). The aim of this research is to investigate the aerodynamics of a disc-wing configuration and assess the feasibility of various aerodynamic control methodologies, for UAV applications. The unconventional nature of the disc-wing shape coupled with the rotation given to the disc for stability requires a novel method of provision for aerodynamic control.

In its simplest form a disc-wing can be described as an axi-symmetric flat plate or a cylinder of approximately zero height but is more broadly defined as a circular planform lifting surface. Disc-wing based flight vehicles fall into two distinct categories:
1. Non rotating, non axi-symmetric body.
2. Spin stabilised, axi-symmetric body.

The first type will typically have a conventional airfoil cross-section when viewed from the side with a rounded leading edge and sharp trailing edge and thus defined flight orientation. This type of vehicle has the characteristics of a flying wing aircraft with low aspect ratio and as such is relatively conventional. The second type of flight vehicle by definition has an airfoil section with fore and aft symmetry and a centre of gravity at the centroid of the disc. This configuration will typically be unstable in pitch and for practical purposes must be inertially stabilised by spinning. Such a disc has no predefined flight orientation and offers novel flight characteristics and diverse possibilities for unmanned systems.

As an introduction to the dynamics of spin-stabilised disc-wing flight consider Fig 1a. For a Frisbee-like disc-wing shape at typical flight angles of attack, if the centre of pressure (cp) of the disc-wing is ahead of the centre of the disc i.e. ahead of the disc cg.

This results in an untrimmed nose up pitching moment. If the disc is rotating, gyroscopic effects dictate that this pitching moment results in a precessional rolling rate, p. Thus spin provides enhanced pitch stiffness at the expense of roll stability. Using the conventional body fixed axes definition (Fig 1b), for a disc rotating in the direction of positive yaw then a positive pitching moment will generate a negative roll rate.

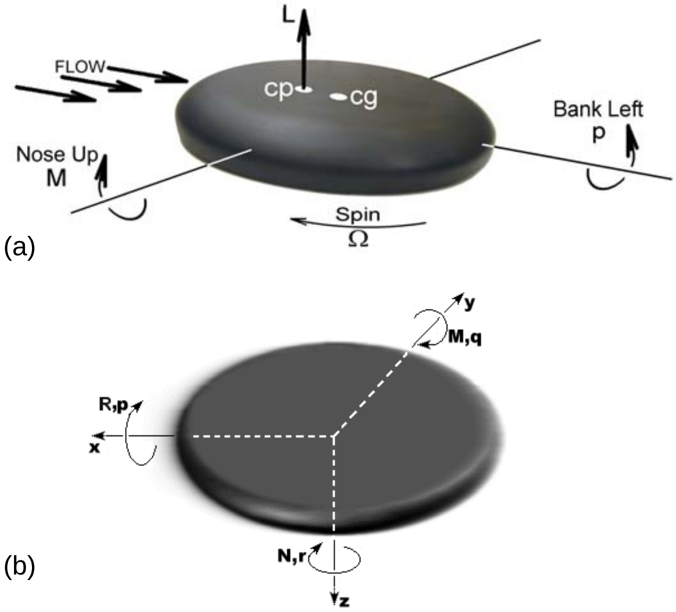

Figure 1 (a) Disc-wing flight dynamics. (b) Schematic diagram of body fixed axes. N.B. for a conventional aircraft the nose would point in the positive x-direction.

<u>Disc-wing Aircraft R&D</u>

Research and development into circular planform air vehicles has a diverse history. The concept of a circular planform flying wing (XF-5U-1) was developed during the 1930s & 40s based on a family of three dimensional circular wings with cross-sectional profile based on the Clark Y airfoil (Ref 1). In the 1950s a circular VTOL (vertical take off and landing) air-vehicle known as the Avrocar (VZ-9AV) was developed with a central 'turborotor' which generated lift and control forces through a combination of annular nozzles and peripheral jets (Refs 2-4). In the early 1960s, NASA researchers investigated the suitability of disk shapes for reentry vehicles (Refs 5&6). The proposed lenticular (bi-convex lens-like) shape was part of a preliminary investigation to develop a lifting-body (wingless) reentry vehicle with conventional landing capabilities. In 1972 the U.S. Navy commissioned a project to further the development of a spin stabilised self-suspended flare (Refs 7&8), which was essentially a spin-stabilised axi-symmetric cambered wing with circular planform. The Moller M200X, a disc planform aircraft with distributed engines driving eight individual fans, was the culmination of over thirty years of research and development. Flown in and near hover (1989) the pilot and chief designer, Dr. Paul Moller, furthered this work to develop a personal air vehicle known as the M400 Skycar (Ref 9).

With the recent development of such a wide variety of UAV body shapes it is not surprising to find the re-emergence of the disc-wing. The 'Cypher' VTOL UAV (Sikorsky Aircraft Corp.) with circular planform encompasses a central rotor and ducted airstream similar to the Avrocar. The Cypher II Marine variant, 'Dragon Warrior', adds a conventional wing and another smaller ducted tail fan for longer endurance and range. The SiMiCon Rotor Craft (SRC) UAV (Refs 10,11) has a circular planform fuselage with airfoil cross-section for cruise (Fig 2) and retractable rotor blades for VTOL capability. Slightly smaller was the AeroVironment (DARPA funded, Phase I) Micro Air Vehicle (MAV), a six-inch diameter circular planform wing, remotely piloted with propeller and elevons for control, developed in the mid-1990s. Phase II, a rectangular planform MAV now, due to redefined design criteria, is known as the Black Widow MAV (Ref 12). Smaller still is a silicon wafer integrated MAV under development by Washabaugh et al (Ref 13) at the University of Michigan. It comprises an array of Helmholtz resonators distributed over a thin disc-plate,

Figure 2 Photomontage of SiMiCon Rotor Craft (SRC), courtesy of SiMiCon AS. (Top Right) SRC cruise concept (Bottom Right) Circular planform aircraft flight demonstrator (Left) Demonstrator aircraft in-flight.

harnessing synthetic jet technology to provide both lift and control.

Previous work by the authors outlined the aerodynamics of a spin-stabilised, axi-symmetric Frisbee-like disc-wing configuration (Ref 14) and visualised the flow field using surface paint and smoke wire techniques (Refs 14&15). More recently they proposed aerodynamic control methods for application to a disc-wing UAV (Refs 16&17). Independently Higuchi et al (Ref 18) investigated the flow over a similar disc-wing using smoke wire flow visualisation and PIV (particle image velocimetry) measurements aiming to provide information for UAV applications.

Flow Control Solutions

Aerodynamic control modifies the flow around a vehicle providing useful forces and moments to alter the flight trajectory and attitude in a desired way. Conventionally aerodynamic control is achieved by varying body geometry, for example the aerodynamic pitching moment acting on a conventional lifting surface is controlled by the deflection of a trailing edge flap. If this method was applied to a rotating disc-wing, the equivalent would be the cyclic deflection of an array of control surfaces on the trailing edge rim.

Broadly speaking, aerodynamic control solutions operate through one of two methods:

1. Geometric modification of aerodynamic surfaces.
2. Fluidic devices which create reaction forces or favourable changes to the near surface flow.

Within these two broad categories are countless devices which could be applied to a rotating disc-wing. Also, as the disc will be spinning there are two ways of applying flow control devices:

1. Collective control – the deployment of an axi-symmetric set of control surfaces/jets which collectively provide a constant control moment throughout the rotation.
2. Cyclic control – the deployment of one or more control surfaces/jets which individually provide an oscillatory/impulsive control moment.

For example, an axi-symmetric set of flow obstructing fences could be applied to the disc in two ways. Deploying the entire set of control surfaces would be collective control, whereas deploying the set impulsively i.e. raised as they pass over the leading edge and lowered for the remainder of the rotation, would be cyclic control.

The authors defined a criteria for the selection of suitable flow control methodologies, proposing a novel set of solutions for testing. The assessment process identified an exhaustive set of both conventional and some unconventional flow control methods, which would potentially yield promising results when applied to the disc-wing. A refined set was put forward for wind tunnel testing with reference to the knowledge gained from the initial work on disc-wing aerodynamics (Ref 14&15) and consultation with Lissaman (Ref 19). This preliminary research by the authors includes extensive flow visualisation studies to identify surface regions receptive to flow control (Refs 14&15). For a more detailed discussion of suitable flow control methodologies applicable to the disc-wing, the reader is referred to Refs 16&17.

The proposed active flow control concepts have been tailored to the novel shape and dynamics of the disc-wing. For simplicity, a wind tunnel based feasibility study was devised to demonstrate the effectiveness of various passive flow control methodologies, which are analogous to the proposed active solutions. A series of wind tunnel tests were planned to acquire data, as a basis for the assessment and comparison of each method. This constituted a feasibility study in aerodynamic control. Selected control methods are forced transition strips, flow obstructing fences, vane vortex generators, annular slots for circulation control, global geometric control (bend and twist), off-centre surface bumps, variable rim height and rotor blades (low aspect ratio) (Ref 19). Load measurements provided a direct comparison with data for a disc-wing without flow control applied.

Previous work by the authors (Refs 16&17) includes results and discussion of forced transition strips and flow obstructing fences as proposed methods for aerodynamic control of a disc-wing UAV. The present paper analyses variable rim height devices and rotor blades for the same purpose. The remaining flow control results from tests on annular slots for circulation control, global geometric control and off-centre surface bumps will appear in Potts' PhD thesis (Ref 20), including a full analysis and comparison of all methods.

This paper presents an experimental investigation into the aerodynamics and control of a spin stabilised axi-symmetric disc-wing UAV. The following describes disc-wing aerodynamics and presents results from the application of passive flow control methods on both spinning and non-spinning disc-wings. Flow control methods such as variable rim height (VRH) devices and low aspect ratio rotor blades were tested in the wind tunnel. Load data for a disc-wing with installed VRH devices and another with installed rotor blades are compared with those from a clean configuration. The feasibility of the disc-wing as a platform for unmanned systems is discussed, with evidence from a wind tunnel based study of disc-wing aerodynamics and the application of flow control methodologies. An appropriate solution for aerodynamic control is identified to maximise control moments.

Experimental Methods

The axi-symmetric geometry of the disc-wing dictates that, irrespective of the disc's orientation to the free stream, the flow over the disc is independent of roll and yaw angle. Which means that the flow speed, angle of attack and the spin rate are the only parameters warranting investigation experimentally. Therefore the flow analysis can be reduced to the wind tunnel testing of a rotating disc-wing at incidence.

Wind Tunnel & Apparatus

The disc-wing was tested in a low speed wind tunnel which had an open-circuit and a test section of 0.9×1.1m, a top speed of 50m/s and a turbulence level of 0.5%. The aerodynamic loads acting on the disc were measured using a six component overhead balance.

A metal frame was used to mount the disc-wing in the wind tunnel (Fig 3). An L shaped arm mounted the disc vertically on a horizontal axle supported by a vertical strut. The disc was mounted on a motor driven axle to test at various spin rates. The disc's centre of mass remained at the balance centre at all times.

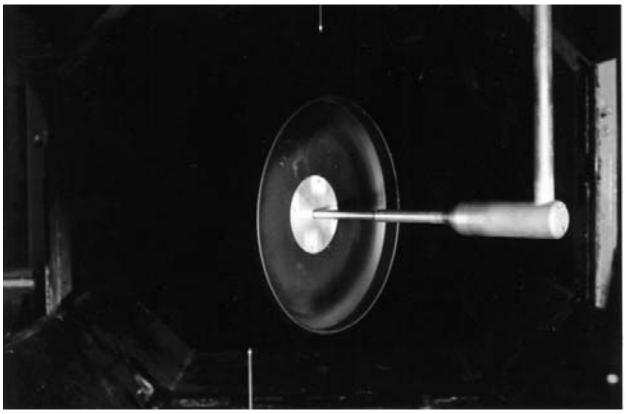

Figure 3 Wind tunnel rig supporting a disc-wing at incidence.

The disc-wing cross-sectional profile can be seen in Fig. 4. The disc-wing chord c is equal to the diameter and the thickness t is defined as the maximum perpendicular distance of the cavity lip from the flat upper surface. The aspect ratio, *A*R, for a circular planform wing is $4/\pi \approx 1.27$, centre line thickness to chord ratio t/c is 0.14, c = 0.275m.

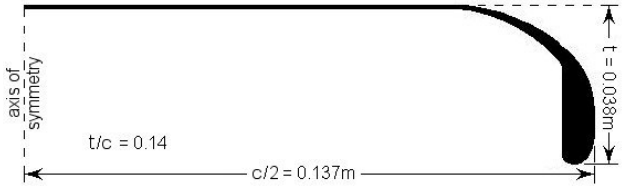

Figure 4 Cross-sectional disc-wing profile.

Two low aspect ratio rotor blades were attached onto the rim of the disc for control, as shown below in Fig 5. The blades were fixed to the surface with super-glue, axi-symmetrically 180° apart, at a desired blade attitude β to the disc planform (Fig 6). The cambered airfoils had 5mm thickness, 26mm chord, 27mm span and blade chord to disc chord ratio c_b/c is 0.1. The two bladed configuration allowed the disc to be balanced easily for spin-up in the wind tunnel.

Figure 5 Low aspect ratio rotor blade, at 10° attitude with respect to the disc planform.

Figure 6 Low aspect ratio rotor blades for control at various attitudes (a) 0° (b) 5° (c) 10°.

Thin aluminium sheet was fixed inside the rim of the disc, protruding at a fixed height above the lip around the entire perimeter, as seen below in Fig 7. The material was 24mm wide and 0.5mm thick, fixed firmly using super-glue. This increased the disc thickness as desired up to a maximum rim height extension to disc thickness ratio h/t of 0.4, equivalent to 14mm protrusion.

Load Data

The load measurement for the disc-wing was taken

Figure 7 Variable rim height device attached inside the disc rim extending the disc thickness by 7mm or h/t = 0.2.

using the apparatus shown in Fig 3 and a six component overhead balance. The rig-mounted disc-wing model was tested over a range of Reynolds numbers from 1.13×10^5 to 3.78×10^5, corresponding to a speed range of 6m/s to 20m/s, with an angle of attack range from -10° to as much as 50° and spin rates up to an advance ratio, ratio of disc rim speed to flow speed (AdvR), of 1.

The aerodynamic forces acting on the rig and disc induced mechanical moments due to the off-centre lone strut configuration. This had a significant effect on the pitching and rolling moment measurements. Taking measurements of the moments caused by the static loading of the strut at the centre of the balance, these mechanical components were removed.

Interference and tare effects due to the strut were measured with the disc mounted on a dummy support. The dummy strut was a mirror image of the measuring strut and held the disc in the correct position, on the balance centre.

Results and Discussion

Disc-wing Aerodynamics

The results for a non-rotating disc-wing are presented first as it is necessary to understand the static case before considering the more complicated spin-stabilised aerodynamics.

The lift and drag trends for a disc-wing are shown in Fig 8a,b for a Reynolds number, Re = 3.78×10^5, equivalent to a flow speed of 20m/s and an AoA (angle of attack) range of –10° to 30°. The linear lift curve (Fig 8a) and parabolic drag (Fig 8b) are typical of a low aspect ratio finite wing (Ref 14). The lift curve has slope 0.05 per degree and the drag curve shows a minimum profile drag coefficient, C_{Do}, of 0.085 at the zero lift AoA, –3°. The pitching moment curve (Fig 8c) is the torque about the half chord position, rather than the more conventional quarter chord position, because this is the location of the centre of gravity. It is non-linear and displays a negative (nose down) coefficient of –0.01 at the zero lift angle of attack (–3°). Zero pitching moment (trim) occurs at 9° AoA and provides a nose up pitching moment for higher angles.

Extending the AoA range up to 50° (Fig 9), a discontinuity is observed at 45° which corresponds to the stall AoA. This marked decrease in lift, drag and pitching moment is visible on all three curves, suggesting a large change in flow characteristics at 45° AoA. The lift coefficient reaches a maximum of 2.1 at 45° (pre-stall) AoA dropping to 1.1 at 45° (post stall) AoA. The drag coefficient reaches a maximum of 1.5 at 45° (pre-stall) AoA dropping to 1.0 at 45° (post stall) AoA. The pitching moment coefficient reaches a maximum of 0.23 at 43° (pre-stall) AoA dropping to 0.03 at 45° (post stall) AoA. The drag continues to rise thereafter for increased AoA whereas the lift and pitching moment decreases.

Previous work by the authors established that the lift and drag characteristics were independent of Reynolds number i.e. the C_L & C_D curves overlay one another for the range of tunnel speeds tested (Ref 14).

The effect of spin on the loads is shown in Fig 10 with curves for a consistent set of advance ratios (AdvR 0 to 1.04) presented on each plot. The positive and negative load components are defined with reference to the conventional body fixed axes definition as depicted in Fig 1b, for a disc-wing rotating in the positive yaw direction.

The first thing to note is that the side force and rolling moment, for the non-spinning case i.e. AdvR = 0 (Fig 10c&e), is essentially zero throughout the AoA range. This is as expected for a symmetrical, non-rotating body such as the disc-wing. By implication it is hypothesised that the yawing moment is zero also, although not measured, for all AoA due to axi-symmetry.

The lift and drag curves (Figs 10a,b) overlay each other for all AdvR 0 to 1.04, which confirms that the lift and drag are unaffected by spin. This is quite remarkable for such a complex fluidic system and unconventional geometry. The effect of spin on the side force, pitching moment and rolling moment (Figs 11c-e) is small but measurable. The detailed plots of Fig 11 reveal more, the side force (Fig 11a) is zero throughout the AoA range for low AdvR 0 to 0.35 but for higher AdvR 0.69 & 1.04 becomes positive. The side force remains approximately uniform across the entire AoA range, C_Y = 0.04 & 0.08 for AdvR of 0.69 & 1.04, respectively. The aerodynamic moments (Fig 11 b&c) exhibit similar characteristics, for low AdvR 0 to 0.35 the pitching and rolling moments remain unchanged. However for higher AdvR 0.69 & 1.04 both moments become more negative for typical flight angles of attack, 0° to 10°. The higher advance ratios 0.69 & 1.04 provide a greater nose down pitching moment (Fig 11b) and a higher trim AoA just above 10°. The rolling moment is zero throughout the AoA range for low AdvR 0 to 0.35 but for higher AdvR 0.69 & 1.04 becomes negative, C_R = 0.006 & 0.012 at 0° AoA for AdvR of 0.69 & 1.04, respectively. At higher AoA, above 20°, the rolling moment curves are independent of advance ratio.

The unstable pitching moment should render the disc-wing useless for UAV applications. However, recall at this point that the rotating disc-wing is a flying gyroscope i.e. aerodynamic moments cause rotating motion perpendicular to the moment itself. This results in the pitching moment being de-coupled from the pitch leaving the AoA unaffected and instead causes roll divergence. Therefore, spin-stabilisation allows the disc to fly with acceptable (precessional) roll divergence, achieved with carefully designed mass distribution for the desired angular momentum requirements. The disc will never be stable in the sense that it will not return to its original aerodynamic orientation when disturbed. However, the favourable mass distribution of the disc i.e. weighted circumference, coupled with the rotation, maximises the angular momentum within the system so that the disc exhibits quite remarkable resistance to motion. The pitching moment for typical flight angles of attack (0° to 10°) has minimum gradient (0.001 per degree) and magnitude ($-0.01 < C_M < 0.004$) which in turn generates minimum precessional roll motion. This minimises the roll divergence to within acceptable levels so that the disc is ‘quasi-stable’ or spin-stabilised. For high advance ratios (above 0.35) the greater nose down pitching moment increases the roll divergence but still remains at an acceptable level.

The (precessional) pitch divergence is therefore caused by the spin-dependent Magnus rolling moment (Ref 8) and has been shown to be zero for all typical flight AoA except for higher advance ratios, approaching 1 (Fig 11c). At this speed (20m/s) the rotation rate would have to be 480rpm or above to start generating a non-zero rolling moment. Although high rotation rates are not unfeasible, much higher than this would be undesirable because of control issues (explained later). Therefore, for a disc-wing flying with low spin rates, the pitch divergence will be negligible.

The aerodynamic Robins-Magnus side force and Magnus rolling moment act on the spinning disc-wing due to the interaction of near surface fluid structures. For discussion of the fluid mechanics the reader is referred to Ref 20. The resultant side force will not be an issue for low advance ratios. However, the disc-wing may be required to operate at higher AdvR above 0.35. In this eventuality the disc could be flown at a non-zero roll angle, with respect to ground, to utilise the gravitational side force component to counteract the aerodynamic side force and thus maintain straight, level flight.

The late stall of the disc-wing is a typical low aspect ratio wing characteristic. Fluidically, the two wing tip trailing vortices are in very close proximity to one another (Ref 15), due to the low aspect ratio, and together drive a strong central downwash which reattaches the separated shear layer up to 45° AoA (Fig 10). This provides the unique ability to fly at low speeds and very high angles of attack.

The profile drag of the frisbee-like disc-wing is high due to the bluff body nature of this geometry. Airfoils are far more efficient, streamlined to minimise drag. For practical purposes the disc-wing UAV must be optimised in a similar vane. This research has focused on an aerodynamic investigation of one specific geometry with the emphasis on demonstrating aerodynamic control rather than design optimisation. However it is possible to offer comment as to the drag reduction which should be feasible for an optimised disc-wing shape.

First of all it is necessary to outline the profile drag coefficients of similar shapes. The disc-wing geometry investigated in this study has a profile drag coefficient C_{Do} of 0.085 and 2D airfoils have a C_{Do} of 0.01 and below. The Zimmerman circular planform wing, with a Clark Y airfoil cross-section, is streamlined i.e. blunt leading edge and sharp trailing edge. Therefore this is a minimum bound for the profile drag achievable for a circular planform wing, that is a C_{Do} of 0.015 (Ref 1). As an upper bound consider the Discus from field athletics which has a C_{Do} of 0.035 (Ref 21). There is no reason why a disc-wing for UAV applications could not be optimised to reduce the profile drag coefficient below that of the un-optimised Discus shape. Therefore the optimum design for an axi-symmetric disc-wing should have minimum drag i.e. $0.015 < C_{Do} \leq 0.035$ whilst retaining the desirable aerodynamics, primarily the favourable pitching moment characteristics. This benchmark for the profile drag coefficient of an optimised disc-wing would be much more efficient and therefore practical for UAV applications.

Aerodynamic Control

The disc-wing investigated in this study is based on a Frisbee-like flying sports disc shape. The Frisbee™ disc has proven its potential on the sports field as a platform for short free-flights. This research harnesses that potential proposing a UAV capable of sustained flight using aerodynamic control to trim the disc in-flight.

If the disc can be flown at an AoA close to the zero pitching moment trim condition, it can maintain sustained flight (9°). This argument neglects the effect of drag which decreases the speed of an unpowered disc-wing and thus increases the AoA above the trim condition as the disc velocity vector becomes more vertical. However, sustained glide is achievable for a steady drop in height.

Once establishing that trimmed flight is possible, it is necessary to demonstrate that aerodynamic control is attainable. A feasibility study in aerodynamic control seeks to find a methodology which gives both positive and negative control inputs e.g. nose up and nose down pitching moment. Before discussing the wind tunnel results, consider an idealised data set for each control method which would look something like Fig 12. The baseline case of Fig 12a represents an idealised pitching moment curve for a clean disc-wing, the other lines show the desired effect from a control methodology with various input magnitudes. Fig 13b depicts a similar idealisation for the rolling moment.

Remember that pitch destabilisation is controlled via the rolling moment and roll is controlled via the pitching moment (as labelled on Fig 12), due to gyroscopic precession. For cruise, the disc-wing would be trimmed on the zero pitching moment AoA (baseline case, Fig 12a). With reference to Fig 12 and the sign convention of the body fixed axes coordinate system defined in Fig 1b. The following example gives insight into how the disc, spinning in the positive yaw direction (Fib 1a), is controlled in-flight: To enter a bank left turn manoeuvre from trimmed flight, the disc first requires a positive pitching moment control input to roll the disc port wing down, followed by a positive rolling moment control input to pitch the disc (nose up) into the turn.

A wind tunnel based feasibility study has demonstrated the effectiveness of various flow control methodologies. The results for two methods are presented here, variable rim height (VRH) devices and low aspect ratio rotor blades. Fig 13 shows the baseline case, clean configuration, for a disc-wing without control surfaces and other curves with control surfaces attached at various attitudes, all at AdvR = 1. The rotor blades are proposed as a simple method of providing pitch control (i.e. destabilising the rolling moment). Consider one of these blades at positive attitude as it rotates through one cycle. As one rotor blade advances, with respect to the centre of the disc, at an AdvR of 1 the relative speed of the blade is twice the flow speed. Whereas the retreating blade travels at zero relative flow speed, moving with the flow. This generates a lift component on the advancing side but minimal change to the lift on the retreating side, which results in a positive rolling moment, with reference to Fig 1b. When the blade attitude is 0° the variable lift contribution from the introduction of control blades causes a positive control moment from the baseline case, trimmed at 3° AoA. Positive rotor blade attitudes increased the positive control moment further $C_R = 0.002, 0.006$ (at 3° AoA) for 5°, 10° attitude, respectively. Whereas negative rotor blade attitudes decreased the control moment $C_R = -0.003$ at –5° attitude and 3° AoA. The wind tunnel tests prove the rotor blades are a promising flow control method, capable of providing both positive and negative rolling moment control inputs. Rotor blades applied to a disc-wing for control is a cyclic methodology, even though the rotors can be operated with fixed (rather than oscillatory) attitude throughout the rotation. The contrasting relative flow speeds experienced on the advancing and retreating parts of the rotation produces cyclic inputs with period 0.5, which give a quasi-steady rolling moment. It is noted that if the spin rate is too high then the angular momentum may exhibit too much resistance to destabilising control inputs rendering the disc-wing uncontrollable. The desired solution will be an optimum spin rate which is not too high, for effective control, and not so low as to compromise the spin-stabilisation.

Fig 14a shows the pitching moment curve for a disc-wing with the rim extended by 7mm, equivalent to h/t = 0.18, and a comparison with the clean configuration h/t = 0. The extended rim causes a nose up change in pitching moment up to 18° AoA and nose down control moment thereafter. The nose up change in pitching moment is particularly large for typical flight AoA, as shown in more detail on Fig 14b. The positive control moment C_M is 0.036 above the trim condition for the clean configuration at 9° AoA. Fig 14c shows that more moderate control moments can be generated for intermediate rim heights of 1, 3mm equivalent to h/t = 0.03, 0.11 respectively. The 14mm rim height extension (h/t = 0.37) yields a minimal control moment improvement on 7mm (h/t = 0.18). The first 7mm rim extension gives a nose up C_M of 0.36 at 9° AoA whereas doubling the extended rim height to 14mm only gives a further 0.03 C_M increment. Therefore it is clear that the most beneficial range of rim height ratios is $0 < h/t < 0.2$, which offer efficient control moments for minimal geometry change.

The extended rim provides nose up pitching moment only (Fig 14). This is potentially a problem if nose down pitching moment control is required to roll the disc both left & right wing down. However, the disc-wing configuration could be redesigned with a reduced baseline thickness. The disc-wing is trimmed with VRH control surfaces half deployed, retracted for nose down pitching moment (Ref 20) or deployed fully for nose up pitching moment control (Fig 14).

This passive method of flow control is analogous to an active system, which varies the rim height to provide rolling moment control. Variable rim height devices are a collective methodology. A set of individual active devices could extend the rim height all around the perimeter and collectively provide a steady pitching moment as shown by tests on analogous passive rim extensions.

The spin-stabilised flying disc design offers novel flight characteristics and diverse possibilities for unmanned systems, from steerable decoys to smart barrel-launched projectiles. The aerodynamic control methodologies previously discussed show much promise as practical solutions for provision of both pitch and roll control. Variable rim extension devices are envisaged to be retractable for on-demand use. The rotor blades are also proposed to be retractable, stowed within the cavity and extended on-demand with active attitude control.

Conclusions

Spin-stabilisation allows the disc-wing UAV to fly with acceptable (precessional) roll divergence and de-couples the pitching moment from the pitch leaving the AoA unaffected.

The disc-wing design must be optimised to reduce the profile drag whilst retaining the desirable aerodynamics, primarily the favourable pitching moment characteristics.

Low aspect ratio rotor blades ($c_b/c = 0.1$) generate a lift component on the advancing side but minimal change to the lift on the retreating side, resulting in destabilising rolling moment control.

If the spin rate is too high, the angular momentum contained within this spinning system may exhibit too much resistance to destabilising control inputs rendering the disc-wing uncontrollable. The desired solution will be an optimum spin rate which is not too high, for effective control, and not so low as to compromise the spin-stabilisation.

Variable rim height devices generate large nose up pitching control moments for minimal geometry change. The most beneficial range of rim height ratios is $0 < h/t < 0.2$. The disc-wing configuration could be redesigned with a reduced baseline thickness to provide nose down pitching moment control also.

Further work will predict the manoeuvrability expected from a disc-wing UAV based on a computer simulation of controlled flight trajectories with aerodynamic control inputs derived from the experimental data. The reader is referred to Refs 22 & 23 for background information on the simulation of disc-wing flight.

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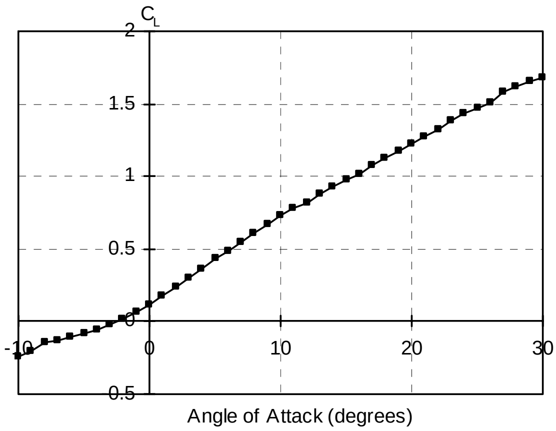
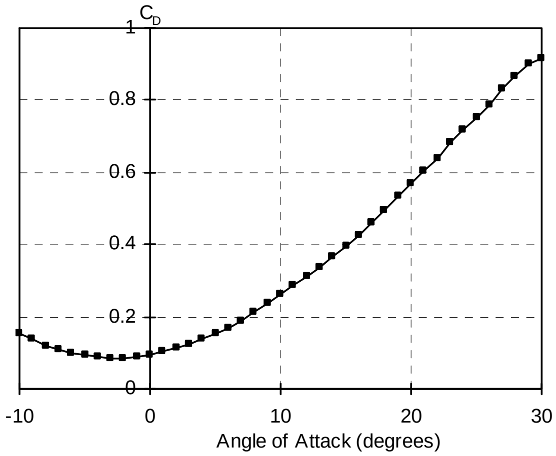
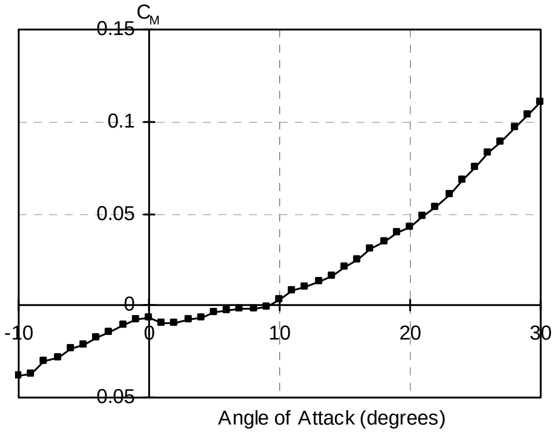


(a) Lift coefficient.

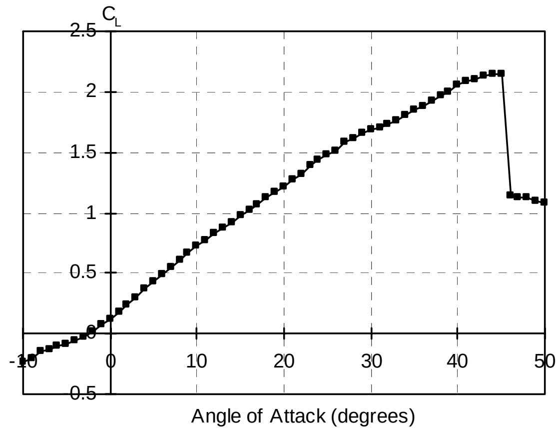


(b) Drag coefficient.

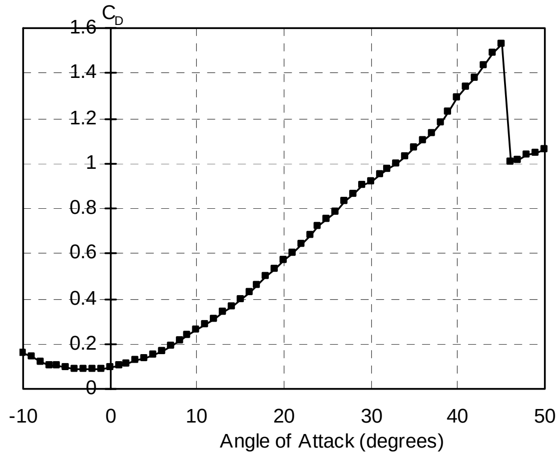


(c) Pitching moment coefficient.

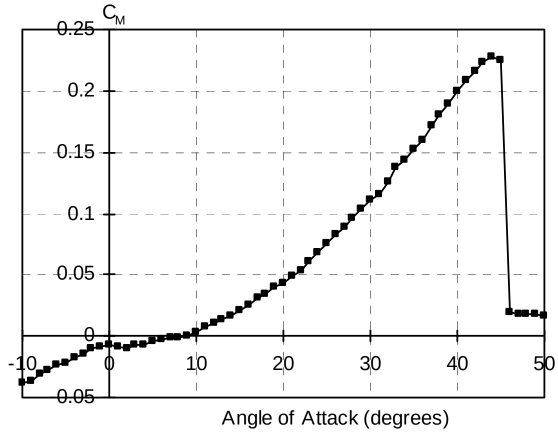
Figure 8 Load characteristics at zero spin rate, AoA = -10^{o} to 30^{o}, V = 20m/s, Re = 3.78×10^{5}.



(a) Lift coefficient.

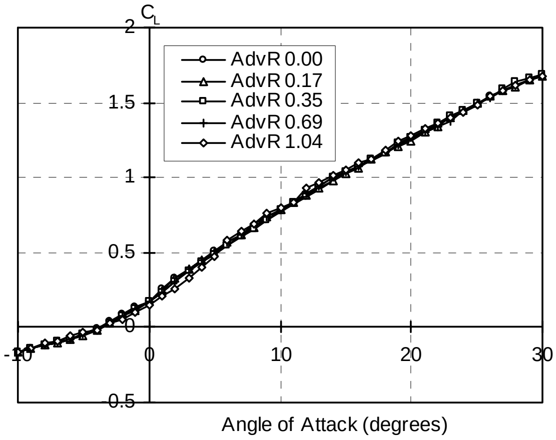


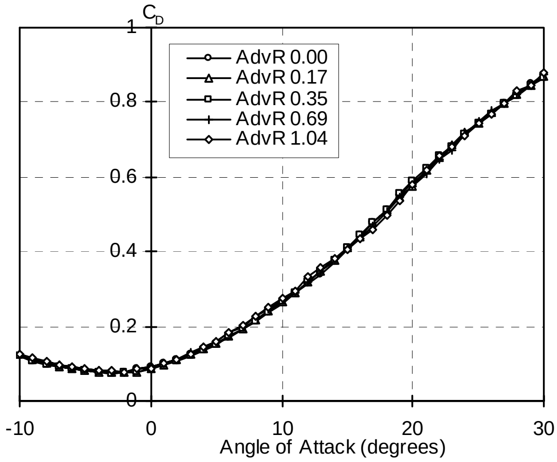
(b) Drag coefficient.



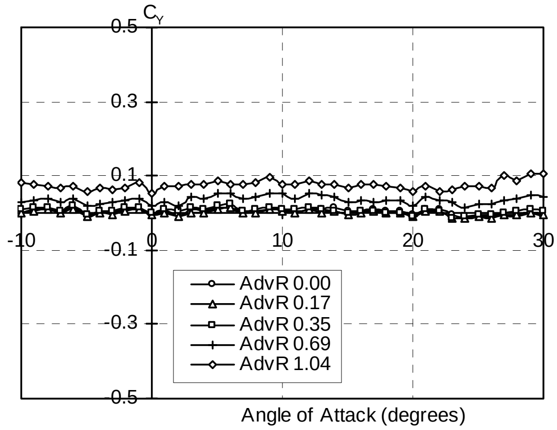
(c) Pitching moment coefficient.

Figure 9 Load characteristics at zero spin rate, AoA = -10^{o} to 50^{o}, V = 20m/s, Re = 3.78×10^{5}.

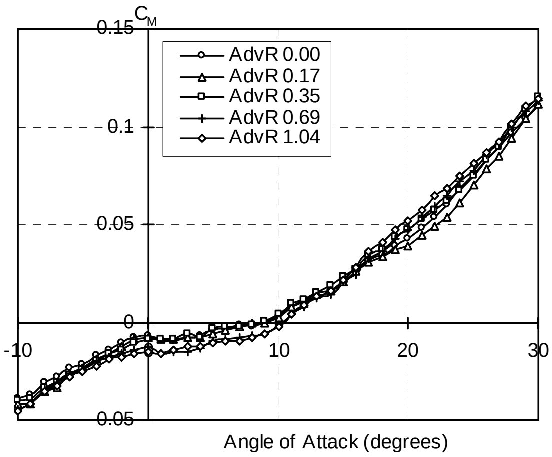


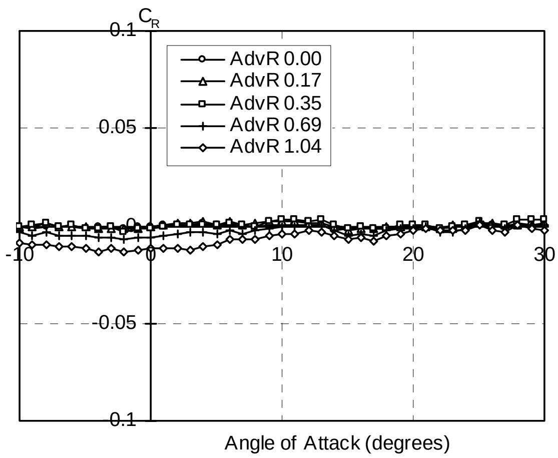


(a) Lift coefficient. (b) Drag coefficient.



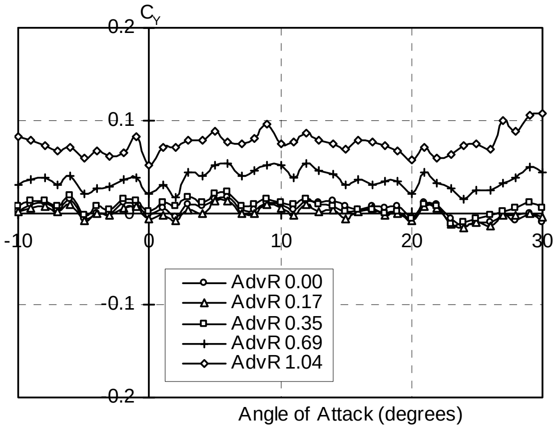
(c) Side force coefficient.



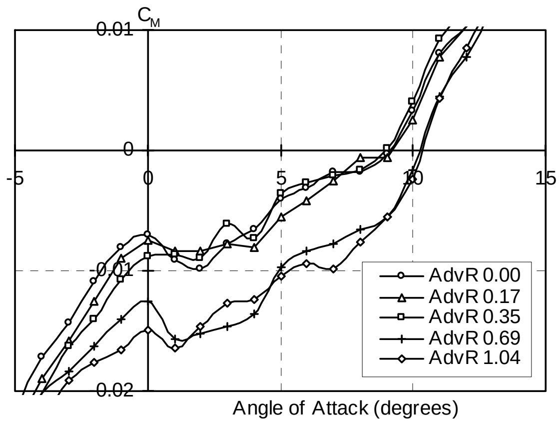


(d) Pitching moment coefficient. (e) Rolling moment coefficient.

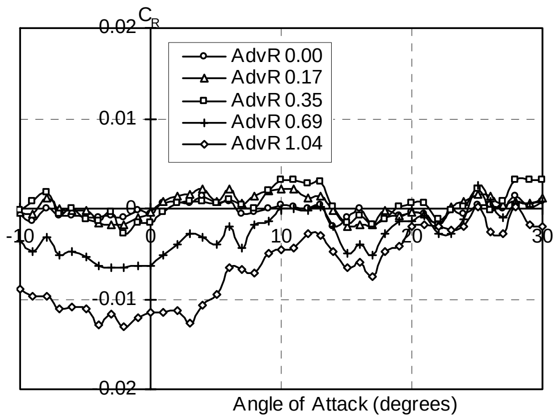
Figure 10 Load characteristics at various advance ratios,
AdvR = 0 to 1, AoA = -10^{o} to 30^{o}, V = 20m/s, Re = 3.78×10^{5}.



(a) Side force coefficient.

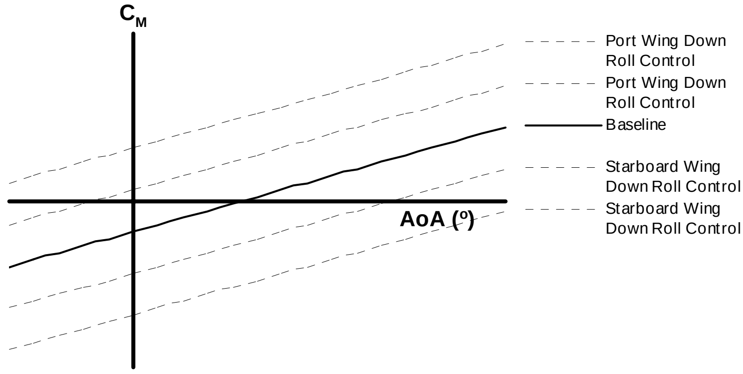


(b) Pitching moment coefficient.

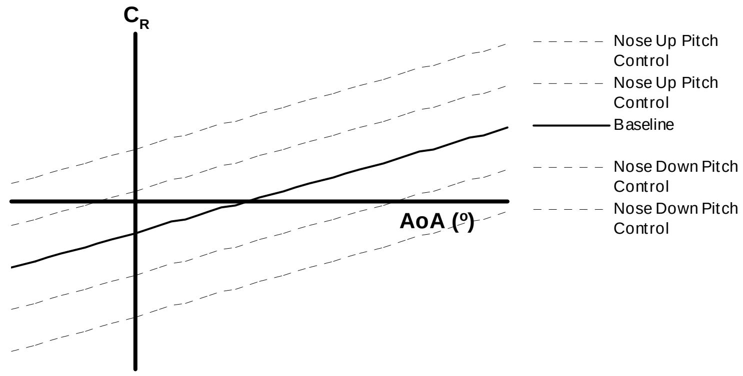


(c) Rolling moment coefficient.

Figure 11 Load characteristics (detail) at various advance ratios, AdvR = 0 to 1, AoA = -10^o up to 30^o, V = 20m/s, Re = 3.78×10^5.



(a) Desired pitching moment control (idealised).



(b) Desired rolling moment control (idealised).

Figure 12

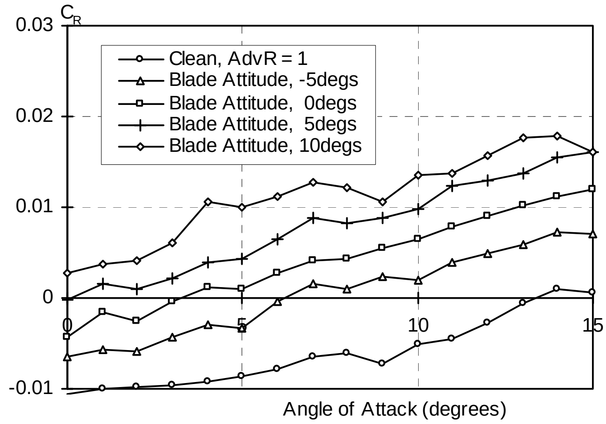
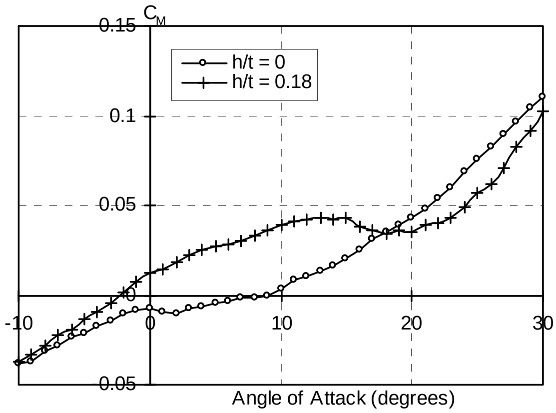
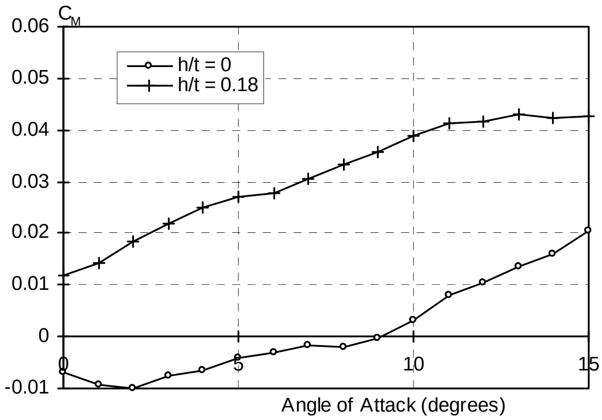


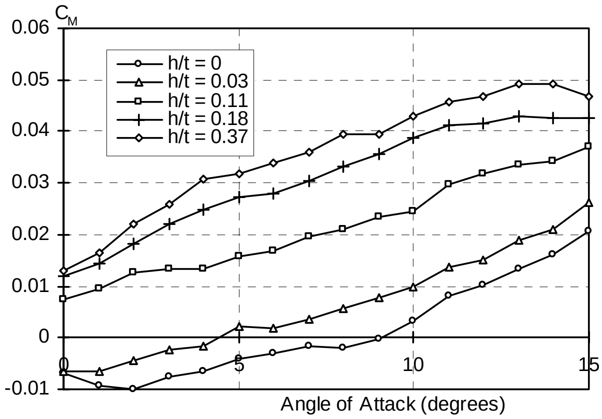
Figure 13 Rolling moment characteristics for a disc-wing with installed rotor blades at various attitudes and the clean configuration, AdvR = 1, AoA = 0^o to 15^o, V = 20m/s, $\beta = -5^o$ to 10^o, Re = 3.78×10^5.



(a) Pitching moment coefficient.



(b) Pitching moment cefficient (detail).



(c) Pitching moment coefficient (typical flight AoA).

Figure 14 Pitching moment characteristics for a disc-wing with various rim height extensions and the baseline case, AdvR = 0, AoA = -10^{o} up to 30^{o}, V = 20m/s, h/t = 0 up to 0.37, Re = 3.78×10^{5}.