CONFIGURATION OF AN UNMANNED GROUND EFFECT VEHICLE

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Keywords: *UAV, Ground Effect, Experimental Testing, Applied Aerodynamics*

Abstract

This paper looks at the processes and considerations involved in using an unmanned aerial vehicle (UAV) as a ground effect test vehicle. IT looks at the possible research avenues and suggests any problems which are foreseen in developing such a vehicle. There is the added issue with the fact that the UAV is not a specifically designed wing-in-ground (WIG) vehicle, so problems are seen there and the necessary modifications made.

Nomenclature

α = Angle of attack

AR = Aspect ratio

b = Span

D = Drag force

$\bar{c}$ = Mean aerodynamic chord

c_L = Lift coefficient

c_m = Pitching moment coefficient

c_{L_α} = Lift curve slope

c_{L_h} = Increment of lift coefficient with height

c_{m_α} = Moment curve slope

c_{m_h} = Increment of pitching moment with height

h_θ = Equivalent boundary layer height at the slot

h_S = Boundary leyer height at the slot

H_C = Ground plate clearance equal to the contraction section inlet height

H_S = Contraction section height at the slot

T = Thrust force

U_∞ = Freestream velocity

U_S = Velocity through the contractio under the slot

U_θ = Equivalent boundary layer velocity

$\hat{v}$ = Non - dimensional speed

W = Weight

1 Introduction

The principle of wing-in-ground-effect or (WIG) has been known for a long time. Ground effect is a natural phenomenon that is experienced as an aerofoil approaches the ground. Upon which its lifting ability increases and the drag reduces, in simple terms. The consequence of this is that the lift to drag ratio increases as the pattern of circulation around the wing changes and thus the overall efficiency increases. This pattern of air around the wing causes a cushion on the underside of the wing to develop.

Figure 1. demonstrates the surrounding air flows of a wing in free flight and in ground effect. Operating a craft in ground effect has the same effect as having a much larger wing area but without the actual physical structure, weight or drag associated with it.

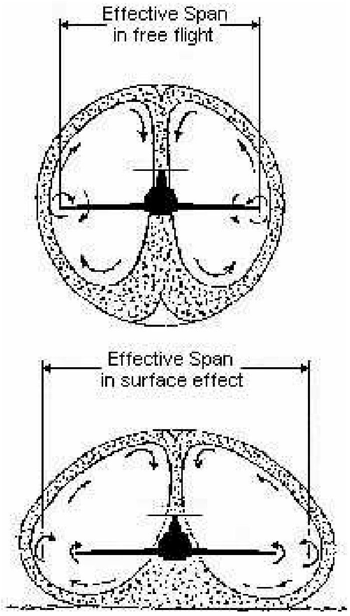

Figure 1.

As a rule of thumb, the definition of in-ground is accepted as being the altitude up to one and a half times the wing span, expressed as height above surface, although WIG vehicles generally operate at heights less than 20% of the span, i.e. $b/h < 0.2$. However, at heights greater than half the chord length (ie $c/h > 0.5$) any vehicle tends to be less efficient.

From a regulatory point of view, the maximum ground effect height is seen as the service ceiling (the height above which a vehicle will not sustain flight under its own power). If the vehicle can operate full time above this height, it legally becomes an aeroplane and must meet all of the associated regulations.

Currently housed at the University of Glasgow's Spencer Street workshop is an unmanned aerial vehicle (UAV). Originally, this was a military craft although modifications are under way in order to make meet the specifications of the Department of Aerospace Engineering. Once complete, the UAV will be a fully operational flying laboratory. However, the first step in this process is to turn the UAV into a ground effect vehicle capable of analysing aerofoil performance. Figure 2 shows the side plan of the UAV with the distance referring to the wing height above ground.

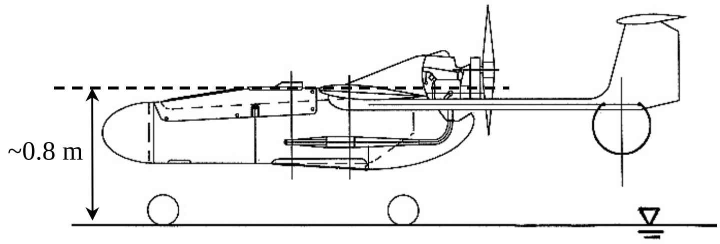

Figure 2.

The way in which the pressure data around an aerofoil will be gained is by the use of a wing glove, the envisaged UAV complete with wing gloves is depicted in figure 3. This is a device that can simply be slid over the existing wing and attached. This wing glove can be manufactured to any aerofoil profile that is desired to be tested. Numerous pressure tappings exist around the circumference of the profile and these are each measured individually and in turn. This enables a pressure distribution around the aerofoil to be formed, which can then be compared with existing data from both freestream and ground effect tests. This will help provide a guide as to the accuracy of any acquired data and also the accuracy of using the UAV in such a way.

It should be noted at this stage however, that vehicles that utilise ground effect have been specifically designed with low altitude flying in mind, this UAV has not. In "converting" an airborne vehicle into a ground effect vehicle some problems are foreseen and a considerable amount of analysis and testing is required before the UAV is used for ground effect testing.

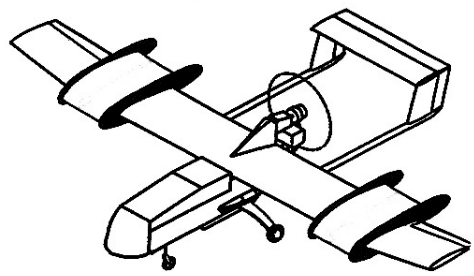
Figure 3.

The need to analyse the ground effect during take off and landing is twofold. Firstly, obviously it is relevant to the current ground effect studying encompassing the UAV project and secondly, because it is necessary to understand how the UAV will handle under these circumstances. These are simply unknown quantities due to the fact that beforehand the UAV was rocket launched and parachute recovered. The modifications carried out tot the UAV mean that the conventional landing will now become the norm. It is important from an operational as well as operational analytical point of view. The controller must be informed as to how the UAV will handle and be prepared, the more information the better. This is vitally important as the chances of accidents are increased here and the safety mechanisms will be virtually ineffective at such low altitudes.

Aircraft only experience ground effect for relatively short stages of take off and landing. It is here that the proximity of the ground in relation to the aircraft dimensions is comparably small.

Published in 1921, a simple method based on the Prandtl lifting line theory was directed towards the performance aspect of ground effect. Of late, reference [1] has discussed the influence of ground effect on short take off and landing aircraft. They explored the more important aircraft design parameters and added perturbation terms to the equations of motion to investigate the flight characteristics close to the ground.

Ground effect is of course of vital importance to WIG vehicles and the stability of such craft has been studied extensively and correspondingly documented. In particular, linearised approaches have been utilised for this very purpose. From this it is deducible that that ground effect will most definitely play a role during the take off and landing phases of a conventional aircraft's flight regime, The figure shows the relationship between this manoeuvre and the characteristics of longitudinal stability in ground effect.

Analysis of this situation may contribute to a more realistic simulation and the risk of an accident during these two phases reduced.

2 Modifications to the UAV

The UAV purchased by the Department of Aerospace Engineering is of military origin. The department basically bought the airframe with a view to modifying for a specific use, and since then the department has been gradually modifying the said airframe and turning into a flying laboratory.

Several modifications have been made to date, in particular:

- Provision of an undercarriage
- Wing Extensions
- Wing Glove (optional fitting)
- Provision of rudder
- Flight Control System
- Data Acquisition System

Since the original airframe was intended for military usage, the above modifications were necessary.

The implementation of the undercarriage was vital as the original UAV was launched by a ballistic device and landed via deployment of a parachute. Both methods required highly skilled and experienced operatives to undertake specific tasks, resources simply not available to the department. The undercarriage made conventional take off and landing possible and so the need for an expensive launcher and suitably skilled staff was dispensed with.

The undercarriage was designed in the department and fitted around the present structural features of the existing airframe.

The wing extensions serve several advantageous purposes. Namely, increasing the range, decreasing the take off distance, landing distance and stalling speeds. Additionally, as will be explained further, they also help to prevent the wing glove being adversely affected by wing tip vortex effects, which could be detrimental to the data received from the glove.

With the conventional take off and landing, additional yaw control was required. The initial design did not have these with the entire yaw being produced by flaperons. To provide this additional yaw, rudders were implemented into the tail fin design.

In addition to these basic modifications to the airframe it was necessary to equip the UAV for low level flying. Essentially this only requires a height sensor and adequate autopilot to ensure proper handling at such low heights. At these heights it is simply not acceptable to be able to expect a human controller to maintain a constant low altitude whilst maintaining safe flight, it is too much of a burden. Certain safety measures will also have to be introduced. This will most likely take the form of one or two braking parachutes to be ejected out of the tailbooms.

3 Experimental Techniques for Testing Ground Effect in Wind Tunnels

Accurate representation of the flow fields for ground effect testing in a wind tunnel is difficult due to the presence of boundary layers on the tunnel surfaces.

Generally, no boundary layer is present on the ground for motion at very low altitudes, thus any tests attempted would ultimately affect the “ram wing” effect.

In reference [2] it is the discovered that this boundary layer has a fairly drastic effect on the on the measured lift coefficient. For a wing with aspect ratio 6, the lift coefficient was altered by 33% at a height of 20% of the span, which equates to 120% of the mean chord.

Considering that the static and dynamic stability is fundamentally based on such derivatives these effects are of vital consideration, along with the incidence and height.

It further attempted to investigate the areas with which the boundary layer affected the lift coefficient by using a flat plate with various aspect ratios and a belt.

The precise height to span ratio where discrepancies appeared showed linear correlation with the lift coefficient according to,

$$\frac{h/b}{C_L} < 0.5,\ \ AR = 6 \qquad (1)$$

Sullivan [3], also analysed this phenomena and arrived at a similar conclusion,

$$\frac{h/b}{C_L} < \frac{1}{AR\pi} \qquad (2)$$

Power augmented ram (PAR) is a phenomenon that many WIG vehicles have utilised recently. This is when the engines are placed forward of the lift producing wing and the exhaust is directed under the wing to provide additional lift. This is beneficial during the takeoff and landing phases as the speeds can be reduced thus increasing the safety aspect. Thought the influence of PAR on the boundary layer during experiments is unclear.

A method proposed by Turner involves removing the boundary layer with suction and having a moving belt running at roughly the same speed as the freestream velocity. A relative insensitivity to the belt speed means that precise speed control is not required.

A schematic of such a method can be seen in the figure. The leading edge of the ground plate has a smoothed leading edge spanning the width of the wind tunnel and a 45^{o} slot cut across. This was chosen as the optimum slot angle as a high angle would have a short length over which the suction would work and a low angle would have a shallow rotation of the boundary layer.

A contraction and expansion section is fitted under the plate with the position of maximum contraction aligned with the slot in the plate. This results in a low pressure that sucks of the boundary layer on the upper surface of the plate. Subsequent testing of the method suggested in reference [4] revealed that the boundary layers were reduced by approximately 50%

Theoretical analysis of the situation by Sowdon and Hori (1996) yields the relationship,

$$H_S = \frac{U_\infty}{U_S}\left(h_S \left(\frac{U_\theta}{U_\infty} \right)\left(\frac{h_\theta}{h_S} \right) + H_C \right) \qquad (3)$$

The advantages of this type of method mean that several parameters can be altered in order to obtain the desired conditions. These involve the plate leading edge shape, the level of suction, slot width and slot shape.

Unfortunately, although in close proximity to the wind tunnel floor the method for verifying the wing glove involved used not wall boundary layer control and so this may well have had an effect on the results.

4 Wing Glove

The wing glove is the fundamental key to the UAV being used as flying laboratory as it is this device which collect all the aerofoil data.

The wing glove is merely a wing mock up which is placed over the UAV. Two gloves are necessary to even out any uneven, detrimental aerodynamic effects induced by the gloves. Full details of the wing glove design and testing can be seen in references [5], [6] and [7].

4.1 Aerodynamic Considerations

In implementing a wing glove, two important aerodynamic phenomena must be considered that of the downwash effect and the crossflow effect. These are typically three-dimensional occurrences associated with finite wings and are not present in infinite wing analysis.

On the UAV, two major sources of vorticity are likely to occur once the wing glove is installed and operational. Vorticity will almost definitely arise from the wing tips and also at the glove edges. Wing tip vortices are unavoidable with a finite wing and are responsible for downwash, which ultimately reduces the effective angle of attack of the wing. They also introduce spanwise flows, or crossflows, which affect boundary layer development. Fortunately however, the UAV is intended as the 2D analysis tool and these phenomena should be reduced dramatically or even eradicated so that there effect on any results can be virtually ignored with the introduction of endplates on the wing glove.

4.2 Experimental Glove Positioning & Geometry

The wing glove is centrally located on the wing, this is in order to keep the unwanted effects of wing tips and wing/fuselage interactions from effecting adversely the flow over the wing glove. Due to the wings being rectangular with no sweep, this is also the shape that was adopted for the wing glove. The attachment of the wing glove means that the inner ailerons are disabled, since they are covered, and the ailerons on the wing extensions used to induce rolling moments. The fact that these wing extensions are easily removable the wing glove can easily be slid over the original wing attached and then the wing extensions reattached.

The minimum chord of the glove is dependent on a combination of factors. Obviously, the chord of the wing plays an important roll and also its profile shape along with the intended profile of the aerofoil wishing to be tested. Finally, the thickness of the material and the need for spacing for the pressure sensing equipment dictates the glove size. The prototype glove was a NACA 0012, as there is plenty of data in existence on this aerofoil section providing a more than adequate comparison. The design, once finalised, possessed a wing chord of 1.05 m.

A series of pressure tappings, sequentially spaced around the glove, are present in the middle of the love; 30 on the upper surface and 30 on the lower. These lead to 2 pressure scanners, via tubing, situated in the RPV fuselage. It is important to realise at this stage that the wing glove does not contain any instrumentation, this allows a certain amount of flexibility when it comes to testing a number of profiles where the tubing can be disconnected and new tubing attached with relatively little fuss.

Two wing gloves are likely to be used, although only one will actually be used for measuring, the other will simply be a dummy in order to balance up the aircraft and prevent any unwanted rolling or yawing moment which may be caused by having only the one wing glove.

4.3 Numerical Modelling & Wind Tunnel Tests

The purpose of numeric modelling was to establish the quantitative effects of endplates on the wing glove. The proposed designs traced the aerofoil shape and ranged from 5 cm to 50 cm in height (see Fig. 4).

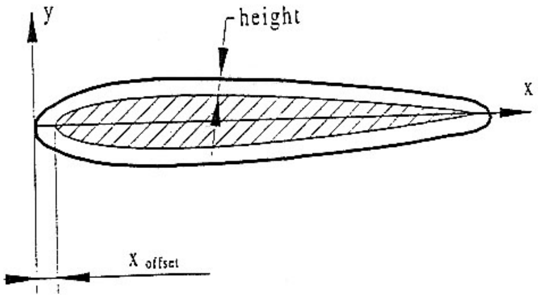

Figure. 4

The analysis chose to primarily look at the downwash effect, resulting from the wing tips and also the crossflow effect and the result of altering the size of end plates.

The conclusion to this was that the downwash could not be reduced, hence this will have to be considered when results are collected and an effective angle of attack obtained. It also found that the larger the end plates the less the crossflow, as may well be expected. Bearing in mind that a balance between size and performance must be found it was discovered that 5 cm end plates would do a sufficient job in reducing cross flow. The special endplates also proved to be fairly efficient in reducing crossflows across the wing glove.

The wind tunnel tests were intended as an extension to the numeric modelling, to establish an effective size and design of end plate, in addition to testing the pressure sensing equipment.

The wing, complete with wing glove, was placed in the wind tunnel with the help of a specially constructed rig. Various configurations and angles of attack looked at, such as with and without wing extension, to establish downwash effect and with and without endplates, to establish the crossflow effect.

A certain amount of agreement with the numerical analysis was discovered at certain angles of attack and also that the downwash could be altered. The tests also demonstrated the need for endplates in order to reduce crossflow, although the wind tunnel tests suggested that the best design to employ was the special one.

The instrumentation involved in the testing performed better than expected and produced some good results, demonstrating that the system works well and will do under proper flight conditions.

5 Wing-in-Ground Effect Stability Criterion

Here, reference [7] extends upon the work of reference [8] stating that the criterion for static stability is F > 0, where F can be factorised into three parts:

$$F \approx \left\{-\frac{\partial c_m}{\partial \alpha}\right\}_{\hat{v},h} \times \left\{-\frac{\partial (T-D/W)}{\partial \hat{v}}\right\}_{c_m,n=1} \times \left\{-\frac{\partial n}{\partial (h/\bar{c})}\right\}_{\hat{v},c_m} \quad (4)$$

The first term is the “static pitching moment stability”, known as “static stability”. The second term gives the “minimum drag speed” at the stability boundary. The third term is a new term containing just the influence of the ground and is called the “static height stability”.

$$\left\{\frac{\partial n}{\partial h/\bar{c}}\right\}_{c_m=0} \quad \hat{v} = \text{const.} < 0 \quad (5)$$

If the equilibrium in height is disturbed, the above equation gives a restoring force. The static height stability can be expressed as a function of the aerodynamic derivatives:

$$\left\{\frac{\partial n}{\partial h/\bar{c}}\right\}_{\hat{v},c_m} = \hat{v}_0^2 . c_{L_h}\left(1-\frac{c_{m_h} . c_{L_\alpha}}{c_{m_\varepsilon} . c_{L_h}}\right) < 0 \quad (6)$$

Generally, c_{L_h} is negative; thus, the condition for static height stability can be expressed in the form:

$$F_m \equiv \frac{c_{m_h} . c_{L_\alpha}}{\left(-c_{m_\alpha}\right)\left(-c_{L_h}\right)} < 1 \qquad (7)$$

When a wing approaches the ground, the lift coefficient increases, $\left(-c_{L_h}\right) > 0$, and also a nose down pitching moment occurs, $c_{m_h} > 0$. Therefore, in order to possess a certain margin of static height stability, a high value of c_{m_h} must be counteracted by high values of $\left(-c_{L_h}\right)$, and the static pitching stability $\left(-c_{m_\alpha}\right)$. The first term is primarily influenced by the aerofoil characteristics of the wing. The second term can be increased by, without increasing c_{m_h} as well, by a high horizontal tail working out of ground effect. The effect of the centre of gravity on static height stability is minimal.

The dynamic longitudinal stability of a vehicle in ground effect is determined by the roots of the fifth order characteristic equation.

$$As^5 + Bs^4 + Cs^3 + Ds^2 + Es + F = 0$$

Out of ground effect the F term disappears and this becomes a quadratic equation with the "short period mode" and the "phugoid mode" as solutions. Flying in close proximity to the ground, an aperiodic mode is obtained in addition to a pair of complex roots.

In ground effect, the aerodynamic coefficients depend strongly on height and angle of attack, a fact which leads to non-linear motions especially in climbs and descents, as well as in response to control inputs. The non-linear behaviour is particularly observed when the flight path crosses the "transition height regime", $0.5 < h/\bar{c} < 2$. Within this region a stable trimmed flight is not possible. At these heights the vehicle will limit-cycle oscillate both in height and pitch motion.

Another very important non-linear characteristic of ground effect vehicles is an "automatic flare" with fixed control. I this case the increase of lift coefficient gives a spring – type force during approach to the ground, whereas the vertical kinetic energy is dissipated in several cycles of height and pitching motions. In principle, elevator and thrust inputs could be used for height and speed control. Application of the elevator mainly induces disturbances in both angle of attack and height. The danger of touching the ground or exciting heavy oscillations is a disadvantage of applying the elevator as a primary longitudinal control. In comparison to the elevator, the thrust control is a very favourable means of height control. Good steady state changes in height can be obtained with small transients in angle of attack and height.

6 Concluding Remarks

At some time in the future it may be the case that the UAV is no longer used as a ground effect vehicle and that this project is merely a stepping stone to a fully operational free flight laboratory. In this scenario a rig would be built to be placed on the front of a car or van and utilise the wing and wing glove of the UAV for testing. This could be used to acquire simple ground effect data using the wing glove or even to acquire take off and landing data by mimicking the motion of the wing under these circumstances and building up a take off and landing profile for the given wing

This paper has addressed the problems involved in producing a reliable UAV to operate in ground effect. It has assessed the potential pitfalls and offers possible solutions to common issues. There is a risk associated with this, in using an UAV which is not designed for the intended purpose, though it is seen as valuable stepping stone in evaluating the system as a whole in preparation for higher altitude free flight. The low heights will ensure a relative amount of safety and hopefully minimal damage should any emergency occur.

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