PROGRESS IN UNDERSTANDING TRANSONIC AND SUPERSONIC GROUND EFFECT AERODYNAMICS

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Abstract

Considerable progress in the understanding of transonic and supersonic ground effect aerodynamics has been made at the University of New South Wales in the last half decade, including development of suitable small-scale wind tunnel techniques and accompanying numerical approaches. This paper provides an overview of these developments as they relate to wings and projectiles, placing them in the context of the limited wider knowledge of this field.

At fully-supersonic wind tunnel conditions, an effective low-cost substitute for a moving ground was shown to be a symmetry method, based on mirror-image models. At high subsonic Mach numbers, both the symmetry method and the use of an elevated ground exhibited limitations. For the supersonic projectile study, it was found that close ground proximity produced significant changes to the aerodynamic forces but the short duration would be insufficient to affect the trajectory to any major degree. Wings and aerofoils at high subsonic Mach numbers were influenced more profoundly by a ground plane; when a shock wave formed between the wing and ground, any potential efficiency gain to be found through flight in ground effect was lost.

1. Introduction

As an object passes through a compressible fluid such as air, the aerodynamic characteristics of the body are affected by density changes around it. This influence is enhanced by proximity to a ground plane, in particular when the flow becomes locally supersonic (as exemplified by the scenario in Fig. 1). Traditionally, aeronautical ground effect research (excluding study of vertical take-off and landing (VTOL)) has concentrated on the properties of wings in incompressible flows. In these cases, proximity to the ground serves to enhance the lift (or downforce) performance of the wing, and often the aerodynamic efficiency (lift/drag, L/D), when the wing, for instance, is within one chord length of the ground plane (a height-to-chord ratio, h/c, of 1 or less). Perhaps the most famous direct attempts to capitalize on this improved efficiency were the substantial Russian Wing-In-Ground-Effect vehicles of the Cold War era [1], which cruised at a sub-critical Mach number within one wing chord length or so of the Black Sea.

In an extensive review of WIG aircraft aerodynamics and technology, Rozhdestvensky [1] categorically affirms "it can be stated that little is still known with regard to GE (ground effect) at high subsonic Mach numbers". Brief test studies [2] indicate that increased aerodynamic efficiency may be possible for a high aspect ratio wing in ground effect at high subsonic Mach numbers, but some simple analytical treatments suggest the opposite [1].

Despite relevance to designs of high speed trains (where local Mach numbers around the vehicle can approach sonic unity), potential future maglev launch systems, store release problems, and more esoteric applications such as land speed record vehicles, very little public research has been conducted into compressible ground effect scenarios. However, much work has been conducted on more fundamental aspects of shock reflection and shock/boundary layer action; in the former instance it is relatively common to find flowfields generated by double-wedge geometries in wind tunnels which are essentially symmetric (designed to produce transition from regular to Mach reflection) [3], and these shock structures are reminiscent of those produced in the wing and projectile studies described here.

Fig. 1. A US Navy Blue Angels demonstration aircraft at approximately Mach 0.95 (photo: Matt Niesen).

With a lack of acceptable and inexpensive wind tunnel testing techniques, increasing emphasis is being placed on the use of computational fluid dynamics (CFD) as the primary or sole design tool, particularly for private, unconventional vehicles such as land speed record cars [4,5]. The use of CFD (with conventional Reynolds-Averaged Navier-Stokes (RANS) modelling), with its persistent difficulties in modelling turbulent structures and boundary layer transition as well as the multi-scale complexities of shock wave interactions and reflections in ground effect, is an endeavour which ought to involve careful experimental validation. For these reasons, the development of a suitable wind tunnel method is vital, and as such is addressed in this

In order to conduct experiments to study the aerodynamics of high speed objects in ground effect, particular consideration must be given to the way in which the ground is represented. In a wind tunnel environment with a fixed model, ideally a moving ground would be used for the greatest physical realism [6], but this is impractical at supersonic speeds. It is arguably more straightforward to move the object through quiescent air using, for example, a rocket-sled testing facility [7] or a ballistic range, but in addition to the enhanced complexity of all diagnostics related to free-flight measurements, these facilities are generally expensive and may also be subject to restricted military access. By contrast, supersonic blowdown tunnels are relatively common and accessible. Literature reports rare instances of an elevated ground being used, whereby the boundary layer is reduced in size but not eliminated – however, for low clearances this boundary layer can still occupy a large proportion of the space between the model and the ground. Furthermore, the presence of the boundary layer can distort and diffuse any shock wave reflections, as witnessed in such blowdown tests conducted on the Blue Flame land speed record car [8].

Studies using rocket sleds are generally related to non-ground effect applications, and the goal of researchers is to place the test object out of ground effect though the rocket sled itself operates in such conditions. Research related to the design and development of such systems offer greater insight for the current topic. Several studies into the design of the Holloman facility in New Mexico were conducted during its life as a supersonic facility (it is now primarily a hypersonic facility) [7]. Wind tunnel testing was conducted from M=1.5 to 4, with an elevated ground plane. Results were shown to agree well with subsequent tests with the actual rocket sled.

Rather than consistent trends, the normal force acting on the model was observed to increase and decrease considerably across the Mach number range tested, as shown in figure 1.6, indicating complex shock interactions from the simulated rail as well as the elevated ground plane, and downstream influences on the model sting and force balance due to multiple reflected shocks.

No systematic, dedicated investigation of the effect of ground proximity on aerodynamics had been conducted experimentally, however, until the present research.

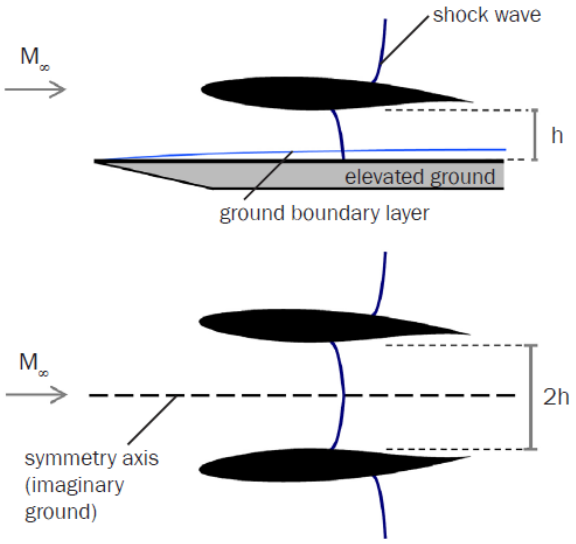

Fig. 2. Example of elevated ground and symmetry approaches for approximation of a moving ground in a wind tunnel.

2 Methods

The work described here involved a fully integrated approach whereby computational fluid dynamic simulations were used to help design wind tunnel experiments, which in turn were able to provide simultaneous preliminary insight into the problems and vital validation data for correlation of the numerical approach with the tests; subsequent to this, the validated CFD was used to investigate a wider range of variables at more subject-appropriate Reynolds numbers.

2.1 A note on numerical approaches

All the numerical results presented here were produced using a commercial RANS code, ANSYS Fluent, in 64-bit double precision. Second-order upwinding was applied and the Spalart-Allmaras turbulence model [9] was used after extensive comparison to experiments. All simulations were run as steady-state, apart from some of the wing simulations which were run as transient due to instabilities in the shock location causing mild separation, in which case values of aerodynamic coefficients were averaged. Convergence was deemed to be achieved when the force coefficients ceased to change by 0.01% over a subsequent 1000 iterations. Fully-structured multi-block meshes were constructed - and tested for grid-independence of results - with some local cell adaption for higher-resolution shock-capturing. The wing/aerofoil (3d/2d) meshes featured approximately 3 million/300,000 cells, with up to 14 million cells for the full spinning projectile. The approaches have been described at more length in literature [10-15] and for the sake of brevity here it is enough to state that extensive validation and verification was undertaken to arrive at the numerical approaches used to produce the results.

2.2 Experimental design

To perform useful, rather than merely perfunctory, wind tunnel testing in the absence of a moving ground, an evaluation of the symmetry and elevated ground methods previously introduced was conducted. An RAE2822 aerofoil section, extruded to an aspect ratio of 3, was chosen for testing in the Mach range 0.5-0.75 range (limited by blockage considerations) in the transonic blowdown tunnel of the United States Naval Academy in Maryland. Testing was conducted at 4 ground clearances and 2 angles of attack to obtain enough different flowfields to thoroughly validate the accompanying numerical work. Supersonic tunnel testing with a non-spinning axisymmetric NATO 5.56mm projectile was conducted in the blowdown tunnel at the Australian Defence Force Academy at Mach 2.4 (with appropriate Reynolds-scaling), at several different height-to-diameter (h/d) ratios, based on live-range testing conducted with an actual fired projectile. For both sets of tests, modeling revealed the influence of stings on pressure tappings to be negligible. In the latter experiments, schlieren photography was also used extensively.

3 Supersonic projectiles

Figure 3 shows direction-indicating colour schlieren images of flows produced by both methods in the wind tunnel at a height-to-diameter ratio of h/d = 0.5, with the symmetry image cropped to the symmetry plane (imaginary ground) for comparison. The boundary layer which grows on the elevated ground is clearly visible and, by the rear of the projectile, it occupies approximately 45% of the space between the model and the ground. Clearly, the presence of this boundary layer would alter the nature of the shock reflection from the ground plane. In addition, the shock pattern under the bullet appears diffused downstream of the first interaction. There is little sign of a second reflection from the ground, as the shock reflecting from the projectile appears to have been absorbed in the boundary layer.

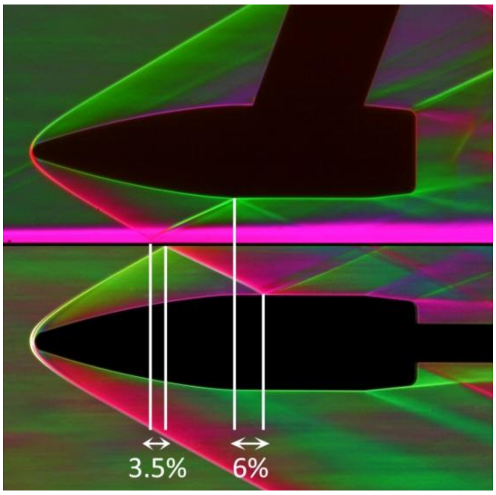

Fig. 3. Colour schlieren images contrasting the projectile at h/d=0.5 using the elevated ground method (top) and the symmetry method (bottom).

In these tests with the solid reflection plane, the initial shock-boundary layer interaction has modified and shifted the reflected shock so that its subsequent interaction with the projectile model occurs at a different location, and with different shock strength. One consequence of these modifications is that the double structure of the reflected shock is much less pronounced in the elevated ground tests. Within the boundary layer, the initially-oblique shock becomes normal before it disappears in the subsonic part of the boundary layer at the wall. The result is an upstream shift of the impingement point on the projectile.

Computational results for the pressure field on the ground (and imaginary ground), on a plane through the centre of the wind tunnel, for both methods, as compared to an idealized moving ground, are shown in fig. 4. The extent of the diffusion of shock reflections due to the elevated ground's boundary layer is clear particularly for the first impingement of the bow wave and downstream where the recompression shock meets the ground. By contrast, the symmetry method provides a near-perfect match to the moving ground; this result was typical of all clearances examined, and thus the symmetry method was determined to be an excellent means by which to examine this fully supersonic problem experimentally. Following further tests to thoroughly validate the numerical facsimile of the tunnel experiments, the CFD was extended to look at the original problem of an actual projectile in close ground or wall proximity – this involved the additional complication of spin, producing an asymmetric wake and a small side-force even without the presence of the wall.

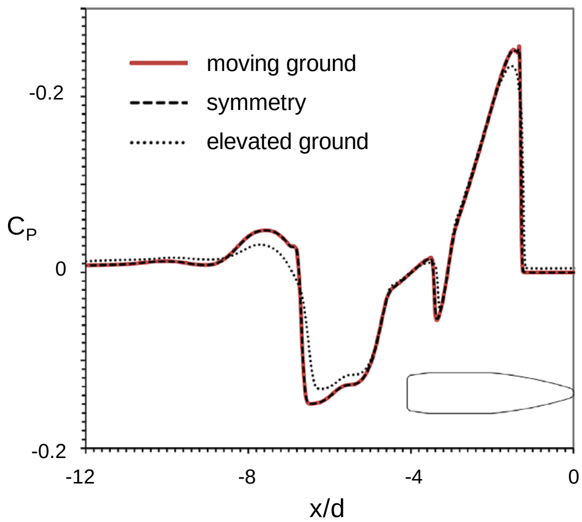

Fig. 4. Ground pressure distributions from CFD for the projectile wind tunnel test at h/d=0.5.

The forces obtained from a simple parametric study of ground clearance pointed towards three distinct types of shock reflection or interaction, as shown in figure 5; a Type A interaction involved the reflection of the bow shock into the far wake, and the recompression wave trailing the projectile reflecting into the wake further still downstream. The overall influence on the aerodynamic forces and moments experienced by the projectile is negligible as the projectile moves with supersonic speed relative to the flow in the wake and is therefore not affected by disturbances in the wake downstream flowfield is fully supersonic. A Type B case involved the bow wave reflection impinging on the near-wake of the projectile (defined in this case as less than 1 projectile diameter from the base, which was observed to be the approximate maximum extent of recirculating flow for a freeflight case). The wake experienced a deflection due to the magnified pressure difference between the region below the wake and that above, and consequently the base pressure (and thus the drag) and, to a lesser extent, the projectile's pitching characteristics would be affected. In a Type C interaction, the bow wave reflected to impinge on the projectile body one or more times, and the recompression shock reflected into the wake to produce its own strong interaction. All aerodynamic forces and moments acting on the projectile are affected to varying extents by this scenario.

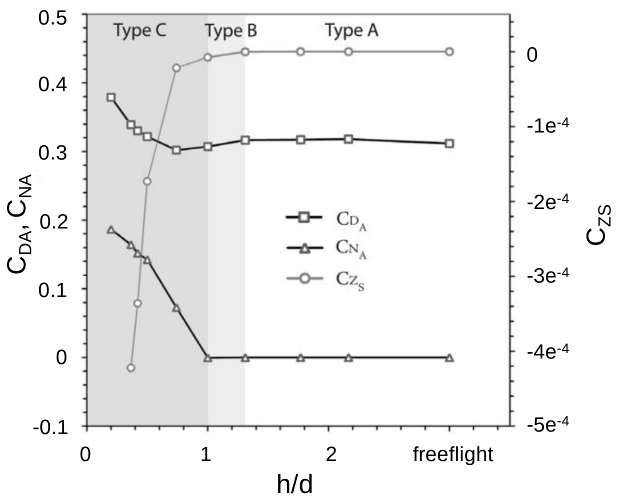

Fig. 5. Drag and normal force coefficients (based on frontal area) and a side force coefficient (based on side area) vs. ground clearance for the full spinning projectile.

The type C situation resulted in a tendency to pitch nose-down as the high pressure built up under the projectile by the reflecting shocks. The normal force coefficient, C_{NA} (based on frontal area), at this stage would result in a significant change in trajectory if the ground plane were long enough for sustained interaction to occur (which is unlikely), and because the projectile is spinning at approximately 17700 rads/s in this instance, a lateral precession would be the likely result rather than a lifting away from the ground.

The flow structures in the near wake and inside the primary recirculation region are strongly influenced by the changes in pressure distribution in the flowfield around the projectile. Figures 6 and 7 present streamlines in the base region for various ground clearances. In freeflight there are two distinct recirculation cells, perfectly axisymmetric. Also of note are small but distinct separated zones on the blend from the boat-tail to the base.

At h/d=1, the bow shock reflection interacting with the wake results in the upwards deflection previously discussed, and the upper recirculation cell becomes compressed as the wake distorts on all planes. The direction of flow is from the lower cell to the upper one. At h/d = 0.5, this trend is reversed, as flow now proceeds from the upper cell to the lower one, although both are now highly distorted compared to the regular structures seen in the freestream case. All recirculation is confined to a region within 0.5d of the base.

This trend continues at h/d = 0.2 where the downwash is at its most extreme, and the recirculation is confined to within 0.3d of the base and is made up of a large upper cell and a weak lower one. The vertical extent of the recirculation has also diminished, and the lower cell has almost ceased to exist. The shear layer on the lower side angles downwards from 0.5d of the base, such that it soon interacts with the ground.

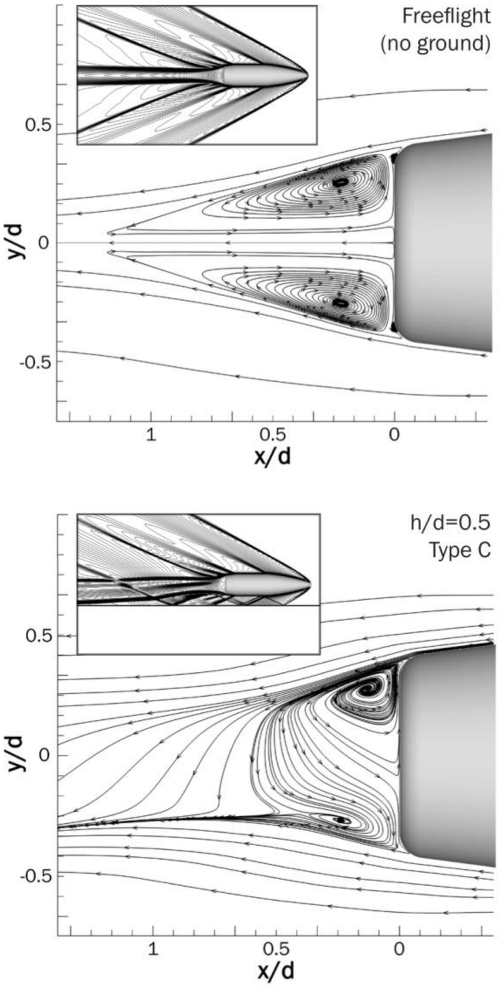

Fig. 6. Flow pathlines in the immediate wake region of the projectile for (top) free flight and (bottom) h/d = 0.5.

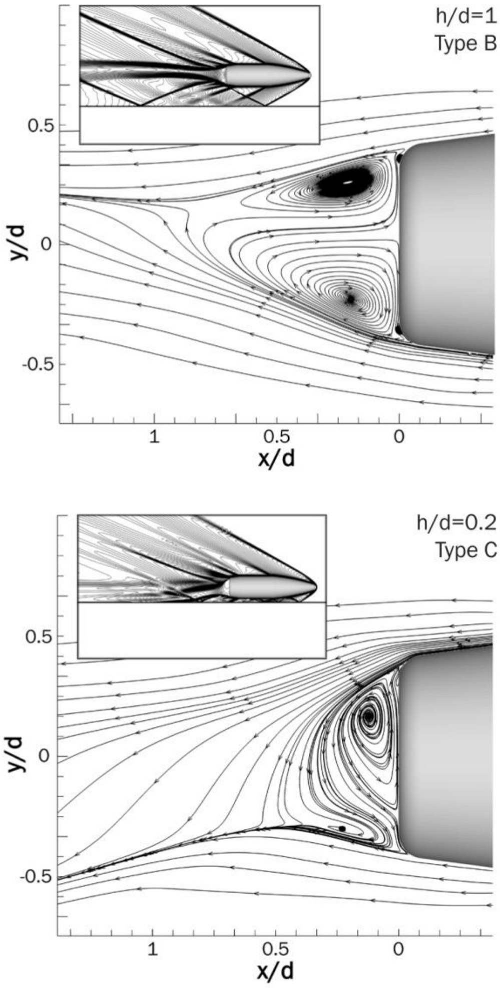

Fig. 7. Flow pathlines in the immediate wake region of the projectile for (top) h/d = 1 and (bottom) h/d = 0.2.

4 Aerofoils and wings at high-subsonic Mach numbers

Wind tunnel testing could not be conducted at a Reynolds number sufficient to replicate that which would be realistic for an aircraft operating at high subsonic Mach numbers close to, presumably, a water surface. Thus the experiments with the RAE2822 model, with a chord of 58mm, were aimed more at validation of the numerical approach than an extensive test of the ground influence in itself. Thus the CFD reproductions of the experiment, indicating a reasonable match to the pressure measurements, were analysed to determine with greater accuracy the effectiveness of the techniques.

Figure 8 highlights a wider discrepancy between methods, again compared to an idealized moving ground scenario, than was observed in the fully-supersonic testing. This particular case was conducted at a freestream Mach number of 0.53 with the wing(s) at zero angle of attack producing a shock-free flowfield.

While the symmetry method again provides a close match to a moving ground, it results in the slight over-prediction of pressure coefficient seen at the suction peak of the lower surface in the channel between the wing and the ground, due to the absence of a ground boundary layer, which does form thinly in the moving ground simulation. The disturbance caused to the ground pressure distribution by the elevated ground leading edge can be seen in figure 8b, and the extra thickness of the ground boundary layer results in an increased deflection of flow over the upper surface, which in turn produces greater lower pressure over the top of the wing and reduces the strength of suction produced by the venturi effect underneath the wing.

At higher ground clearances and angles of attack, where there lower surface of the wing does not accelerate the flow as greatly under the wing and the two methods are essentially comparable in terms of accuracy. However, the window of usefulness for the elevated ground is narrow, as eventually it would reach its own critical Mach number, with accelerated or even separated flow likely to form at even a well-designed leading edge and, consequently, a distorted flowfield would adversely influence the flow reaching the model downstream. Thus the symmetry method remains the preferred option, though it does feature the disadvantage of potentially increased blockage.

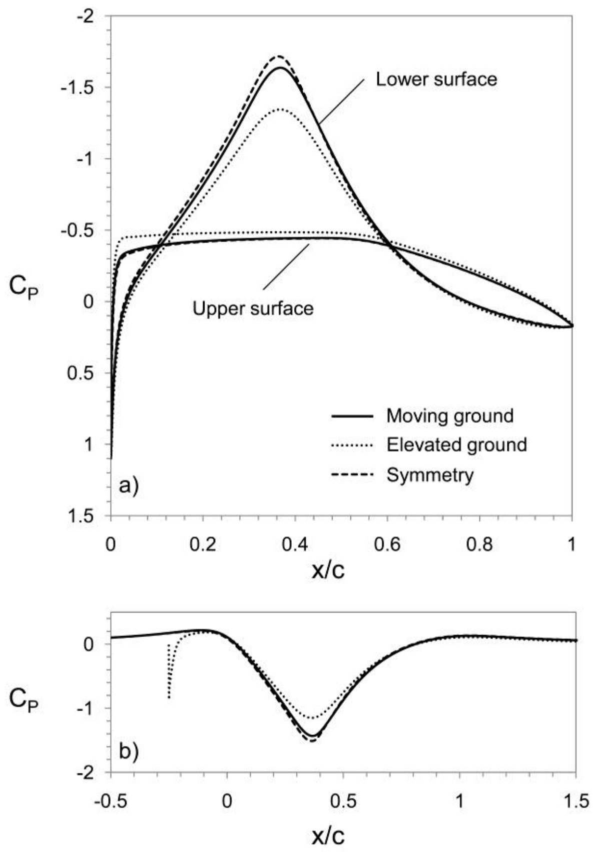

Fig. 8. Comparison of ground representations from CFD of RAE 2822 transonic wind tunnel experiments; a) wing semi-span pressure coefficient and b) ground plane semi-span pressure coefficient: h/c = 0.13, M = 0.53.

For a much larger wing chord of 3.05m, figure 9 illustrates the way in which the pressure distribution around the aerofoil changes as the ground clearance is reduced in stages. The upper surface shock location moves progressively upstream from its freestream location, by about 25% of the chord by h/c = 0.1. It also gradually reduces in intensity, resulting in a less severe pressure increase across the wave. One of the main reasons for this behaviour is the downward movement of the stagnation point at the leading edge, which also increases the strength of the suction peak near the leading edge on the upper surface. This increase in the effective angle of incidence draws the shock upstream, and creates a stronger adverse pressure gradient across the forward portion of the upper surface leading to the earlier, weaker shock and a reduction in the region of "rooftop" pressure distribution.

C_L increases slightly from the freestream value, up 2% to h/c = 0.5 and peaking at 5% higher at h/c = 0.25. This is due to the increase of effective angle of incidence caused by increasing ground proximity, and the greater build up of higher pressure already noted between the aerofoil and the ground on the foremost portion of the aerofoil, which increases the maximum suction the section produces. The formation of the lower shock at h/c = 0.1 destroys much of this capacity to create lift, as the flow is greatly accelerated under the aerofoil and produces a large amount of low pressure prior to the shock on the aft portion of the wing. This creates very strong gradients over the entirety of the chord on the lower surface.

For several combinations of Mach number, ground clearance and angle of attack, the simulations tended towards unsteady, with an indication that early onset of buffet would be probable, and in almost all cases the critical Mach number was reached earlier in ground effect than unbounded flight.

A key finding from the wing study, as highlighted by figure 10, was that the overall aerodynamic efficiency of lift upon drag was not particularly improved by flying in ground effect, in contrast to the established advantage at lower Mach numbers.

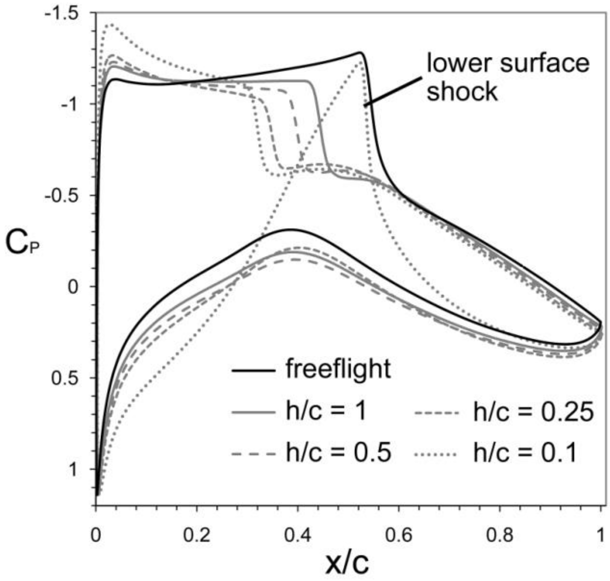

Figure 9. Chordwise pressure distribution around an RAE2822 aerofoil at an incidence of 2.79^o and a freestream Mach number of 0.73, for decreasing ground clearance.

This is particularly true at the higher end of the speed range examined, where a shock between the wing and the ground is difficult to avoid, resulting in significant increases in drag and a destruction in the lift-producing capacity as a result of the severe low pressure forming on the lower surface.

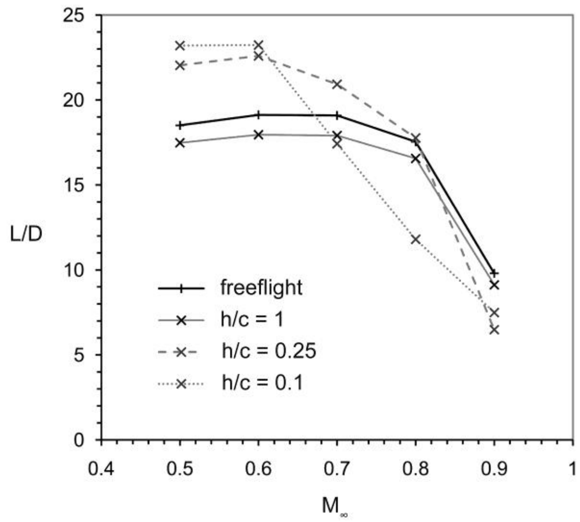

Fig 10. Wing aerodynamic efficiency (lift/drag) vs freestream Mach number for decreasing ground clearances.

5 Continuing Investigations

While the research described here, into projectiles and wings, has thrown up some interesting conclusions, investigation is currently underway into a different aspect of shock waves at ground level. The notion of using shock waves to extinguish a large-scale bushfire, using a technique not dissimilar to that used most notably by Red Adair to quench oil and gas well fires, is not a new proposition. Various studies conducted in Russia in the 1980's and 90's indicated the promise of the approach [16, 17], and the idea is being revived in China as well as in Australia [18]. While the more fundamental fluid dynamic aspects of shock/fire interaction are being explored, the ability of shocks generated by an aircraft to achieve the same effect is being considered as a form of rapid-response alternative. Small scale testing with a projectile (fig. 11) and a non-combusting plume has shown that the shocks may have a relatively small effect on a constant gas source, but similar testing and accompanying numerical simulation on laminar flames suggests that the force need not be strong to separate the fire from the fuel. Whether this can be scaled up to the size and complexity of an actual bushfire remains to be addressed and is currently being studied.

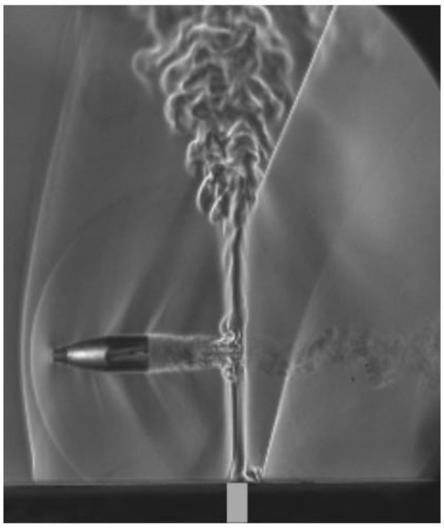

Fig 11. A supersonic projectile passing over and through a helium plume (photo: Harald Kleine)

4. Conclusions

Compressibility effects change, often substantially, the aerodynamic characteristics of a body. This occurs in particular when a shock wave reflects from the ground plane to interact again with the body or its wake.

Simple techniques for compressible ground effect problems in blowdown wind tunnels were developed and evaluated in lieu of a moving ground: a symmetry (mirror-image) method, and an elevated ground plane. Both these methods were assessed for the projectile at Mach 2.4 and the RAE 2822 in the US Naval Academy wind tunnel in the Mach 0.5 to 0.75 range. In all cases, the symmetry method was found to be the most effective; at supersonic speeds it was an excellent facsimile of a moving ground, and at high subsonic Mach numbers it was generally superior to the elevated ground, moreso as Mach 1 was approached due to shock formation and separation at the leading edge of the ground plane.

The presence of the ground was found to affect the critical Mach number, and at low angles of attack and low ground clearances, a shock wave was prone to form on the lower surface prior to that on the upper surface, causing a significant drop-off in lift (and in some cases the production of downforce), and an accompanying increase in drag. The aerodynamic characteristics across all Mach numbers and clearances proved to be highly sensitive to ground proximity, with a step change in any variable often causing a considerable change in lift, drag or moment coefficient.

As a result of these factors, sustained transonic flight in ground effect would require a rapid-response control system, and the wing section used would have to be carefully optimised to provide acceptable lift and handling characteristics while avoiding the formation of a lower surface shock. Without this, sustained flight in ground effect at high subsonic Mach numbers would not be more efficient than flight at altitude.

For a fully-supersonic project in close ground proximity, a more predictable relationship between ground clearance and the effect on lift and drag was established based on whether the bow wave reflected from the ground into the wake (at high clearances) or onto the projectile (lower clearances). The complex series of shock/ground and shock reflection/projectile interactions resulted in a considerable increase in drag, a change to pitching moment (increasingly nose-down), and a notable increase in normal force which would produce a lateral precession due to the spin of the body. For a projectile this would make little difference to trajectory due to the short duration of ground effect possible, but for a missile or rocket sled system then this would cause potentially-unanticipated strain on the object.

Much of the work described has confirmed or uncovered the reasons for unusual results from wind tunnel testing of transonic and supersonic models in the 1960's and 1970's, and paves the way for a clearer understanding of ground effect flows in the compressible regime.

References

[1] Rozhdestvensky KV. Wing-in-Ground Effect Vehicles, *Progress in Aerospace Sciences*, 42, (3), pp. 211-283, 2006.

[2] Maskalik AI and Rozhdestvensky KV. A View of the Present State of Research in Aero-and Hydrodynamics of Ekranoplans. *RTO AVT Symposium on Fluid Dynamics Problems of Vehicles Operating near or in the Air-Sea Interface*, Amsterdam, 5-8 October 1998.

[3] Ben-Dor G. A State-of-the-Knowledge Review on Pseudo-Steady Shock-Wave Reflections and their Transition Criteria, *Shock Waves*, 15 (3-4), pp. 277-294, 2006.

[4] Goldberg U, Akdag V, Palaniswamy S, Oberoi R, Bachchan N, Glessner P, Fredrick W. CFD Analysis of the American Challenger Rocket Car. *SAE 2006 World Congress & Exhibition (Vehicle Aerodynamics)*, pp. 251-258, 2006.

[5] Noble R and Tremayne D. Thrust (text), Partridge Press, ISBN 1-8522-5268-5, 2002.

[6] Barber TJ, Leonardi E, Archer RD, Causes for Discrepancies in Ground Effect Analyses. *The Aeronautical Journal*, 106 (1066), 653-657, 2002.

[7] Strike WT and Lucas EJ. Evaluation of Wind Tunnel Tests on AFMDC Monorail cone and spike nose sled configurations at Mach numbers from 2.0 to 5.0. AEDC-TR-68-198 (AD679206), 1968.

[8] Torda TP and Morel TA. Aerodynamic Design of a Land Speed Record Car, *Journal of Aircraft*, 8 (12), pp1029-1033, 1971.

[9] Spalart P and Allmaras S, A one-equation turbulence model for aerodynamic flows. AIAA Paper 92-0439, 1992.
[10] Doig G, Barber TJ, Neely AJ, Myre DD. Aerodynamics of an Aerofoil in Transonic Ground Effect: Methods for Blowdown Wind Tunnel Scale Testing. *The Aeronautical Journal* (In Press, accepted 09/ 2011).
[11] Doig G, Barber T, Neely A. Aerodynamic Characteristics of a Swept Wing in Close Ground Proximity at High Subsonic Mach Numbers. *ASCE Journal of Aerospace Engineering*, (In press, accepted 06/2011).
[12] Doig G, Barber TJ, Neely AJ, Myre DD, Aerodynamics of an Aerofoil in Transonic Ground Effect: Numerical Study at Full-scale Reynolds Numbers. *The Aeronautical Journal* (In Press, accepted 06/ 2011).
[13] Barber TJ, Doig G, Beves C, Watson I, Diasinos S. The synergistic integration of CFD and EFD for ground effect aerodynamics studies. *Proc. IMechE Part G: Journal of Aerospace Engineering*, (In press, available online)
[14] Doig G, Barber TJ, Leonardi E, Neely AJ, Kleine H, Aerodynamics of a Supersonic Projectile in Proximity to a Solid Surface. *AIAA Journal*, 48(12):pp. 2916-2930, 2011.
[15] Doig G, Barber TJ, Leonardi E, Neely AJ, Kleine H. Methods for investigating supersonic ground effect in a blowdown wind tunnel. *Shock Waves*, 18(2): pp. 155-159, 2008.
[16] Grishin AM, Zima VP, Mashovich AY, Samoilov VI. *Proc. Common Prob. on Mech. and Eco.*, Tomsk, Russia, pp.83-85, 2000.
[17] Grishin AM, Tsimbalyuk AF. *Combustion, Explosion and Shock Waves*, 43, 3, pp.329-335, 2006.
[18] Xue YP, Qiao XH, Jin GJ. Research on Ignition and Extinguishing by Explosion of High Explosive *Blasting*, 2-2009, 2009.

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