View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by University of Queensland eSpace

16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

Force and pitching moment variation of inverted aerofoils at high angles of attack in ground effect

D. Walter and S. Watkins
School of Aerospace, Automotive, Mechanical and Manufacturing Engineering
RMIT University, Melbourne, Victoria, 3083 Australia

Abstract

The effect of ground proximity on the moment coefficient of inverted, two-dimensional aerofoils was investigated. The purpose of the study was to examine the effect of ground proximity on aerofoils post stall, in an effort to evaluate the use of active aerodynamics to increase the performance of a race car. The aerofoils were tested at angles of attack ranging from 0° – 135°. The tests were performed at a Reynolds number of 2.16 x 10^5 based on chord length. Forces and moments were calculated via the use of pressure taps along the centreline of the aerofoils. The RMIT Industrial Wind-Tunnel (IWT) was used for the testing. Normally 3m wide and 2m high, an extra contraction was installed and the section was reduced to form a width of 295mm. The wing was mounted between walls to simulate 2-D flow. The IWT was chosen as it would allow enough height to reduce blockage effect caused by the aerofoils when at high angles of incidence. The walls of the tunnel were pressure tapped to allow monitoring of the pressure gradient along the tunnel. Decreasing ground clearance was found to reduce pitch moment variation of the aerofoils with varied Angle of Attack (AoA). Decreasing ground clearance increased lift and decreased drag for varied AoA.

Introduction

Aerodynamic devices such as wings are used in higher levels of motorsport (Formula-1 etc) to increase the contact force between the road and tyres (downforce). This can increase the performance envelope of the race car; however the aerodynamic downforce is only beneficial when the car performance is traction limited. In the situation when the car is unable to break tyre traction, the extra downforce increases aerodynamic drag which (apart from when braking) is generally detrimental to lap-times. The drag acts to slow the vehicle, and hinders both available drive power and fuel economy. By actively altering a wing's AoA, the lift/drag relationship and magnitude can be significantly altered. This would allow high downforce when required (cornering and braking) and low drag when downforce was not required (driving in a straight-line when not traction limited). An active system would provide the benefits of wings, without the drag-induced power/economy cost.

Variable geometry aerodynamic devices have been used in various forms of motorsport in the past, but have invariably been banned for various reasons (usually due to safety reasons). The use of active aerodynamics is currently legal in both Formula SAE (an engineering competition for university students to design, build and race an open-wheel racecar) and production vehicles. A number of car companies are beginning to incorporate active aerodynamic devices in their designs.

While some research has been done with airfoils at very high angles of attack [6.], the majority of data on different airfoils have been collected for aeroplanes, and as such does not include data beyond the normal operating envelope of aircraft (i.e. at angles of attack beyond the stall of the airfoil). For automobiles the effect of the close proximity of a plane is important due to proximity to the ground at the front, and the vehicle body at the rear [4.]. The pitching moment is of particular interest to designers of an actively variable-geometry aerodynamic system as this determines the torque required to alter / maintain the attitude of a wing about a pivot. These data could be used by race teams and automotive designers in the development of active aerodynamic systems.

Equipment

The experimental method was chosen for this investigation, primarily due to the presence of complex flows that if solved by other means, would still require experimental validation.

The RMIT Industrial Wind-Tunnel (IWT) was used for the testing. Normally 3m wide and 2m high, an extra contraction was installed and the section was reduced to form a width of 295mm. The IWT was chosen as it would allow enough height to reduce blockage effect caused by the aerofoil at an incidence of 90º. The aerofoil has a chord of 150mm, thus the constructed tunnel will experience a maximum solid blockage of 7.5% when the aerofoils are at 90° AoA. The walls of the tunnel were pressure tapped to allow monitoring of the pressure gradient along the tunnel. The wing was mounted between walls to simulate 2D flow. Slots in the tunnel allowed the wing to be restrained outside the tunnel, and the pressure tubes to exit. These slots were fitted with foam to allow movement of the wing while still sealing the tunnel. The height and AoA of the wing were adjusted separately. One of the difficulties of working in ground effect is simulating the presence of ground experimentally. Ideally when testing in ground effect a moving floor should be used to eliminate the effect of the ground boundary layer on the results. In this situation this was not practicable. The effect on accuracy of moving ground compared to stationary has been studied quite thoroughly. Hoerner [2.] has details of early wind-tunnel testing of different ground simulation techniques, and compares the effects of different types of ground simulation. Howell & Hickman [3.] compare the difference between fixed and moving ground, concluding that fixed is usually sufficient, unless trying to find absolute drag figures, or investigate flow around wheels. In this work, the effect of the tunnel boundary layer on the floor was reduced greatly by the large contraction and a slightly raised floor. In the area of the aerofoil, the displacement thickness was less than 10mm (0.067 c).

The forces acting on the wing were measured by plumbing the wing section with pressure-taps, and integrating across the surface for the force. A Differential Pressure Measuring System (DPMS) supplied by TFI Hardware was used to capture the pressure data and provide time averaged results.

The air velocity in the tunnel was measured with a Dynamic Cobra Probe. Dynamic Cobra probes provide pressure and velocity data.

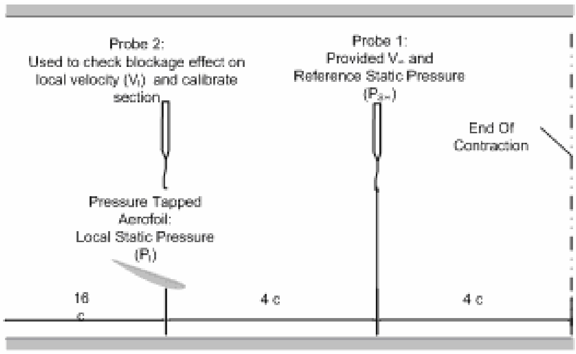

Figure 1 Cobra Probe positions in tunnel

Data from the Cobra probe were used to non-dimensionalise the pressure data.

In order to get a good understanding of the behaviour of the aerofoils a series of wind-tunnel tests were conducted. The AoA was varied from 0 to 135 deg. This shows a range of behaviour, from pre-stall through stall to post-stall and inversion (post 90 deg). The ground clearance was varied from 0.17 to 3.33 chord heights for all AoA tested. Some additional tests were run close to the stall in close ground effect to give better resolution of this region. The ground clearance was taken as the gap between the lowest point on the aerofoil surface (not the pivot) and the ground. The design of a custom aerofoil was beyond the scope of this project, and thus appropriate shapes were chosen. Considering this is an early study in this area, it was decided that the actual specific profiles tested were not particularly important, provided the profiles differed in camber. Ideally for an active aerodynamic system, the aerofoil camber used should be chosen to provide a high lift coefficient pre-stall, while providing low drag at low AoA; post-stall the effects of camber are minimal. The decision was made to use a set of existing wings. The models all had a span of 295mm and chord of 150mm and were all pivoted at 25% chord. The models were manufactured in two halves (top and bottom), pressure-tapped, then glued together and painted. The pressure-taps generally ran down the centreline of the model however a number of taps near the leading edge on the Clark Y model were staggered left and right of the centreline, no more than 0.04c. The pressure tap locations are displayed in Figure 2.

The first aerofoil to be tested had a Clark Y profile; a shape that is well documented and understood. The Clark Y typically exhibits slow stall characteristics, and limited Centre of Pressure (CoP) migration, however the drag tends to be higher and lift lower than other more recent aerofoil shapes [5.].

The second profile tested was that of a 6-Series aerofoil, designated 63-412. The 6-series aerofoils were specifically designed using inverse methods to maintain laminar flow over most of the section, thus reducing drag for a certain operating range. This is an advantage of the 6-series, coupled with higher maximum lift co-efficient. Disadvantages include rapid stall characteristics and higher drag when not operating in design range [5.].

The third profile to be tested was the second profile with the addition of a "Gurney Tab" to the trailing edge. The Gurney tab effectively increases the camber of the aerofoil, altering the lift and drag characteristics. While more efficient means of achieving this are available, the Gurney tab is a quick and simple way, and is commonly used in race cars for tuning purposes [4.], where a slight increase in drag is a tolerable for increased downforce. The tab used had a height of 0.067 chord.

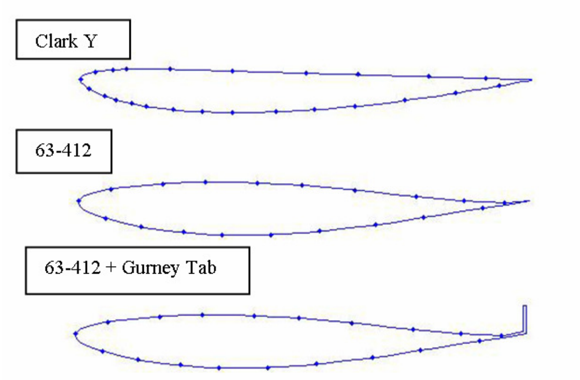

Figure 2 Aerofoil shapes tested with pressure tap locations

In order to check geometric accuracy and allow comparison to official co-ordinate data, the aerofoil shapes were measured with a 3-D GOM. Both aerofoils were found to be within 2% of the published shape, and 2-D to within 1%.

To give a visual indication of the potential magnitude of errors Figure 3 shows a plot with error bars superimposed on a datum point.

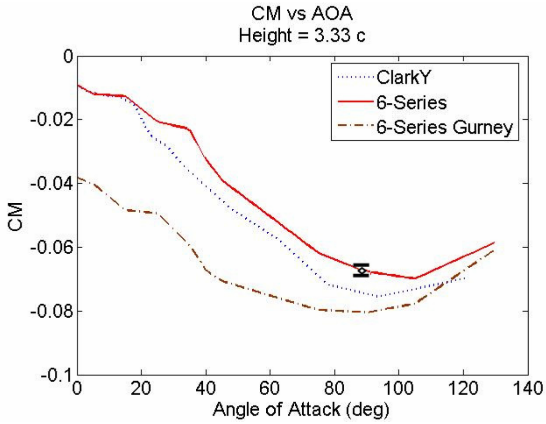

Figure 3 Moment Coefficient error

Only the error bars for the coefficient are shown, as the errors for AoA and ground clearance are not visible on this scale. It can be seen that the errors are relatively minor compared to the trends seen in the plot, thus it is safe to conclude the trend is due to physical phenomena, not errors.

In an effort to get an idea of the repeatability of the study, a number of trial runs were repeated at different times throughout the study. The standard deviation of the moment coefficient was 3%.

Results and discussion

The forces and moments acting on the wing were calculated from the surface pressures, resolving and integrating across the surface for the force. The pressures were first calibrated to suit the calibration of the sensors in the DPMS. The pressure data were converted to non-dimensional pressure coefficients (CP) and plotted as a function of x/c.

The non-dimensionalised pressure data were then used to integrate the pressure contour across the aerofoil surface. The axial and normal forces acting on the aerofoil were calculated, along with the moment. The moment referenced to point at 25% chord. The axial and normal forces were then used to calculate the lift and drag.

Calculations were done with the aid of MatLab, which streamlined and automated the compression and analysis of data. Over 140 different runs were tested. Rather than display all pressure contours, only those pertinent to the discussion will be displayed.

The variation of pressure distribution with various AoA for the 6-series aerofoil is shown in Figure 4.

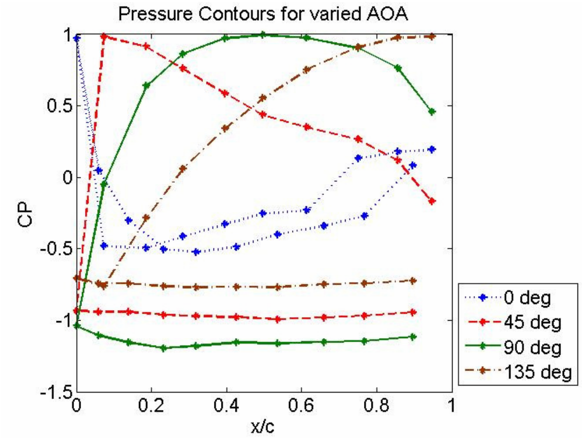

Figure 4 Pressure contours for different AoA

As would be expected, the stagnation point moves rearward after the stall. The pressure on the lower side of the aerofoil also varies in the general manner expected, with the maximum negative pressure occurring at 90º AoA. This general trend is the same for all the aerofoil shapes tested.

Figure 5 shows the variation of pressure distribution with ground clearances for a set AoA.

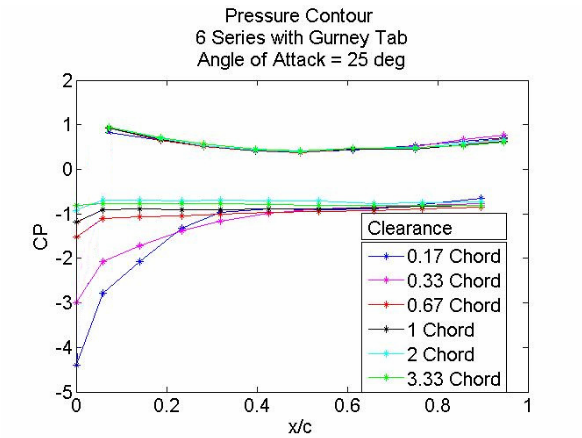

Figure 5 Pressure contours for different ground clearances

As can be seen in Figure 5 the majority of change with varied clearance occurs on the underside of the aerofoil, specifically the suction at the leading edge. This trend was also seen in the other aerofoil shapes.

Pitching moment variation

The contours from each run were simplified to a C_m. These points were then used to generate a surface for moment, as shown in the following sections. This surface was constrained to pass through the points tested; spline interpolation was used between points. The test results are also plotted with the surface, and are shown with a marker.

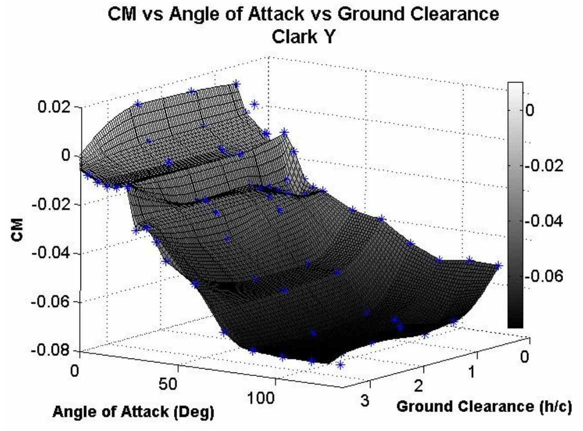

Figure 6 Moment coefficient variation - Clark Y

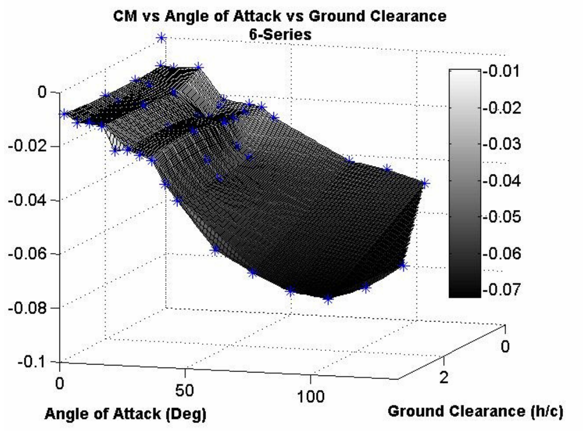

Figure 7 Moment coefficient variation - 6-Series

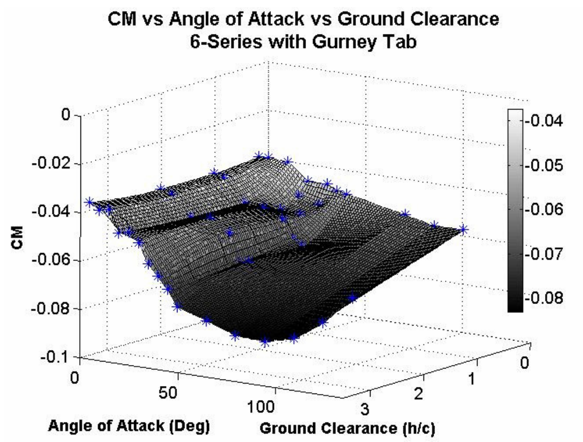

Figure 8 Moment coefficient variation - 6-Series with Gurney

Generally the moment coefficient became more negative (acting to reduce the AoA) with increased AoA. The variation of pitching moment was reduced with decreased ground clearance.

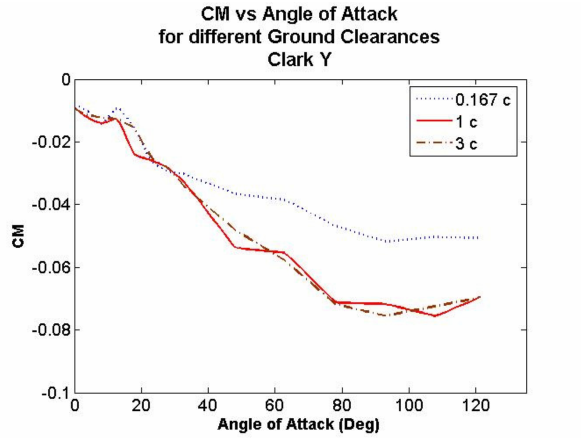

Figure 9 Moment coefficient variation with AoA as a function of non-dimensionalised ground clearance - Clark Y

Figure 9 shows the variation of moment coefficient with AoA. While the actual values of C_m differed, the aerofoils all showed similar trends for the variation of pitching moment throughout the range of AoA. The location of the CoP moved aft post stall to a position approximately mid-chord at 90° AoA.

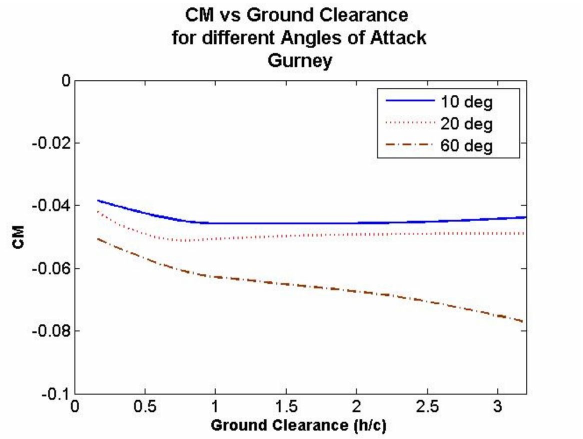

Figure 10 Moment coefficient variation with ground clearance as a function of AoA - 6-Series with Gurney

Figure 10 shows the variation of C_m with ground clearance. Close ground presence tended to reduce the magnitude of the C_m. The presence of the ground is most visible in the post-stall case (60 ° AoA); the C_m being reduced by approximately a third.

In the case of the Clark Y and 6-Series aerofoils, the lift force did not vary as expected prior to stall, with force slightly decreasing with decreased ground clearance. The aerofoil with the Gurney tab displayed the typical characteristic of increased lift force with decreased ground clearance. All aerofoils displayed a decrease in drag with decreased ground clearance. Close ground clearance delayed the stall of the three aerofoils tested however this effect could be influenced by the ground simulation. The pre-stall trend of decreasing lift with decreased ground clearance is contrary to the expected increase in lift as the ground is approached. A possible explanation for both the stall delay and decrease in lift with decreased clearance would be interference from the ground boundary layer. Similar trends were found by Barber et al. [1.] at close (<0.2c) ground clearances with a fixed ground. The interaction with the ground boundary layer is complex, and the boundary layer thickness is a function of number of variables, including the pressure gradient caused by the aerofoil. The closer proximity to the boundary layer will give results similar to those of closer ground clearances without a boundary layer. The ground boundary layer may also help maintain attached flow on the suction side of the aerofoil. Post-stall, the three aerofoils showed a decrease in lift and drag force with decreased ground clearance. Further study is required to determine how the ground simulation has affected these results. It is possible that the trends in the lift and drag data are a result of interaction with the ground boundary layer, and further study conducted in the field or with more accurate ground simulation may produce alternate findings.

Conclusion

The CoPs of the aerofoils were found to move rearward with increased AoA. The magnitude of this effect was reduced with decreased ground clearance. This effect however may also be exaggerated by the ground simulation used, due to boundary layer interaction effects. The rearward movement of the CoP was expected for these aerofoils; however the reduction of C_m variation potentially enables designers of an active aerodynamic system to use a lighter actuator to control the system. Sensible placement of the wing pivot relative to the CoP would minimize the magnitude of torque such a system would have to counter. Of interest would be a test with an aerofoil designed for zero / low pitch moment variation with AoA. A wing with this type of aerofoil could be mounted with a lighter actuator owing to the reduced moment throughout the range of AoA. A decrease in lift and drag force with decreased ground clearance was observed on the stalled aerofoils.

References

[1.] T.J. Barber, E.Leonardi, R.D. Archer, Causes for Discrepancies in Ground Effect Analyses, *The Aeronautical Journal*, Vol 106, No. 1066, pp 653-667, December 2002

[2.] S.F. Hoerner, *Fluid-Dynamic Drag,* Hoerner Fluid Dynamics, Vancouver, WA, 1965

[3.] J. Howell & D. Hickman, *The Influence of Ground Simulation on the Aerodynamics of a Simple Car Model,* SAE 970134, Society of Automotive Engineers, Warrendale, USA, 1997

[4.] J. Katz , *High-Lift Wing design for Race-Car Applications,* SAE 951976, Society of Automotive Engineers, Warrendale, USA, 1995

[5.] J.Scott. *NACA Airfoil Series,* http://www.aerospaceweb.org/question/airfoils/q0041.shtml, Aug 2001, accessed 20/8/05

[6.] R.E Sheldahl, P.C. Klimas, *Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines*, SAND 80-2114, Sandia National Laboratories, Albuquerque, NM, 1981