GROUND EFFECT TESTING CAPABILITIES IN THE FILTON 12' X 10' LOW SPEED WIND TUNNEL

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Abstract

The wind tunnel testing required to simulate the parts of the flight regime close to the ground provides unique challenges. Aerodynamic data is required for these conditions to calculate take off and landing performance to satisfy field length requirements. Traditionally, wind tunnels are used to provide this information. This paper discusses the approach taken by the Filton Low Speed Wind Tunnel in obtaining this data.

The technique for testing aircraft models in ground effect in the Filton Low Speed Wind Tunnel is based upon a movable ground plane, which spans the Tunnel Working Section. An innovative system for effectively removing the unrepresentative boundary layer formed on the ground plane has been developed. This is an important part of this technique, which was shown to give results comparable with facilities equipped with a rolling road.

The ground plane boundary layer is removed and the flow re-energised by a compressed air driven ejector arrangement. The velocity of the re-energising jet can be controlled to give an integrated boundary layer thickness of zero at the required streamwise position.

Results are presented which show general agreement with data from other established ground effect data sources.

1 Nomenclature

Alpha	Model incidence
b	Wing span
C_L	Lift coefficient
$C_{L\ BLC}$	Lift coefficient in ground effect with boundary layer control or rolling road running
$C_{L\ plain\ ground}$	Lift coefficient in ground effect without boundary layer control or with the rolling road stationary
$dC_{L\ ground\ effect}$	C_L increment due to ground effect
h	Height of moment reference point above ground plane
δ^*	Boundary layer integrated displacement thickness

2 Introduction

Wind tunnels are traditionally used to investigate the effect of ground proximity on aircraft performance. This aerodynamic data is required to calculate take off and landing performance, to ensure that the aircraft meets its field length requirements.

The ground effect test technique used in the Filton Low Speed Wind Tunnel makes use of a movable ground simulation plane. This philosophy is adopted because the aerodynamic forces acting on the wind tunnel model are measured by an external balance mounted above the working section. The model must therefore remain at the measurement centre of the balance, at a fixed height relative to the Tunnel floor. The ground plane is required to bring the Tunnel floor close to the model to investigate the effects of ground proximity.

Using this technique, there is relative motion between the air and ground plane, which forms a boundary layer on the ground plane, unrepresentative of the aircraft flight situation. In flight, the aircraft is moving through nominally still air over a stationary runway, so there is no relative movement between the air and ground plane. The elimination of this unrepresentative boundary layer is therefore central to providing a good wind tunnel simulation of flight in ground effect.

Traditionally, one solution to this problem is offered by a rolling road integrated into the tunnel floor. The speed of the rolling road belt is matched to that of the tunnel air, eliminating the relative motion between air and ground. The tunnel floor boundary layer is also removed just upstream of the rolling road.

During the late 1970’s, work began on improving the ground effect testing technique in the Filton Low Speed Tunnel. It was recognised that a method of removing the unrepresentative boundary layer from the ground plane was required. The integration of a rolling road into the movable ground plane was concluded to be impossible and so an alternative was sought. The use of a compressed air jet to re-energise the boundary layer was considered as an alternative.

In an innovative move, the re-energising jet was supplied by the flow from a compressed air driven ejector, or jet pump, integrated into the ground plane. This arrangement is referred to as a Boundary Layer Control Unit, (BLCU). The ejector nozzles are in the form of two-dimensional slots, providing uniform re-energisation across their span. The use of the ejector principle gave the advantage that the intake for the entrained secondary flow could function as a boundary layer scoop. This removes the boundary layer that has developed on the ground plane upstream of the intake slot. This secondary flow mixes with the compressed air drive, or primary, flow to form the re-energising jet. The amount of re-energisation downstream of the BLCU is controlled by the pressure fed to the primary nozzle.

It was concluded that the best match to the conditions produced by a rolling road would be achieved when the displacement thickness of the boundary layer, δ^*, is reduced to zero in the region of interest.

Initially, two BLCUs were manufactured giving boundary layer control over a span of 1.53 m (60 ins). Comparative tests were then conducted using a two-dimensional VC10 section high lift model. Results measured using the ground plane equipped with BLCUs were compared with results from the rolling road equipped Warton 5.5metre VSTOL tunnel. The good correlation of the results showed that the BLCU concept could provide an alternative to a rolling road for aircraft ground effect work.

Since then, a further two BLCUs have been manufactured to provide boundary layer control over almost the whole width of the ground plane. During 1998, an A340-300 model was tested with this new BLCU arrangement to provide further data for comparison with agreed A340 ground effect data. Following this, the facility was used to provide early data for ground effect on the A3XX.

3 The Facility

3.1 Filton 12’ x 10’ Low Speed Wind Tunnel

The Filton 12’ x 10’ Low Speed Wind Tunnel was completed in 1957 and is an atmospheric, return circuit tunnel. The geometry of the working section and plan of the circuit are shown by Figure 1.

The tunnel has a contraction ratio of 6.65 and a conservative main diffuser angle of 5°. Power is supplied by a 2000hp A.C. electric motor driving the 6.7m (22ft) fan via a 90° gearbox mounted in the bullet. Flow conditioning is by two gauzes producing a turbulence level of 0.16%. The tunnel can achieve Mach 0.28 when empty.

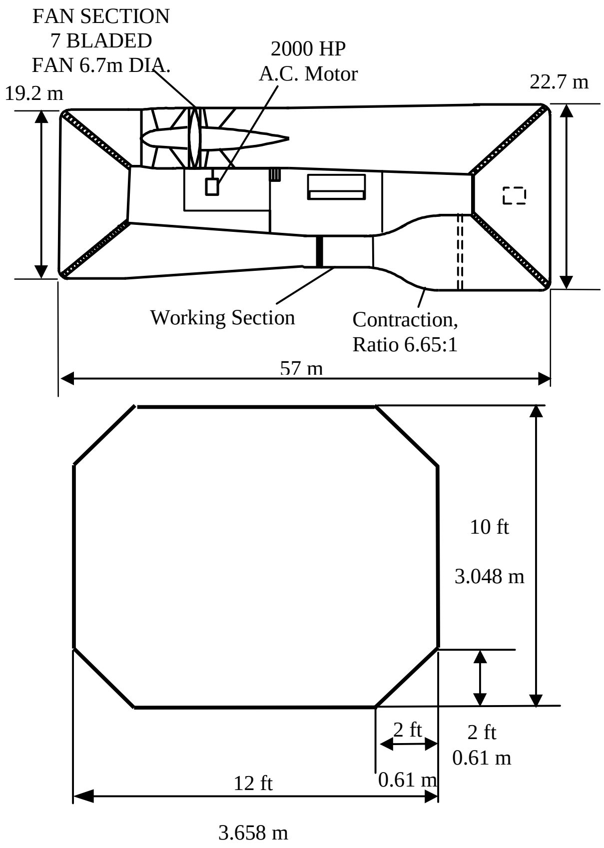

Figure 1. The Filton Low Speed Wind Tunnel circuit plan and working section geometry

At present, the forces acting on the model are measured by external six-component electro-mechanical balances. The balance situated above the working section is used for ground effect testing and is the original balance built for the tunnel, although its electro-mechanics have been upgraded since then. For ground effect work the model is mounted on a single central strut and the incidence controlled by twin pitchwires. This convenient arrangement is shown by Figure 2.

In 1992, a new six-component electro-mechanical balance was installed under the working section. This balance can accommodate both full and half models. The location of this balance precludes its use for ground effect testing.

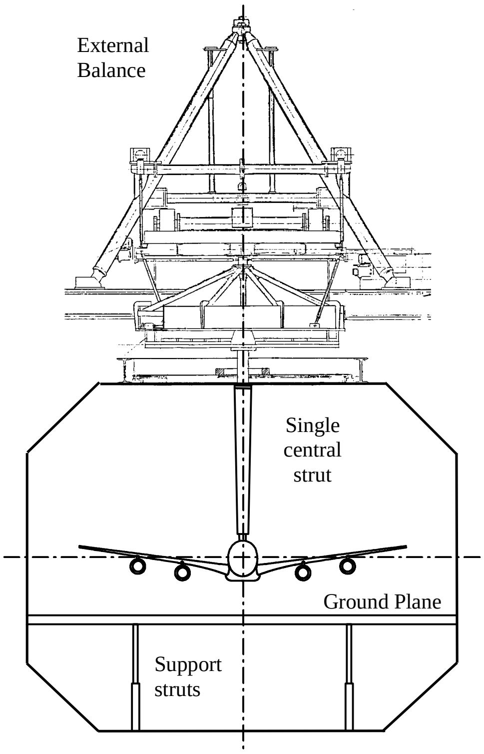

Figure 2. Ground effect testing arrangement

3.2. The Ground Plane

The movable ground plane spans the tunnel working section, giving it a width of 3.66m (12ft), for a length of 6.36m (20.8ft). This is illustrated by Figures 2 and 3.

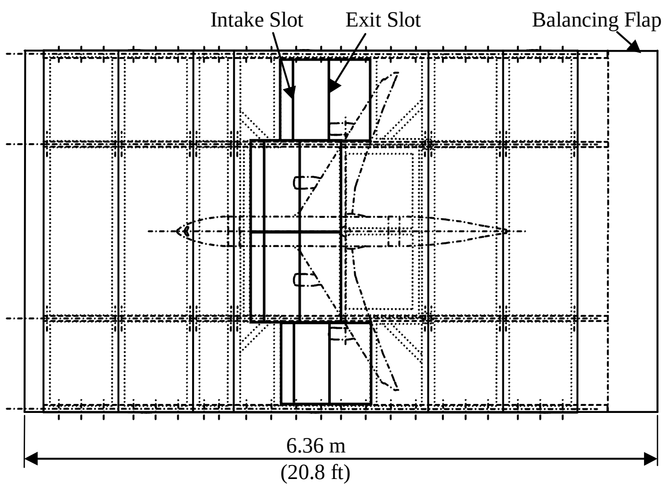

Figure 3. Plan view of the ground plane showing the BLCU positions and A340 model

To minimise tunnel blockage, the ground plane has a thickness of only 61mm. It is supported on rails fixed to the tunnel walls and extra stiffness is imparted by four support struts fixed to the tunnel floor. The holes for the support rails in the tunnel walls allow the ground plane height to be adjusted in pitches of 1 inch (25.4mm). The lower limit of ground plane movement is defined by the mounting rails contacting the lower corner fillets. This happens with the ground plane rigged 0.74m (29ins.) below the tunnel centreline.

The ground plane itself is made in modular sections to ease rigging and allow the BLCUs to be positioned as required. The ground plane leading edge of is formed by a symmetric aerofoil section equipped with a splitter plate. The aerodynamic loads on the ground plane are neutralised by adjusting the electrically driven flap section at the rear. These adjustments are made manually, based on the readings on two rows of static pressure tappings in the leading edge section, on either side of the splitter plate.

3.3. The Boundary Layer Control Units

The elimination of the boundary layer on the upper surface of the ground plane is achieved using four separate BLCUs. The outboard units are installed downstream relative to the inboard units to match the sweep of the model being tested. This arrangement was adopted to ensure that the $\delta^* = 0$ condition could be reached in the region of the wing's trailing edge.

A BLCU is shown in section by Figure 4. This shows how the ejector ducting is integrated into the thickness of the ground plane. The compressed air to drive the BLCU is supplied by a single 64mm diameter flexible pipe. This is connected to a manifold section, which feeds the primary nozzle through six smaller tubes. The Pitot pressure in each of these tubes can be monitored, although usually the one with the lowest distortion from the mean is taken to represent the nozzle pressure, Pn.

To improve the flow uniformity at the primary nozzle exit, gauzes are fitted upstream in the plenum section of the nozzle. The nozzle exit gap itself is only 0.61mm and it is challenging to maintain the required uniformity of gap across the span of the BLCU.

The ducting around the primary nozzle is shaped to assist the entrainment of the secondary flow by the primary jet. Beyond the primary nozzle exit, there is a short parallel sided section, where the primary and secondary flows mix. The upper face of this duct contains a hinge, so that the exit duct gap can be adjusted. Large exit slots increase the secondary flow, but make the re-energising jet rather deep. Conversely, small exit slots may reduce the secondary flow until the upstream boundary layer is no longer removed by the suction slot.

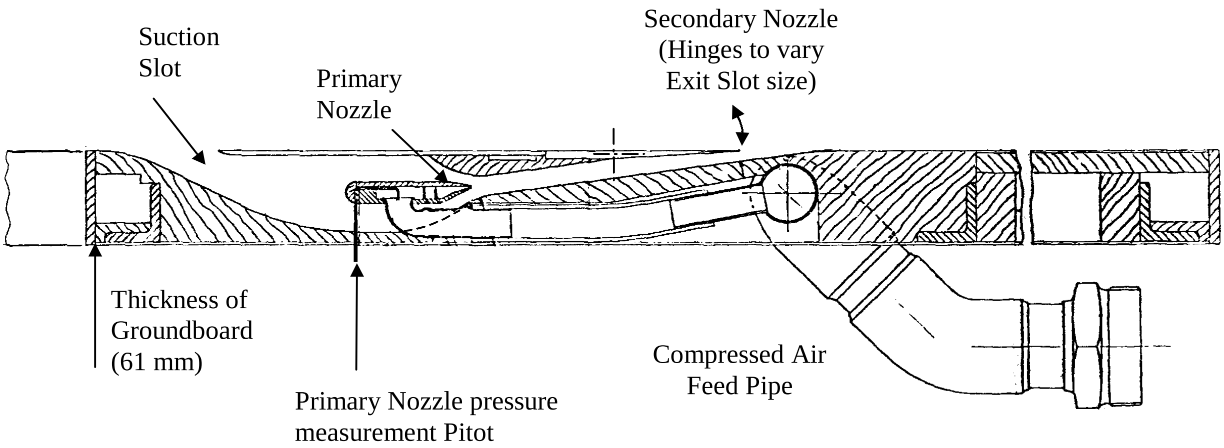

Figure 4 Section through a Boundary Layer Control

3.4. The compressed air system

The compressed air system used to drive the BLCUs is supplied by air at 6.8 bar from the Filton site compressors and is then boosted to 19 bar by a compressor in the Wind Tunnel building. This arrangement can supply a mass flow of 0.5 kg/s. The compressed air is stored in two buffer tanks with a combined volume of 100 m^3. This is sufficient to run the four BLCUs for over an hour, with the compressor running.

The air drawn from the tanks passes through an automatic pressure control valve and then on to a manifold section with four outlets, one for each BLCU. In each BLCU feed line there is a remote controlled ball valve to adjust the relative pressures in each line. These four feed lines enter the tunnel through the diffuser floor and are connected to the BLCUs by flexible pipes.

4 Test Procedure

4.1. BLCU Calibration

Initially, the ground plane is tested in isolation to calibrate the BLCU settings required to achieve the desired boundary layer conditions. The boundary layer characteristics are measured by an array of boundary layer rakes. For the A340 and A3XX test series, these rakes were distributed across the span of the A340 model, in line with the wing's trailing edge.

The impact on the boundary layer profiles as the primary nozzle pressure is increased is then evaluated. A typical sequence of boundary layer profiles is shown by Figure 5. Values of δ^* are calculated and the primary nozzle pressure required to achieve $\delta^* = 0$ recorded for each rake. A judgement is then made on the primary nozzle pressure required to give the best distribution of $\delta^* = 0$ behind each BLCU. This then becomes the setting that is used when the model is installed.

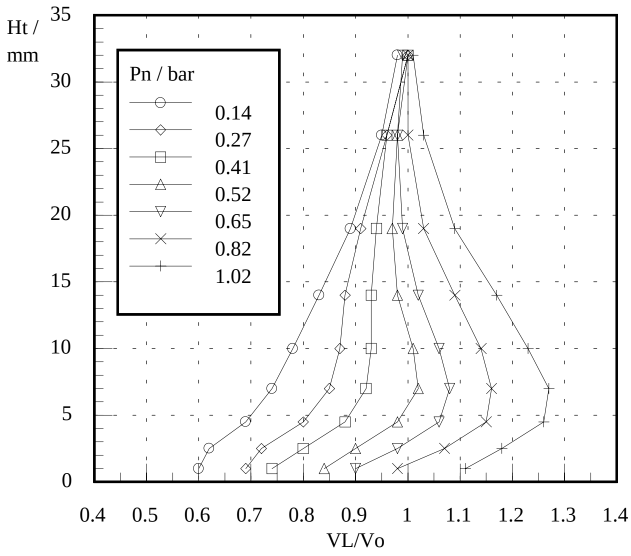

Figure 5 Boundary layer profile sequence as primary nozzle pressure is increased

It may be necessary to change the exit slot gap to achieve the required conditions. This was required for the newly constructed centre BLCUs during the calibration for the A340 test series. The effect of this on BLCU performance is shown by Figure 6.

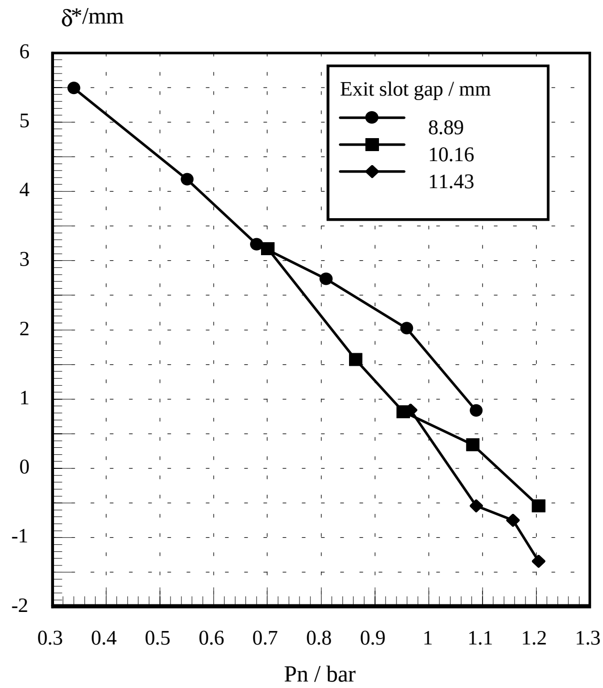

Figure 6. Effect of increasing the exit slot gap

The increase in exit slot gap was required because the central BLCUs were placed further upstream than is usual to ensure that the exit slot was upstream of the wing root's leading edge. Increasing the exit slot gap enables the BLCU to operate efficiently at higher primary nozzle pressures. This is illustrated by Figure 6, by the clear general relationship between δ* and primary nozzle pressure which breaks down at a given point for each exit slot gap. Increasing the exit slot gap has the effect of continuing the original trend to a higher primary nozzle pressure.

4.2. Testing with model installed

Once the required primary nozzle pressures and exit slot gaps are defined, the model is installed to begin the test programme. The boundary layer rakes are removed when testing with the model installed, as shown by Figure 7. This shows an early development test with an A340 model before the additional BLCUs were constructed.

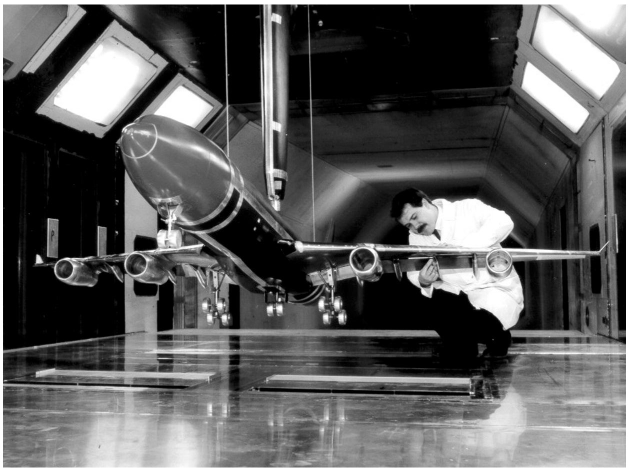

Figure 7 An early A340 ground effect test using two BLCUs

The required test polars can be conducted as for a usual test. In the Filton Low Speed Wind Tunnel, ground effect polars are generally incidence sweeps conducted using a pitch-pause technique at a constant ground plane height.

The operational simplicity of the ground plane test technique enables the testing to be conducted with little extra test crew resource than for a conventional force and moment measurement test.

5 Results

5.1. Comparisons Between the BLCUs and a Rolling Road

During 1979, a two-dimensional high lift panel model of a VC 10 wing section was tested to compare ground effect results from a rolling road equipped facility and the Filton BLCU system. At this early stage, only two BLCUs were available, giving a continuous 1.53 m (60 ins) span of boundary layer control. The model had a span of 1.22 m (4ft) and an aspect ratio of 6. The model was configured with landing flap and slat angles.

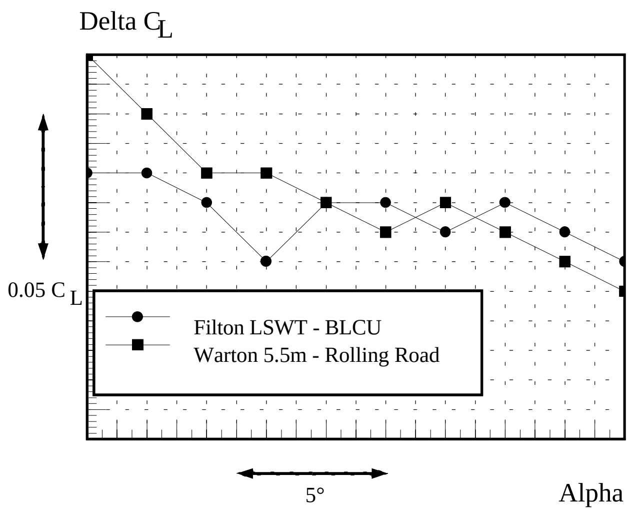

Figure 8 Comparison of C_L increments due to the rolling road or BLCU

For the rolling road part of the programme, the Warton 5.5 metre VSTOL tunnel was used. For comparison, runs were also made with the road stopped and without boundary layer control.

Figure 8 shows the C_L increments due to boundary layer control and running the rolling road, against model incidence. That is:

$$Delta\ C_L = C_{L\ BLC} - C_{L\ plain\ ground}$$

The results presented are for a h/b of 0.15.

The results show that boundary layer control can give results comparable to those from a facility equipped with a rolling road.

5.2. Data from the A340-300 tests

During 1998, two further BLCUs were manufactured to give boundary layer control across almost the whole width of the ground plane. These new units are slightly larger, with a total span of 1.69m and are used as the central units in the arrangement shown by Figure 3.

The 19th scale A340-300 model was then tested in a range of high lift configurations over the range of possible ground heights. The configurations were also tested without the ground plane to provide free-air datums to allow ground effect increments to be calculated.

The BLCUs were configured as described above, to provide $\delta^* = 0$ in the region of the wing trailing edge. Figure 9 presents some results for ground effect, for take-off and landing configurations. These results are for a h/b of 0.109.

The data from the Filton Low Speed Wind Tunnel is compared with agreed reference data for the A340-300, from established ground effect measurement facilities.

5.3. The A3XX test series

During 1999, the 28th scale A3XX model was tested using the same ground plane configuration and test methodology as for the A340-300 entry. This arrangement is illustrated by Figure 10. A range of high lift configurations were tested over the available range of ground heights. These included the aircraft-on-ground condition.

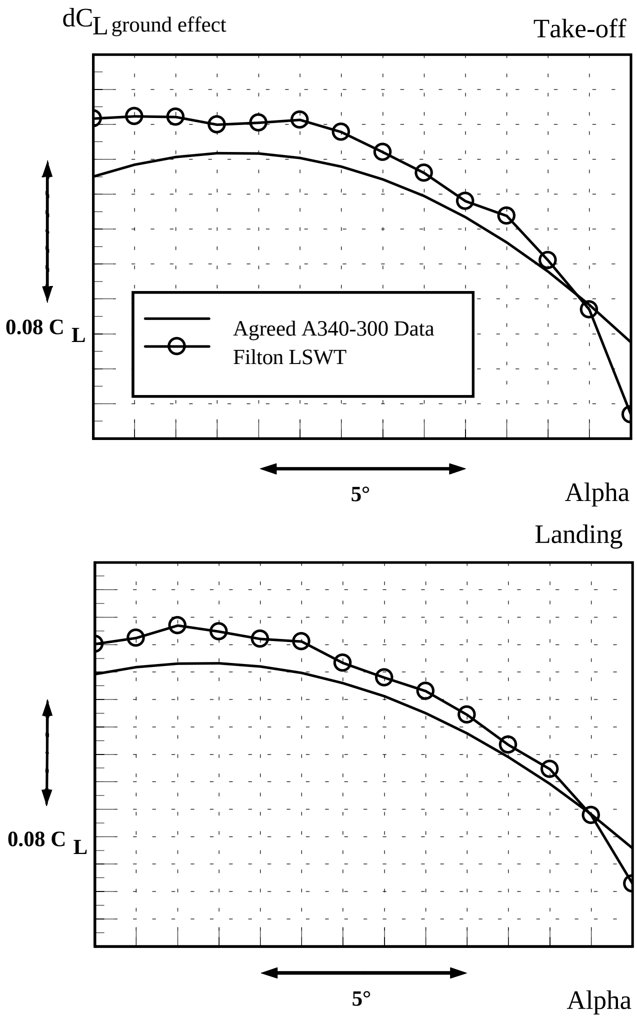

Figure 9 Ground effect comparisons for the A340-300

Figure 11 shows the effect of boundary layer control on the ground effect results at the aircraft-on-ground condition. This clearly shows the significance of boundary layer control in producing results for ground effect.

6 Concluding remarks

From the above, it may be concluded that the Filton Low Speed Wind Tunnel have been successful in developing and validating a ground effect measurement technique based upon boundary layer control as an alternative to a rolling road. This system has been demonstrated to produce credible results for aircraft configurations at lower cost than that required for a rolling road.

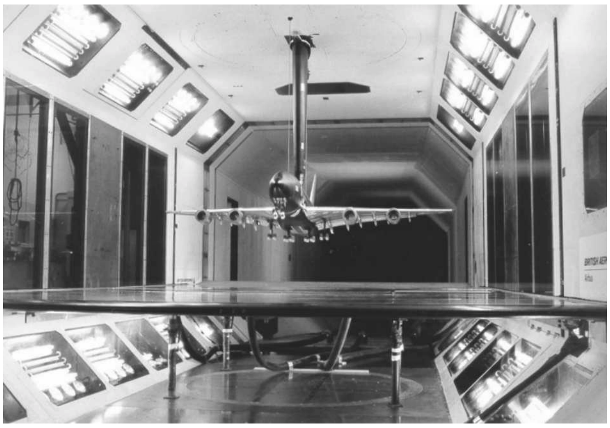

Figure 10 The A3XX model in the Filton Low Speed Wind Tunnel above the ground plane

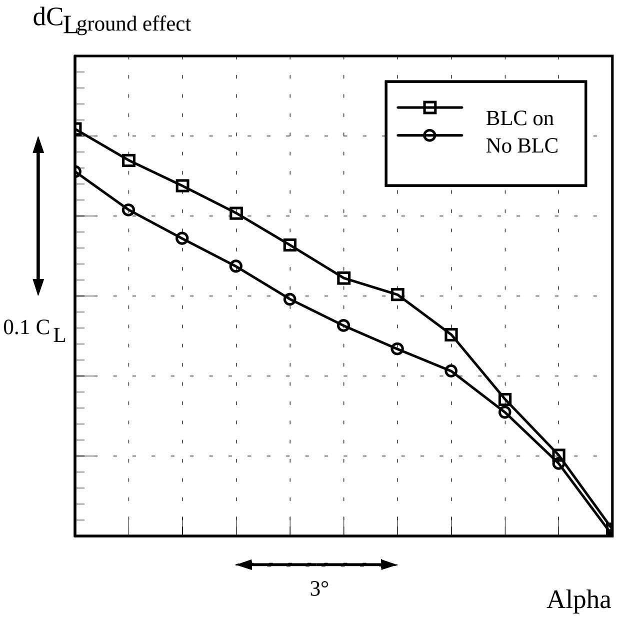

Figure 11 Influence of boundary layer control on ground effect on A3XX, aircraft-on-ground