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THE AERODYNAMICS OF THE *AURORA* SOLAR-POWERED VEHICLE

Simon Watkins[1], Bill Liu[1] and Clive Humphris[2]
[1] Mechanical and Manufacturing Engineering
RMIT University, Victoria, AUSTRALIA
simon@rmit.edu.au 03 9925 6084
[2] The Ford Motor Company of Australia

ABSTRACT

Experimental results are presented for force coefficients under a range of yaw and pitch angles for the full-size *Aurora* Solar Vehicle. Flow visualisation showed negligible separation, except at the rear of the wheel spats. High speed tests at extreme yaw and pitch angles indicated that under the worst operating conditions all three wheels would remain in contact with the ground. Boundary layer measurements over the top surface (ie the solar array) indicated that under normal driving conditions a laminar boundary layer would be maintained for approximately 3/4 of the vehicle length. It was concluded that only very minor drag reductions could be achieved with further design refinement.

INTRODUCTION AND OBJECTIVES

"On 7 January 1983, Australian adventurer, Hans Tholstrup arrived at the steps of the Sydney Opera House driving a type of car the world had never seen before - one powered solely and directly by sunlight. Twenty days earlier, he and engineer/racing driver Larry Perkins had set off from the west coast of Australia in the fragile *Quiet Achiever.*" See Figure 1.

Since then the World Solar Challenge (WSC), an event in which solar-powered cars race from Darwin to Adelaide, has been held four times attracting teams from all over the world. Tholstrup's first crossing of Australia was at an average speed of 23 km/h - in October 1996 the WSC was won by the Honda *Dream* at an average speed of 90 km/h and several solar-powered vehicles are now able to maintain a speed of well over 100 km/h. The power available is limited by the surface area permitted in the WSC rules (8 square metres), the solar flux on the earth's surface (about 1000 W/m^2) and the efficiency of solar cells. With the highest solar cell efficiency reaching about 24% the total power available is less than 2 KW, with many teams solar arrays producing just over 1 KW. Clearly the minimisation of aerodynamic drag and the maximisation of the projected array area are important requirements, consistent with aerodynamic stability of a vehicle which has low mass and a large potential lifting area.

There are many possible exterior geometries; these include flat solar arrays attached to streamlined bodies or a more integrated approach where the vehicle body is covered with solar cells such as the GM *Sunraycer* and the Honda *Dream*. In the 1996 WSC the first six vehicles were of the latter type; (see Roche et al (1997) for further details).

In this paper some of the aerodynamics of the Australian *Aurora* vehicle are presented including full-scale wind-tunnel testing. The vehicle is shown in Figure 2 undergoing testing in the Monash/RMIT Wind Tunnel. As can be seen, the *Aurora* vehicle is also a vehicle with an integrated solar array although it differs from the *Sunraycer* and *Dream* by having a less curved solar array/body and a small "bubble" canopy. The main part of the upper surface of the body is covered with 4,000 high efficiency solar cells.

Force measurements, flow visualisation and boundary layer measurements were made in order to understand the drag mechanisms and to look for possible areas of drag reduction. In addition, the aerodynamic safety of the vehicle was determined by setting the vehicle to a combination of high yaw and pitch angles whilst subjecting it to a velocity of 140 km/h.

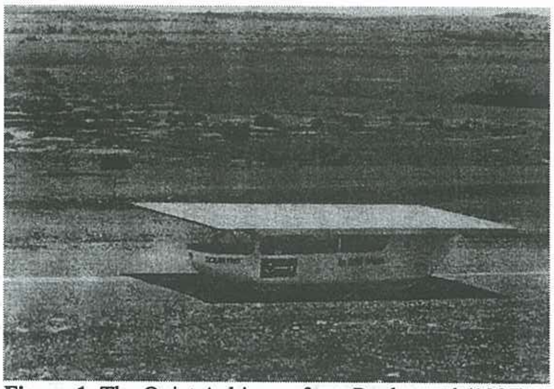

Figure 1 The Quiet Achiever, from Roche et al (1997).

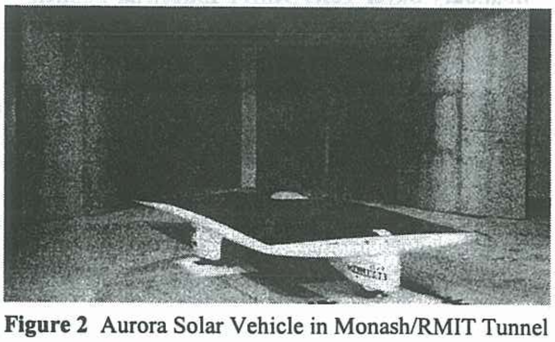

Figure 2 Aurora Solar Vehicle in Monash/RMIT Tunnel

EXPERIMENTAL DETAILS

Two different tunnels were utilised - The Monash/RMIT Aeroacoustic Tunnel and the RMIT Industrial Tunnel. Force and moment measurements and flow visualisation were conducted in the Monash/RMIT Tunnel and boundary layer measurements were conducted in the RMIT Industrial Tunnel.

Force, Moment and Flow Visualisation Tests (Monash/RMIT Tunnel)

The Monash/RMIT Tunnel is a 3/4 open jet tunnel capable of accommodating full-size road vehicles and has been described by Saunders et al. (1997). The blockage effects were insignificant for the tests described here.

Initial testing on a representative vehicle was carried out in early 1995 (not reported here). Subsequent tests were performed on the road vehicle. It is normal practice when testing roadgoing vehicles in wind tunnels to rely on the hand or park brake and the friction at the tyre/floor interface to restrain the vehicle. However, this was not thought sufficient for the Aurora vehicle due to the relatively light weight and the large potential lifting surface provided by the body (and the vehicle's considerable cost!). A system of "lazy chains" was utilised so that if the vehicle moved more than approximately 100 mm during testing it would be restrained by the chains, whereas if the vehicle did not move the tare drag should be relatively low. Initial runs with the vehicle at high pitch and yaw angles and at the maximum tunnel speed indicated that it was safe to remove the chains and eliminate the tare drag of this safety system. Further, this also indicated that even under the worst possible operating conditions (eg very strong atmospheric crosswinds giving a high relative velocity and yaw angle, combined with a nose up pitch from a suspension movement) all three of the vehicle's wheels would remain in contact with the ground.

The force balance was a modified version of the piezo-electric four-point, three-component, balance normally used for four-wheeled road vehicles. One three component balance was placed under each of the *Aurora* vehicles three wheels and the force data were sampled for about one minute. PC-based software reduced the nine forces to three force and three moment coefficients.

The vehicle was yawed (to reproduce the relative wind velocity under crosswinds) from -20 to +20 degrees in 5 degree increments. The effect of vehicle pitch was also investigated by raising and lowering the heights of the two rear suspension mounts. This was to investigate the pitch angle for minimum drag.

Boundary Layer Tests (RMIT Industrial Tunnel)

The RMIT Tunnel has a closed test section of size 3m x 2m. Due to the size of the vehicle (approximately 2m wide by 4.4m long) considerable modification had to be made to the RMIT Tunnel to get the vehicle into the test section and the length of the vehicle precluded yawing. The blockage ratio was 12% and no corrections were made. A boundary layer rake was used to measure velocity close to the surface and measurements were made along two lines parallel to the vehicle centreline, one on the vehicles top surface and one on the lower surface.

RESULTS AND DISCUSSION

Force, Moment and Flow Visualisation Tests

Figure 3 depicts the force coefficient characteristics as a function of yaw angle. As expected, the sideforce is a linear function of yaw angle, with a minor (less than one degree) shift in the effective zero yaw angle, probably due to minor set-up or flow angularity errors. The negative lift coefficient indicates a downforce, which whilst beneficial to tyre traction forces, may indicate that a lower drag coefficient may be achieved if the component of drag due to induced lift could be reduced. However upon examining the drag versus pitch curve (Figure 4) it is evident that the pitch angle for zero lift is not the same angle for minimum drag. The changes of drag coefficient with pitch angle are, however, minor and the vehicle will normally be set to zero degree pitch.

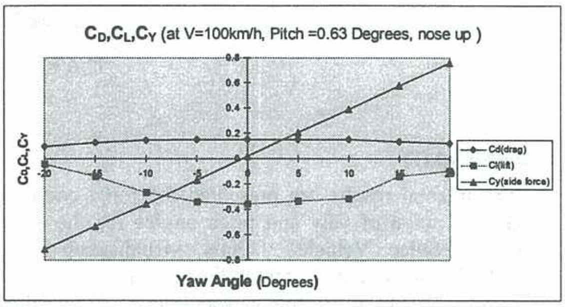

Figure 3 Force Coefficients vs Yaw Angle

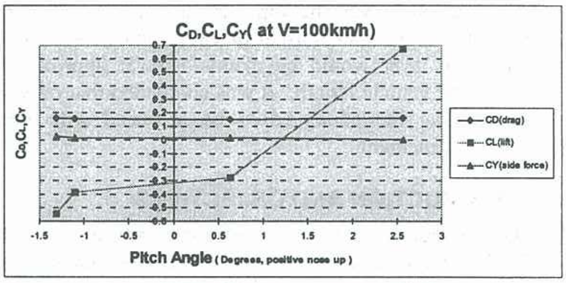

Figure 4 Force Coefficients vs Pitch Angle

Woollen tufts were used to visualise the flow around the vehicle (via a long telescopic rod) and also on the surface of the vehicle, in order to identify areas of separated flow. It was evident that there was minimal separation around the body/solar array, including at the rear of the bubble canopy. However some separation was evident at the rear of the wheel spats, even under zero yaw, see Figure 5. The wheel spats had been recently widened (to allow the fitting of an upgraded braking system). A reduction in width of the spats is clearly beneficial and this is the subject of on-going work.

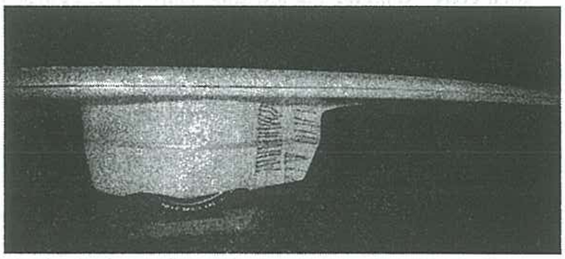

Figure 5 Flow at the Rear of the Wheel Spats

Boundary Layer Tests

Boundary layer measurements along a line parallel to the vehicle centreline, but laterally removed by 480 mm, are presented in Figure 6 and the growth in boundary layer heights are plotted as a function of distance along the vehicle in Figure 7. It appears that the layer undergoes transition at approximately 3m from the vehicle leading edge, which, since the tests were conducted in air at a test velocity of 25 m/s gives a Reynolds number at transition of 5 million. Similar work on the underside of the vehicle (not presented here) indicated that the boundary layer was disturbed by cooling air intake and outlet and the presence of the wakes of the wheels spats.

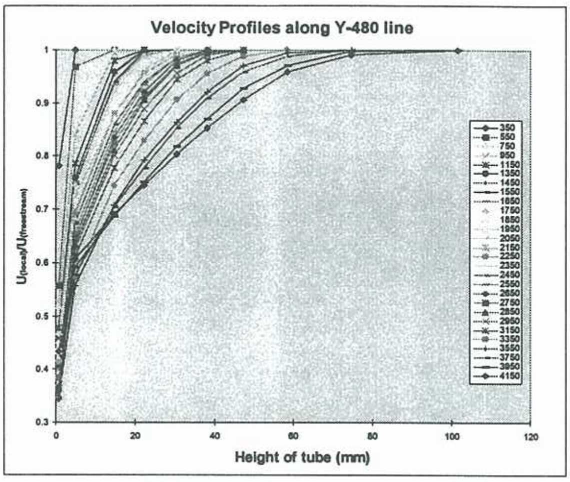

Figure 6 Boundary Layer Profiles

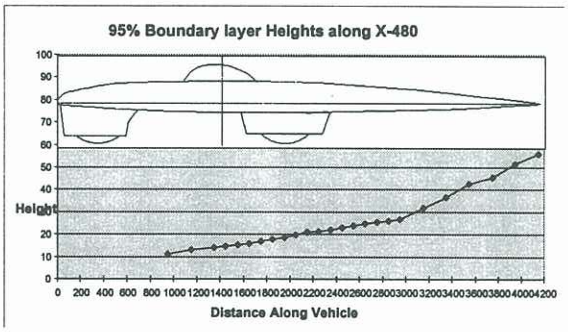

Figure 7 Growth of the Boundary Layer

CONCLUSION

- The *Aurora* Solar vehicle has a body-axis drag coefficient of 0.15 at its intended design pitch. Changes of pitch from this setting will make no significant reduction to the drag coefficient.
- The lift coefficient is slightly negative under all typical road conditions.
- All three wheels will remain in contact with the ground under all normal operating conditions.
- Minor separations were only evident around the rear of the wheel spats. Reduction of spat width, consistent with careful streamlining will permit further minor drag reduction.
- A laminar boundary layer is evident for 3m along the top surface of the vehicle. It seems unlikely that further refinements to surface finish will give significant further drag coefficient reductions.

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