Aerodynamics Analysis of Formula One Vehicles

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ABSTRACT

Formula One vehicles are fitted with a variety of aerodynamic devices. This produces complex mutual interference in the air flows around the vehicles, generating highly nonlinear flows. The clarification of these aerodynamic phenomena helps to enable efficient optimization of aerodynamic devices. This paper will provide some examples of findings regarding the air flows around Formula One vehicles obtained using wind tunnels and CFD.

1. Introduction

The shapes of the aero parts employed on Honda Formula One vehicles were optimized using 50% model wind tunnel tests and CFD[1]. The chief consideration during this process was the tradeoff between downforce, the front-rear balance of downforce, and drag. Mutual interference between the air flows around these aero parts produced a strong non-linearity in the air flows around the vehicles, and in practice it was not possible to clarify the mechanism of all aerodynamic phenomena. However, the use of CFD to analyze the core aerodynamic phenomena did generate new findings concerning the air flows around Formula One vehicles. This paper will discuss some of these findings.

2. The Entire Air Flow around the Vehicle

2.1. Ground Effects

This section will provide a simple discussion of two-dimensional and three-dimensional ground effects. The chief two-dimensional ground effect is an increase in dynamic pressure and a decrease in upwash (a change in the angle of the wake in an upward direction) due to mirror images of the wings (Fig. 1). Because the upwash of the wing is the angle of attack for aero parts behind it, it plays a particularly important role in aerodynamics involving multiple bodies, as in Formula One vehicles. A reduction in upwash and a reduction in induced drag due to mirror images of tip vortices can be indicated as three-dimensional ground effects (Fig. 2).

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2.2. The Entire Flow around the Vehicle

For the reasons discussed in Section 2.1., in addition to generating downforce close to the ground, it is also important to actively generate lift, which may initially appear disadvantageous, in areas more distant from the ground. In parts in which the influence of ground effects is minimal, a significant downwash can be generated by a small lift, and this can be used to increase the downforce of the rear parts. To do so, lift-generating parts called “bunny ears” and “fox ears” (see Chapter

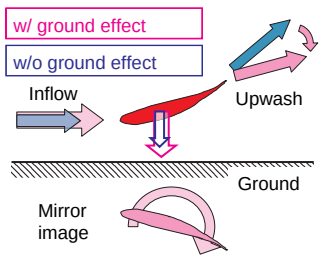


Fig. 1 2D ground effects

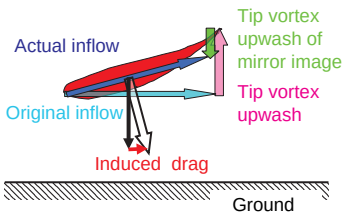


Fig. 2 3D ground effects

4) were fitted on the upper part of the vehicle in order to direct the upwash from the front wing (FW) downwards and boost the performance of the floor, the diffuser, and the rear wing (RW) (Fig. 3). The front suspension arm and the nose also play a role in generating downwash. This can be seen from the static pressure distribution on the upper and lower surfaces of the vehicle (Fig. 4).

This section has offered a rough picture of the air flow around the vehicle, but the actual flow is composed of countless small and large flow phenomena. The following pages will present a discussion of some of these phenomena.

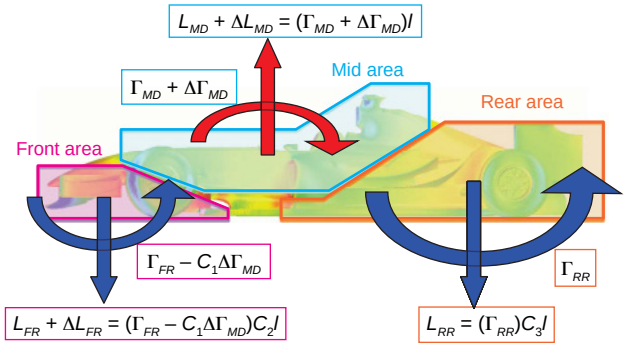


Fig. 3 Ideal chassis circulation

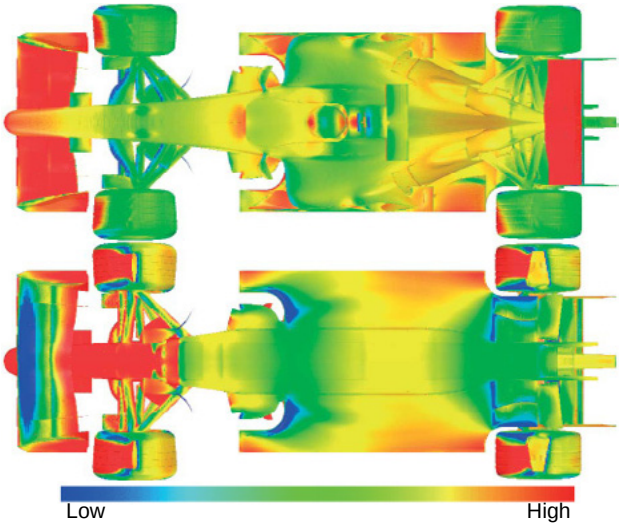


Fig. 4 Surface static pressure

3. Front Wings (FW)

The downforce produced by the FW (Fig. 5) represents approximately 20-25% of the downforce of the entire vehicle. In addition, the aerodynamic balance (CoP) of the vehicle is extremely sensitive to the FW downforce, and it therefore plays a role in the adjustment of the CoP of the entire vehicle, through alteration of the flap angle.

Because the FW is positioned upstream, the upwash and tip vortex it produces have a significant effect on flows at the rear of the vehicle, and they also display a high degree of sensitivity to changes in vehicle orientation produced by steer, pitch, and other factors. These characteristics, in addition to the fact that the range of adjustment of the CoP must be considered, make the FW the device on which most time is expended in wind tunnel development.

3.1. Effect of FW Downforce and Consequent Upwash

The ground effect of the FW has a beneficial effect on the lift-drag ratio, and also controls upwash to a certain extent. However, if the downforce generated by the FW is too strong, the limit of the lift generated by the suspension arm and other parts behind the FW can be reached, and upwash from the FW can reduce the angle of attack on the devices at the rear of the vehicle, and consequently reduce the downforce of the vehicle. In addition, the wake from the FW and the suspension arm can also reduce the dynamic pressure close to the RW, resulting in a decline in the RW downforce (Fig. 6). Because of this, it was necessary to control the downforce of the FW to a specific value or below, rather than maximizing it. The surplus that this produces in the regulation box[1] was used for a variety of purposes, including the reduction of steer sensitivity.

In concrete terms, the height and shape of the FW were adjusted in the Y direction in order to help improve the upwash distribution and the steer sensitivity. It was necessary to optimize the wing tips in coordination with the front wing end plate (FWEP), which will be discussed below.

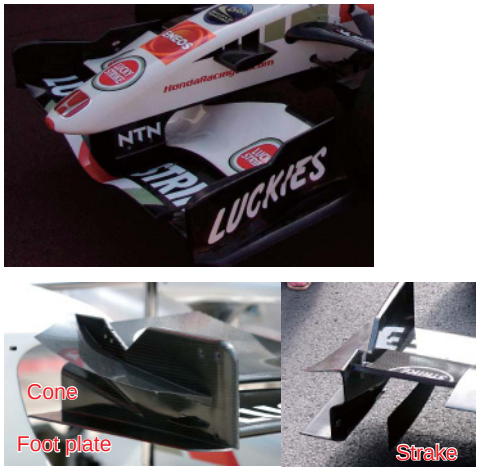


Fig. 5 Front wing

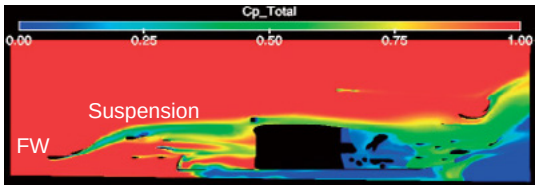


Fig. 6 Suspension stall (CpT, Y=300 mm)

3.2. FW Tip Vortex and Tires

Another issue in FW development was the treatment of the tip vortex shed by the FWEP. Until 2008, the FWEP vortex was shed to the lower sections of the inboard faces of the tires. A separation vortex generating a significant total pressure loss was shed from the leading edges of the lower sections of the inboard faces of the tires (Fig. 7). One measure considered was to merge the separation vortex and the FWEP vortex; the merged vortices would remain in the same position (the YZ position)as they go downstream, which would prevent the vortices from going into the inboard side of the vehicle and help to prevent the loss of dynamic pressure underneath the vehicle floor (Fig. 8). It was necessary for a stable FWEP vortex to be shed at an appropriate position and at a strength at which vortex breakdown would not occur.

In addition, the effect of steer could not be ignored in FW development. Steer accompanies yaw angles in the flows, and FW was optimized to help ensure that it would not result in large variations between steer case and no-steer case in the relationship between the positions of the separation vortex shed from the inner lower section of the windward tire and the FWEP vortex.

The FWEP tip vortex could be controlled by adding appendages to the FWEP, or using a flat plate called a foot at the bottom of the FWEP and a semi-conical plate called a cone at the rear-end of the FWEP. It was also possible to adjust the strength and position of the tip vortex by means of the longitudinal vortex produced by the strake, a perpendicular plate positioned in the center of the FW (Fig. 5).

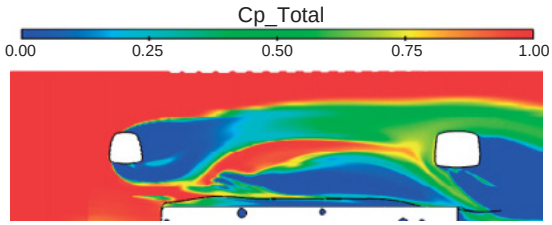


Fig. 7 Tire LE separation wake (CpT, Z=0 mm)

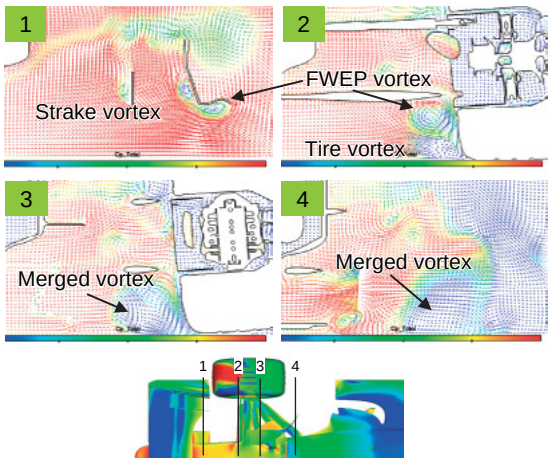


Fig. 8 FWEP and tire vortices (CpT, velocity vector)

In addition to this, a variety of other methods were employed, including raising the mounting position of the outboard sides of the lower front suspension arm in order to help prevent changes in air flow around the front suspension due to changes in the vehicle ride-height from affecting the position of the FWEP vortex.

4. Chassis Upper Devices

The chassis upper refers to the area extending from the nose and the upper section of the monocoque to its sides. While there are virtually no stipulations in the regulations regarding limits on the vehicles in the direction of height, the height of the front rollhoop is the effective maximum height based on considerations of visibility for the driver and safety around the cockpit.

Chassis upper devices mainly contribute to increasing downforce under the floor of the vehicle and from rear components such as the RW by means of the downwash generated by lift.

4.1. Front Suspension Arm

The front suspension arm is the part that plays the greatest role in deflecting the upwash flow from the FW downwards by means of lift (Fig. 9). If no front suspension arm was used, control of the position of the barge-board vortex (see section 5.2.) would cease to function entirely.

However, as the suspension is not allowed to be used as an aero part, there are restrictions on the aspect ratio of the cross-sectional thickness to the chord length of the suspension members and their angle of attack. Because of this, the upper section of the suspension arm can be stalled by the upwash from the FW. The cross section of the suspension arm and the suspension geometry were therefore adjusted, among other measures, in order to maximize the aerodynamic effect.

4.2. Bunny Ears and Fox Ears

Bunny ears that attach to the upper section of the nose (Fig. 10) are another device that creates a downwash. However, the bunny ears have more effect in increasing the angle of attack to the RW than in increasing the suction underneath the vehicle. Consequently, while they increase downforce, the lift-drag ratio of the vehicle, being dependent on that of the RW, does not improve. For this reason, bunny ears can be indicated as a device that is particularly effective on

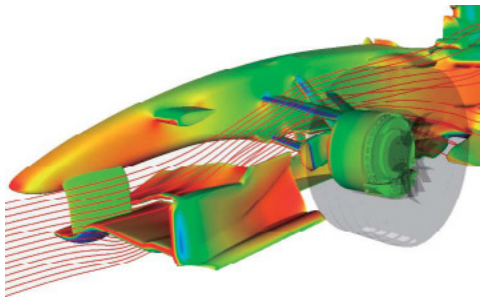


Fig. 9 FW upwash deflection by suspension arm

high-downforce circuits. In addition, because there are few aero parts on the upper section of the chassis, the position of the tip vortex from the bunny ears remains stable to vehicle orientations and disturbances, which makes the bunny ears effective in crosswinds (Fig. 11). The use of bunny ears resulted in an increase of approximately 2% in maximum downforce.

Fox ears (Fig. 12) are fin-shaped devices mounted in front of the mirrors. Like bunny ears, fox ears increase the angle of attack to the RW, in addition to which they contribute to increased downwash to the vehicle floor. This downwash also affects the position of the longitudinal vortex of the barge board. The Formula One regulations state that aero parts in this area can only be positioned above parts fitted to the floor of the vehicle (the shadow rule). This added the limitation that the fox ears must not extend past the projection on the XY plane of the water wings (”WW” below; Fig. 13) directly below them. In addition, while the effect of the fox ears would increase the higher the outer tips were positioned, the potential obstruction of the driver’s field of vision significantly limited the degree of freedom of the shape of the device.

Fig. 10 Bunny ears

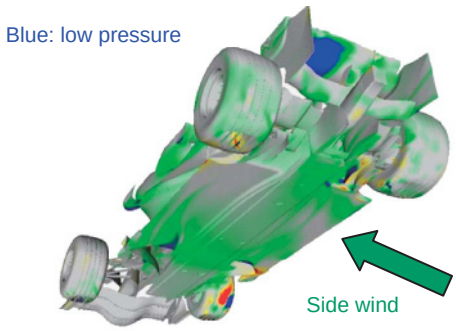


Fig. 11 Effect of bunny ears (delta Cp)

Fig. 12 Fox ear

5. Chassis Lower Devices

The chassis lower area refers to the area from the front axle to the front ends of the side pods (Fig. 13). There are many regulation stipulations regarding minimum heights and maximum widths in this area. The shadow rule also applies across almost the entire area, and there are many regulations concerning the shapes of parts. In addition to the increase in downwash by means of lift, as achieved by chassis upper devices, downwash is also generated by longitudinal vortices. By this means, the mass flow under the floor is increased, and downforce is generated even by devices in front of the floor. Because of this, it is necessary to consider interference between almost all devices from the FW to the diffuser, and the level of contribution of this area to vehicle performance is high, making it important in terms of aerodynamic performance.

5.1. Barge Board Longitudinal Vortex Control

The barge board (Fig. 14) functions to generate a downwash in front of the floor of the vehicle by controlling the longitudinal vortices that it produces. The shape of the barge board varies between teams, but its role in each case is generally identical.

The cambered barge board produces upper and lower tip vortices (Fig. 15). Directly behind the barge board, the flow induced between the vortices is directed outboard of the vehicle. As it moves downstream, the upper vortex moves outboard and downwards by the lower vortex, the vanes, the suspension, the side pods,

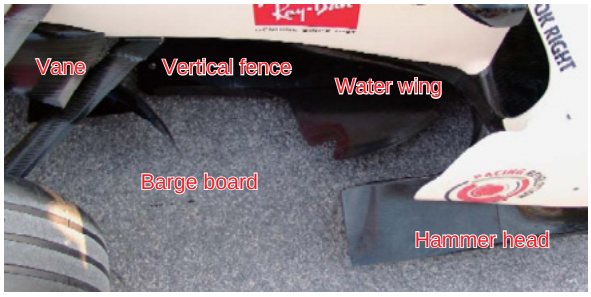


Fig. 13 Devices on chassis lower section

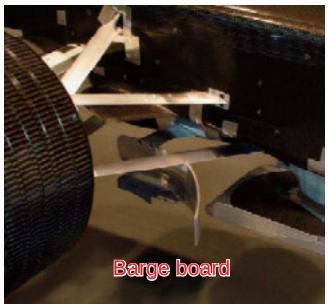


Fig. 14 Barge board

and other parts. The lower vortex proceeds downstream, increasing in intensity as it induces longitudinal vortices at the vertical fence and the WW. Because of this, and also due to ground effects, the lower vortex, shed from the barge board, remains in the same YZ position as was shed from the barge board. In this way, a displacement in the Y direction is produced in the upper and lower vortices, and the flow induced between the vortices is directed downwards. This is a downwash produced by the barge-board longitudinal vortices. This downwash increases the angle of attack towards the underfloor, and increases suction at the leading edge of the floor. In addition, while the effect is small, downforce is also increased by the suction of the lower vortex itself that flows under the floor of the vehicle. However, excess suction at the leading edge of the floor and total pressure loss at the center of the lower vortex can promote growth of the boundary layer on the floor and result in a decrease in diffuser performance. Because of this, the sequence of aero parts to be optimized and setting priorities in optimization are important issues.

The barge board does not produce any other effects as significant as the downwash effect produced by the longitudinal vortices, but it does play another role. Figure 16 shows a comparison of streamlines with and without a barge board. The outward flow created by the barge board pushes the separation wake of the leading edge of the inboard lower section of the front tire outwards, helping to prevent a decrease in diffuser performance. However, very little change is observed in the large separation flow at the back of the tires whether or not a barge board is used. Along with the fact that the separation wake from the leading edges of the tire interacts with the FW tip vortex, as indicated before, these results show how strongly the barge board interacts with front and rear aero parts.

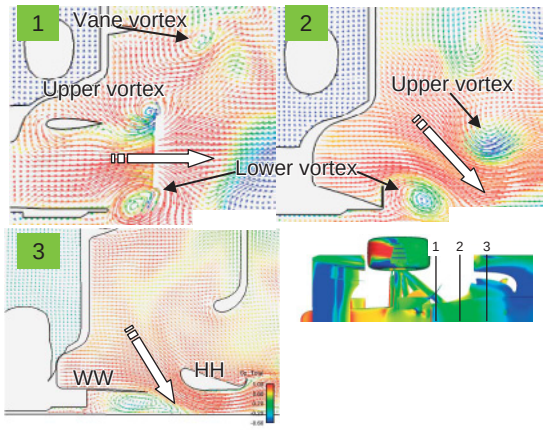


Fig. 15 BBD vortices

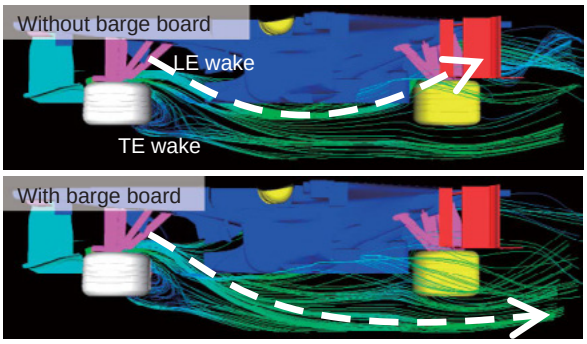


Fig. 16 Tire wake direction

5.2. Development of O-nose Fence

Adding to the effect of the barge board in controlling longitudinal vortices, the O-nose fences (ONF) (Fig. 17) increase downforce by means of the suction they produce.

The ONF generates strong suction below the nose by means of a Venturi effect produced between the left and right fences extending from the nose towards the ground (Fig. 18). In addition, the bottom edges of the fences are close enough to the ground to seal the flow through the gap between the ground and the fences, which increases this effect further. However, if strong suction is generated at the lower section of the nose, an upwash is also generated as a consequent reaction, and this can result in a decrease in underfloor performance. Further, as in the case of the barge board, as a result of the strong suction generated by the fences, the separation vortices from the leading edges of the inboard lower sections of the tires are caught up in the lower vortices of the fences, and this can also result in a decrease in underfloor performance.

To resolve these issues, the downwash was strengthened through the use of a high-lift vane, a strong longitudinal vortex was generated through the use of biplanar ONF, the use of locally high camber profiles on the ONF, and the addition of a shadow

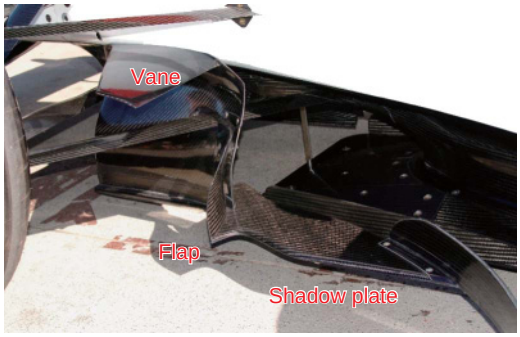


Fig. 17 O-nose fence

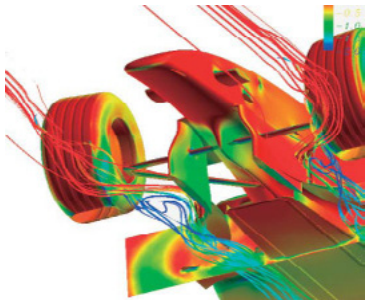


Fig. 18 ONF suction

plate, and the position in which the upper vortex was shed was controlled by adjusting the relationship between the ONF flap height and the position of the vanes. These measures helped to control the generation of upwash. The optimal placement of the cambers also alleviated the drawing-in of the separation vortices from the leading edges of the tires.

The application of these measures helped to enable the ONF to generate the same level of downwash as the barge board with no loss of suction at the lower section of the nose (Fig. 19). As a result, the ONF used at the time increased the lift-drag ratio of the vehicle by 1.5%.

5.3. Effective Use of Downwash of HH and WW

Hammer heads (HH) are parts attached to the vehicle to maximize the use of the downwash of the barge board and other parts. To obtain an effective aspect ratio from the hammer heads, they are extended forwards in the X direction, rather than the Y direction, in which regulations stipulate the maximum vehicle width. The fact that the downwash flows outboard is another reason that the HH, with their leading edges positioned towards inboard, are effective. In addition, gurneys and other parts are attached to the upper section of the trailing edge in order to increase circulation.

The role of the WW, touched on above, will now be discussed in a little more detail. In passing the lower section of the WW, the lower vortex generated by the barge board produces a pressure difference between the upper and lower sections of the WW, which generates the tip vortex from the WW and increases the intensity of the barge board lower vortex. The WW also play another important role. As Fig. 20 shows, the flows at the leading edges of the HH are accelerated and the suction at the HH is increased by narrowing the gap between the WW and the HH. However, if too much downforce is generated, the downforce of the rear aero parts will be reduced as a result of upwash and the growth of underfloor boundary layers.

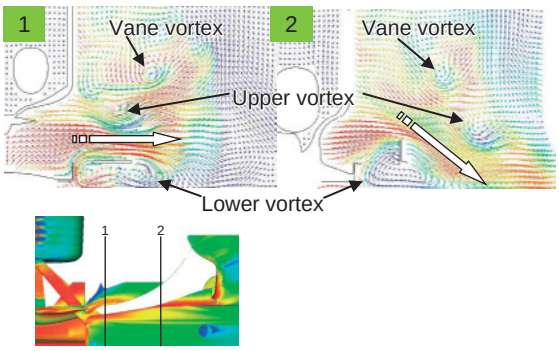


Fig. 19 ONF vortices

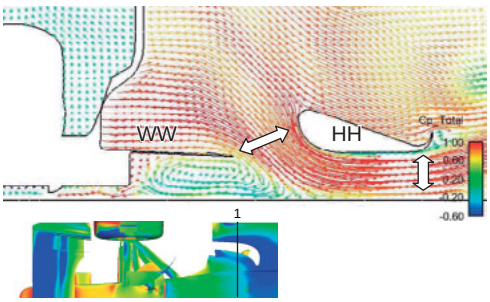


Fig. 20 Channel flow

5.4. Downwash produced by SPLEF

The side-pod leading-edge flickups (SPLEF) are vertical plates with L-shaped YZ sections that are positioned on the exterior of the side pods (Fig. 21). The role of the SPLEF is to intensify the downwash to the HH by providing a blockage and producing circulation. The use of the SPLEF increases the downforce of the HH, but they also generate high levels of induced drag and pressure drag acting on them. However, it was possible to increase the lift-drag ratio through the application of treatments to the leading edges of the vertical plates and the optimization of their shape.

5.5. Ideal Flow

Figure 22 shows the surface streamlines from the nose to the chassis. The figure shows that the use of chassis upper and lower aero parts has resulted in the FW upwash being rapidly directed towards the underfloor – the ideal flow for a Formula One vehicle, as described in section 2.2.

Fig. 21 SPLEF

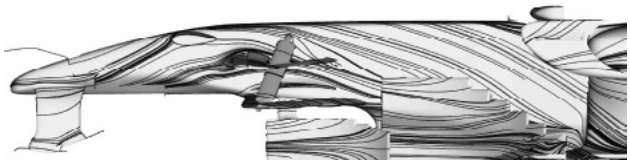


Fig. 22 Surface streamlines

6. Bodywork

The bodywork refers to the areas around the side pods (SP) and the cowl.

6.1. Effect of SP Undercut

From 2000, most teams began using a curved shape called an undercut for the lower sections of the anterior halves of the SP [Fig. 23(b)].

The SP undercuts can be indicated as having three main effects. The first of these is an underfloor seal effect. The circle in Figure 24(b) shows a hypothetical side wall connecting the side edges of the floor and the ground vertically. Without such a side wall, the flows from the leading edges of the SP flow out from under the floor and flow back under the floor and towards the diffuser, but part of the flows also flow out towards the rear tires [Fig. 24(a)]. By contrast, with side walls in place, the underfloor flows are sealed in and flow in straight lines to the diffuser. This accelerates the underfloor flows, boosting suction and increasing downforce [Fig. 24(b)]. However, because the flows towards the rear tires are also blocked, the suction at the leading edges of the SP tends to become weak. In other words, if only the middle and the rear section of the floor was sealed, the maximum benefit of the seal effect could be obtained.

The SP undercuts help to enable this effect to be realized within the scope of the regulations. First, as a result of the undercuts, the influence of the downwash from the front half of the vehicle is extended to the center of the floor (Fig. 25). There, the downwash plays the role of side walls, producing a floor seal effect and increasing underfloor suction (Fig. 26). An increase in the suction at the sides of the SP also accelerates the downwash, further intensifying the seal effect.

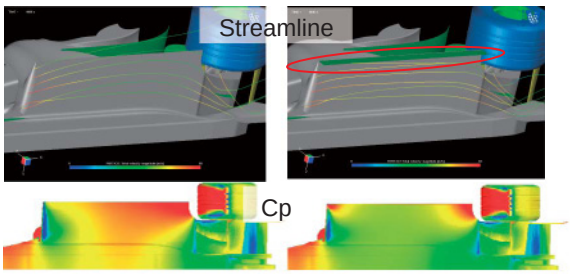
The front of the floor, where no seal effect is necessary, could be used to extend the HH, and it was possible to increase suction on the lower sections of the HH through the use of devices such as gurneys on the trailing edges. This was the second effect of the undercuts.

Depending on the type of barge board employed, the barge-board upper vortex might directly pass the undercuts (Fig. 27). This upper vortex also produces a seal effect, but has a greater effect in optimizing the suction on the lower section of the HH in the direction of the span, by means of the position at which it passes the HH. This is the third effect of the undercuts. However, the effects are not uniform, due to the fact that the intensity and height of the upper vortex differ with different types of barge boards, and its optimum span-wise position to pass the HH also differs. The large barge boards employed by almost all teams generally function to promote the effects of the undercuts.

The use of undercuts rather than linear side pods produced a 1.5% increase in downforce in model-scale wind tunnel tests. The undercuts also helped to increase the underfloor suction in line with predictions. It is also confirmed that the undercut shape was effective even when a barge board was not used.

(a) Flat SP (b) Undercut SP

Fig. 23 Side pod variations



(a) Without side fence (b) With side fence

Fig. 24 Floor seal effect

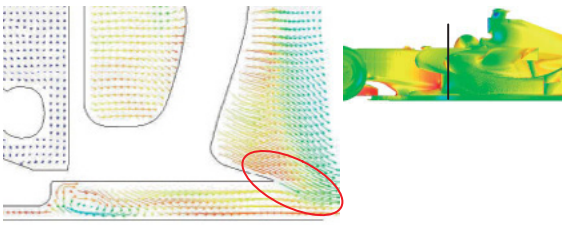


Fig. 25 Downwash flow

6.2. Analysis of Chimney Exhaust Air Flow

The flows that pass the radiators and oil coolers located inside the SP are exhausted through openings in the sides and rear end of the cowl. Cooling performance is adjusted by changing the area of the side openings, but the exhaust flows have a considerable effect on aerodynamic performance of the vehicle.

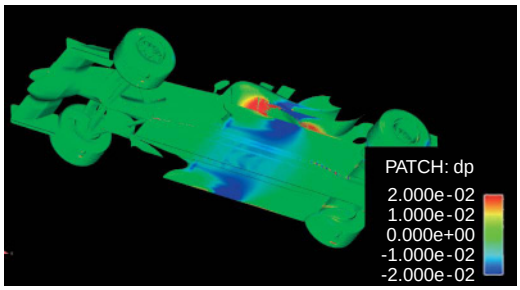


Fig. 26 Undercut SP effect (delta Cp)

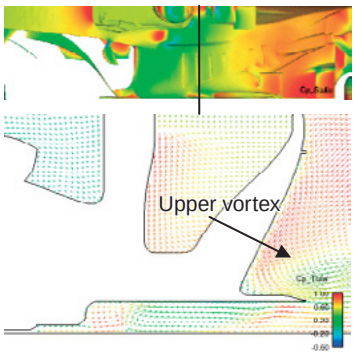
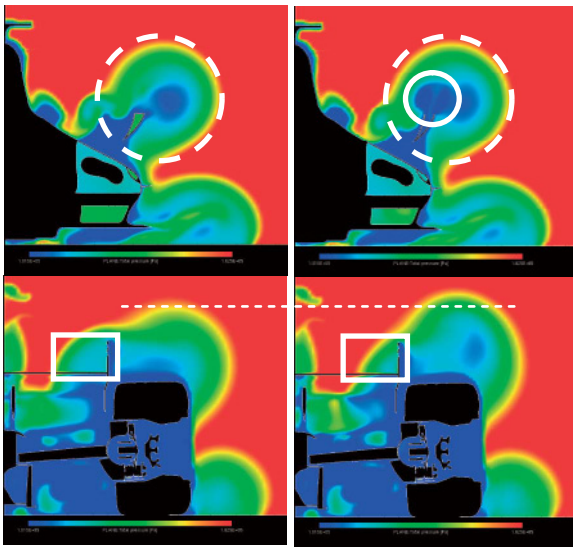


Fig. 27 BBD upper vortex path

From the beginning of the 2000s, chimney-shaped exhaust holes (termed "chimneys") began to be employed (Fig. 28). Cooling performance was adjusted by means of the openings at the top of the chimneys. Wind tunnel tests using a model showed that fully opening the openings from a fully closed state increased vehicle downforce by 4% and vehicle drag by 5%. The exhaust flow affects the RW load, and half of these increases were due to the change in the load on the RW.

Figure 29 shows the total pressure distribution when the openings of the chimneys are fully closed and when they are fully open. The areas surrounded by the broken circles are wakes from the back of a front tire, and include areas of high-pressure loss (Cpt=0.3). This wake passes above the openings of the chimneys, and part of the wake flows close to the tips of the RW (shown surrounded by the solid squares in the figure). When the chimney openings are fully open, the wake from the front tire is shifted upwards and towards the outboard of the vehicle by the exhaust flow from the chimneys (shown surrounded by the solid circles in the figure). By this means, the area of pressure loss at the RW is reduced in size, and the load on the RW is increased. Because this change in load is due to a change in dynamic pressure, there is almost no change in the lift-drag ratio of the RW.

Fig. 28 Chimney and upper flick-up



(a) Closed (b) Open

Fig. 29 Total pressure distribution in section around chimney trailing edge and RW leading edge

It was also necessary to consider the increase in downforce and induced drag due to the upwash from the chimneys, and the increase in pressure drag due to the increase in the cooling flow. In addition, because the chimneys generated suction on the sides of the SP, like the SP undercuts they produced an underfloor seal effect (Fig. 30).

CFD was employed to study the effect of the blockage, and it was determined that the direction of the wakes from the front tires was affected by the size of the blockage, and the degree of change in the load on the RW due to the opening of the chimneys was affected by the blockage. It was necessary to give sufficient attention to this point in wind tunnel tests.

7. Diffuser

The Formula One regulations strictly determine the dimensions of the diffuser (Fig. 31). Within the scope of these regulations, the suction of the diffuser and the underfloor area was increased by maximizing the effective sectional area and minimizing the static pressure at the exit.

7.1. Maximization of Effective Sectional Area of Diffuser Exit

Separation in the areas in which pressure is recovered, the in-flow from the upper section at the diffuser tips, and the entry of the leading-edge separation vortices of the rear tires can be indicated as factors that reduce the effective sectional area of the diffuser exit [Fig. 32(a)].

Pressure recovery is optimized by the kick-up shape, the section shape, and the fence to produce as uniform

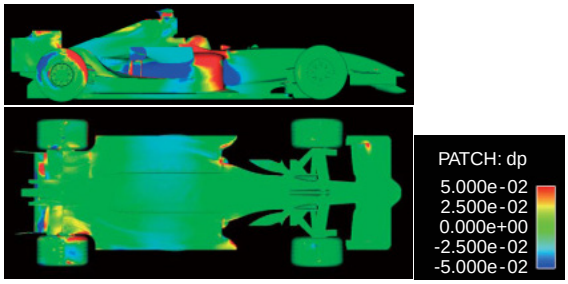


Fig. 30 Chimney effect (delta Cp)

Fig. 31 Diffuser

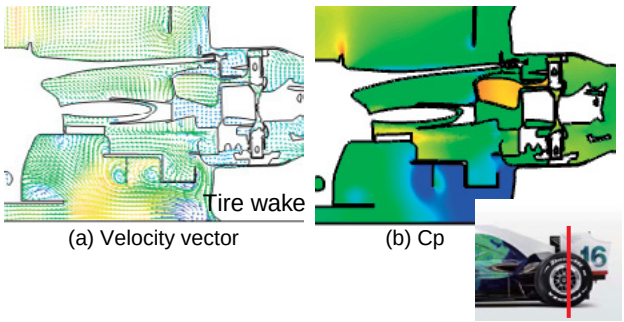
a pressure distribution as possible in the Y direction without generating separation locally (Fig. 33). The flow from the upper section and the entry of the tire-separation vortices are controlled to a certain extent chiefly by the shape of the foot [Fig. 32(b)].

7.2. Minimization of Static Pressure of Exits

Figure 34 shows the static pressure distribution at the diffuser exit. The static pressure at the diffuser exit is affected by the position of the suspension members and the lower rear wings. The static pressure at the exit can be reduced, and the diffuser flow-rate increased, by adjusting these positions and shapes and optimizing the suction peak location of the upper rear wings.

7.3. Effect of Front Half of Vehicle

The diffuser, positioned at the rear of the vehicle, is affected by the flows from the front half of the vehicle. For example, if the suction at the inlet of the floor is increased, or the lower vortex of the barge board is intensified, boundary-layer thickness will increase under the floor, and the separation toughness of the diffuser will decline. Because of this, the choice of which area aerodynamic development proceeds from, and at what timing, have a significant effect on the aerodynamic characteristics of the vehicle.



(a) Velocity vector (b) Cp

Fig. 32 Flow around diffuser

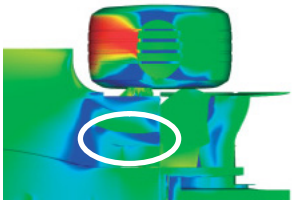


Fig. 33 Diffuser Cp

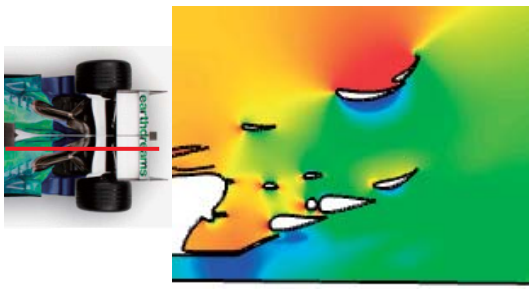


Fig. 34 Diffuser exit static pressure

7.4. Aerodynamic Characteristics produced by Changes in Ride Height

The area ratio of the entrance and exit of the diffuser change with the ride height of the vehicle, and the relative position of the diffuser in relation to the suspension also changes. Because of these changes, the downforce generated also changes.

The downforce characteristic produced by ride height is determined based on a variety of considerations, including the CoP characteristic at low- and high-speed cornering and during braking. In most cases, the CoP during braking is shifted to the rear of the vehicle for the sake of braking stability. This means that aerodynamic development is conducted to produce an increase in the dimensionless rear downforce as the rear ride height increases due to braking (Fig. 35, broken line).

In order to realize this characteristic, vehicle design attempts to ensure that at a low rear ride height there is partial separation from the diffuser and the downforce is reduced. However, caution is necessary, because if the level of separation is too great, hysteresis may prevent the downforce from being recovered when the vehicle is braking (Fig. 35, solid line).

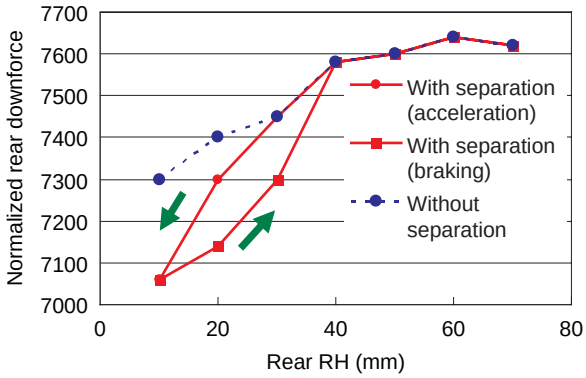


Fig. 35 Ride height aero characteristics

8. Rear Wings

The RW are positioned in an area specified by regulations, behind the rear axle and 300 mm higher in the Z direction than the reference flat section of the vehicle bottom. From 2004, the regulations allowed two elements in the upper section and one element in the lower section of the RW regulation box.

Because the RW have low aspect ratios, an upwash distribution is formed by the tip vortices in the direction of flow (Fig. 36), and massive separation does not occur even when an airfoil with a high camber is used.

Induced drag represents the major component of RW drag, and an increase in drag necessarily follows from an increase in downforce. In addition, the downforce and drag generated by the RW represents a considerable percentage of the downforce and drag for the vehicle as a whole, and is therefore used in the adjustment of the

balance between maximum speed and cornering performance. This is to say that it is necessary to use several RW generating different levels of downforce in order to cover the speed characteristics of all circuits. The purpose of RW development is to help increase the lift-drag ratio for the vehicle as a whole by developing, among other considerations, efficient airfoils, load distribution in the Y direction, and RW end plates for each of these various downforce levels.

8.1. RW with Raised Tips

Figure 37 shows the distribution of the angle of attack when the upper RW is not in place, as obtained by CFD. These results show that there is a significant upwash at the tips of the RW.

Figure 38 shows a YZ section of the total pressure distribution close to the tips of the RW. The tips of the RW are exposed to the wake from the front half of the vehicle, and the total pressure declines. Because of this, the load on the tips declines. An upwash is generated close to Y 300 mm, and a downwash close to the wing tips, alleviating this sudden change in load in the Y direction (Fig. 39). This phenomenon can also be seen from the fact that at the tips the pressure distribution in the direction of flow (Fig. 40) shows characteristic of high angles of attack such as a strong peak at the leading edge (Y = 450 mm) though the angle of attack forms an upwash at the tips when no upper RW is placed.

The reduction of the camber of the tips in order to reduce the load could therefore be expected to reduce pressure drag and increase the lift-drag ratio. Other than this, optimization was conducted in the RW development with consideration of changes in induced drag.

8.2. Increasing Robustness by means of Pillar Shape

In most cases, pillars are used to support the centers of RW, and have the function of reducing the weight of the entire structure. However, the air flow undergoes a sudden acceleration between the left and right pillars, necessitating strong pressure recovery. In rearward-

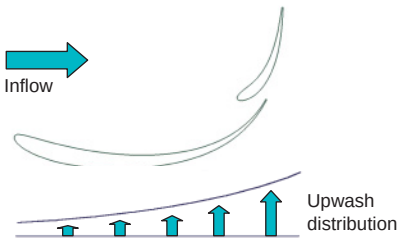


Fig. 36 Upwash by tip vortices

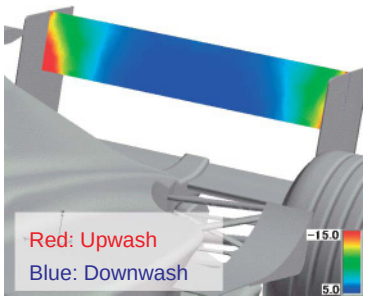


Fig. 37 Inflow angle for RW

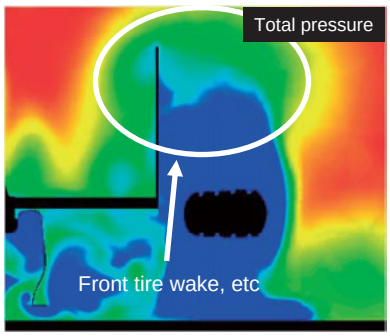


Fig. 38 Cp total around RW

Fig. 39 Secondary vortex due to RW load distribution

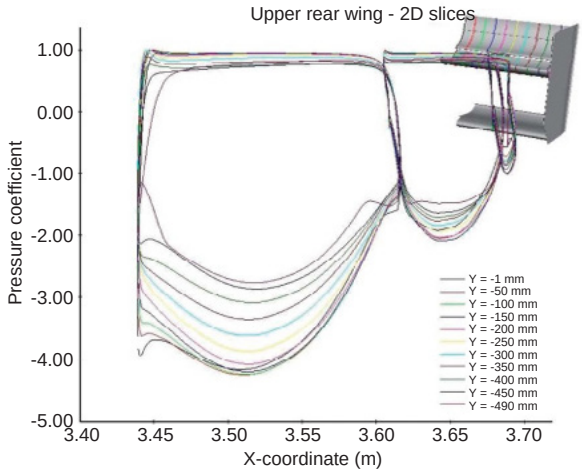


Fig. 40 Sectional Cp distribution

Fig. 41 RW with raised tip

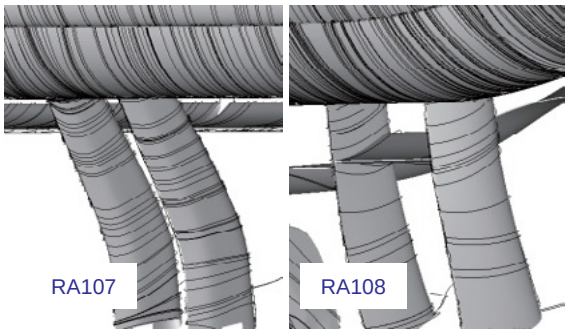


Fig. 42 Boundary layer shear direction on pillars

leaning pillars like those used in the RA 107 (Fig. 42), the spanwise suction distribution produced by the rear inclination directs the flow in the boundary-layer upwards, extending the distance at which boundary layers grows; at the same time, a crossflow occurs between the boundary layer and the outer flow. As the boundary-layer of the pillars merges with that of RW, these are thought to be the factors behind a decline in the separation stability of the RW.

The following changes were made in order to resolve the instability produced by the pillars in the wings developed for the RA 108. First, the space between the pillars was increased to the regulation limit and the sectional shape of the pillars was modified in order to ease pressure recovery. The pillars were also moved to the leading edges of the wings in order to separate the pressure recovery areas of the wings and the pillars. In addition, small wings were positioned between the pillars in order to ease pressure recovery on the RW. Finally, the rearward inclination of the pillars was minimized in order to control the upward inclination of the pillar boundary layer flow.

9. Afterword

The air flows around multiple bodies such as the chassis of Formula One vehicles display a strong non-linearity, and it is not possible in practice to understand the detailed mechanisms of all the aerodynamic phenomena involved. However, aerodynamics developments were conducted efficiently by the use of CFD for qualitative analysis of the core aerodynamic phenomena, backed up by quantitative data obtained in wind tunnel tests. These methods also enabled the accuracy of predicting the aerodynamic performance of the vehicle when it is actually running on a race track to be increased.

10. Acknowledgments

The authors would like to take this opportunity to offer their sincere thanks to all the staff members of the former BAR and HRF1 for their many years of shared developments in aerodynamics, and to the other members of the Honda team and staff members of other companies who generously assisted in a wide variety of ways in development projects.

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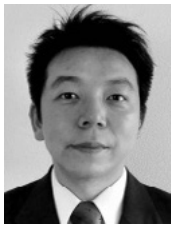
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