Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 17. Improving the Aerodynamic Performance of Formula One Racing Cars

1. Summary of the impact (indicative maximum 100 words)

Since the 1970's the influence of aerodynamics on racing car design has risen substantially, and now in the modern era it is seen as one of the most important factors in producing a race-winning car. Research carried out in the Department of Aeronautics at Imperial College London, into flow control techniques and the development of cutting-edge numerical and experimental methods has allowed specific and significant improvements in the aerodynamic design of Formula One racing cars. This has led to reduced lap times and a more competitive racing environment. These advances have also contributed to improving handling, resulting in a safer racing environment. This research has provided the Formula One industry, which has an estimated annual turnover of $2 billion, with a means to employ engineers who have the key knowledge and insights that allow them to continue to innovate in a tightly controlled engineering environment. The Chief Designer or Chief Aerodynamicist in six out of the twelve 2012 F1 teams have carried out relevant research at Imperial College London.

2. Underpinning research (indicative maximum 500 words)

Basic research on bluff body flow control (non-streamlined flow) is undertaken at the Aerodynamics Department of Imperial College London led by Professors P.W. Bearman, J.K. Harvey*, J.F. Morrison and S.J. Sherwin (* left in 2009). Specific research findings by the group that led to substantial impact are outlined here.

<u>Stability analysis of vortex dominated flows around complex geometries</u>
Professor Sherwin began working at Imperial as a lecturer in 1996. Once here he made key developments to the high order numerical code, Nektar, which allowed the accurate and transient simulation of flow around or over complex geometries. These developments were:

- the concept of the high-order unstructured discretisations (using triangular/tetrahedral as opposed to rectangular/hexahedral meshes), [1]
- the parallelisation of the code using algorithms that were based on the new class of hierarchical spectral methods appropriate for tensor-product representations in hybrid subdomains, i.e. tetrahedra, hexahedra, prisms and pyramids [2]
- an efficient preconditioning strategy for substructured solvers based on a transformation of the expansion basis to a low-energy basis. [3]

Prof Sherwin has been awarded a Royal Academy of Engineering Research Chair, part-sponsored by McLaren, to assist in the further development of this work.

Insights gathered by use of the Nektar code were complemented by experimental investigations led by Prof Bearman and Prof Harvey from 2002-2006. Obtaining a full understanding of the flow around a rotating road wheel presented a challenging problem. Working in a wind tunnel frame of reference, it was clearly illustrated that the flow travelling along the ground meets flow driven by the no slip condition at the tyre surface, which is a thin layer of flow rotating with the wheel, in the region of contact between the wheel and the ground. The result of these flows coming together is the sideways jetting flow that can be seen in instantaneous particle image velocimetry (PIV) velocity fields. The jet and resulting large region of locally disturbed flow were clearly visible in the PIV plots from a study of a racing car wheel undertaken in 2006 by Pegrum, a PhD student supervised by Bearman [4]. Also the vortex system produced by the wing and endplate configuration as it travels downstream was characterised and better understood.

Passive Methods to control flow

Professor Peter Bearman has a long established research record in the use of passive control techniques to reduce bluff body drag and suppress vortex-induced vibration. Specifically, between 1997 and 2001 Prof Bearman investigated the geometry changes that were needed to produce significant reduction in drag [5] and determined that small changes can have a very significant effect. More recently (in 2010) Prof Morrison also investigated the relationship between transient-growth disturbances in the boundary layer and the wall-shear-stress signature and the effect on the relative placement of sensors and actuators in feedback control implementation [6]. Through this research it became clear that controlling flow to maximize stability and minimize drag can be achieved by subtle body shape changes and through the use of small appendages.

3. References to the research (indicative maximum of six references)

* Outputs that best indicates quality of underpinning research.

1. *S.J Sherwin, Hierarchical hp finite elements in hybrid domains,, Finite Element Analysis and Design, 27, 109 - 11 , 1997
2. C. Evangelinos, , SJ Sherwin, GE Karniadakis, Parallel DNS algorithms on unstructured grids, Comp. Meth. Appl. Mech. Engrg.,184, 401-425 , 2000
3. *S.J. Sherwin, M Casarin, Low-energy basis preconditioning for elliptic substructured solvers based on unstructured spectral/hp element discretization, J. Comp. Phys.,171, 394 - 417, 2001
4. P.W.Bearman, Bluff Body Flow Research with Application to Road Vehicles. *The Aerodynamics of Heavy Vehicles II: Trucks, Buses, and Trains*. Springer Berlin Heidelberg, 2009. 3-13. DOI 10.1007/978-3-540 85070-0_1
5. *N. Tombazis and P.W. Bearman, A study of three-dimensional aspects of vortex shedding from a bluff body with a mild geometric disturbance, J. Fluid Mech. 330, 85-112, 1997. DOI: 10.1017/S0022112096003631. Times Cited: 59 WoS as at 16/09/13.
6. A. M. Naguib, J. F. Morrison, and T. A. Zaki On the relationship between the wall-shear-stress and transient-growth disturbances in a laminar boundary layer, Phys. Fluids 22, 054103 (2010). DOI:10.1063/1.3415220

4. Details of the impact (indicative maximum 750 words)

Stability analysis of vortex dominated flows around complex geometries

Being able to accurately identify and manage the generation of vortices is key to competitive racing car design. Using the insights from the Nektar code Prof Sherwin carried out work, directly sponsored by the Formula One team McLaren Racing Ltd. to numerically simulate the unsteady flow around the complex geometry of a Formula One car. This involves multiple vortices, some of which are subject to fast, dynamically driven external effects such as merging or obstacle interactions and some to large scale effects such as strong pressure gradients. These external effects can lead to vortex breakdown. The industry supported work looked at the systematic characterisation and identification of the vortices present in a typical Formula 1 racing car configuration. Due to the new Nektar code it was carried out with an improved level of accuracy and the systematic identification of the vortices intrinsic parameters was achieved [A]. This has allowed for the effective management in the design of Formula One cars and has been used since 2011 in the computational fluid dynamics data analysis of McLaren's F1 Cars. Formula One is an extremely competitive arena where any resultant modification in the design of a racing car is considered to be highly confidential information. For this reason we are unable to go into the specific detail of the impact of the above on design and performance, but the significant impact is confirmed by McLaren's Engineers:

- "I implemented computational tools... which is now regularly used in the CFD data analysis of McLaren's F1 Cars" (CFD Engineer, McLaren Racing Ltd, May 2012) [B] ;
- "Managing these vortical structures efficiently around the car can lead to significant performance gains at the race track. At McLaren, I also implemented techniques to identify vortical structures, which helped us a lot" (Senior Concept Aerodynamicist, currently at Ferrari Racing, June 2012) [C].

The improved experimental understanding of the vortex system [4] has according to the Front Team Leader in Aerodynamic of McLaren Racing Ltd, been used "several times for correlation work with CFD (for both RANS and unsteady simulation)" April 2012 [D].

The significant impact of this research is also clearly acknowledged by the Head of CFD at McLaren Racing Ltd where in May 2012 he states: "First the application of high order spectral/hp element methods to complement and enhance the flow analysis capabilities at McLaren, particularly in capturing unsteady vortices in the flow around the complex geometries of Formula 1 cars. Second your work on understanding the stability of single and multiple vortices relevant to Formula 1 flow regimes has also provided valuable insight for our design process".[E]

<u>Passive Methods to control flow</u>

Subsequent and more specific studies building on the general findings on passive methods and focusing on Formula One cars was supported by McLaren from 2011-2013. Here passive methods employing small geometric changes were developed specifically for a Formula one car. These looked at small geometric modifications (roughness) to the rear wing geometry that transformed straight flow separation lines into wavy ones to reduce the strength of shed vortices [F]. Small yet significant changes to the external geometry, within the regulations allowed for that year, gave improved performance to their car. Again the specific of the effect of this on performance cannot be reported however a Computational Fluid Dynamics (CFD) engineer at McLaren states that: the concept was "...implemented and tested and shown very encouraging results" [G]. McLaren Racing Limited are one of the most successful teams in Formula One, having won 182 races, 12 drivers' championships and 8 constructors' championships.

The knowledge has primarily been disseminated through the movement of people into the engineering teams and McLaren have heavily recruited from the research teams involved in the research outlined in section 2. Owing to the tight regulations laid down by the FIA (the international governing body for motor sport) to control racing car design, the recruitment of talented and highly expert aerodynamicist has become ever-more important, so that they can maximise performance gains. The research activities at Imperial have created the insights that are needed for effective race car design, allowing it to be a key source of experts that understand and can successfully improve car design. Twenty-two researchers active within the Department of Aeronautics since 1993 are currently employed by F1 teams and work on various aspects of aerodynamics. These include the current Chief Designers of Ferrari and Mercedes and the Heads of Aerodynamics of Red Bull, Lotus and Mercedes. Recruitment of so many expert engineers has helped the UK racing car industry to remain at the forefront of international motorsport. The Chief Designer of Mercedes GP, who carried out the research with Prof Bearman states that "researching the fundamentals of flow control has been invaluable in the innovation I have been able to achieve within F1 over the past few years" [E].

Positions held (as at July 2012) in Formula 1 by those that carried out research at Imperial College Department of Aeronautics since 1 Jan 1993:

Mercedes GP
Chief Designer, Head of Aerodynamics and one Aerodynamicist.
Ferrari
Chief Designer, Senior Concept Aerodynamicist, 3 Aerodynamicists.
Hispania (HRT)
Head of Aerodynamics
Red Bull
Head of Aerodynamics
Virgin
Aerodynamicists
Lotus Renault
Head of Aerodynamics and Team Leader Computational Fluid Dynamics
Toro Rosso
Senior Computational Fluid Dynamics Aerodynamicists
McLaren Racing Ltd
Head of Future Concepts, three Aerodynamicists and a Vehicle Dynamists.
Williams
Principal Aerodynamicist

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Confidential research report "Direct numerical simulations and stability analysis of vortex dominated flows around complex geometries" December 2011

B. CFD Engineer, McLaren Racing Ltd. to confirm the impact from the use of CFD tools in F1 car design.

C. Senior Concept Aerodynamicist, Ferrari to confirm the impact from techniques to identify vortical structures in F1 car design.

D. Aerodynamics, Front Team Leader - McLaren Racing Ltd to confirm the impact from the use of research in the interaction between flow from front wings and rotating wheels.

E. Head of CFD, McLaren Racing Ltd to confirm the impact from the use of high order spectral/hp element methods and CFD modelling in passive design.

F. Confidential research report "Dual Velocity-Component Investigation of Transient Growth", July 2013.

G. Chief Designer, Mercedes-Benz GP Ltd to confirm corroboration of the impact on the expertise available to industry as a result of the research.