ExaFLOW use cases: Wing tip vortex, Imperial Front Wing and McLaren front section

J. F. A. Hoessler, J.-E. W. Lombard, S. Dhandapani, S. J. Sherwin

May 17, 2016

Abstract

This document will list three cases proposed for the ExaFLOW project, by ascending order of geometric complexity. The first, simplest case, referred in the following as the wing-tip vortex case, was introduced by Chow *et al.* (1997). The second, based on the McLaren 17D race car, was introduced by Pegrum (2006) and referred as the Imperial Front Wing. Finally, the McLaren front section is proposed as a final demonstration case of the steps towards exascale computing to be achieved by the consortium.

1 Introduction

1.1 Wing tip vortex

The wing tip vortex was studied experimentally by Chow *et al.* (1997), and later numerically, ammongst other sources, by Jiang *et al.* (2008); Lombard *et al.* (2015), albeit at reduced Reynolds numbers. An advantage is the relative simplicity of the geometry, hence allowing the use of block-structured meshes (Jiang *et al.* (2008)): simulation could thus be achieved using two of the codes available, $Nek5000$ and $nektar++$.

1.2 Imperial Front Wing

The second test case under consideration is based on the McLaren 17D race car, and was studied experimentally by Pegrum (2006), hence providing validation data for the simulations. After describing the geometry (3.1) and the wind tunnel setup (3.3.1), a short description of the vortical system shed by the front wing is given, before detailing possible configurations (3.5) of increasing complexity. Detached Eddy Simulations (DES) results are referenced in order to provide rough estimates of the resolution and averaging times required to perform such simulations.

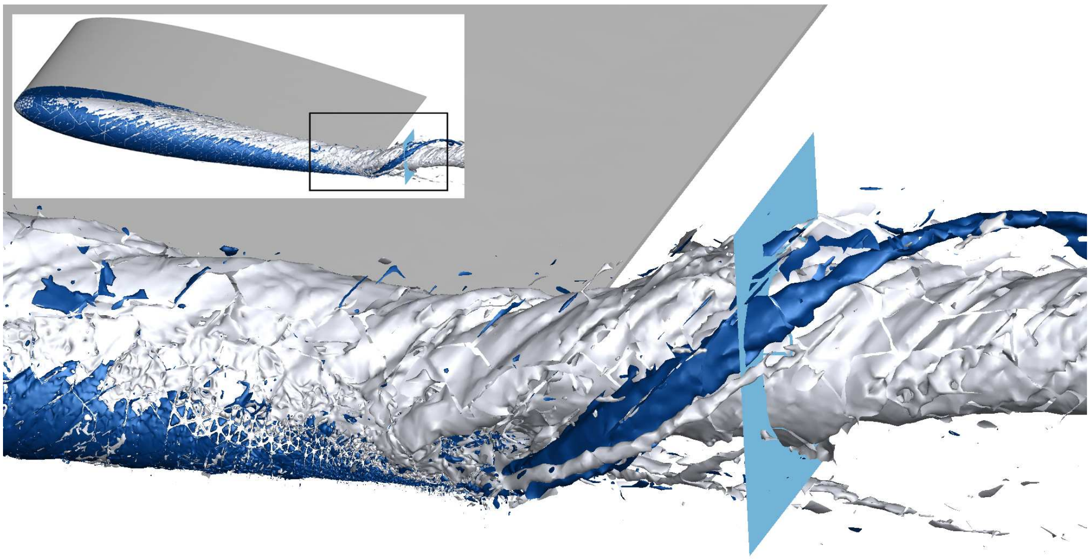


Figure 1: Contours of isohelicity showing interaction between primary and secondary wing-tip vortices Lombard *et al.* (2015)

2 Wing tip vortex

2.1 Geometry

The geometry for this test case includes a rectangular half-wing, of aspect ratio 0.75, with a NACA 0012 profile and a rounded wingtip mounted in a wind-tunnel section at an angle of attack of 10 degrees.

2.2 Experimental setup and boundary conditions

The numerical computations aim to reproduce the experimental setup where the wind-tunnel was operated such that the chord Reynolds number $Re_c = 4.6 \times 10^6$. Numerical computations differ from experiment in that the wind-tunnel walls are treated as slip boundary conditions. A uniform inflow velocity is prescribed at the inflow and details regarding the outflow boundary condition can be found in Lombard *et al.* (2015).

2.3 Benchmark case for quantifying development progress

The geometry in CAD format, the timings, the mesh, the session file for the published case are freely available to the consortium. Additionally we have a lower resolution 4^{th} order case as well as a higher resolved 7^{th} order accurate computation. These can be used as benchmarks for both the improvements in computational efficiency but also in terms of flow physics modeling. Unless a full DNS is desired this case does not require an exascale machine but it is large enough case that it can be used for benchmarking incremental improvements. Table 1 provides some initial figures to characterise the performance at different polynomial order and MPI ranks ran on ARCHER as a reference.

Spacial accuracy	MPI Ranks	Time-step	Avg. CPU time/time-step	Global DOFs
4^{th}	960	3×10^{-5}	0.18	1.5×10^{6}
6^{th}	1920	1×10^{-5}	0.32	6.9×10^{6}
7^{th}	1920	1×10^{-5}	0.45	11.9×10^{6}

Table 1: Average CPU time per time-step for the wing-tip case run on

2.4 Validation data

Chow *et al.* (1997) provides detailed characterisation of the vortex position and core axial velocity and static pressure, as well as Reynolds stresses components at different streamwise locations for the vortex core.

3 Imperial Front Wing

3.1 Geometry

The test case consists of a front wing attached to a simplified nosebox and a front wheel, as depicted in fig. 2. The outboard section of the wing sheds multiple co-rotating vortices which form a complex system (fig. 3). This system will need to negociate an adverse pressure gradient generated by the front wheel.

3.2 Nomenclature

The front wing is a three elements cascade, respectively the mainplane, vane and flap when moving downstream, and the mainplane chord ($c = 0.25m$) along the centreline will be used in the following as reference length. The second length scale of interest is the ride-height h, namely the distance between the outboard lowest point of the wing and the ground (see red dotted line in fig. 2). The non-dimensional number h/c quantifies the ground effect on the wing, and will be used to define two distinct configurations. Finally, the averaging time required to capture accurate statistics will be based on the wheel diameter $d_w = 0.652m$, which represents the largest scale in this problem.

3.2.1 Conventions

In the following, x is the streamwise direction, y the spanwise direction, where $y = 0$ is the car centreline, and z the vertical direction. Only half of the car is represented (consistent with the experiment where a splitter plane was used at $y = 0$), and $y < 0$.

3.2.2 Model preparation

The CAD model has been recently improved to allow parametric changes of the h/c ratio (this was done experimentally by increasing the hanger height). Secondly, the wing is being resurfaced to avoid curvature discontinuities that could prove problematic for high

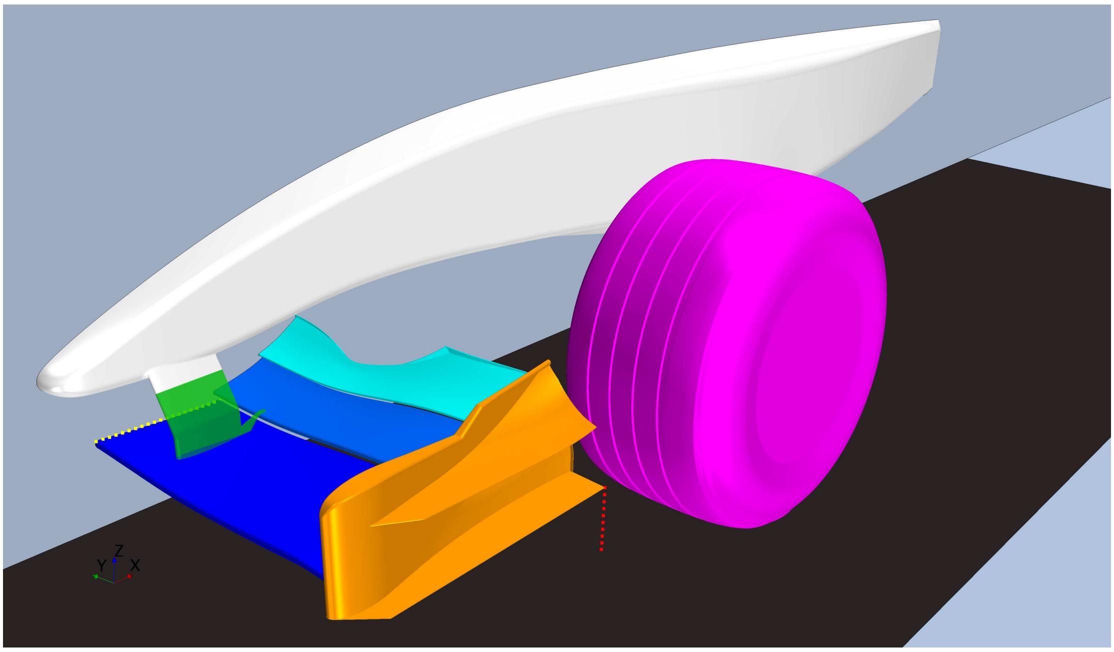


Figure 2: Use case geometry showing the ride height h (red dotted line) and chord c (yellow dotted line). Nomenclature: mainplane (blue), vane (light blue) flap (cyan), endplate (orange), hanger (green), nosebox (white), moving belt (dark gray)

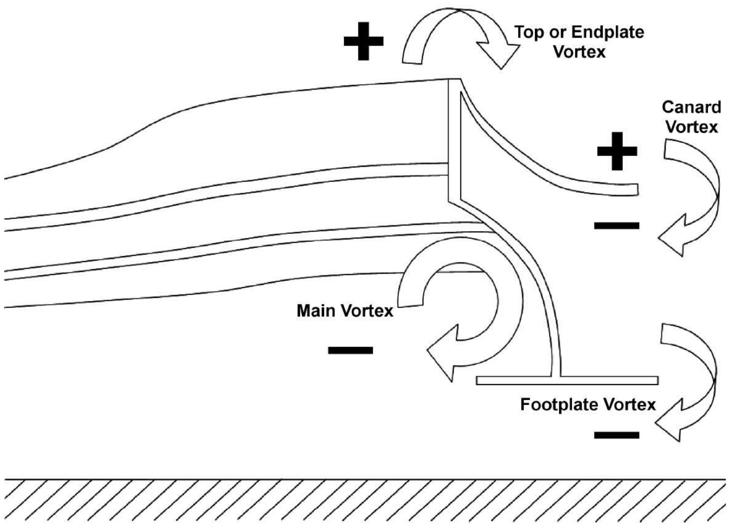


Figure 3: A schematic of the topology of the vortex system downstream of the front wing and endplate, courtesy of Pegrum (2006)

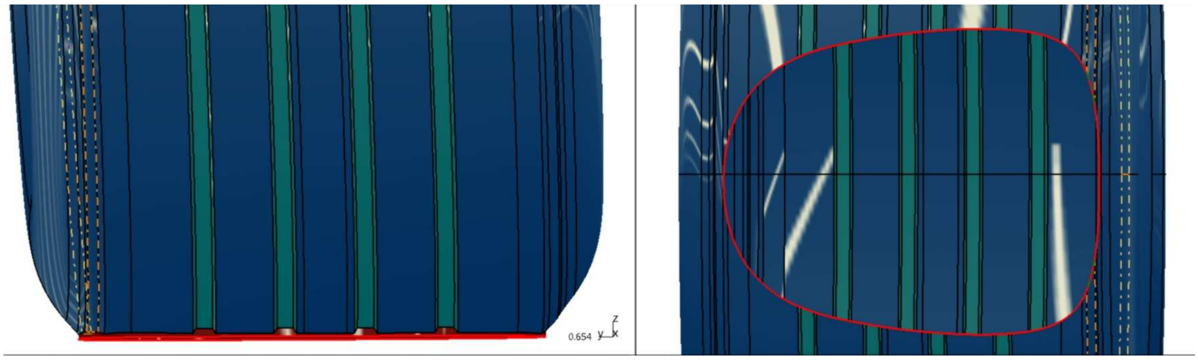


Figure 4: Tyre curtain used to model the point contact between the tyre and the ground (red), and tyre grooves (cyan)

order mesh generators, and the final model is expected to be available by the end of Spring 2016.

3.3 Run conditions

3.3.1 Experimental setup

The experimental dataset used as reference was produced at the Donald Campbell Wind Tunnel at Imperial College London using a 50% scale model. The test section is equipped of a rolling road and the maximum turbulence intensity was measured at 0.15%.

3.3.2 Tyre/ground contact point

During the experiment, no active load was applied to the wheel, which is therefore undeformed.
To represent in the simulations the point connection between the tyre and the ground, the standard approach is to use a tyre curtain (see fig. 4) which will be one of the key details in obtaining accurate tyre wake shape. Its height, shape and mesh resolution will also be a limiting factor for time step selection as the inboard side of that curtain is the region of peak velocity (typically $\approx 2U_\infty$).
Secondly, the tyre used in the experiment was grooved (see fig. 4). The influence of those groove is being quantified by McLaren and the model provided will be available with and without this feature. Croner (2014) reported, on different grooves depth-to-width ratio, a jetting of nearly $2U_\infty$ within said grooves near the tyre curtain, and showed they had a significant impact on both drag and wake structure.

3.4 Boundary conditions

The use case model is at full scale, and thus to maintain an equivalent blockage to the experiment, the simulation test section is of $W = 2.68m$ by $H = 2.44m$. The Reynolds number Re_c based on chord length c and the free stream velocity U_∞ is $Re = 2.0 \times 10^5$. The boundary conditions are as follows:

- wing and nosebox are walls

h/c	$\boldsymbol{Origin}(mm)$	$\boldsymbol{e_0}$	$\boldsymbol{e_1}$	$\boldsymbol{e_2}$
0.36	$[39.2, -879.4, 320.9]$	$[1, 0, 0]$	$[0, -0.4362, 0.99905]$	$[0, -0.99905, 0.04362]$
0.56	$[38.3, -879.4, 271.0]$	$[1, 0, 0]$	$[0, -0.4362, 0.99905]$	$[0, -0.99905, 0.04362]$

Table 2: Wheel coordinate systems for both h/c ratios

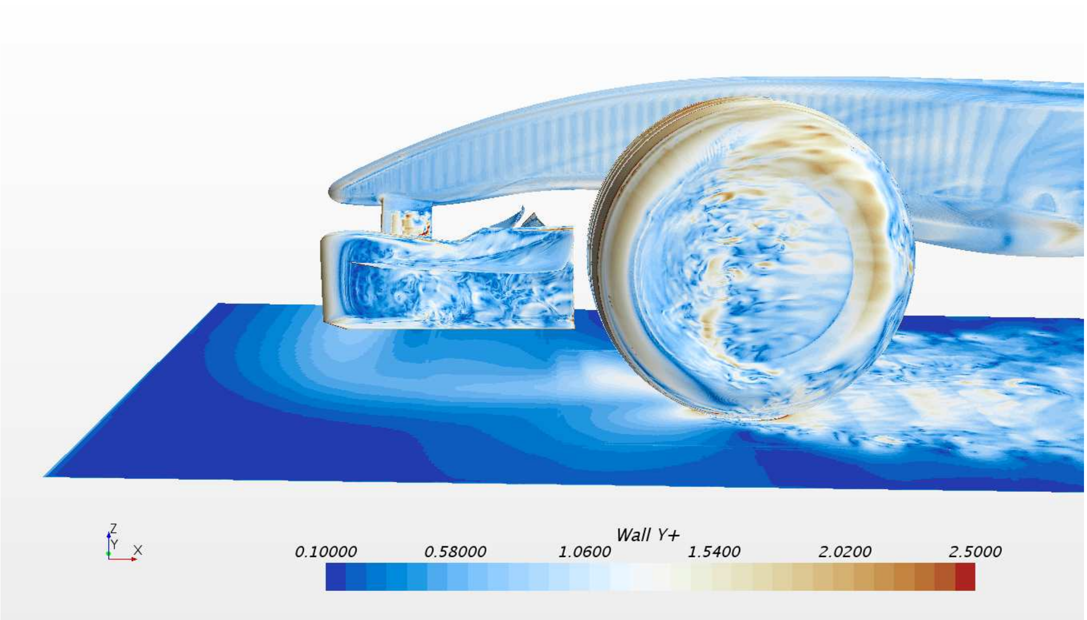


Figure 5: Instantaneous y^+ distribution for a first cell height $l/c = 2 \times 10^{-4}$

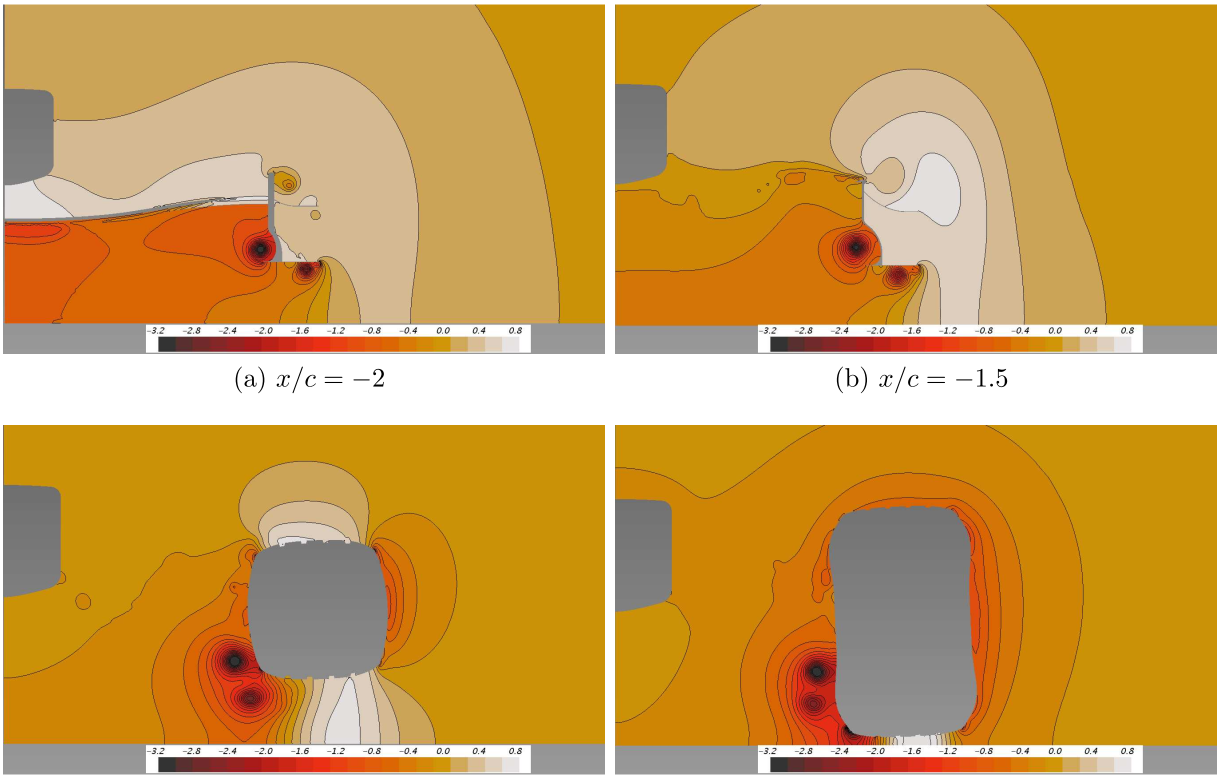
- The tyre rotates along the $\boldsymbol{e_2}$ vector of the coordinate systems defined in table 2
- The ground has a prescribed velocity $[U_\infty, 0, 0]$ (moving belt)
- A uniform velocity profile is used at the inlet as the boundary layer suction and moving belt guarantee a negligible boundary layer buildup before reaching the model
- The ceiling and far side should be treated as symmetry planes
- Symmetry plane at $y = 0$

At the considered Re_c, the typical first cell height to obtain a $y^+ \approx 1$ should be set at $l/c \approx 2 \times 10^{-4}$ on all surfaces (see fig. 5 for a snapshot of y^+ on the model):

3.5 Proposed configurations

3.5.1 Isolated wing

The front wing endplate sheds a system of four vortices (see fig. 3), and detailed total pressure probe surveys are available for the front wing in isolation (no front wheel) in Pegrum (2006). This could be considered as a first configuration of interest as the time-step restrictions and resolution requirements would be less severe than for the full



(a) $x/c = -2$ (b) $x/c = -1.5$

(c) $x/c = -1$ (d) $x/c = -0.5$

Figure 6: Contours of time averaged pressure coefficient at different x positions showing the vortex system from the front wing endplate negociating the tyre

geometry. Detailed RANS and DES simulations at two h/c ratios (0.36 and 0.56) are being performed.

3.5.2 Isolated wheel

A second sub-problem of interest is the isolated wheel, for which a few simulations have been performed in Nektar++ prior to the ExaFLOW project.

3.5.3 Full geometry

Two h/c ratio are considered (0.36 and 0.56) and documented in Pegrum (2006), also including vortex trajectories around the tyre. Fig 6 shows a few snapshots of the time-averaged pressure coefficient when moving downstream.

3.6 Initial results

The isolated wing was run at $h/c = 0.48$ on a McLaren Cluster for three different core counts, resp. 1024, 2048 and 6144 cores for 500 iterations in order to obtain initial performance indicators. The session file and restart have been archived to ensure this simulation is reproducible, although issues with the mesh were identified. The table 3 presents those results. It is worth mentionning that the mesh in question was small

MPI ranks	Average time per its (s)
1024	5.9
2048	4.5
6144	1.5
8192	1.4

Table 3: Average time per iteration for a run of Imperial Front wing without the wheel at $h/c = 0.48$ for different core counts

enough for weak scaling to become an issue for the greatest of the three core count, and a more thorough test will be performed during August when our production cluster becomes available.

4 The need for exascale capabilities

The McLaren front section (which could be extended to a full model at full resolution) is proposed as a demonstration case for the steps towards exascale computing to be achieved during the project. To justify the need for exascale computing on this geometry, let's start by a few numbers. The free-stream velocity reached in race conditions is $U_\infty \approx 70$m/s, and the tyre length scale is $L_T \approx 0.6$m, yielding a Reynolds number $Re \approx 2.8 \times 10^6$. The scales range from 1mm based on the thinnest trailing edges to 2m for the topbody characteristic length.

On top of resolving the structures of the boundary layers present around the different lift generating devices, the geometry yields large fully separated regions in the wakes of the tyres, which interact off-body with vortical structures. Finally, vortices which are shed from the front wheel and track to the rear corner create a strong coupling between the front and rear of the car, hence activating scales of $\approx$ 5m. As a consequence, obtaining statistical moments would require an averaging period of $\approx$ 0.6s assuming $\approx$ 10 characteristic lengths for the largest scale involved.

Secondly, from our Industry perspective, the development time scales have to be taken into consideration: the full life of one of our race cars is a year, along which four to five major upgrades and their associated change of Aerodynamics concept will be considered. Thus, for fully resolved computational Fluid Dynamics simulations to be accepted within our production process where the time scales are of the order of weeks, there is a strong need to be able to scale up the simulations

References

Chow, Jim S, Zilliac, Gregory G & Bradshaw, Peter 1997 Mean and turbulence measurements in the near field of a wingtip vortex. *AIAA journal* **35** (10), 1561–1567.

Croner, E. 2014 Etude de l'écoulement autour des ensembles roulants d'un véhicule en vue de l'optimisation aérodynamique du pneumatique. PhD thesis, Université de Toulouse.

Jiang, Li, Cai, Jiangang & Liu, Chaoqun 2008 Large-eddy simulation of wing tip vortex in the near field. *International Journal of Computational Fluid Dynamics* **22** (5), 289–330.

Lombard, Jean-Eloi W., Moxey, David, Sherwin, Spencer J., Hoessler, Julien F. A., Dhandapani, Sridar & Taylor, Mark J. 2015 Implicit large-eddy simulation of a wingtip vortex. *AIAA Journal* **54** (2), 506–518.

Pegrum, J. M. 2006 Experimental study of the vortex system generated by a formula 1 front wing. PhD thesis, Imperial College London.