Viability of the overset method for geometrical sensitivity studies

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Abstract

In the following thesis the overset method, also called chimera or overlapping meshes, is discussed and applied to a formula race car, in order to calculate its aerodynamic map. The proposed method would allow reducing set-up time through automation and avoided re-meshing process. A theoretical background is presented before the discussion of the way this kind of approach has been set-up in Star-CCM+. Results are obtained and discussed for various car positions. Further investigations are finally suggested to further assess the viability of the method.

Acknowledgement

The present project was carried out at qpunt GmbH in Hart bei Graz, to which goes my gratitude for welcoming me and letting me use their facilities and resources with the purpose of developing and writing this master thesis. The software used was Star-CCM+ by CD-Adapco, which I have to thanks for providing me with the much needed license to their program. A special mention goes to Enes Aksamija, my supervisor for the whole project, and David Koti, for the help received during the project.
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Nomenclature

\( \mu \)  Shear viscosity
\( \rho \)  Density
\( \tau \)  Shear stress
\( \mathbf{u} \)  Velocity vector
\( C_D \)  Drag coefficient
\( C_L \)  Lift coefficient
\( C_{Mx} \)  Roll moment coefficient
\( C_{My} \)  Pitch moment coefficient
\( C_{Mz} \)  Yaw moment coefficient
\( C_S \)  Side-force coefficient
\( p \)  Pressure
1 Introduction

Reducing turnaround time, especially when it comes to simulation set-up and post-processing, is one of the main drives in the CFD community nowadays, together with its automation. This is sought in order to attain a reduction in both direct and indirect costs (manpower, hardware...). It is especially evident in the automotive sector, chiefly the racing one, where numerous and reliable simulations are to be run once after the other, most of the time with just a slight change in geometry.

The present thesis presents one possible way to obtain these two different goals, applying them to a fictional formula car geometry, comparing its outcomes to results obtained using already consolidated procedures.

An overview of the different strategies, which can be used to reduce set-up time and obtain automation, is given in table 1. The overset is the most promising method of the ones taken into account, being able to satisfy the various requirements set at the beginning of the project, simultaneously.

In the following sections the various steps made in order to set-up and run an overset simulation in Star-CCM+ are presented and discussed, after a short overview on theoretical background of both CFD modelling and overset, which constitutes the core of the thesis.

The goal of the project was to be able to predict the aerodynamic map of a formula race car. Ride height and yaw variation are discussed in their appropriate result section. The overset methodology was anyway set-up considering other possible variations, such as pitch (‘nick’) angle, wheels and camber angle as well as swapping of front and rear wing. Moreover, also the various suspension assemblies can be moved independently, even if this was not done in the present work.

Macros in java were written to automate the simulation process. Nonetheless the author thinks that a human supervision is still needed, to prevent possible problem arising during the various simulations, being them due to the overset or missing convergence of the solution.

2 Theoretical background

The following sections gives a brief overview of fluid dynamics, turbulence modelling and overset, necessary to better understand the rest of the paper. Wall treatment is also discussed.

2.1 Fluid dynamics

The flow of a fluid can be completely described by the use of classical mechanics. The derivation of its equations stems from conservation equations, namely conservation of mass, momentum and energy. As the fluid
is considered incompressible for the rest of the paper, coupling between pressure, velocity and temperature fields can be neglected, so that the energy equation does not have to be considered in calculating the solution.

The conservation of mass, also called continuity equation, is usually written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

(1)

If the fluid can be considered incompressible, such is the case here, the continuity equation can be simplified to

$$\nabla \cdot \mathbf{u} = 0$$

(2)

The momentum conservation can be expressed for a fluid as follows:

$$\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}) \right) = -\nabla p + \nabla \cdot \left( \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} + \mathbf{F}$$

(3)

Once again, as the fluid is considered incompressible, and so $\nabla \cdot \mathbf{u} = 0$, the previous equation can be rewritten as

$$\rho \frac{\partial \mathbf{u}}{\partial t} = -\nabla p + \nabla \cdot \left( \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right) + \mathbf{F}$$

(4)

The previous two equations assume the fluid to be Newtonian, meaning that the viscous stress can be related to the strain rate by the following equation

$$\tau = \mu \frac{\partial \mathbf{u}}{\partial y}$$

(5)

Equations (2) and (4) form a system of 4 equations for 4 unknowns, the 3 velocity components and the pressure. The system, together with the energy equation if needed, are referred as the Navier-Stokes equations, from the name of the first two people who derived them, independently of each other. The system is composed by partial differential equations (PDE). For most of the cases an analytical solution is not available. A numerical solution coming from a discretization of the equations is then needed to be sought.

2.2 Turbulence modelling

The flow field normally studied during CFD simulations can have two different distinguished behaviours, depending on its Reynolds number, laminar in case of low and turbulent for high Reynolds numbers. The transition area is usually not well treated in commercial software, for the lack of consistent theory and modelling.

In the turbulent case, running direct numerical simulations is most always not possible, due to the too strict meshing requirements to capture the different turbulent phenomena, down to the smallest scale, which rapidly drive up turnaround time. An approximation of the turbulent phenomena is then required in order to make the simulation times feasible.

The workaround to this problem is decompose the flow parameters into two different components, the time-averaged and the fluctuations parts. This procedure goes by the name of Reynolds decomposition, and the corresponding equations are called Reynolds Averaged Navier-Stokes (RANS) equations. This are derived directly from equations and are here written using Einstein notation, where the overline symbol indicates averaged values and ‘ the fluctuating component

$$\left\{ \begin{array}{l} \frac{\partial \overline{\rho u_i}}{\partial x_i} = 0 \\ \frac{\partial \overline{\rho u_i u_j}}{\partial x_j} = \rho \overline{f_i} + \frac{\partial}{\partial x_j} \left[ -\overline{p \delta_{ij}} + \mu \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} - \frac{2}{3} \rho \overline{u_i u_j} \right) \right] \end{array} \right.$$  

The last term, $\rho \overline{u_i u_j}$, is generally referred as Reynolds stress and is an apparent stress term due to the fluctuation velocity field. This term has to be modelled in order to obtain a closed solution. This is done in various ways, the most common industrially used models being the $k$-$\varepsilon$ and $k$-$\omega$ models and their various derivations. In particular, for this project the Realizable $k$-$\varepsilon$ model was used. A derivation can be found in Shih [1].

2.2.1 Wall treatment

As the flow comes to a halt near wall boundaries, the region in this proximity is viscosity driven, compared to inertia driven for the rest of the domain. This region, called viscous or laminar sublayer, has to be properly modelled. Different approaches are available, depending on the value of $y^+$, which is defined as

$$y^+ = \frac{u^* y}{\nu}$$

(6)

where $u^*$ represents the friction velocity, $y$ the distance of the centroid of a particular cell from the wall and $\nu$ the local kinematic viscosity.

Depending on the maximum value of $y^+$, different modelling strategies can be used

- Low $y^+$ wall treatment, if $y^+ < 5$, better if $y^+ \approx 1$ or less. $u^+ = y^+$
- High $y^+$ wall treatment, for $y^+ > 30$. Here $u^+ = \frac{1}{10} \ln(y^+) + C^+$. The two constants are fixed, according to experiment, to $k \approx 0.41$ and $C^+ \approx 5$ for smooth walls
- All $y^+$ wall treatment, being a combination of the two above. Turbulence quantities (TQ) are calculated weighing solutions coming from both of the previous models, $TQ = gTQ_{low} + (1 - g)TQ_{high}$, $g$ being based on the local Reynolds number of the considered cell. [3]

2.3 Overset

The overset methodology, also known as chimera or overlapping grid technique, has been firstly developed
and used by Steger et al. [3] in 1983. This approach was initially studied to give better control over the mesh generation of particularly complex geometries, which could not be meshed using an unstructured approach back at the time. Dividing the domain in smaller sub-domains opened the possibility to generate high quality local structured meshes, thus better representing real-life geometries.

Nowadays, the commercial software packages are capable of generating high quality unstructured meshes through the use of local grid refinement of other similar features. Nonetheless, the overset method is still useful in case of transient simulation or sensitivity studies involving part movements and/or swapping, such as the case under consideration.

The implementation of the overset methodology in Star-CCM+ is described by Hadžić [5]. The following paragraph are an extract of his paper, trying to present the main features of the method without going too deep into the mathematical domain.

The overlapping grid technique can be divided into two different steps, the first one being the decomposition of the domain in the different sub-domains and the second one being the coupling method between these sub-domains, in order to obtain a accurate, unique and efficient solution.

Each singular sub-domain is covered by an appropriate mesh grid and should overlap enough for the coupling between the grids to be possible. Cells of background grid covered by higher overset regions are deactivated and do not take part to the simulating process. These cells can be anyway reactivated later on, if by means of movements they become active again.

At the boundaries between the different overset regions, active (discretization), and interpolation cells are present. The solution is computed at the active cells of the simulation, while it is interpolated at the interpolation cells, like the name already suggests. Figure 2.2 and 2.3 help having a better understanding of the concept. The process identifying the three kinds of cells goes by the name of hole-cutting process.

For each interpolation cell a corresponding cell, or set of cells, belonging to the overlapping grid has to be found, in order for the interpolation to be derived. These cells are called donor cells. If just one of them is used, this takes the name of host cell and is individuated as the one having the centroid the closest to the centroid of the interpolation cell. If needed, the other donor cells are located in the immediate surrounding of this first host cell. A detailed description of the selecting process is given in Hadžić [5].

Once the host cells for each interpolating cell is found, the interpolation stencils are generated. Even if higher order stencils are possible, linear shape stencils are used to prevent possible oscillation in the solution. The required numbers of donors can be used to build the stencil. Unfortunately Star-CCM+ does not allow this option to be selected, nor indicates the number under utilization.

Finally, the involved values are interpolated using the following equation, regardless of the stencils used

$$\phi_{P_i} = \sum_{k=1}^{N_D} \alpha_{\omega_k} \phi_{D_k}$$  \hspace{1cm} (7)
3 Simulation set-up

The following section introduces the simulation set-up, which precedes the actual simulating process shared between the two different kind of approaches, the non-overset and the overset one. The geometry, the meshing process, the different boundary conditions and modeling are introduced and discussed.

3.1 Geometry

No CAD file of a formula race car was readily available at qpunkt GmbH. The geometry was then sought on the net, looking especially at free CAD websites. The geometry used hereby was found of on GrabCAD, as it represents a simplification of a formula race car appropriate for the simulation process. The selected CAD is a creation of Gergő Farkas, freely downloadable from the net. A representation is given in figure 3.1.

Figure 3.1: Geometry

This geometry went through a series of different modifications, in order to fit to the intended simulations, using both ANSA and Star-CCM+ software. A preliminary modification process is most always needed to polish errors coming from the CAD software used or from importing to the CFD package (for the specific case it did not take more than a few hours). This included creating a base under the four different tyres, a common process in CFD simulations, done in order to prevent the creation of highly skewed and small cells around the contact area between the tyre and the road, thus avoiding problematic cells which would lead to divergence during the simulation. This step is known to introduce discrepancies to wind tunnel measurements, but is nonetheless needed and used. Another solution would have been to simply lower the tyre position. The first described approach was used.

More time was used to adapt the geometry to the overset method. This required the division of the car in its different parts, each one corresponding to an overset region, as will be explained later in this section. The different parts were the body (also comprising the diffuser and the rear wing vertical structure) the front wing, the rear wing (further divided in the two upper spoilers and the lower one) the four wheels and the four suspension systems (each comprising all the rods linked to one tyre). A better understanding of the division carried out can be drawn from figure 3.2. Small patches are visible at the intersection between the suspension rods and the car body. These are areas were mesh refinement was made, as will be further explained in section 4.3.

Figure 3.2: Part division

One of the advantages and the reason the overset method is used is to allow relative movements between different parts. If this involves pierced parts, an opportune axial or radial inflation is needed to take into account the different positions the affected parts takes during the different simulations. For the case considered, the inflation was applied to the front wing supporting structure and to the different suspension rods. They were axially inflated inside the body of the car and inside the respective tyres just for the rods. The simulations carried out did not anyway take advantage of these possible movements, especially of the suspensions, kept fixed even if movement was needed. This is due to the small difference in results coming from the movement of the suspension system compared to one with this movement not done (see 3.3). Finally, also the rear spoilers were inflated inside the wing vertical structure, this time to facilitate the hole-cutting process.

In the last step the various overset regions were created, each corresponding to one of the part the car was previously divided. The different overset regions are shown in figure 3.3, with the absence of the bigger overset region around the whole car, comprising also the wake refinement. Two ways of defining the wake are available in Star-CCM+, one being a surface control of the parts of which the wake should be refined, the other simply defining a block and then use a volume control. The first one being chosen. If the car is meant to undergo a variation of yaw angle, the yaw maximum angle should be taken into account, as also the wake is go-
ing to rotated together with the car. This angle should then be prescribed as the spread angle for the wake refinement, or a frustum should be defined instead of a simple block.

Figure 3.3: Overset regions

A list of the different overset regions, or similarly parts, is given by the following:

- Car body
- Front wing
- Rear wing
- Rear lower wing
- Front left suspension
- Front right suspension
- Rear left suspension
- Rear right suspension
- Front left tyre
- Front right tyre
- Rear left tyre
- Rear right tyre

For a singular suspension assembly, all the rods comprised in it were assigned to the same overset region, comparably to what was done during the division of the car in its different parts.

Most of the different overset regions were directly created in Star-CCM+, defining a block around one part and re-scaling or reshaping it to the required dimension, which should include in all cases the boundary layer cells and a few layer of cells outside of it. A different approach was anyway required by the suspension rods, due to their elongated geometry and to avoid the refinement of too large volume in the area. In this case, the different rods were axially inflated using ANSA, which gives a better control of the process.

The wind tunnel was set up defining a block directly in Star-CCM+, the dimension of it being of 75x50x25 meters, dimensions already established for car simulations at qpunkt GmbH. This corresponds to a blockage ratio, of less than 0.1%, below the minimum suggested value of 0.2% [7]. The blockage ratio is defined as the ratio between the car frontal area, here 1.246 m², and the wind tunnel inlet area. The car was positioned at one third of the total wind tunnel length, in other words the tip of it being at 25 meters away in the x-direction from the inlet. The coordinate system was placed here, with the x-axis having the same direction of the car, the y-axis pointing to the left and the z-axis up.

3.2 Meshing

As for the wind tunnel dimensions, the mesh was also generated following established company procedure, adapted for the case under consideration.

The mesh was generated taking advantage of the automated mesh process offered by Star-CCM+. It builds the volume mesh based on a preexisting surface mesh, which could be created internally by the software itself starting from a CAD file, or imported from a different source. In the treated case, it was decided to import a surface mesh from ANSA, once again to benefit from the extended options given by this software in this respect.

Coming to the various settings concerning the volume mesh, the trimmed cell option was chosen. It generates cells aligned with the flow direction in most of the domain. Moreover the process can be parallelized, thus enabling the use of more than one processor at a time and consistently reducing the overall mesh creation time compared to a polyhedral mesh. This proved to be quite useful at later stages, when the mesh had to be changed numerous times to correct errors emerging during the hole-cutting process or the simulation itself, thus being best suited for debugging process. Nonetheless, not having a preferred flow direction, polyhedral cells could be better considering significant movements in car positioning, yaw angle immediately coming into mind.

The mesh size was specified to be of 80mm for all of the parts with the exception of the wind tunnel, where it was fixed to 1 meter. The boundary layer was composed of 8 layers with a total thickness of 16mm. This was reduced to 8 mm for the rear wings, the four tyres, the suspension rods and the underbody area, both for the car and the ground, to avoid interference during the hole-cutting process and to keep it easier to have a comparable mesh in this region with the no-overset simulation. To this respect, increasing the gap fill percentage for the no-overset simulation helps preventing the boundary layer thickness being reduced in case of close surfaces.

Apart from the boundary layer below the car, other problems arose in trying to obtain a no-overset mesh.
as similar as possible to the overset one. This is mainly due to the different treatment Star-CCM+ gives to part-based meshes and volume controls. In the overset simulation every different part was assigned to a different region and meshed by itself, thus giving access to more option and enabling a stricter control of the final result. On the other hand, in the no-overset simulation just one region was created, forcing all the different settings to be mimicked through the use of volume controls, thus introducing discrepancies between the two different simulations, which in the end could be a cause, if not the major cause, of differences in obtained results.

Volume controls defined at the various overset regions were also used to have a smooth transition at the various interfaces. As practically all the overset regions were comprised in the body region, equal volume controls were prescribed on this one. This is sufficient if only small relative movements are involved, in case of large movements, as the smaller part would actually move outside of the original overset box, a bigger volume control could be needed at the body level in order to successfully go through the hole-cutting process. Table 2 summarizes the different volume controls defined.

<table>
<thead>
<tr>
<th>Volume control</th>
<th>Region</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>Wind tunnel</td>
<td>Custom cell size: 0.016m</td>
</tr>
<tr>
<td></td>
<td>Body</td>
<td>Prism layer thickness: 0.008m</td>
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<tr>
<td>Body</td>
<td>Wind tunnel</td>
<td>Custom cell size: 0.016m</td>
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<tr>
<td>Wake</td>
<td>Body</td>
<td>Custom cell size: 0.01m</td>
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<tr>
<td></td>
<td></td>
<td>Distance: 6m</td>
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<tr>
<td></td>
<td></td>
<td>Spread angle: 7.5°</td>
</tr>
<tr>
<td>Front wing</td>
<td>Body</td>
<td>Custom cell size: 0.008m</td>
</tr>
<tr>
<td>Rear wing</td>
<td>Body</td>
<td>Custom cell size: 0.008m</td>
</tr>
<tr>
<td>Rear lower wing</td>
<td>Body</td>
<td>Custom cell size: 0.008m</td>
</tr>
<tr>
<td>Suspension</td>
<td>Body</td>
<td>Custom cell size: 0.004m</td>
</tr>
<tr>
<td>Tyre</td>
<td>Body</td>
<td>Custom cell size: 0.008m</td>
</tr>
</tbody>
</table>

Table 2: Volume controls

A side-view of both meshes is given in figure 3.5 and 3.6 where a slight difference in cell size is visible. Moreover, in figure 3.6 the interface between the wind tunnel region and the body region is clearly visible. Both meshes showed to consist of about 65 million cells.

3.3 Numerical modelling

The simulation was set up to be time-independent, even though the high Reynolds number of about 11.5x10^6 clearly indicates a completely turbulent developed and thus unstable flow.

The velocity at the inlet was imposed to be 40 m/s, velocity common to car CFD studies (see for example [6]). This correspond to a Mach number of 0.117, lower than the compressible limit of 0.3. The working fluid, air, was therefore considered incompressible.

Motion was also imposed to the road, having the same velocity of the inlet, to account for the movement of the car. This implies that the flow does not come to a halt at ground level, thus theoretically allowing the removal of the boundary layer. Rotation was also set for the tyres, with the exception of the bases, whose creation was explained in section 3.1. The rotational speed was imposed to be of 120.37 radian/s around each tyre center-point, corresponding to a tangential velocity of 40 m/s at the tread of each tyre, equal to the inlet and road velocity.

The outlet was set to a pressure outlet with outer pressure equal to the atmospheric one. The two sidewalls, together with the wind tunnel roof, were set to be slip-wall, thus neglecting the shear forces exerted by them to the flow, and enabling the omission of the boundary layer for these particular boundaries. Turbulence intensity was set to 0.01 and turbulent viscosity ratio to 200, as suggested by Star-CCM+ guide portal [8], for both the inlet and the outlet.

The k-ε two-layer segregated turbulence model was used throughout the simulation span. Previous results obtained using both the Ahmed body and the SAE reference car showed better agreement with wind tunnel results of the k-ω SST segregated or coupled model. Nonetheless, as results had to be compared between simulations and not experimental results, k-ε was chosen as it has faster time per iteration and converged more quickly to slightly oscillating values, anyway a little larger than k-ω. These preliminary simulations also showed that going for a full resolution of the boundary layer did not improve the quality of the results. Because of that, the all y+ plus wall treatment, as implemented in Star-CCM+, was selected. A discussion of this model is given in section 2.2. Anyway, briefly, it combines a logarithmic wall function for areas where the y+ is over 30 with a fully resolved viscous sub-layer where y+ is below 1, trying to give meaningful results also for transition regions where the y+ is comprised between the two aforementioned numbers.
Table 3 summarizes the boundary conditions and the fluid properties used. The models used are summarized in the following list:

- 3D Simulation
- Cell quality remediation (only for no overset simulation)
- Steady state
- Incompressible flow ($M < 0.3$)
- RANS - Realizable k-Epsilon - 2nd order convection
- Segregated solver
- Two-layer all y⁺, wall treatment

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Density</td>
<td>1.18415 kg/m³</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$1.85508 \times 10^{-5}$ Pa-s</td>
</tr>
<tr>
<td>Pressure</td>
<td>101325 Pa</td>
</tr>
<tr>
<td>Turbulence intensity</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence velocity scale</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Turbulence viscosity ratio</td>
<td>200</td>
</tr>
<tr>
<td>Velocity</td>
<td>40 m/s</td>
</tr>
</tbody>
</table>

Table 3: Boundary conditions and fluid properties

4 Methodology

The following sections explain aspects which are typical for a simulation including at least one overset region. The interface creation, the hole-cutting process and the various options related to them in Star-CCM+ are presented and explained. A theoretical background was already discussed in section 2.3.

The set-up for a simulation of this type can be time consuming, to the point of overshadowing the benefit coming from the possible automation obtainable at a later stage, once the simulation is finally working. Section 4.3 is then dedicated to the debugging of the various problems encountered.

Some preliminary aspects, sometimes shared with the no-overset simulation, were already introduced in section 3, and will thus not be repeated here.

4.1 Overset Interface

Once all the different parts are assigned to a region (one for each part), the overset interface between the involved parts has to be manually selected. In order to make the option available, at least one of the boundaries of the two regions has to be set to overset mesh.

Two different possibilities are given by Star-CCM+ regarding overset interface, normal or zero-gap overset interface. The second one is indicated for cases in which the two parts are in contact between each other. If this option is selected, a so called zero-gap wall is created around the contact area of both bodies. The number of layers this wall is composed by is selected again at region level, two being the minimum. A normal overset interface is also selectable even in case of contacts. In both of the case cells at the contact area becomes inactive and are removed from the domain during the simulation. Nonetheless, selecting the zero-gap overset makes the hole-cutting process more consistent, giving less errors overall.

Once the overset interface has been set, other options are available through the corresponding menu. First, the hierarchy of the two selected parts can be swapped. This defines the region which retains most of the cells after the hole-cutting process and should not be overlooked. Examples of the impact of this setting is shown in figures 4.1 and 4.2, where the car keel is shown for the two different options regarding hierarchy. In this case the tip of keel is inside the front wing overset region, thus making clear the different outcomes that could result by just swapping the two regions. In most of the cases this has no effect on the hole-cutting process.

4.3 Debugging

On the other hand, the situation is completely the opposite if the two regions hierarchy is swapped, as shown in figure 4.2. The body is set to have a higher position in hierarchy compared to the front wing. The cells at the front of the keel are no longer removed but are maintained during the hole-cutting process. The boundary layer is also kept.

Two other options are available once an overset interface is created, namely close proximity and alter-
nate hole cutting. Close proximity should be used when a close gap is present between an overset region and boundary, such as a wall. If this option is activated, cells remain active as long as their centroid is outside the boundary, instead of their vertex. This option was tried out for the interface between the suspensions and the body, anyway not showing a better interface creation than with the option deactivated. It is intended to help in case of failure of the hole-cutting process. Similarly the second option (alternate hole cutting) could be helpful in case of errors, not improving the the quality of the mesh at critical points. In this case, the hole-cutting process follows a global approach instead of a layered one, meaning that instead of having a watertight container of active cells around the overset region, each cell centroid of the background region is checked to be inside the overset, and becomes inactive if this is the case. This option was used for the interface between the body and the wind tunnel, to take into account the possible interference between the two different boundary layers below the car.

Finally, the way values are interpolated at the interface between the different mesh can be decided and set. Star-CCM+ offers four different options: distance weighted, linear Quasi2D and least square. The linear option was selected as a trade-off between numeral accuracy and computational time.

Table 4 recapitulates the various interfaces and their type. The naming of each interface represents the assigned hierarchy, the first region name being the region higher in the hierarchy list. The order of the different interfaces does not have any effect on the hole-cutting process, as the overall hierarchy is already defined for all the different interfaces. Even though the front wing and the body share a contact area, the interface here created is not the zero-gap interface. This is due to the fact that in this case, contrary to the rest of the parts, an error aroused during the hole-cutting process if a zero-gap overset interface is imposed, error strangely not present using a normal overset interface.

### Table 4: List of interfaces

<table>
<thead>
<tr>
<th>Interface</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body - Wind tunnel</td>
<td>Overset</td>
</tr>
<tr>
<td>Body - Front wing</td>
<td>Overset</td>
</tr>
<tr>
<td>Rear lower wing - Body</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear wing - Body</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Front left tyre - Body</td>
<td>Overset</td>
</tr>
<tr>
<td>Front left tyre - Wind tunnel</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Front left tyre - Front left suspension</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Front left suspension - Body</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Front right tyre - Body</td>
<td>Overset</td>
</tr>
<tr>
<td>Front right tyre - Wind tunnel</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Front right tyre - Front right suspension</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Front right suspension - Body</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear left tyre - Body</td>
<td>Overset</td>
</tr>
<tr>
<td>Rear left tyre - Wind tunnel</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear left tyre - Rear left suspension</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear left suspension - Body</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear right tyre - Body</td>
<td>Overset</td>
</tr>
<tr>
<td>Rear right tyre - Wind tunnel</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear right tyre - Rear right suspension</td>
<td>Overset zerogap</td>
</tr>
<tr>
<td>Rear right suspension - Body</td>
<td>Overset zerogap</td>
</tr>
</tbody>
</table>

#### 4.2 Hole-cutting process

Once all of the overset interfaces are properly set, the hole-cutting process can be started. Figure 4.3 shows a side-view of the car before the hole-cutting process. Even if it is not possible to notice at a first glance, more than one mesh coexists in the same region. Easier to notice is that the body overset region extends below the road level. Even if this is not strictly needed, it was made in order to account for possible pitch movement of the car more efficiently during the hole-cutting process, avoiding mesh removal if the front wing or the body itself get too close to the road surface. The tyres bases are also inflated below the road surface, in this case to take into account possible camber variation between different simulations.

In contrast, figure 4.4 shows the side-view mesh after the hole-cutting process. First thing to notice is that no cells remain under the road level, as they are cancelled during the hole-cutting process. It is also evident
that wind tunnel cells are removed from the body overset region, as it happens for the body cells inside the other different regions. The interface between the wind tunnel and the body region is also not difficult to spot. At the boundaries of the two regions overlapping cells coming from both regions are present. Here is where the interpolation of the solution happens, from one to the other overset region.

4.3 Debugging

During the set-up and simulation process various errors were experienced. This section is then aimed to their description and possible solutions, so that it should be easier to get to a solution if these problems should emerge again in similar simulations with overset.

The first complication can show up during the hole-cutting process. If the cell size at the interface of the two (or more) regions differs significantly, it can cause the failure of the entire process. As a subset of interested cells created, it is possible to look at the location where the error is present. The problematic cells are usually found to be in the vicinity of the contact area between one of the suspensions and the body and/or the related tyre for the considered case, where three different overset regions coexist. A local refinement of the overset mesh and the contact area usually solves the problem, even tough sometimes bigger cell size is actually needed. A trial and error approach is thus inevitable.

What cannot be considered an error, but is anyway worth mention in this section, is not having enough RAM memory to actually conclude the hole-cutting process. As stupid as this problem can look, Star-CCM+ crashes without giving any warning, thus making troubleshooting difficult. If this happens, looking at RAM usage while the process is run can reveal if this is the case.

Floating point errors proved to be more difficult to solve, as in this case Star-CCM+ did not give any hint regarding the possible causes. Moreover floating point errors could also emerge in simulations without overset, due to a bad mesh quality.

Two different reasons were found out to induce the floating point error. The first one was related to the boundary layer below the car once the body was moved closer to the road, causing the two boundary layers (the one of the car and the ground one) to interfere during the hole-cutting process, even though the hole-cutting process itself is completed without error messages. The solution to this is to reduce the overall thickness of the boundary layer, taking into account the lowest height needed.

Similarly, the second problem was caused by the body movement, but this time in the front suspension area, probably due to the curved surface of contact. In this case a patch area was defined around the contact area, then cancelled and recreated at CAD level, also changing the surface mesh, and consequently the volume mesh.

Other problems were found, though not preventing the simulation to be run. Figure 4.6 shows the first problem. It is possible to see that sticking out cells are created in the body region, due to the interface between the body and the suspension rods. Local refinement of the contact are mitigated the problem, as did switching the wall boundary dynamic overset behaviour in the region menu to active. A definitive solution was not found. If the relative movement of the suspension can
be neglected, the problem can be simply avoided by not assigning the suspension to a different overset region than the car body one.

The second problem is the presence of cells belonging to the background region remaining in the smaller overset region, without being removed during the hole-cutting process. Such is the case shown in figure 4.7. Again, a mesh refinement proved to be helpful, without completely solving the problem. Once again the problem seems to vanish if the suspensions are assigned to the body overset region.

5 Results

The next sections shows the results obtained for the different simulations carried out during the project. A comparison of each result with a normal simulation, meaning not using the overset methodology, is always present in order to assess the error introduced by the various interfaces and/or removed cells. A further discussion of the results is given in section 5.4.

5.1 Base simulation

The base simulation was performed without taking advantage of the moving capabilities of the overset, simply keeping the car fixed at the original position.

Figure 5.1 shows a comparison of the results obtained. For both the drag and lift coefficients the error remains below 2%, while it is consistently higher for the pitch coefficient, around 30%. Nonetheless, if the absolute error is considered, it is only slightly higher in absolute size than drag and lift errors. The large mean average percentage error is higher due to a smaller value of the pitch coefficient itself.

Side-force, roll and yaw are not presented as the car was positioned with no angle with respect to the flow direction. Moreover the considered car was perfectly symmetrical. Variation from zero can then be easily linked to numerical error introduced by the simulation. Their values were anyway negligible compared to the shown results.

Figure 5.2 and figure 5.3 show the accumulated drag and lift coefficients in the car longitudinal direction.

Overset no suspension present in figures 5.1, 5.2 and 5.3 refers to a simulation where the suspension rods were positioned in the same overset region of the body, thus eliminating the interface between them. The interface with the tyres was still present. This was done to investigate the discrepancy between the no-overset and the overset simulation, easily seen in the accumulated lift coefficient, figure 5.3. The difference is starting to develop from an area around the front suspensions and then almost cancelled out from the rear ones. The interface between the body and the four suspensions were then thought to be a possible cause of this difference. Even if this is not shown to be the case, at least for a margin of it, others are probably the causes of these discrepancies, the prime suspect actually being the interface between the road and the bases of the tyres. Unfortunately, removing this interface would consistently limit the use of the overset, restricting not only the possibility of independently changing tyre angle and camber, but also yaw angle variation for all of the car altogether. It is important to note that even the creation of the tyre base is known to cause problems when the simulation is compared to wind tunnel measurements. More studies in this area are then required to achieve a deeper insight of the problem.

The contribution of the different parts to the overall lift is given in table 5. The difference in body and front wing values is probably due to a transfer of cells from one to the other region due to the overset interface, as the sum of the two gives about the same value. Most of the difference comes from the front suspensions and the tyres. It is clearly visible that the error introduced by overshooting in the front tyres is then cancelled out by the rear ones, actually reducing the overall error for the whole car, confirming the hypothesis made in the previous paragraph.
It is important to note that the values shown in table 5 come from just the last iteration of the simulation, as for figures 5.2 and 5.3 thus being one particular value selected from the oscillation in results due to steady-state turbulence. On the other hand, the other values presented were obtained taking the mean of the last 2000 iterations, thus dampening out the typically present oscillations due to the turbulent nature of the simulation, which cannot be completely solved using a time-independent simulation.

### 5.2 Ride height

Following the base simulation, the variation of the ride height was investigated, once again to understand how the overset would fare compared to the a normally executed simulation. The ride height was varied from the base simulation ride height of about 37 mm, both in upward and downward directions.

Results are shown in table 6. The error for the drag coefficient remains under 2% for all the three considered cases, while it gets larger for the lift, still remaining anyway below 5%. Surprisingly the pitch coefficient shows an error reduction, which anyway keeps being of more than 20%.

The +20mm simulation is the one achieving the lowest error in results, not considering the base simulation, while the -10mm has the highest one. This is probably due to a bigger difference in mesh due to the boundary layer below the car, as this proved to be a critical area when comparing no-overset and overset meshes. On the other hand this constraint is relaxed the more the car is moved upward. In this case the rise in the error value compared to the base one is probably due to the overset interface.

Nonetheless, the overset method is capable of predicting the trend in both drag and lift coefficient. Especially for the second one, it predicts a reduction of the down-force once the the car gets closer to the ground, as it is for the no overset simulation. This behaviour is probably due to the under-body starting to undergo a stall situation.

Results for side-force, roll and yaw are not shown as not considered relevant, as it was explained in the previous sections.
5.3 Yaw angle

The last variation examined concerned the yaw angle. This proved to be quite difficult for both simulation types. Due to the yaw angle, the car can undergo through a large movement from the initial position. This reflected in a higher degree of oscillation compared to base, or ride height variation simulations.

Tables 7 and 8 show the results obtained, this time including side-force, roll and yaw coefficients. Drag coefficient remains in the same error range for all the involved simulation, staying below 1.19% for all of them. On the other hand the lift coefficient error is way higher coming to the 7.5° simulation, where it is well above 25%. This is probably due to a too large movement of the car which the mesh was not set up to account for. It is important to note that a simulation without the overset just slightly changing the boundary layer for the upper part of the car body showed the lift coefficient to change by the same percentage downwards. The overset on the other hand proved to be more consistent in predicting this value.

Once again moment coefficients show higher error in all of the cases. Particularly interesting is the yaw error, which is close to 100% in the +7.5° case. Once again this is probably due to the small value in itself, suggesting that the car center-point is the aerodynamic center for the whole car in z-direction.

Also surprising is that the error is reduced slightly rotating the car, as it happens in the 2.5° case. This is probably due to shading effects of at least half of the removed cells at body-suspensions connection, whose cells are less affected by the fluid flow, being in the wake. This reduction is no more present as soon as the angle is further increased.

5.4 Discussion of results

The results obtained show that the error introduced by the overset methodology is the same, if not higher, than just the difference between the simulations considered, even in the best case. Nonetheless, the error is of the same range which is known to be introduced by the simulating process itself, thus making quite hard to reach a final conclusion on the validity of the over-
<table>
<thead>
<tr>
<th></th>
<th>( C_D )</th>
<th>Error</th>
<th>( C_L )</th>
<th>Error</th>
<th>( C_S )</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.662</td>
<td>0.655</td>
<td>1.00%</td>
<td>-0.614</td>
<td>-0.603</td>
<td>1.76%</td>
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<tr>
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<td>0.663</td>
<td>0.666</td>
<td>0.41%</td>
<td>-0.579</td>
<td>-0.577</td>
<td>0.32%</td>
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<td>0.676</td>
<td>0.678</td>
<td>0.26%</td>
<td>-0.591</td>
<td>-0.608</td>
<td>2.96%</td>
</tr>
<tr>
<td>+7.5°</td>
<td>0.726</td>
<td>0.717</td>
<td>1.19%</td>
<td>-0.452</td>
<td>-0.574</td>
<td>27.2%</td>
</tr>
</tbody>
</table>

Table 7: Yaw angle variation - Force coefficients

<table>
<thead>
<tr>
<th></th>
<th>( C_{Mx} )</th>
<th>Error</th>
<th>( C_{My} )</th>
<th>Error</th>
<th>( C_{Mz} )</th>
<th>Error</th>
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<tbody>
<tr>
<td>+Base</td>
<td>-</td>
<td>-</td>
<td>0.101</td>
<td>0.073</td>
<td>28.0%</td>
<td>-</td>
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<tr>
<td>+2.5°</td>
<td>-0.023</td>
<td>-0.020</td>
<td>15.8%</td>
<td>0.100</td>
<td>0.086</td>
<td>13.7%</td>
</tr>
<tr>
<td>+5°</td>
<td>-0.036</td>
<td>-0.031</td>
<td>13.5%</td>
<td>0.122</td>
<td>0.091</td>
<td>25.5%</td>
</tr>
<tr>
<td>+7.5°</td>
<td>-0.053</td>
<td>-0.046</td>
<td>13.6%</td>
<td>0.084</td>
<td>0.073</td>
<td>13.4%</td>
</tr>
</tbody>
</table>

Table 8: Yaw angle variation - Moment coefficients
set methodology. This is further aggravated by the use of another not validated simulation to validate results. This has proved to be quite difficult, due to the lack of mesh equivalence or cell size independence caused by the turbulent behaviour of the flow around a car such as a formula one. Going back to simpler geometry, even better with known and proved values, could actually help understand if the error introduced is not too large to let the overset methodology be used on a daily bases or if this should be discarded altogether, at least for cases with pierced parts.

Convergence of the solutions was usually attained after a few thousands iterations. In most of the cases the stop criterion adopted was fixed to 10000 iterations, even if the solution usually stabilized after about 6000 iterations. In some occasions more iterations were needed to completely assess the convergence of the solution, especially considering yaw angle variation, due to increased result oscillations. In this case the simulations were carried out for 5000 or even 10000 more iterations. In all of the cases the solution was obtained averaging the last 2000 iterations of each monitor (lift, drag, side-force, roll, pitch and yaw).

The hole-cutting process removes the most problematic cells at contacts area between different parts, thus making the overset simulation less prone to divergence once running. Indeed the cell quality remediation option offered by Star-CCM+ had to be used for the no-overset simulations, but was not required to assure convergence once the overset set-up was used.

The author thinks the overset has great potential for reducing manpower needed due to its easy automation, especially for sensitivity study involving movements. In industry time to run a mesh convergence study is not available, and the overset assure that the mesh is constant between the different simulation run, thus at least avoiding discrepancies coming from the re-meshing process. During the project, the mesh was slightly change multiple time to solve the most different errors, and simulations run before the last version of it showed a better uniformity in result for the overset methodology.
A Comparison between fixed and rotated suspension rods

To assess the effect of keeping the suspension rods fixed, a comparison was set up with a variation of riding height of 10mm up. This loosely corresponded to a rotation of 2° of the suspension rods. Results coming from the two different simulations are shown in Table 9.

<table>
<thead>
<tr>
<th></th>
<th>Fixed</th>
<th>Rotated</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>0.670</td>
<td>0.669</td>
<td>0.204%</td>
</tr>
<tr>
<td>CL</td>
<td>-0.608</td>
<td>-0.605</td>
<td>0.520%</td>
</tr>
<tr>
<td>CMy</td>
<td>0.101</td>
<td>0.101</td>
<td>0.263%</td>
</tr>
</tbody>
</table>

Table 9

For the three coefficients, the error remains way below 1%.

REFERENCES


