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Active Aerodynamics Design Methodology for Vehicle Dynamics Enhancement

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Abstract. This paper presents a workflow methodology for the CAD design and the Computational Fluid Dynamics (CFD) analysis of an active aerodynamic package for a sports vehicle. The objective is to provide a method in case of limited resources, such as time and computational power, in order to enhance the vehicle dynamic performances by the improvement of its aerodynamic characteristics. The use of the superposition principle is necessary to perform fast evaluation of the results having three different entities: base vehicle, active front splitter and active rear wing. The dynamic behavior of the vehicle is entangled with the properly made workflow. The results usefulness is related to the understanding of the improvements achieved on the baseline vehicle. The results point out the importance of the aerodynamic improvements connected to the vehicle dynamics enhancement of a sport vehicle.

Keywords: Vehicle Dynamics, Active Aerodynamics, CFD Analysis, CAD design, Design Workflow

Introduction

In race and road sports vehicles, the result of the competition, in the former case, and the feelings of the driver, in the latter situation, are related to the dynamic and aerodynamic characteristics of the car. Accounts on the aerodynamic shape are deeply related to the body design [1,2] and several techniques have been studied to reduce drag [3,4] and optimize vehicle consumption [5,6]. An equally important problem is faced when the aim is finding the best aerodynamic efficiency and balance for performance goals.

The aim of the paper is to develop an aerodynamic package made by two different active devices, among the several different illustrated in [7]: front spoiler and rear wing (in Fig. 1 two commercial examples), in order to tackle the request of the vehicle dynamics engineers in terms of vehicle dynamic performance in different states of the vehicle, such as: Oversteering Mode, Understeering Mode, Minimum Drag Configuration, Maximum Downforce Configuration and Airbrake Mode.

The aim is to control the configuration of the active devices in order to have a degree of freedom on the repartition of the downforce on the front and rear tires. Remer et al. [8] describe the effect of the downforce repartition on different dynamic maneuvers for sports vehicle.

Fig. 1. Front Spoiler (left) and Rear Wing (right)

The first phase is a conceptual phase, which is used to discern among all the most suitable solutions from aerodynamics and packaging point of view. The second one is the implementation of the most interesting solutions from a theoretical and empirical point of view. Thus, a closed loop, including CAD design, FEM mesh generation and CFD analysis, is implemented. The aerodynamic results are analyzed, and conclusions can be extrapolated about the vehicle behavior. This is the most critical step due to the importance of checking carefully each aspect of the solution implemented. The last point is to act on further refinements and flow control optimization of a reliable and well-designed solution or acting to solve different issues. In the latter case a close loop is performed while in the former situation a subsequent step in the complete design process of the aerodynamic package is started, which is not described in this article.

In Fig. 2, the baseline vehicle, i.e. Aston Martin Vantage 2019 (left), and the aerodynamic-enhanced version of the vehicle (right) are shown.

Fig. 2. Aston Martin Vantage 2019 (left) and aerodynamic improved vehicle (right)

Dynamic Requirements and Baseline Analysis

Vehicle Dynamics Requirements

The vehicle dynamics and the aerodynamics engineers have to work in conjunction, in order to set the target necessary to achieve a dynamic balance of the vehicle. The dynamic requirements are expressed with the aim to design the balance of the vehicle and the aerodynamics team has to design an aerodynamic package capable of exerting the necessary amount of downforce and drag in order to move the global Center Of Pressure (COP) in the desired position.

Aerodynamic Baseline Analysis

The baseline vehicle (Fig. 2 left) is analysed from the external aerodynamics point of view. The most important hypothesis made, in order to reduce the computational power and time required by an external CFD simulation, is to cut the vehicle by a y-normal symmetry plane. Another relevant simplification made is to get rid of all the suspension systems. Moreover, a bluff wheel is considered of the same dimensions of the real wheel, i.e. rim and tire. The error, provided by these simplifications, is negligible for a feasibility analysis of the solution proposed. The simplifications, in addition to the closure of all the gaps in the external surface, represent the 1st step to analyse the baseline vehicle. The base of the bluff wheel is cut by few percent to consider the deformation of the tire itself, while it is spinning.

The 2nd step is the generation of the surface mesh in the Hypermesh environment.

The 3rd and final step is the generation of the three-dimensional mesh in Star-CCM+ environment [11] and the setting of all aerodynamics-related parameters to perform the CFD simulation. The boundaries of the control region are defined in order to replicate, as close as possible, an open road. Indeed, the ground it is moving at the same speed of the vehicle, the velocity inlet of the air is synchronised with the moving ground itself; the outlet pressure surface is set at the reference pressure.

The results of the steady-state CFD simulation using k-omega turbulence model, which is one the CFD method presented in [12] for external aerodynamic simulation in the automotive industry, are visible in Fig. 4, for what concern the velocity pattern of the air past the vehicle. The Fig. 5 shows the generation of the vortices at the side of the vehicle and wake.

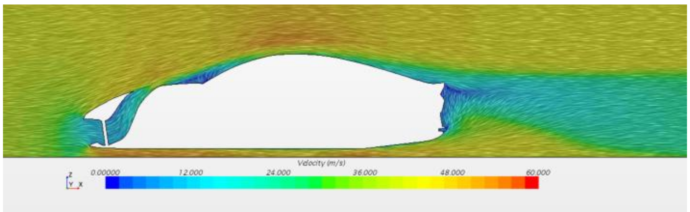

Fig. 3. Airflow velocity pattern past the vehicle (baseline)

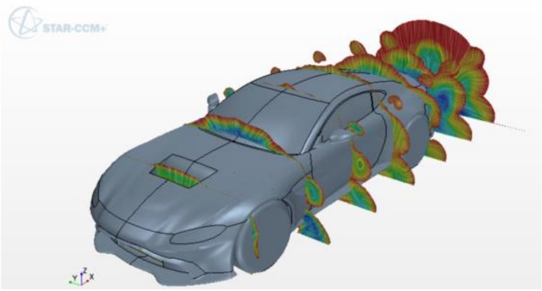

Fig. 4. Vortices generation at the side of the vehicle and in its wake (baseline)

Vehicle dynamics enhancing workflow

The proposed workflow, Fig. 6, is designed in order to implement an active aerodynamic package starting from the analysis of the baseline vehicle and the requirements defined by the vehicle dynamics and aerodynamics team. Three main sections are highlighted: Rear Wing; Baseline Vehicle Analysis; Front Splitter.

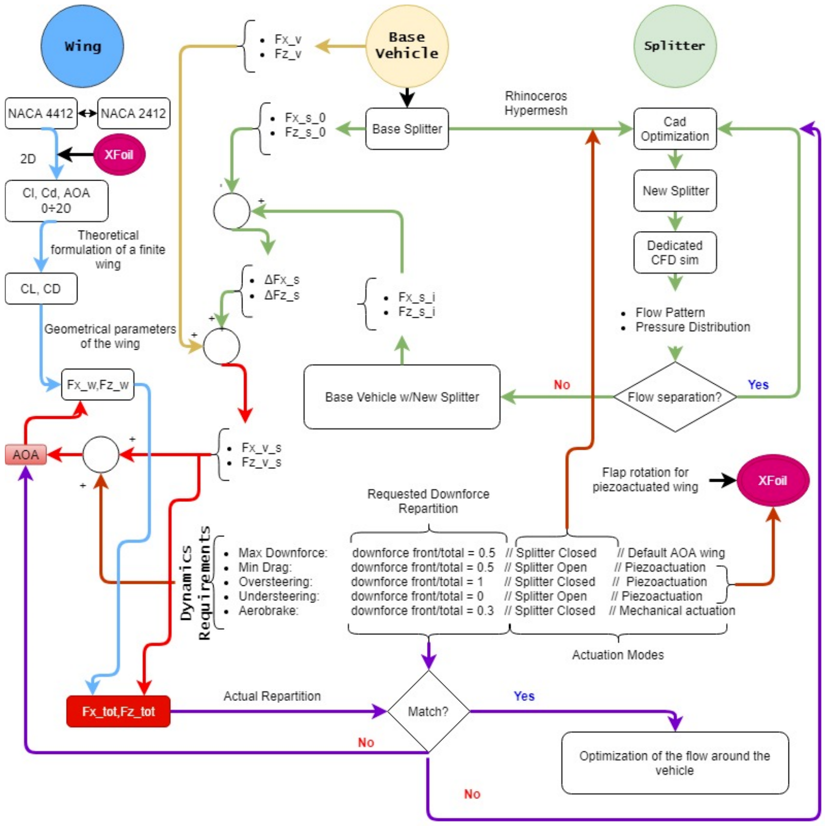

Fig. 5. Vehicle dynamics enhancing workflow

The rear wing design phase, light blue path in the Fig. 6, starts with a theoretical selection of the most suitable airfoil [9, 10], for sports vehicle application. The aerodynamics characteristics of the airfoils are extrapolated by the usage of XFoil, a two-dimensional fluid dynamics software. In order to obtain the characteristics of the actual wing, the 1st step is to define its geometrical characteristics: span and chord. The 2nd step is represented by the usage of the ‘Finite Wing Theory’, which it is able under some defined hypothesis to derive the 3D coefficient of the wing, starting from the 2D coefficients of the wing. The last step is to design the position of the wing with respect to the exterior body of the vehicle, which is necessary to understand its effect on the position of the global COP. The wing pitch i.e. Angle Of Attack (AOA), is varied to consider the active feature of the wing.

The front splitter design phase, green path in the Fig. 6, is strictly dependent to the baseline analysis, since it is an empirical method, based on CAD and CFD simulation loop, employing a quarter car model to save computational time. Thenceforth, the optimal flow behavior is achieved on the top and bottom surfaces of the splitter, the aerodynamic effects of the new splitter are compared to the original ones. The delta difference between the new and old splitter is added to the baseline vehicle result. An active opening, obtained by a translational movement of the upper and lower surface, is designed on the splitter surface, which allows the passage of the flow from the top to the bottom surface. Thanks to the active opening, the splitter passes from the high downforce mode (pocket closed) to the low drag mode (pocket open).

The actual load repartition on the front and rear axle, achieved by the base vehicle and the new-splitter delta-contribution, is compared to the downforce repartition, defined by the initial requirements. The comparison output is necessary to select the correct AOA of the active wing in the different driving modes.

The output of the workflow is the comparison between the actual performances, in terms of load repartition, downforce and drag generation, obtained through the usage of the superimposition principle, considering the contribution of the active wing and the baseline vehicle with the addition of the brand-new active splitter, and the aerodynamic requirements stated at the beginning of the process. The purple lines, in Fig. 6, graphically represent this last step.

'Yes' or 'No' matching statements represent the further optimization, in the former case, and the closure of the loop (feedback), in the latter case.

Aerodynamics Improvements Achieved

This paragraph summarize the main points for the aerodynamic enhancement of the vehicle with the active solutions.

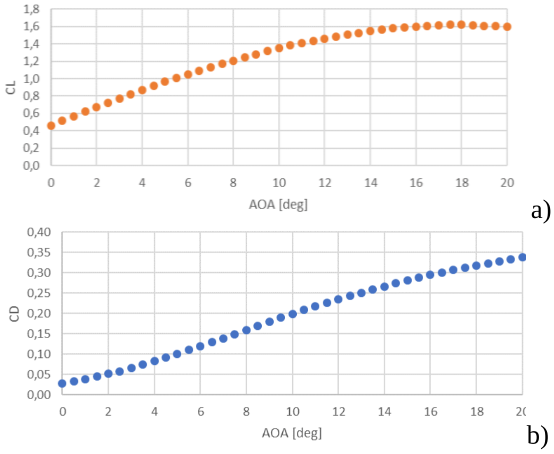

Fig. 6. CL vs. AOA (a) and CD vs. AOA (b)

For the design of the rear wing, the 2D analysis combined with a theoretical approach is employed to extrapolate the performance of the rear wing of the sports vehicle. In Fig. 7, the coefficient of lift (CL) and drag (CD) of the wing are presented.

The value of the Drag Force (Fx) or Downforce (Fz) of the wing is derived by CL and CD together with the geometrical characteristics of the wing. Indeed, a detailed analysis of the direction of the velocity vectors (Fig. 8) is important to the position of the wing, and the subsequent derivation of the distances for the global COP position. The wing has to be located in a region where the speed of the air is equal to the one undisturbed, in order to apply the superposition principle.

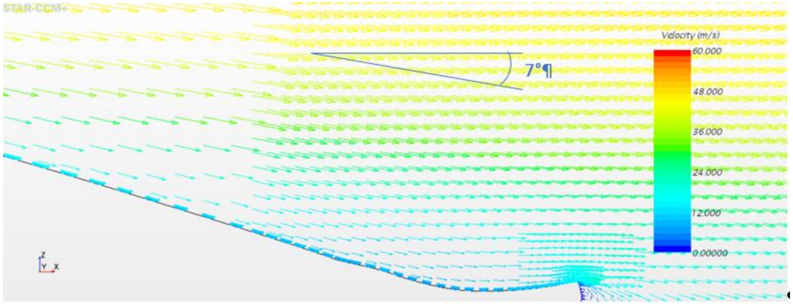

Fig. 7. Velocity vectors direction

The CAD design and the CFD analysis loop, for the splitter optimization, leads to results, in terms of flow behavior, presented in Fig. 9.

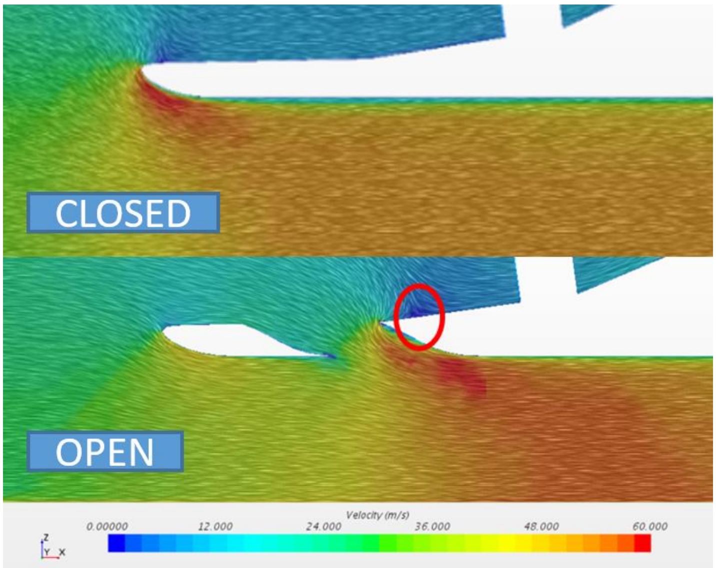

Fig. 8. Velocity distribution for high downforce mode (up) and low drag mode (down) splitter

The left figure shows the new-splitter in high downforce mode while the right figure represents the active opening; the generation of a second stagnation point is highlighted, red circle. The drag reduction benefit of the open solution has to be considered taking into account the AOA of the wing, for a drag reduction mode of the vehicle. Indeed, reduced front downforce leads to lower AOA, which results in lower drag generation of the whole vehicle.

Table 1 presents the global results, at vehicle level, achieved through the proposed workflow for the different dynamic modes/configurations with respect to the baseline configuration of the vehicle.

Table 1. Aerodynamic Results

Parameters	Base	High Cd	Low Drag.	Over steer	Understeer	Aero-brake
Relative AOA	/	6°	3.5°	0°	12°	25°
Fx [N]	740	788 (+6,4%)	755 (+2%)	740 (-)	840 (+13%)	898 (+21%)
Fz [N]	-280	-937 (+234%)	-733 (+161%)	-627 (+123%)	-836 (+198%)	-934 (+233%)
Cx	0,29	0,313	0,299	0,293	0,333	0,356
Cz	-0,11	-0,372	-0,290	-0,249	-0,331	-0,370
Aero Eff.	0,379	1,18	0,97	0,84	0,99	1,04
COP position	1,56	0,5	0,51	0,89	0,32	0,29

Indeed, Aerodynamic Efficiency (Fz/Fx) of the vehicle shows the benefits obtained through the aerodynamic package implementation with respect to the baseline vehicle. The position of the wing relative to the direction of the incoming flow, as presented in Fig. 8, is stated in the first row of Table 1. The second important point is the COP position, defined as the ratio between the downforce on the front axle on the total downforce (Fz_front/Fz), which is shown in the last row of Table 1, to understand the improvement of the dynamic behavior of the vehicle in each mode.

Conclusions

In this paper, a workflow that describes the methodology to implement an aerodynamic package for a sports vehicle with limited resources in terms of time and computational power has been described. In particular, the important passages for the design of the two active aerodynamic devices, front splitter and rear wing, are highlighted. This methodology can be applied for the design of the aerodynamic package of a sports vehicle, which has enclosed wheels. The superimposition principle, for a Formula type vehicle, does not hold anymore due to the great interaction of all the components from a fluid dynamics point of view. The results are obtained through a fast and simple methodology, which allows the reduction of the lead time for the evaluation of the feasibility of a proposed aerodynamic solution and the reduction of the computational power, requested to perform the complete analysis of the vehicle.

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