Aerodynamic Design of High Performance Car

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***Abstract*- In the initial phase of the aerodynamic car project, difficulties arise from the large number of parameters involved. A systematic aerodynamic analysis taking into account the effects of all these parameters appears to be difficult. The use of a direct numerical optimization technique appears very attractive to solve this complex survey. In this paper a critical analysis of the most significant optimization methodologies is presented. The characteristics and the use of a specific optimization tool are also described, to highlight the capabilities offered by the optimization approach. The use of this procedure to increase the car safety, increasing the vertical down-load without affecting car performance, is detailed. Furthermore, the problems arising from the present implementation and the relevant indications for a more efficient and effective optimization procedure are discussed.**

1. INTRODUCTION

The traditional design processes cannot longer be met competitive with the increasing performance requirements and the economical pressure to increase efficiency of ground transportation vehicles. Current practice is to move the design of complex equipments away from a process involving a sequence of specialist departments and to emphasize its multidisciplinary nature through the use of integrated product teams. These commercial trends, together with the immense volume of design, manufacturing and maintenance data inherent to complex modern equipments, demand for a heavily computerized environment. Multidisciplinary Design and Optimizations (MDO) envisions a parametric description format of input data, which will generate, for a specific set of values of the parameters, a new vehicle description that in turn is used to generate input for Computer Aided Engineering, including Computational Fluid Dynamics (CFD).

The aerodynamic design plays a crucial role in the development phase of new automotive configurations and, due to its intrinsic complexity, the designer needs as much aids as possible to strengthen his/her choices and discard unsuitable solutions. In this context, the possibility of evaluating performances of different configurations is of utmost importance; however, difficulties arise due to the high number of geometrical parameters involved, which are necessary for defining each configuration. A systematic analysis taking into account the effects of all these parameters is very difficult, given the complexity related to both aerodynamic load evaluation and the assessment of mechanics, stylist, commercial and others requirements.

The first aspect is the need to improve the accuracy and the validity range of the results, to obtain a realistic representation of the aerodynamic flow; this implies using a sophisticated flow solver within the optimization procedures.

The second aspect is the requirement to obtain the results in short time.

In recent years, different methodologies have been proposed to solve this classical accuracy-time dilemma. In general the results are procedures with high accuracy coupled to long processing time or, conversely, rapid time responses obtained with simplified aerodynamic solvers. An example of the first type is the FRONTIER procedure [3], partially supported by the EC as a part of the ESPRIT program. An example of the second type can be the HIPEROAD procedure [4, 5], partially supported by the EC as a part of the ESPRIT program, where a simple potential flow solver was used. A recent example that combines sophisticated flow solvers and efficient optimization techniques for aerospace is the Growth AeroShape project (currently running). The technical strategy is to merge together computational fluid dynamics (CFD) and numerical optimization, thereby facilitating a much broader utilization of these simulation technologies in vehicle design. The potential impact of this technology extends across many aspects of vehicle engineering. Fluid dynamic analysis, including heat transfer, is the basis of design not only for the external shape of the vehicle, but also for the prime mover and power train (cylinders, valves, intake and exhaust systems, transmission, and cooling), passenger comfort and climate control (noise reduction, heating, ventilation and air conditioning), and subsystems (such as windscreen de-icing). Automatic aerodynamic optimization can be used in the context of any of these design tasks by helping to achieve the best possible solution in each case, while simultaneously reducing the duration of the design cycle and time to market.

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2. AN EXAMPLE OF APPLICATION TO AUTOMOTIVE PROBLEMS

A preliminary application of the optimization approach was developed. The project, named HIPEROAD (HIghPErformanceRoadvehicle Optimized Aerodynamic Design), had the object to make the optimization loop in large part automatic, in order to reduce the time needed to evaluate and improve the sketch design provided by the stylists.

The complete procedure is described in [4, 5]. In this paper the most significant aspects of the procedure are presented, and the capability of the methodology is shown by means of a specific application.

2.1 DESCRIPTION OF THE METHODOLOGY - In the analysis through direct numerical optimization, an aerodynamic code is coupled with an optimization routine, giving rise to an iterative procedure which is able to automatically manage the values of the design variables – typically concerning geometry modifications – by minimizing a given scalar quantity (the objective function). This approach is extremely flexible, and capable of meeting multidisciplinary requirements.

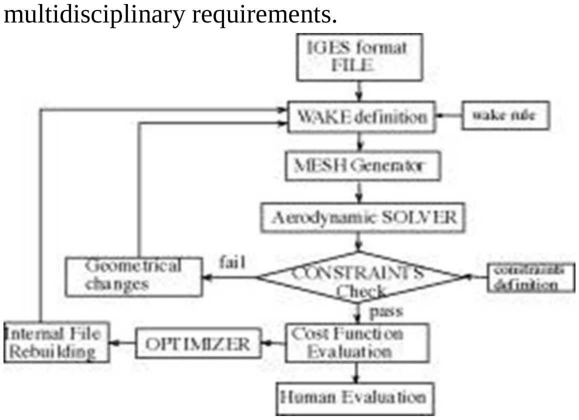

Fig. 3 - The optimization loop

In Fig. 3 a flow chart of the optimization loop is shown; the main components will be shortly described in the following sections.

2.1.1 CAD input and repair module - The solver acts on a surface mesh derived from a car description provided by the engineering department. This CAD description is generally made of a number of separated patches (as many as a few hundred), describing different parts of the car. The optimization procedure requires a single surface, which must be obtained from the separate patches, correcting geometry imperfections in an automatic way; it is important to note that this is one of the most critical aspects in the optimization process. This task is accomplished by CADRE (CAD input and REpair) module. This module was developed to produce a single surface, described by Bezier points, [5]. This surface can be subsequently modified and meshed during the optimization loop.

2.1.2 Aerodynamic module - A loop involving several hundreds of optimization steps is possible only if the evaluation of the pressures over the surface of the car is very fast and accurate. Consequently, a “potential flow” model was assumed, which is well suited for evaluating the flow around aerodynamic bodies. Naturally, this implies that the present version of the procedure may be applied to study the flow around a car only if a «streamlined» shape characterizes it, with the boundary layer separation occurring only at its rearmost end. This may be considered to be the case for the high performance sport cars. However, the effects of the separated wake on the flow upstream of the separation must be taken into account, by some means, to accurately predict the pressures on the attached flow region.

Previous researches [20] demonstrated that the pressures acting on the portions of bluff bodies characterized by attached flow can be accurately evaluated, by means of a potential flow code, practically up to the separation region. This if the separation is positioned only at the rear end of the body, is practically fixed by the geometry, and the wake is modeled as a closed continuation of the body and treated as a solid surface with unknown pressures. The validity of the present approach is also confirmed by the results shown in [21]. During the project an effort has been made to develop a model for the wake, which depends on the characteristics of the car surface and which allows the vertical loads up to the end of the car to be accurately predicted [22].

The used potential flow code [23, 24] is based on Morino's method [25], which is widely used for the evaluation of the loads on aerodynamic bodies, and is characterized by robustness to variations in surface discretization. As already pointed out, in order to take the effects of the separated wake into account, a fictitious after body is added to the portion of car characterized by attached flow.

Wind tunnel tests were carried out to validate the whole system [4, 5]. A first model was constructed and tested in the Ferrari Auto wind tunnel. Force measurements and pressures measurements, with 90 pressure taps, were carried.

The comparison between the experimental and calculated pressure coefficients obtained in the longitudinal plane for the upper surface of the car is shown in Fig. 4. As can be seen, the comparison is very satisfactory. Furthermore, it is seen that, as predicted, the agreement extends up to the very end of the model, demonstrating a good performance of the wake model.

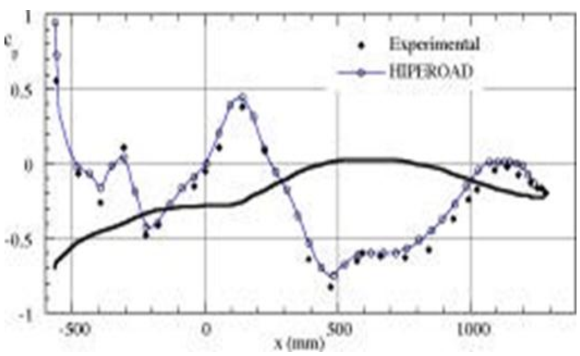

Fig. 4 - Comparison between experimental and calculated pressure coefficients

2.1.3 Optimization module- The optimization module has the purpose of defining a new car geometry that minimizes a cost function related with certain aerodynamic characteristics of the car, while keeping a set of constraints into account. The constraints in turn are of two kinds: some are related to aerodynamic quantities, and some derive from design limitations.

2.1.3.1 Degrees of freedom for geometry update - The mesh of the car surface, namely a set of points and a connectivity matrix, is completely determined by a set of Bezier points through a deterministic spline algorithm. However, the set of Bezier points is too large to be a good set of variables to be changed during optimization. Moreover, changing a single Bezier point induces modifications confined in local portions of the geometry, thus easily resulting in parameter evolutions that are not acceptable from the point of view of the constraints and of the general style of the car.

The hierarchy of the geometry moves from the control elements, C (points and lines), to the Bezier points and, finally, to the mesh; while control points can move in three dimensions, control lines can be moved only along two dimensions; their role is typically to allow geometry modifications that are coherent along the whole width or length of a macro panel element.

The optimizer code acts displacing the control elements. These displacements change the position of the Bezier points with a prescribed influence curve, for instance a gaussian. By tuning the width of the gaussian for the different control points it is possible to change the locality of the elementary optimizer steps. More details can be found in [5].

2.1.3.2 Cost function - The design variables used in the optimization process are the Bezier points defining the external shape of the car, by means of the hierarchy structure defined in the previous paragraph.

By integrating the pressures acting on the car surface (i.e. on the car fore body and base), previously computed by the aerodynamic solver, it is possible to obtain the pressure forces acting on the car. For this evaluation the lower surface of the car may or may not be considered, according to the choice of the user. The quantities evaluated by the solver, and thus involved in the optimization process, are Vertical Force, Pitching Moment, Vertical Force acting on the fore and rear axles, Pressure Drag force acting on the fore body part of the car and Base Drag.

The cost function is defined as a linear combination of these quantities, with the weights given by the user.

2.1.3.3 Minimization algorithm - Once the cost function is defined, by means of a linear combination of the quantities evaluated by the aerodynamic module, its minimization proceeds by a steepest descent gradient algorithm: we note that each control point counts for 3 degrees of freedom (DOF) and each control line for 2 DOF. Hence we have:

$N_{DOF} = 3\ N_P + 2\ N_L$

The gradient of the cost function along each DOF is approximated by a finite difference. The direction $d=(-\nabla\Gamma)$, is chosen for an optimization step; therefore, the new value of the control point vector is

$C_{i+1} = C_i + \mu d$ where the parameter μcontrols the size of the step.

As described in the previous paragraphs, the steepest descent algorithm, adopted for the minimization of the cost function, is not in general the most effective. However, it presents the advantage that at each step the evolution of the car shape can easily be followed and understood in terms of the geometry of the cost function surfaces, thus allowing the designer to gain insight in the aerodynamics, which is one of the objectives of this project, and, therefore, it was assumed as the most appropriate in an initial stage of the development of an optimization procedure.

2.1.3.4 Constraints - To carry out the optimization procedure following chosen requirements, several constraints may be assigned to the different quantities that are evaluated. Moreover, the modifications to the external shape of the car are not completely free, but they are clearly limited by esthetic and functional requirements (volume specification for the engine, passengers, wheels, etc.). These constraints are considered in the optimization procedure by defining certain specific zones of the car and imposing, with respect to the initial car geometry, a maximum displacement and/or a maximum mean displacement, for each defined zone. The choice of the constraints to be activated is left to the user.

The geometrical constraints are in turn defined as a modification of the cost function Γ. A repelling "potential" is introduced, which results in a very small modification of Γ when the mesh is inside the boundaries, while close to the boundary and outside a high gradient drives the evolution back within the limits. More details can be found in [5].

Aerodynamic constraints can be activated for each of the aerodynamic quantities evaluated by the solver. These quantities are clearly available only at the end of a certain step and, therefore, these constraints are not included in the cost function, and are checked on the output of each optimization step, by means of a recovery procedure described in [5].

2.2 EXPERIMENTAL VERIFICATION - The HIPEROAD code was then used to produce, starting from the previously described geometry, a new optimized shape having as cost function the reduction of the vertical load. However, the allowed geometry modifications were strictly constrained (maximum allowed displacement of 3 cm at full scale), in order to obtain a new shape maintaining all the main stylistic features of the original one, and a constrain on the drag (that could not increase) was imposed.

It is important to note that the entire optimization procedure was carried out within one day. The obtained shape produced a variation of the vertical force coefficient due to the pressures acting on the upper part of the car of _CZ=-0.042. A wind tunnel model with this geometry was then constructed and tested with the same methodology already used for the original model. The experimental results gave _CZ =0.035, with a reduction slightly smaller than predicted, and CD=0.181, smaller than 0.185 given by the original shape. Considering the very small geometrical modifications with respect to the first model, the reduction in vertical upload, obtained together with a slight reduction in drag force, was considered to be more than satisfactory.

In conclusion, the validation tests showed that the code is capable of satisfactorily carrying out its required task, i.e. producing in a very small time a modified configuration with small geometrical modifications but technically significant improvements in the aerodynamic loads.

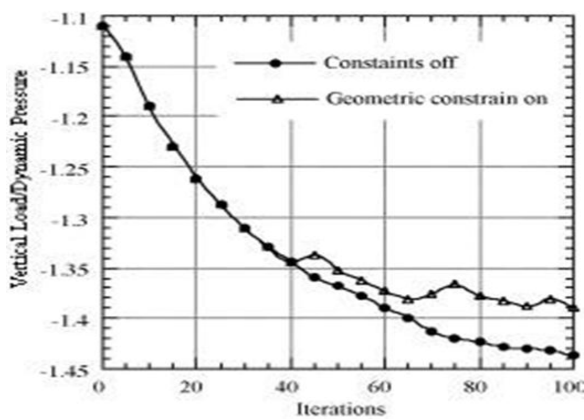

Fig. 6 – Object function for basic and geometrically constrained evaluations

Clearly, it is necessary to verify also the other aerodynamic characteristics, for instance the drag or the axles balance. As an example, the pressure drag is reported in Fig. 7, together with the object function for a better comprehension. As can be observed, this quantity decreases up to iteration 70, and, successively, increases.

It is interesting to note that a single operator carried out the described analyses in two days. At this point different strategies can be used, depending on the specific problem.

A further step could be to impose a defined load distribution between the wheels axles that is a constraint of aerodynamic type. Clearly, this parameter changes in the optimization process. A calculation of the same case, with the same constraint on the displacement of the car surface, and an additional constraint on the load distribution (variation in the fore/total load less than 1%) has been carried out. The final shape (after 100 iterations) shows again a very small modification in the car shape, but the improvement in the object function, as can be seen from Fig. 8, appears significantly less important. This is important information to the designer, i.e. that the significant increases in the performances are related to modification in the longitudinal load distribution.

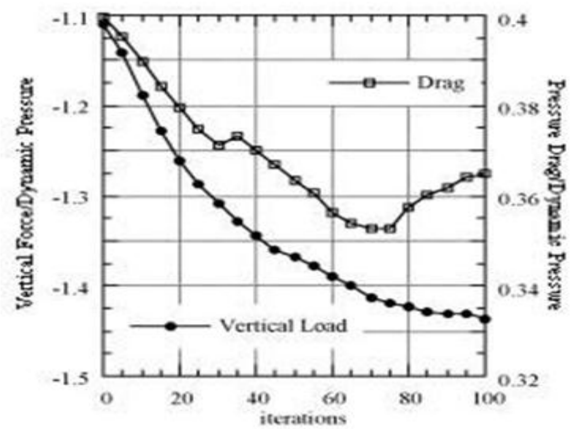

Fig. 7 - Pressure drag (Forebody drag + Base drag) on the car

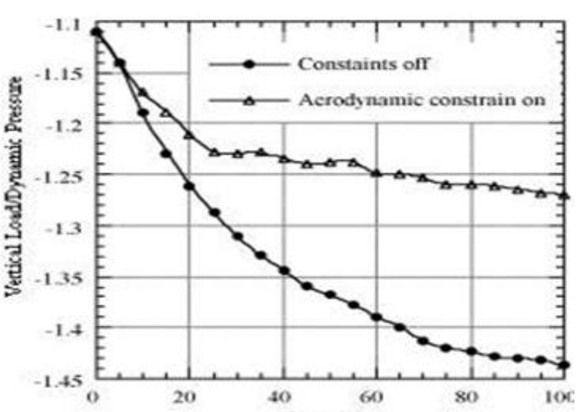

Fig. 8 – Object function for basic and aerodynamically constrained evaluations

It should be noted that the results of the presented procedure cannot be assumed as definitive, but must be critically reviewed, since a significant number of different configurations must be considered and several points need to be more accurately analyzed.

3 CONCLUSIONS

A study of the capabilities of different optimum design strategies has been presented. The hybrid procedures, which combine stochastic global search and deterministic local search techniques, are more particularly considered. In an industrial context, the computational cost of a design optimization procedure appears as a critical point and, thus, a suitable strategy must give a good compromise between costs and effectiveness in reaching the global optimum. As expected, an important improvement on the final optimized solution is obtained using Genetic Algorithms instead of classical gradient-based methods. Moreover, the hybridization process applied with an adequate switching criterion also permits to considerably reduce the computation costs. The efficient strategies and consistent stop criterions presented in this study can be directly incorporated in car optimization procedure like the aerodynamic design optimization described in the last part of the paper.

The described optimization procedure satisfies the main requirements given by the end user. In particular, it is capable of yielding shapes having more favorable aerodynamic characteristics with very small geometry modifications, thus keeping the style substantially unchanged. Obviously, by this means it is not expected that very high decreases of the vertical load may be obtained. The objective is to find rapidly the best configuration within a certain small range of shapes that are considered to be acceptable from the style point of view, without resorting to time-consuming and expensive wind tunnel tests. In other words, while it is relatively easy, for an experienced operator, to devise significant changes to a shape producing substantial increases in the vertical load, but also considerably altering the style of the car, it is almost impossible to predict the effects of very small modifications of the geometry. In any case, the cost and the time for a wind tunnel campaign for this purpose would be prohibitive.

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