DESIGN OF AUTOMOTIVE COMPONENTS USING ADVANCED CAE SYSTEMS

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ABSTRACT
Simulation and other computer aided tools are often used in automotive design, since the design process is strictly oriented to the optimization of the performances through an iterative synthesis and analysis cycle aimed to understand the effects of changes in the geometry and layout of the various components. The search for the optimal performances is at the moment carried out empirically by the "trial and error" approach because parameters and constraints are too many for a global optimization of the vehicle dynamics to be performed. Nevertheless it is possible to introduce in the current design process some optimization algorithms or tools that can guide the designer in the decision process. This paper presents a methodology, applied to the conceptual design of the upright for a Formula SAE prototype, in which a multi-body simulator, CAD and a topological optimization tool are sinergically employed in order to support the suspension design.

Keywords: multi-body, topological optimization, integrated approach

1. INTRODUCTION
The design of an automotive component has always been a complex process strictly dependent on the functions that the component must perform within the vehicle system. Therefore the final solution is almost never obtained directly but it is rather the result of an iterated optimization process which incorporates the capacity, the intuition, the experience and the know-how of the designer [1-3].

The "build and test" method, historically adopted in engineering, is until now the only one that can be used to solve those problems which are not supported by suitable design instruments. The "build and test" method requires a physical prototype to be constructed and the boundary conditions in which it operates to be reproduced. This approach allows to find results that although accurate, are strictly related to the lay out of the experiment; it is hence practically impossible to gain any knowledge insight. Moreover, repeating the experiment is very onerous given of its high costs and of the long time required. For these reason the build and test method is mostly adopted for the final validation of the results of design methodologies, rather than as a tool to search for the optimal solution.

The disadvantages of this method have been overcome by the development of CAE systems that allow to create digital mock-ups of the prototypes and to test them in the operating conditions in a completely virtual way. This latter approach allows to make changes at high speed and low cost so that the trial and error method becomes an extremely powerful design approach. The trial and error method in the case of multi-domain and complex problems, such as vehicle design problems, often involves the use of different CAx systems that, if utilized in an integrated manner, allow to reduce the time for developing the process and to achieve a high efficiency in comparison with the traditional methods.

The development process of a vehicle (fig.1) consists of four main phases starting from the definition of the vehicle specifications and ending with the identification of the characteristics required to the singular component.

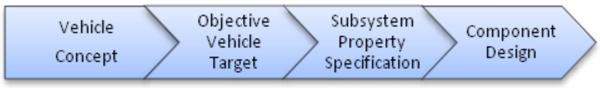

Figure 1: Vehicle development process.

In the first phase the vehicle concept is defined by identifying the characteristics and functionalities that the designer wants it to possess. In the next phase, the functional and performance macro-requirements, established in the previous phase, are objectified. In the third phase, the characteristics of the sub-systems are defined, taking into account the objective characteristics of the entire vehicle.

During the last phase the design process is utterly refined focusing on the single components of the different sub-systems.

It is hence possible to define three design levels (component, sub-system, vehicle) for each of which an iterative design process is identified within an analogous higher level design process; every level sends inputs to and receives feedbacks from the upper level (fig.2).

The design of the upright is performed in the design process of the suspension subsystem and, indirectly, in the design process of the whole vehicle.

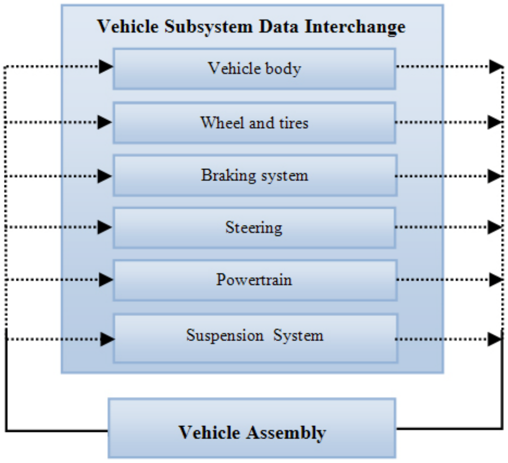

Figure 2: Chart flow subsystem design.

This paper presents an improved approach for an interdisciplinary combination of multi-body, CAD and topological optimization systems. In particular, the paper deals with the integration of the multi-body ADAMS/Car system with SolidWorks CAD system and Altair Optistruct topological optimization system, in order to achieve the optimal design of the upright of a Formula SAE prototype.

2. SUSPENSION COMPONENT DESIGN: THE STANDARD METHODOLOGY

The identification of requirements and constraints for the upright design descends from the dynamic behavior analysis of the whole vehicle. The ride and handling analyses allow to define design parameters for all components (damping, springs and structural suspension elements). In particular the handling analysis allows to determine the K&C suspension characteristics that are the basis for the structural component design. The suspensions are modeled generally in *multi-body* environments through kinematic constraints and shapeless elements, depending on the appointed architecture.

The use of these environments enable the designer to submit the system to K&C and optimization analyses in order to find a topology of the system that satisfies both the kinematic requests and the component compliance according to the elasticity requirements of the suspension.

The topological information are used in CAD system in conjunction with the data inferred from multi-body kinematic analysis in order to carry out a packaging analysis. Vice versa, the definition of the geometry of the components leads the kinematic optimization in MB system. Information concerning the component compliance are utilized in FEM systems in order to carry out the structural test. Depending on the success or unsuccess of the structural test, these results are transferred to multi-body systems to either support or correct the values of the compliance.

Data exchange occurs between CAD and FEM systems: the geometrical modelling systems allow to define a geometry of the components compatible with packaging analysis, while structural simulators pick out a geometry that satisfies structural requirements. This iterative data exchange between MBS, FEM and CAD systems enables the optimal solution to be found for the entire system (fig.3).

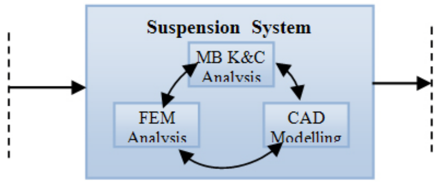

Figure 3: Vehicle suspension design.

2.1. Upright design

Design requirements and constraints of each component ensue from the analysis of the specific vehicle sub-system to which the component belongs (fig.4). Depending on the functionalities that the upright has to execute in the suspension sub-system, the requested properties are:

- An assembling geometry and a kinematic behavior into a predefined volume
- Specific compliance
- Light-weight structure

The upright compliance requirement is defined by means of the compliance analysis of the suspension sub-system (the suspension must undergo a given deflection under specified loads).

The kinematic and packaging analyses allow to determine the volume necessary to achieve optimal kinematics, functional surfaces essential for assembly, and overall dimensions such to avoid interferences during the dry run. In this way it is possible to specify geometric constraints that determine the maximum dimensions and the initial shape of the component.

Usually the material of the component is defined a priori on the basis of know-how, survey of competitors and economic valuations. Similar evaluations allow to choose an appropriate factor of safety. The loads with their application points, values and directions are the last characteristic to be determined.

The final optimal result will be a component with the minimum mass that satisfies the specified requirements.

Establishing loads and optimal geometry is the critical point of this approach. In fact, without a physical prototype it is necessary to calculate accurately the normal operation loads. As a consequence, a robust virtual modeling is necessary in the multi-body system in order to simulate the normal operation of the suspension.

Concerning structural optimization, the traditional trial and error method enables the designer to make subsequent and iterative modifications motivated by geometry, stiffness and safety requirements.

The rate of convergence and the convergence itself depend strictly on the designer experience; the time could be very long; and the result could not be the best one.

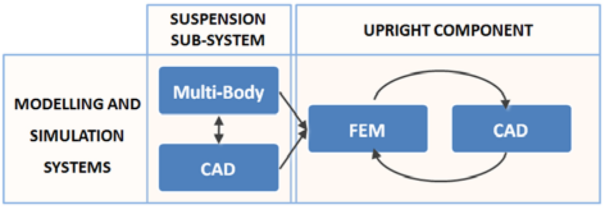

Figure 4: Specification and process for upright design.

3. SUSPENSION COMPONENT DESIGN: INTEGRATING TOPOLOGY OPTIMIZATION

As stated in the previous section, the use of a TO system during the development process (fig.4), allows to redefine the design methodology. In particular, the definition of the optimal geometry does no more depend only on the designer capabilities but it is supported by the three-dimensional topology optimization results. The integrated use of MB and TO systems allows to support more effectively the crucial points encountered during the design development process of an automotive component, that are: loads and optimal geometry definitions.

Figure 5 illustrates the proposed methodology. The methodology integrates three different systems and specifies the procedure for data exchanging.

As stated above, within the multi-body simulator the designer determines topological information, loads and constraints related to each component that has to be designed in detail. The topological information on the component (axis, distances, characteristic points, etc.) are used to define, through CAD system, the overall dimensions of the component geometry.

The use of TO systems simplifies the modeling phase because it is no longer necessary to specify the geometry in detail, but it is sufficient to define the component overall dimensions.

In the proposed approach, CAD automation tools have been adopted to improve the integration and interoperability between CAD and TO system [4-6] thus further simplifying the modelling phase. By adopting this tool the designer can specify in the model the invariant volumes which will not be modified during the optimization process. This knowledge can be stored and transferred directly to the next CAE phase to be reused in the redesign phase. This operative method offers several advantages. It allows to export the model in CAE system no longer as a unique entity, but distinguishing invariant volumes from volumes to be optimized and, above all, it preserves this knowledge throughout the optimization process.

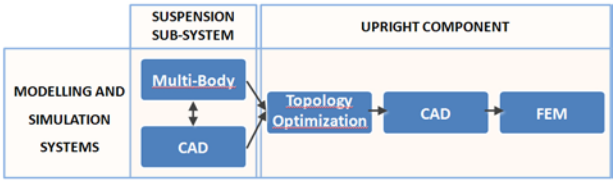

Figure 5: MB and TO integrated approach

In order to illustrate its capability, the approach is applied to the design of a FSAE upright.

4. CASE STUDY: FSAE UPRIGHT DESIGN

4.1. Problem definition

The vehicle taken as reference for the design of an upright is a prototype for Formula SAE competition realized in University of Calabria.

Following the development procedure previously described, in the first phase the fundamental characteristics of the vehicle have been defined, among them the suspension system double wishbone with pull rod for the front.

Subsequently, a first improvement of the set-up was achieved by a simplified model of the vehicle implemented in Matlab-Simulink. The model considers only the mass, the center of mass, the moments of inertia, the roll center, the geometric vehicle parameters and the tire characteristics. In this way the following parameters have been determined: wheelbase, track, mass distribution, suspension rates and suspension kinematics and compliance characteristics. The multi-body models of the suspensions and of the entire vehicle have been realized by the commercial software ADAMS/Car (fig.6).

During the maneuver operations of the vehicle, the adjustment of loads has been carried out by applying specific requirements on the spherical joints connecting the upright to the suspension. Values and directions of loads have been specified by giving the space coordinates relative to the coordinate system integral with the upright.

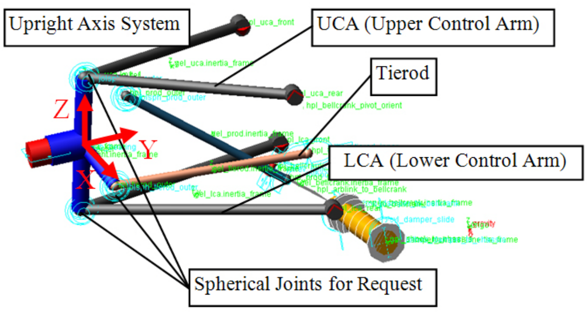

Figure 6: Multibody ADAMS\Car front-left suspension model.

4.2. Specifications for upright design

The stiffness requirements have been defined directly while modeling the set-up of the vehicle in Matlab-Simulink.

With regard to the material Aluminum 7075-T6 was selected because of its excellent ratio between weight and strength [7-9]. The safety factor was chosen equal to 2.5 taking into consideration the contemporary presence of braking and cornering [7-9]. When defining the functional surfaces, all the components which must be directly assembled with the upright have been considered (fig. 7). The dimensions of the wheel have been defined according to the pneumatic characteristics. These dimensions allow to determine the volume into which the upright has to be positioned. The selection of the bearing for the coupling with the hub and of its blocking system has permitted to establish the dimension of the seat of the bearing on the center of the upright.

The rod end bearing for the coupling with the lower control arm has determined the dimensions of the hole and of the slot located on the bottom part of the upright: the vertical distance between the opposite faces of the slot has been defined on the basis of the dimensions and of the mounting of the bearing; the space occupied during the kinematic movements of the suspension has dictated the horizontal distance between the opposite sides of the slot; the location of the hole has been established by kinematic analyses.

Because of the necessity, dictated by kinematics of shifting the rod end bearing, coupled with the upper control arm, towards the inner part of the vehicle and also to use plates for the camber regulation. A separate component, joined to the upright by two screws, has been added to accommodate the bearing seat. Starting from the dimensions of this new component, the surface and the position of holes for its assembly have been defined. A similar solution has been adopted to join the upright to the tie rod; the holes for its assembly connection have also been identified. The selection of the brake gripper has permitted to define the holes and the surface for the assembly.

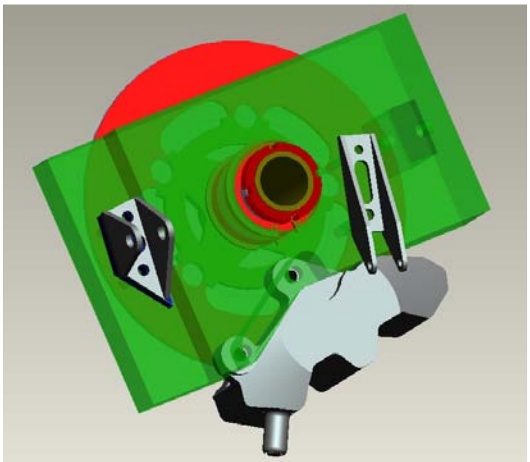

Figure 7: Upright and related sub-assembly

The optimal geometry of the upright will be found in the next TO phase; at this stage the CAD upright model is defined in a "rough" manner. In fact, during this first phase, the model must contain information about overall dimensions and the functional surfaces, resulting from the packaging analysis, that will remain unchanged during optimization.

To support these modelling operations a tool has been developed in SolidWorks which allows to specify and distinguish the invariant volumes from the volumes to be optimized. In this way the feature-based models of the invariant volumes can be transferred and reused in the redesign phase thus avoiding remodelling them [4-6].

4.3. Determination of dynamic loads

The loads to adopt in the design of the upright have been defined making reference to the worst conditions in relation with the maximum lateral and longitudinal accelerations recorded during standard maneuvers in a Formula SAE race.

Dealing with a frontal upright, braking and cornering simulations have been performed considering the combination of the two as the worst operative condition [8].

The loads taken as references in the analysis refer to the wheel mostly overloaded. The loads are given through their components in the SAE coordinate reference system of the upright and they are specified on the three points where the upright is connected to the tie rod, the upper control arm and the lower control arm.

Where cornering was concerned the model of the vehicle has traveled along a 30 meters diameter circular trajectory, at a reduced longitudinal acceleration, starting from the first gear and changing up to the limit of the cornering.

The braking maneuver has started from a velocity of 100 Km/h, in fourth gear, and jamming on the brakes until the complete stop of the vehicle.

For sake of brevity, only some of the charts of the analysis results are presented on the following (fig. 8-9):

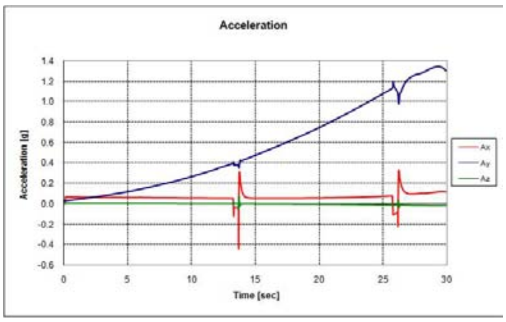

Figure 8: Chassis acceleration during cornering analysis (Vehicle Axis System).

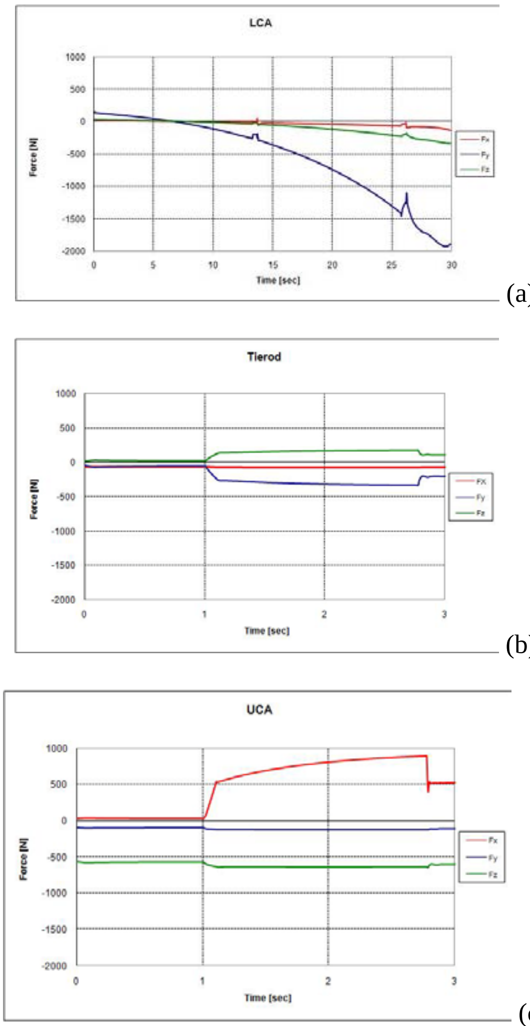

Figure 9: Time-history (a) LCA loads during cornering analysis, (b) Tierod and (c) UCA loads during braking analysis (Upright Axis System).

The maximum upright load values are shown in table 1.

Table 1: Upright load values

Braking and cornering combination loads value			
	Fx [N]	Fy [N]	Fz [N]
UCA	936.6	1357.5	-765.7
LCA	-1620.0	-1926.9	-341.3
TCA	153.1	-539.9	279.2

4.4. Topology optimization analysis

The topological optimization analysis was performed using Altair Optistruct. Before starting the analysis, it is necessary to create the mesh of the model. Altair offers, in the Geometry panel, various tools that allow the designer to create the model but, as stated before, it is possible to import the upright surfaces in IGES format. In this phase, the designer has simply to define the collectors, that is to declare the physical properties of the model and the boundary conditions identified during multi-body analysis.

It is possible to create a collector for specifying the type of material, another for loads and constraints, other ones to define variant and/or invariant volumes. The import of invariant volumes from CAD system facilitates the operation of selection of hexahedral elements assigned to "no design" mesh (fig.10).

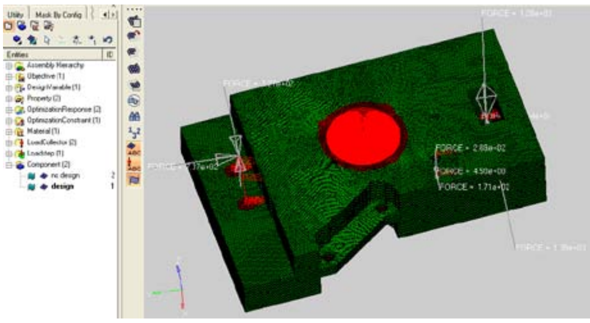

Figure 10: Mesh generation and loads and constraints assignment

The topology optimization problem is then defined as follows: minimize the volume of the upright.

At the end of the optimization process it is necessary to execute the OssMooth module, present in Altair Hyper Works, in order to translate the topological optimization results into an STL format file and export it in CAD environment (fig.11).

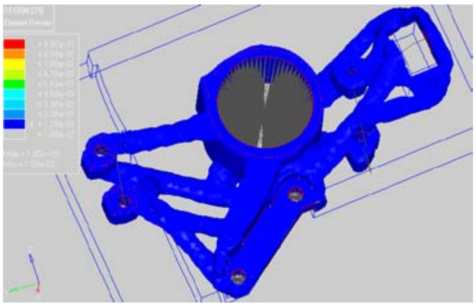

Figure 11: Topology optimization results

4.5. Model redesign

In this phase, the result of the optimization is imported into a CAD environment for modeling the optimized feature-based upright. At present, the translation of optimization results into a feature-based model is not an operation adequately supported by CAD systems. One of the main problems regards the loss of all feature data in the optimization process. The output of topological optimizers is a voxel model, so it does not take into account either functional and technological features, either rules and attributes associated to the various parts of the product. There are many interpretation techniques available in the literature but most of them focus on 2D or 3D simplified structural optimization applications [10-11].

In order to simplify this phase, a SolidWorks macro was implemented that allows to automatically input invariant geometries identified during the initial phases of the procedure.

In future, during this phase, we will introduce the geometric analysis for investigating topologically optimized geometries in order to reduce user interactions and decision-makings in the solid model reconstruction [5-6]. In figure 12 the final upright model is shown.

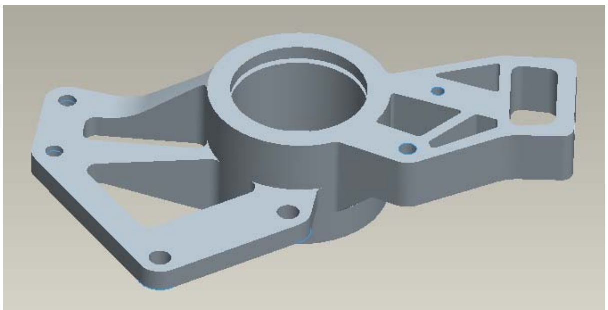

Figure 12: Final feature-based model

4.6. Finite element analysis

In the last phase of the proposed methodology, classical FE approaches are applied to test and validate the new shape of the optimized model (fig.13).

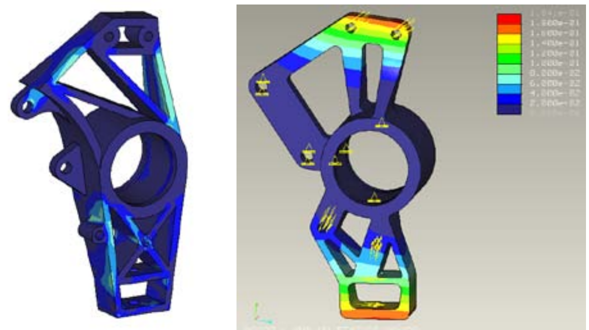

Figure 13: Comparison among FEM model of the upright 2008 and the new upright.

The comparison, between this model and the upright currently present in the FSAE car, shows a significant improvement in term of weight and stiffness (Table 2).

Table 2: Data comparison

	Upright 2008	**Upright 2009**
Maximum Stress (Mpa)	94.2	168
Maximum Deflection (mm)	0.24	0.18
Weight (Kg)	0.966	0.721

5. CONCLUSION

In the paper a methodology has been proposed in which multi-body simulation, CAD and topological optimization are synergically employed to support the suspension design. The methodology has been applied to the conceptual design of the Upright for a Formula SAE prototype.

The results have shown that the integrated design approach can be an efficient support in the optimum conceptual design of a mechanical component with complex dynamic behavior, particularly when almost no experience on the system is available. The comparison between FSAE Upright version 2008 (designed by the traditional approach), and FSAE Upright version 2009 (designed by the proposed approach) show a significant improvement of the mechanical properties.

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