The Use of Virtual Prototypes in Automotive Suspension Design

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***Abstract*- Automotive vehicles are among the most complex systems to improve and design due to nonlinear dynamics in the multiple systems that compose it. This article exposes some considerations that had arisen in the process of modeling a quarter with control purposes. This process goes from the conceptualization of the model, determining complexity and precision, to simulation and validation of the model and tests. Two study cases are presented, one where an active controller is applied to a quarter of a vehicle and one where the packaging of a suspension is reduced in both cases a virtual prototype is used. One study case presents a co-simulation with a mathematical solver.**

***Keywords*- Component; Modeling; Multibody Systems; Suspensions; Control; Active Suspensions**

I. INTRODUCTION

More companies around the world are investing several millions in research and development; engineers have the pressure to produce more and better designs in a shorter period of time. In the automotive industry, for example, millions are invested in new prototypes, only one of the top five manufacturers of automobiles plans to spend $100 million during the next four years on advanced research and modeling [1]. Virtual modeling can and is changing the design process, not only because it facilitates the review process of highly complex products as ground vehicles, but also because it gives freedom to the engineer to try an infinite number of possibilities [2].

The use of virtual models is becoming imperative in cutting edge technologies from control to alternative fuels considering that the design tendency worldwide is to abbreviate the design process and at the same time obtain better and more precise results in the simulation process before the prototype experimentation. Virtual models are particularly useful in suspension design due to the complexity of the systems [3, 4].

Simulation and modeling is a versatile and cost effective tool, if understood and used properly. This paper proposes a methodology to integrate virtual models in the design process, discuss some of the issues that arise from the integration of such models and ends with some remarks on the interpretation of data and some issues concerning the use of simulation in industry [5].

II. VIRTUAL MODELS

A. Definition

One widely accepted definition of virtual prototypes is the one proposed by Wang (2002):

> *"Virtual prototype is a computer simulation of a physical productthat can be presented, analyzed, and tested from concernedproduct life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physicalmodel. The construction and testing of a virtual prototype iscalled virtual prototyping (VP)."*

In other words a virtual prototype is a digital model of a product that will be used for testing, to evaluate form or design and to evaluate its performance in a dynamic simulation. It has to prove design concepts, but also and most importantly, be the framework to evaluate design alternatives. It can be used to analyze product manufacturability as well. The goal is to replace the physical prototype. The advantages of such model are enormous; first the model is parameterized and can be modified as will, allowing designers to perform iterative designs and numerous testing that will reveal errors early in the design process. In the vehicle design process, a 3D model of the vehicle can be develop and used for dynamic tests, that means accurate measures of distances, inertias and physical characteristics should be available.

B. Updating the Design Process with Virtual Prototypes

The traditional vehicle development process initiates with a concept that will satisfy the needs of the client and then proposing several designs that will meet those needs. This process is highly iterative; engineers often modify costly prototypes to meet not only customer's needs, but performance and safety requirements. There are statistics that show that more than 1/3 of the design failures are due to limitations in the design process [2], which means that the engineer takes decisions in the design in spite of significant uncertainties, but is oblige to do so because of time and mostly economic limitations. When the design process is updated with virtual models,it is considered to improve some of the steps. A virtual prototype can indeed make a change in the way products are designed, tested and manufactured because many times it replaces the physical prototype saving both money and time. With the virtual model very different operation conditions can be tested, also the engineer can prove some design constraints and refine the design with software before proceeding with the physical prototype.

Virtual prototypes can also assist in solving reverse engineer problems. That includes the analysis of outputs like displacement, acceleration, natural frequency and velocity, which are difficult and costly to obtain in the physical prototype. Having a virtual model that you can change and modify in an iterative loop may simplify the hard task of adjusting the model.

Referring to the product lifecycle management, including virtual prototypes may help attaining the new goals in design, such as:

1) Reduced time to market: this can be achieved by substituting real prototypes with virtual prototypes, because even when the elaboration of both prototypes is hard, then making subtle changes and adjustments in the virtual prototype is fairly easy and as far as the real prototype is concerned this is far more difficult and expensive.
2) Improved product quality: using virtual prototypes can reduce uncertainties in the design process when engineers are taking decisions in the vehicle design.
3) Reduced prototyping costs: the virtual scenarios that can be achieved are far more diverse in a virtual environment, the adjustments of the prototype can be easier to perform in a virtual file than in a real object, never the less a real prototype is necessary at the end of the design, but a far more tested and finished model can then be used.
4) Framework for product optimization: virtual models are precisely adequate for product optimization, they can be modified and adapted to algorithms where an infinite number of test can be performed seeking optimization goals while respecting multiple constraints. Many of the modeling software have tools for optimization integrated in the multi-body modeling approaches.

III. CONSTRUCTION OF THE MODEL

A. Determine What Type of Model

Modeling a complex system implies an interdisciplinary array of data. This is a difficult task for many engineers, particularly in the early stages of the design process.

There are several types of models that are standard in vehicle design:

1) Quarter of vehicle: a model of quarter of a vehicle is mostly build for the study of the suspension, a virtual model will include characteristics of the tire (Pacjeka model or real data), geometric characteristics, information of damper and spring (data, curves or constants), weights and inertias.
2) Half a vehicle: the designer will have to know the suspension system, but also part of the transmission system and steering system, which will include inertias and precise coordinate system.
3) Full vehicle: the bare minimum of the model will include:
    a. Suspension and steering system (made of rigid bodies with masses inertias, characteristics of springs, dampers for the suspension system).
    b. Engine and transmission system (made with rigid parts with weights and inertia and motor torque could be represented by a mathematical equation or curve).
    c. Drive train.
    d. Tires (can be represented by the Pacjeka model, actual data or even a rigid body with a special joint with the floor).
    e. Chassis.

B. Model Conceptualization

To develop a virtual model it is necessary to define the parts that will compose the model, the role that each part has and the connection between them. This is a conceptual map that serves as a guide for the designer and is called topology of the model. Figure 1 is the example of the topology of a front suspension, where the components of the suspension are represented in ovals and the connection between them is represented with lines.

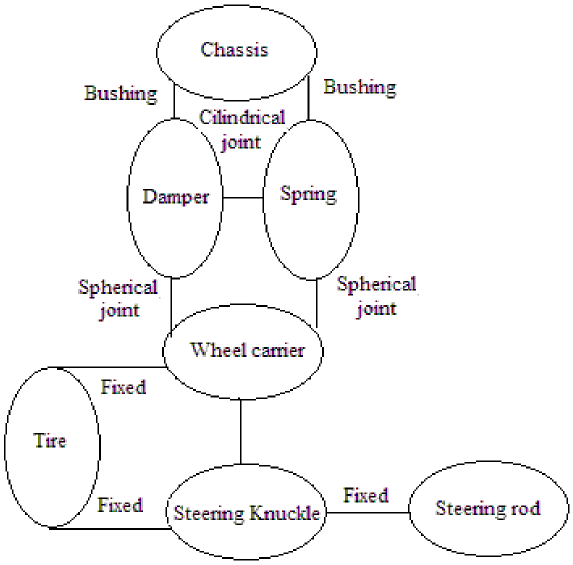
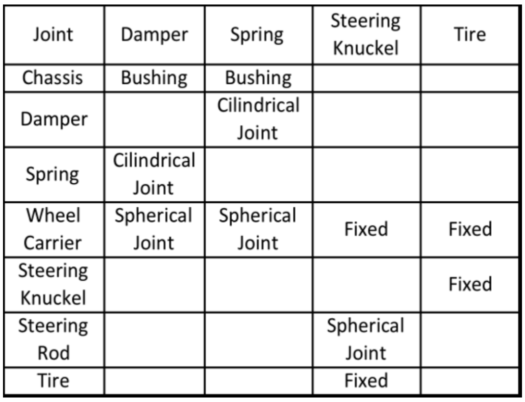


Fig. 1 Topology of a front suspension

There are several programs that can be chosen, where not only the dynamic system of the vehicle is to be analyzed, but also it can calculate the behavior of fluids for example. The fluid in the damper could be analyzed or perhaps using the same model, a finite element analysis could be performed to improve the model while maintaining the strain limitations of the material. More and more software is integrating dynamic behavior with strain analysis or finite element analysis. A virtual model is difficult to obtain due to the complexity of the systems modeled, but also to the detail that has to have. Sometimes with the same accurate model both analysis can be run separately or concurrently. In addition to that optimization tools are integrated. With the software that is now available, these models can be as precise and costly as the engineer will require. It is up to the designer to obtain a cost effective simulation and model. It is relevant as well to have a table where all the parts are listed as well as the connections to each other Fig. 2 is the interrelation table for the same suspension as Fig. 1.



Joint	Damper	Spring	Steering Knuckel	Tire
Chassis	Bushing	Bushing		
Damper		Cilindrical Joint		
Spring	Cilindrical Joint			
Wheel Carrier	Spherical Joint	Spherical Joint	Fixed	Fixed
Steering Knuckel				Fixed
Steering Rod			Spherical Joint	
Tire			Fixed	

Fig. 2 Table for connections between elements of a front suspension

These connections are actual joints in the suspension and can be model as precise as necessary. The impact of the joints is really important in the dynamical behavior of the model.

C. Model Goal

The precision of the model will depend on the objectives. It can be used to change or improve an existing design. If that is the case the virtual model will need to be a replica of the original model. There may be other purposes to make a model, for example to implement a control system in the suspension, or manufacturing. For each case the model will be more precise in the areas that will be studied and other areas could be simplified. There is a simplified and appropriate model that serves every purpose. Not all the detail is necessary in every case, the choice of a simple and yet representative model is the first step in a successful modeling process.

D. Co-Simulation

Co-simulation is widely used for several purposes, first it validates the model, on the other hand many controllers have been designed in some other software, it is now interesting to run applications that can communicate and send data to each other. There are mathematical solvers where many controllers have been tested and design. To integrate those controllers to a vehicle multi-body model can be performed in several ways. First, multi-body analysis software can create a mathematical model to be imported to a mathematical solver, the equations can be introduced the dynamic multi-body analysis software, it may even have already tools of control, and the last option is to run them simultaneously with the controllers in one software feeding entries to the other back feeding data to the first. This proves to be somehow difficult because different solvers may be difficult to integrate.

The clue here is to homogenize the step of integration in each solver. Figure 3 represents precisely a module of mathematical solver and a multi-body analysis software running in co-simulation. The quarter vehicle was modeled in a multi-bodydynamic software and the controller was modeled in a mathematical solver because of the complexity of the control algorithm. The blue module in Figure 3 is the plant imported from the multi-body dynamic software and they are run concurrently. V2 is the displacement of the strut in the suspension, V3 is the velocity of the damper, V4 is vertical acceleration of the chassis, V5 is the vertical displacement of the chassis (also known as sprung mass), V6 and V7 are the vertical displacement and velocity of the wheel (also known as unsprung mass). These variables are not only costly, but also difficult to obtain in real life, using a multi-body software these variables are imported to the mathematical solver to evaluate the performance of the controller also shown in the Figure 3. With these measurements the controller in the mathematical solver uses a control algorithm to calculate a force that will be added to the damper force (V1), like a variable damper. The control algorithm and the results are explained in one of the case studies [6].

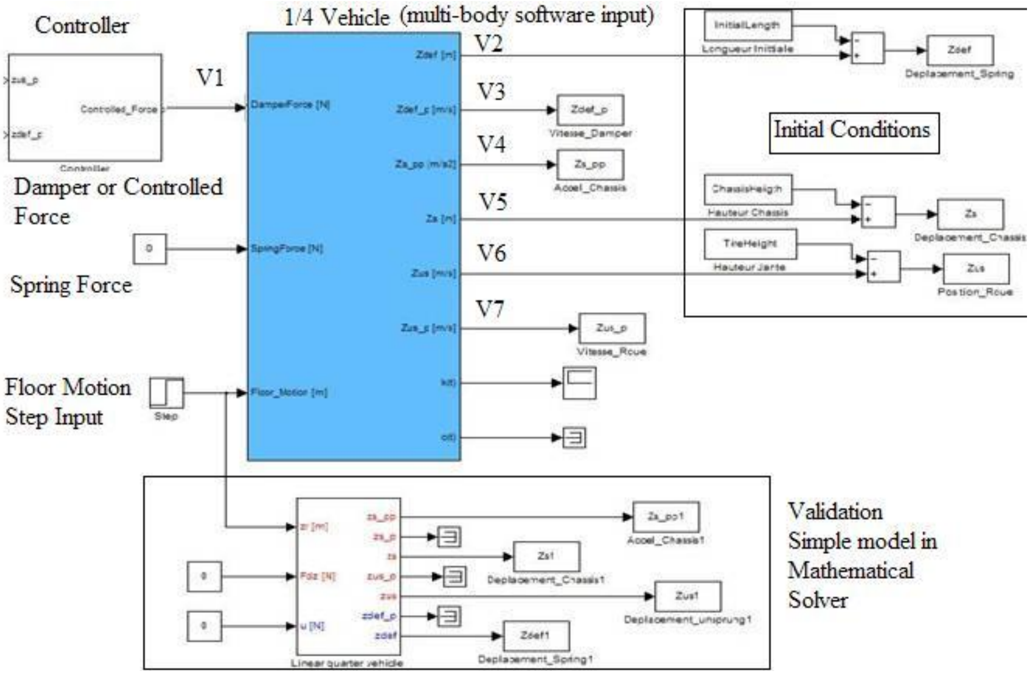


Fig. 3 Co-simulation of multi-body dynamic software and mathematical solver

E. *Model Validation*

Validation should and can be done for *all* models, regardless of whether the corresponding system exists in some form or whether it will be built in the future. Validation is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study.

A model that has been validated can be used to make decisions similar to those that would be made if it were feasible and cost-effective to experiment with the system itself.

The ease or difficulty of the validation process depends on the complexity of the system being modeled. It is necessary to validate the virtual model with real life prototypes. For that purpose the real prototype will have to be fully instrumented to compare results. To validate the model, all experimentation must be reproducible. Once established the need of the real prototype, another consideration must be made, asvalidation with real prototypes is expensive and should be done at the very end of the design process. The designer must have some raw results of what he expects to happen, that way figuring out the source of inconsistency will be far easier. For that purpose a validation with simple but yet illustrative mathematical models should be develop concurrently to the virtual prototype and tested with the same inputs. These will give an idea to the designer, if the model still consistent. In Figure 3 the dynamic Equations [7], [8] of a quarter of a vehicle are modeled as well in the mathematical solver to validate the results obtained with the virtual model.

IV. CASE STUDIES

A. *Effect of the Geometry in Suspension Design*

To illustrate the process of integrating a virtual model in the design process, there is a simple case study where it was necessary to reduce the packaging of the suspension and see how is impacted the toe angle. In this case a quarter of the vehicle model was used. The most important feature of the model was of course the precise space coordinates [9]. In Figure 4, every curve represents a different rod bar length; as the rod bar length varies the angle increases.

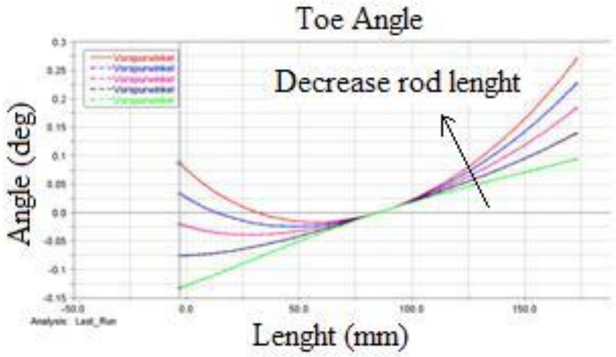


Fig. 4 Variation of the toe angle while reducing the suspension packaging

There is certain length of the rod bar in the suspension package where the toe angle is still in the tolerable zone, after that, the angle is too high.

B. *Trial of a Controller in an Active Suspension*

In this studycase a virtual model of the Renault Scenic was needed to implement new controllers in the suspension to ameliorate ride and comfort [10], [11].

The model was obtained by data acquired directly from the vehicle to build the model in a reverse engineering fashion. The new model was used to obtain accelerations, velocities and position for several points in the vehicle with the intention to evaluate controller's performance.

1) *Building the Model:*

Proceed to disarm the device and take precise measurements. These measurements could be obtained via a coordinate machine.

Fig. 5 Front suspension of renault scenic

2) *Draw all Pieces in CAD Software:*

In order to assemble an accurate model of the quarter of vehicle it is necessary to have all weights, inertias and material properties.

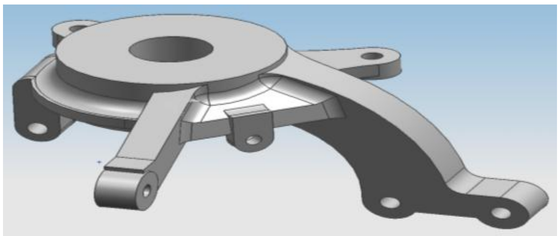


Fig. 6 CAD design of a suspension part with all properties

3) *Obtain All Curves and Nonlinear Characteristics:*

In a suspension the spring and damper have nonlinear curves depending on force and acceleration. When obtaining a virtual prototype even if those elements are usually modeled by simple equations, the model is significantly improved by obtaining the real data and introducing these curves either in the multi-body software or as a table in a mathematical solver. In this particular study case a universal machine was used as shown in Figure 7 and the curve obtained as shown in Figure 8, where the hysteresis loop may be observed. See details of experimentation in [14].

Fig. 7 Obtaining data from spring and damper in a Universal machine

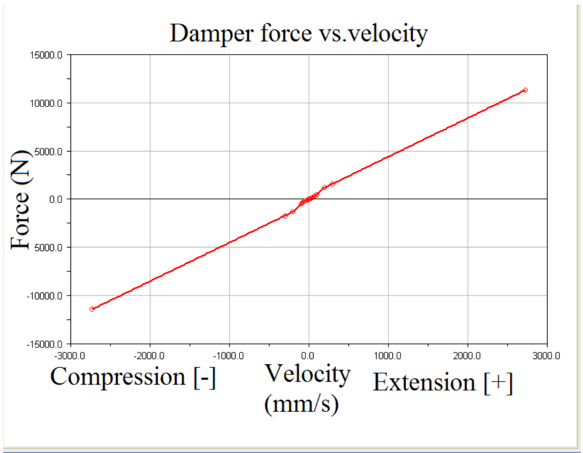


Fig. 8 Damper Force (Newton) vs. Velocity(mm/s)

When using an active suspension regularly the passive suspension is preserved and the active force is added to the suspension.

4) *Assembly of the Virtual Model:*

In most dynamic simulation software these steps are required for building a successful prototype:

1. Configure the tree dimensional model by returning to the topology of the model and placing all the principal joints in coordinates, depending on the software a high accuracy is needed in this procedure.
2. Import the CAD representation of every part of the assembly into the software, introduce all properties, inertia and weight.
3. Establish all the joint characteristics, very few information is available on bushings and on stiffness of most joints, some of these joints are modeled as zero degree freedom joints and results may vary from the real prototype.
4. Introduce magic formula or Pacjeka formula for tires, it is imperative to model the proper dynamic of the suspension [10]. An approximation is better than modeling as spring and damper for the tire stiffness.
5. Apply the quarter of vehicle weight in the center of gravity of the vehicle or if a quarter of a vehicle is considered in the center of gravity of half vehicle.
6. Evaluate the place where the active force will be applied, sometimes it will be applied in the same joints as the damper/spring, [12]. The force should have limits in the simulation and the calculation of the force might be from
   - An equation. A simple skyhook controller:

$$F(t) = -V_z(t) \times K \tag{1}$$

Where $F(T)$ is the force of the damper, $V_z(t)$is the strut velocity or damper velocity and K is a constant.

- A table or a curve.
- Model in a mathematical solver.(in the study case, the force is calculated in a Mathematical solver in co-simulation with the virtual prototype).

The objective to develop this virtual model was to test different controllers. In this case the controller was developed in a mathematical solver the objective was to attain the next objectives:

- Comfort at high frequencies(> 5Hz)
- Comfort at low frequencies (0−5)Hz
- Minimize gain of the function between the road and the un-sprung mass: Road holding.
- Limit the deflection of the strut.

To attain these objectives the *Power Spectral Density* (PSD) a criteria was proposed where each of the previous objectives goals is weighted. The development of the controller and test results are available in [6].

$$J_K(\gamma) = k_1 \frac{I_{4\to 30}(\ddot{z}_s)}{\max I_{4\to 30}(\ddot{z}_s)} + k_2 \frac{I_{0\to 5}(z_s)}{\max I_{0\to 5}(z_s)} + k_3 \frac{I_{0\to 20}(z_{us})}{\max I_{0\to 20}(z_{us})} + k_4 \frac{I_{0\to 20}(z_{def})}{\max I_{0\to 20}(z_{def})} \tag{2}$$

Where $\ddot{Z}_S$ is the vertical acceleration of the chassis, Z_s is the vertical displacement of the chassis, Z_{us} is the vertical displacement of the wheel, Z_{def} is the deflection of the strut, k_1, k_2, k_3, k_4 are constants.

The virtual model was connected to the controller in the mathematical solver in co-simulation. First comfort was weighted 10 times more than handling. The virtual model ran through a 4 cm step and data was recollected, in Figure 9 two tests are shown. First, the virtual model has no controller at all and then the model with a controller focusing on comfort. The improvement in the behavior is radical; it presents no oscillations and a smooth passage through the step. In Figure 10 we include another test where the controller is now focusing on road holding. In both cases the improvement of the behavior is radical, but in one case the transition is smoother and on the other case the stabilization is faster. It is up to the designer to establish the more convenient behavior for his design.

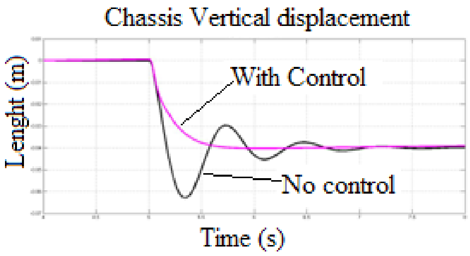


Fig. 9 Displacement of the chassis of the virtual model of a Scenic with no control (black) and controller focusing on comfort (pink)

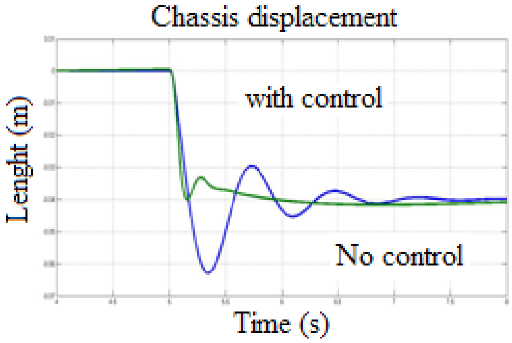


Fig. 10 Displacement of the chassis of the virtual model of a Scenic with no control (blue) and controller focusing on handling (green)

Similar results are shown in [13].

V. CONCLUSIONS

The innovation of new active suspensions can be developed with the helpof virtual prototypes;however, it is necessary a physical model, a real prototype. In this paper, the multi-body nonlinear model has been integrated in a quarter of vehicle model. In order to improve the performances of the quarter vehicle model, some industrial criteria have been used to study comfort and road-holding. The performances of the passive and semi-active suspensions have been simulated in time domain and emphasize the interest of controlled dampers. The next step is to do real tests of the controlled damper that can achieve the performance demanded by the controller.

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