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OPTIMIZATION OF THE STEERING MECHANISM OF A MOTOR VEHICLE USING PARAMETRIC DESIGN TECHNIQUES

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Abstract: The dynamic model of the guiding system of the motor-vehicles includes the kinematic elements - bodies (car body, axle, wheel carrier, guiding links), as well as the elastic and damping elements (springs, dampers, bushings, bumper and rebound elements). Having in view the complexity of these systems, for their analysis and optimization is useful to use multibody systems software (MBS). This paper puts forward the optimization of the steering linkage of a motor-vehicle using the MBS environment software ADAMS of MSC Software. The virtual model was optimized by parameterizing the mechanism, and performing design studies to identify the main design variables, with great influence on the functional parameters that define the behavior of the steering system (ex. steering angles, pressure angles).

1. INTRODUCTION

The increasingly growing demands for more comfortable passenger cars impose new methods for analyzing and optimizing the guiding (suspension and steering) systems, considering virtual prototypes close to real systems on the vehicle. The virtual prototyping solution allows conceiving and equipping virtual models that permit a large-scale evaluation of the vehicle behavior [4]. Virtual prototyping platform (fig. 1) includes MBS (Multi-Body Systems), CAD (Computer Aided Design), FEA (Finite Element Analysis) and DFC (Design for Control) software solutions. The virtual prototyping provides the ability to work within CAD environment, having in view to model mechanical systems, to easily transfer geometry between CAD and MBS software, respectively to transfer loads from MBS to FEA, and to bring component flexibility from FEA back into MBS. In addition, for the mechatronic systems, DFC is used to design the actuating & control system model, in the concurrent engineering concept.

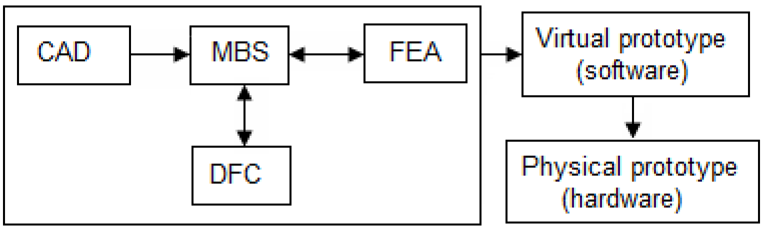


Figure 1. The virtual prototyping platform

The main component of the virtual prototyping platform is the mechanical systems analysis and optimization software (MBS). The steps to create a virtual model mirror the same steps to build a physical prototype: build, test, validate, refine, parameterize and optimize. The working precision is very high, so that the dynamic behavior of the vehicle may be predicted at early design stages. This reduces the number of costly physical prototypes, improves design quality, and reduces product development time [2, 3]. In these terms, the present paper puts forward the optimization of the steering system of an off-road vehicle using a virtual prototype realized with the MBS software ADAMS (Automatic Dynamic Analysis of Mechanical Systems) of MSC Software.

2. DESCRIPTION OF THE VIRTUAL MODEL

The virtual prototype of the suspension – steering system corresponds to an off-road vehicle with independent suspension of the front wheels, respectively of the rigid rear axle (fig. 2). The front wheels are guided with spatial four-bar linkage mechanisms (double-wishbone suspension), which perform the guidance through driving three points per wheel. The lower and upper control arms are connected to the car body through compliant joints (bushings) that allow 6 elastic restricted degrees of freedom. Spherical joints constrain the wheel carriers to the upper and lower control arms, respectively the wheel carriers to the steering tierods. The left and right suspension linkages are symmetrically disposed relative to the longitudinal plane of the vehicle. For the rigid rear axle, a guiding mechanism with four bars is used. This achieves the axle guidance through driving four axle points on four spheres. The upper and lower longitudinal arms are connected to the car body and to the rear axle through compliant joints (bushing elements).

On the other hand, the suspension system contains the elastic and damping elements, which represents forces acting between two parts over a distance and along a particular direction. For the front wheels suspension, the springs and dampers are disposed between the car body and the upper control arms. In the case of the rear axle suspension, the elastic and damping elements are disposed between the car body and the axle. The suspension spring is modeled as a double active (tension & compression) elastic element of translational nature. For limiting the suspension stroke, the front and rear suspension systems contain bound-stop and rebound-stop elements, which act between the upper and the lower struts of the dampers. These internal forces have transitory character, so that the bumper and rebound elements have been modeled as translational springs with unidirectional rigidity/stiffness (which are active only when spring is in tension or in compression), using one-sided impact forces.

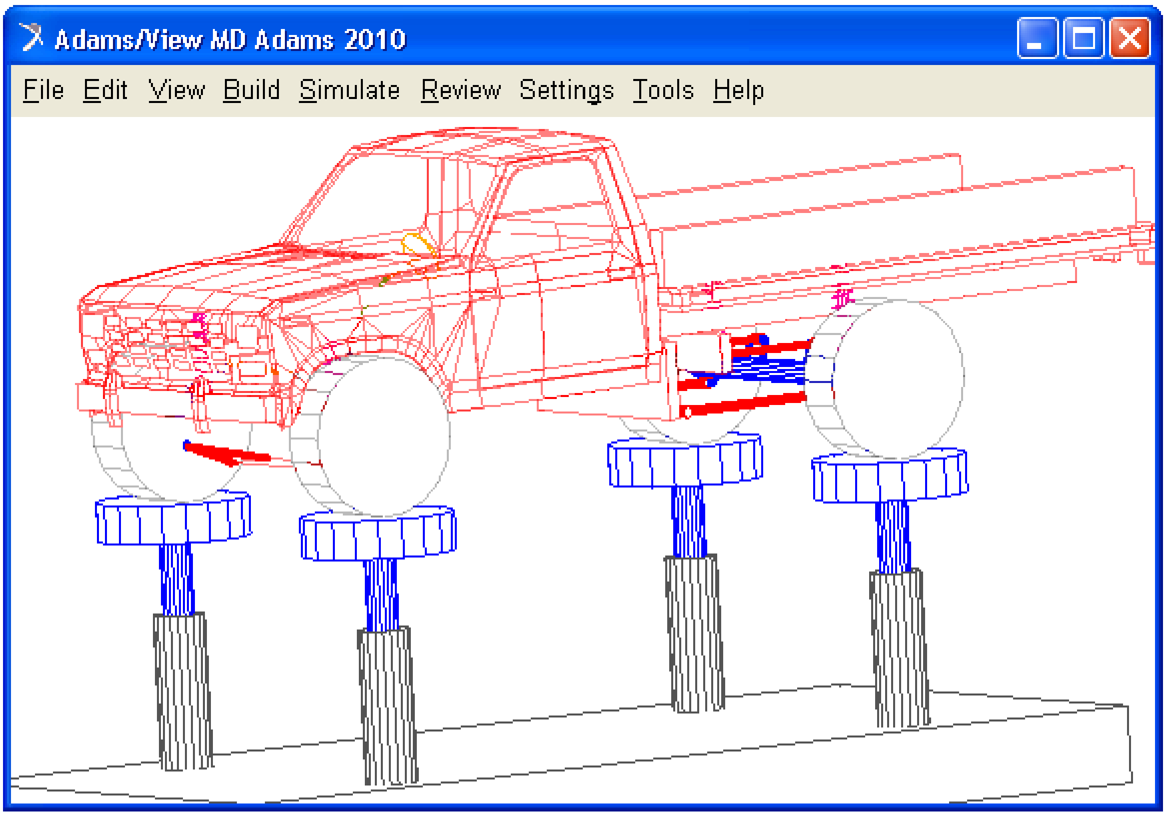


Figure 2. The MBS virtual model of the vehicle

The steering system (fig. 3), in detail analyzed in this paper, contains a four - bar mechanism with three mobile parts: pitman arm (4), center link (6) and idler arm (5). Two universal joints transmit the revolution motion from the steering wheel (1) to the input shaft (3), through the intermediate shaft (2). The worm gear transmits the motion from the input shaft to the pitman arm that rotates to impart motion to the center link and idler arm. The translation of the center link pulls and pushes the tierods to steer the left & right wheels.

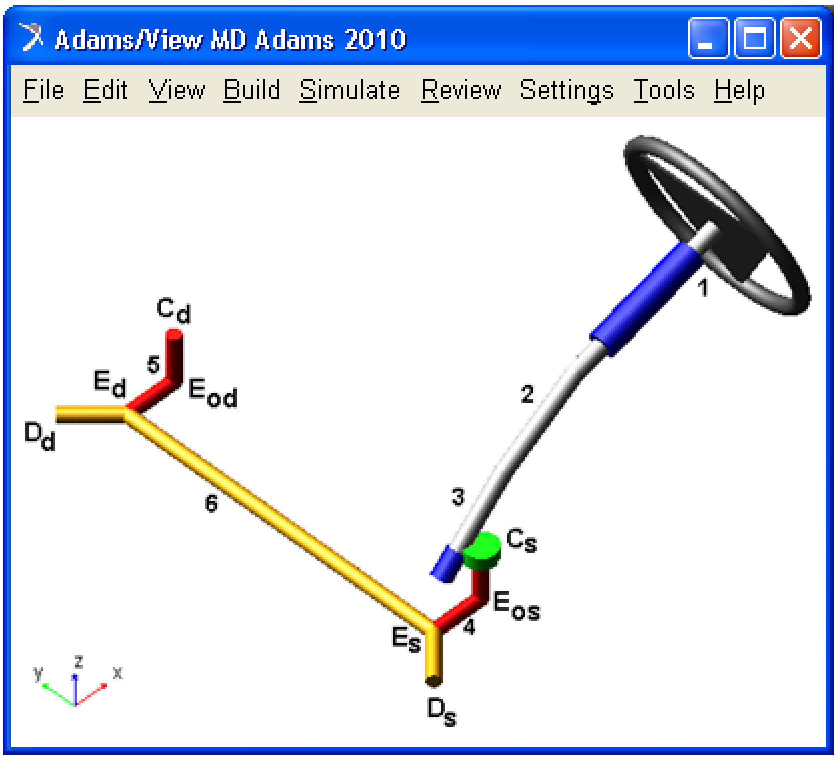


Figure 3. The steering system with four-bar mechanism and worm gear

3. OPTIMIZING THE STEERING MECHANISM

Usually, the steering gear box is disposed on the inner surface of the frame girder, but having in view to obtain more free space to mount the engine, the box can be disposed on the outer surface. In this way, some functional problems can appear [5, 6]: great steering errors (the difference between the real steering angle realized by the mechanism and the theoretical angle from the Ackerman relation); self-locking of the steering mechanism due to the pressure angle between the tierod and the steering knuckle lever; turning motion of the wheels induced by the vertical displacement of the suspension (when the wheels pass over road bumps).

Having in view to minimize the above-described negative phenomenon, the optimization of the steering system was made with the following steps: parameterizing the model, defining the design variables, defining the objective function for optimization, performing design studies and design of experiments for determining the sensitivity of the objective function, optimizing the model by changing the main design variables.

Parameterizing the steering system simplifies changes to model because it helps to automatically size, relocate and orient objects (ex. bodies, joints). In this way, relationships into the model can be created, so that when a modeling object is changed, ADAMS updates any other objects that depend on it. Design variables allow creating independent parameters and tie modeling objects to them. In addition, using design variables, parametric studies (design study and design of experiments) can be performed. The design study represents a set of simulations that help to adjust a parameter to measure its effect on the performance of the steering system. Design study describes the ability to select a design variable, sweep the variable through a range of values and then simulate the behavior of the various designs in order to understand the sensitivity of the overall system to these design variations. Design of experiments (DOE) is performed for identifying the effects of varying several design variables simultaneously, being a collection of procedures and statistical tools for planning experiments and analyzing the results, having as goal to identify which variables and combinations of variables most affect the behavior of the steering system.

The virtual prototype has been parameterized using the points that define the geometric - dynamic model of the steering system (see figure 3). The geometry of the parts and the locations of the joints from the steering system have been attached to the design points. In this way, in the optimization study, when a global coordinate of the point will be modified, the objects that depend on it will be accordingly changed.

In the next step, the global coordinates of the design points have been transformed in design variables, having in view to control the steering mechanism in the optimization process. Each coordinate is a design variable, therefore, for a point P, three design variables will result: DV_1 $\rightarrow X_P$, DV_2 $\rightarrow Y_P$ and DV_3 $\rightarrow Z_P$. Having in view the relationships between the design variables, a lot of expressions are used. These are the basis of parameterization: when an expression is created, ADAMS stores the expression and updates the value whenever a value in the expression changes. For example, the transversal coordinate of the point D_s (in which the left tierod is connected to the center link) can be specified as an expression depending on the coordinate of the similarly point D_d from the right side, DV_1 = -1*DV_2, where DV_1 $\rightarrow Y_{Ds}$, and DV_2 $\rightarrow Y_{Dd}$.

At the same time, having in view to keep the steering system in rational constructive limits and to respect the available space for mounting / functioning, different constraints that control the design variables can be imposed, for example a certain design variable do not exceed a lower or upper limit. The optimization study improves the design objective as much as possible without violating the constraints. With other words, the constraints are boundaries that directly or indirectly eliminate unacceptable designs, taking the form of additional goals for the steering system design. Part of the design process is to manipulate the unknowns (i.e. the design variables) to arrive at a good steering system that satisfies all objectives and constraints.

The objective functions for optimization are represented by the parameters that describe the behavior of the steering mechanism, as follows: the steering angle, the pressure angle between the tierod and the steering knuckle lever, and the induced turning motion. For beginning, measures that define these functions have been modeled, and then the design objectives have been attached to these measures. Design studies have been performed having in view to identify the influence of the design variables on the design objectives. In this way, two types of design variables have been obtained: main design variables (with great influence on the design objectives), and secondary variables; only the main design variables have been considered in the effective optimization process.

4. RESULTS AND CONCLUSIONS

For evaluating the above-described design functions of the steering system, the following motion generators (kinematic constraints) have been applied in the virtual model:

- vertical displacement of the wheels, which are anchored on the actuators in translational motion relative to ground (see figure 2); the motion generator is applied in the joint between the moving piston and the fixed cylinder (rigidly attached on ground);

▪ rotational motion of the steering wheel, which is transmitted to the pitman arm, and then through the center link to the left and right wheels; the motion is applied in the revolute joint between the steering wheel and the car body frame.

Considering the numerical values that define the dynamic model for an off-road vehicle [1], the initial design functions realized by the steering mechanism are presented in the diagrams shown in figure 4. The pressure angles for the left and rear wheels (a) are evaluated considering the suspension (wheels) in the maximum expansion position. For the induced turning motion (b), the suspension passes the expansion - compression stroke, while the steering system is fixed. The steering angles (c) correspond to the suspension in the static load position.

In accordance with these diagrams, the left and right steering angles are close in value, and this generates steering errors - the Ackerman relation [5]. At the same time, when the suspension is in the expansion position, due to the pressure angle between the tierod and the knuckle lever, the steering mechanism is self-locked before the extreme position of the pitman arm. On the other hand, when the steering system is fixed, the vertical displacement of the suspension induces great turning motion of the left & right wheels.

Performing the parametric design studies, considering as design variables the global coordinate of the points that define the structural model of the steering mechanism (see figure 3), the main design variables, with great influence on the objective functions, have been obtained, as follows: $X_{E(D)}$, $Z_{E(D)}$ and Y_D. The results of the parametric studies represent a summary of the sensitivity of the design functions to a given change in a geometric location, keeping all other locations fixed. We found sensitivities by using the plot statistics function and finding the slope of the design study curve plotted against design variable value.

The effective optimization of the steering mechanism has been performed by using the GRG (Generalized Reduced Gradient) algorithm from the OptDes code of Design Synthesis. This algorithm,

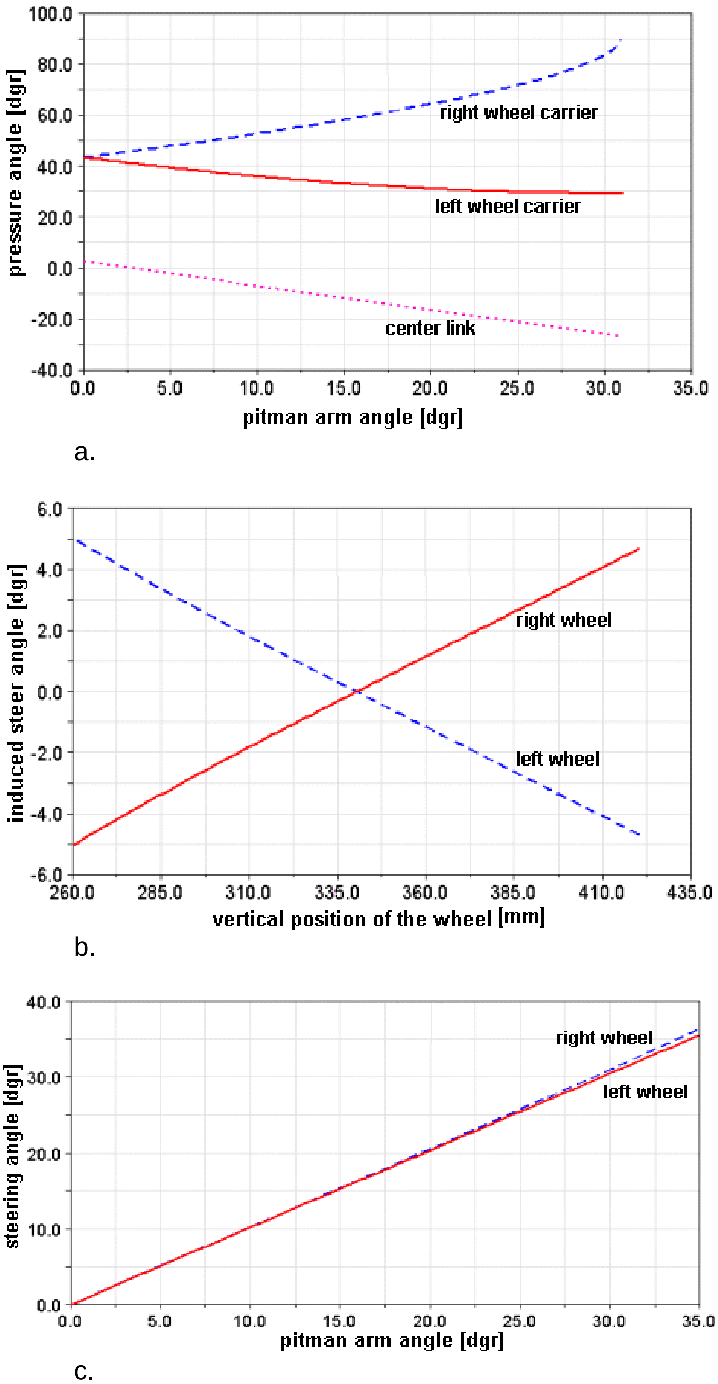
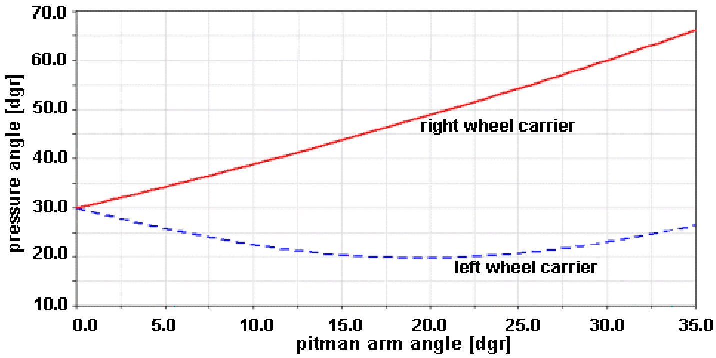


Figure 4. The initial design functions

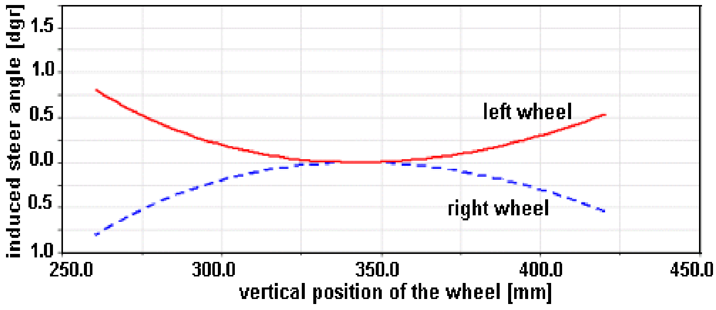
which is provided with ADAMS, requires that variables have range limits, since it works in scaled space.

In this way, the optimum mechanism (whose behavior is presented in figure 5) has been obtained by following changes: increasing the length of the pitman / idler arms, moving below the vertical position of the joints between the pitman / idler arms and the center link, and modifying the transversal location of the spherical joints between the center link and the tierods.

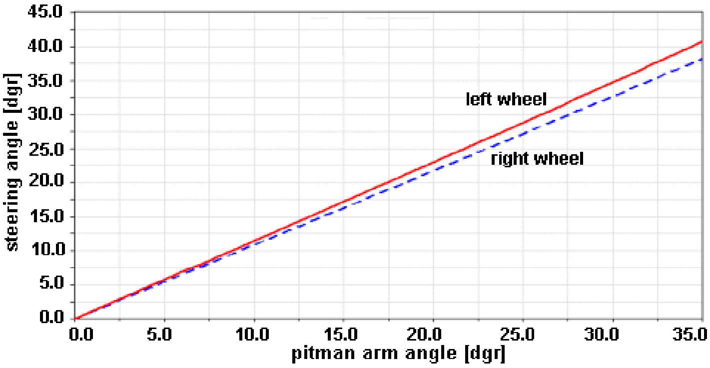
In this paper, specific aspects regarding the optimization of the steering systems in the virtual prototyping concept have been presented. One of the most important advantages of this kind of simulation consists in the possibility of taking easy virtual measurements at any point and/or area of the steering system and for any parameter. Virtual prototyping-based optimization tools allow realizing the projected reductions in cycle times while maintaining and increasing the performance, safety, and reliability. This helps us to make quick decisions on any design changes without going through expensive prototype building and testing.



a.



b.



c.

Figure 5. The optimized functions

ACKNOWLEDGEMENT

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References

[1] Alexandru, C. Testing the Guiding - Suspension System of the Motor Vehicles in Virtual Environment. International Review of Mechanical Engineering, Vol. 3 (5), 2009, p. 521-528.
[2] Bernard, A. Virtual Engineering: Methods and Tools. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 219 (5), 2005, p. 413-421.
[3] Haug, E. J., Choi, K. K., Kuhl, J. G., Vargo, J. D. Virtual Prototyping Simulation for Design of Mechanical Systems. Journal of Mechanical Design, Vol. 117 (63), 1995, p. 63-70.
[4] Hegazy, S., Rahnejat, H., Hussain, K. Multi-Body Dynamics in Full-Vehicle Handling Analysis. Journal of Multibody Dynamics, Vol. 23 (1), 1999, p. 19-31.
[5] Maclaurin, B. Comparing the Steering Performances of Skid- and Ackermann-Steered Vehicles. Journal of Automobile Engineering, Vol. 222 (5), 2008, p. 739-756.
[6] March, C., Shim, T. Integrated Control of Suspension and Front Steering to Enhance Vehicle Handling. Journal of Automobile Engineering, Vol. 221 (4), 2007, p. 337-391.