KINEMATIC OPTIMIZATION OF THE FRONT SUSPENSION SYSTEM FOR A FORMULA STUDENT CAR

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Abstract: *This paper attempts to present some aspects regarding how to use a multi-body systems software solution in the optimization process of the mechanical systems. The optimization of a mechanical system has to pass true the following steps: parameterizing the virtual model, defining the design variables and the design objectives for optimization, performing design studies for identifying the main design variables and optimizing the model on the basis of these varibles. To implement the optimization algorithm, the front suspension mechanism for a Formula Student car has been taken into acount, using the multi-body system (MBS) enviroment ADAMS of MSC Software.*

Key words: *multibody system, suspension system, optimization.*

1. Introduction

The traditional CAD/CAM/CAE methods were focused on a concept called "art-to-part", which refers directly toward the design, development and manufacturing of the system components. Unfortunately, optimal component design does not always lead to optimal system design. The overall product quality is defined by the interaction between form, fit, function and assembly of all parts of a system. Virtual prototyping applied at the system level reduces cost, time and increases quality.

A growing interest in analysis methods for multi-body systems, which may facilitate the self-formulating algorithms, was revealed in representative publications, the decreasing of the processing time - for making possible the real time simulation - being its main goal [2], [5]. Powerful modeling and simulation programs were developed around these methods.

Using these advanced programs, the design engineers have the possibility to build models of entire systems or subsystems, then to simulate the system behavior and to optimize the design before creating the physical prototype. The virtual prototyping is based on an engineering process that enables mechanical systems modeling, simulating their behavior under real operating conditions, and finally optimizing the form, fit, function and manufacturing characteristics of the system [3].

The virtual prototyping generates a detailed digital model, using it in a virtual experiment. The most important advantages for virtual prototyping are: it reduces design time and cost, reduces the product cycles, reduces the number of expensive physical prototypes, allows taking virtual

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measurements at any point and area of the system and for any parameter, as well as optimizing the mechanical system long before building the first hardware prototype.

In this paper, we attempt to present some aspects regarding the usage of virtual prototyping tools in the optimization process of a mechanical system, by using ADAMS of MSC Software as a virtual prototyping environment.

2. The Virtual Prototyping Process

The prototyping platform includes CAD, MBS and FEA systems. The analysis, optimization and simulation of the mechanical system are performed by using the MBS software.

The CAD software is used for creating the geometric model of the mechanical system (i.e. solid model). This model contains information about the mass and the inertia properties of the rigid parts. The part geometry can be exported from CAD to MBS using standard format file, for example IGES or STEP.

The FEA software is used for modeling flexible bodies in mechanical systems. Integrating flexibilities into model allows to capture inertial and compliance effects during handling and comfort simulations, to study deformations of the flexible components, and to predict loads with greater accuracy, therefore achieving more realistic results.

The steps to create a virtual prototype mirror the same steps to create a physical model, as follows: build (modeling parts, constrain the parts, create forces), test (measure characteristics, perform simulation, review animation), validate (import test data, superimpose test data), refine (add friction, define flexible parts, define command - control systems), optimize (add parametrics, define design variables, define objective functions, perform design studies, perform optimization studies).

During the build phase, virtual prototypes are created of both the new product concept and any target products which may already exist in the market. The geometry and mass properties of the bodies are obtained from component solid models. The structural and vibratory characteristics result from component finite element models or experimental tests.

One of the most important axioms for successful functional virtual prototyping is to simulate as a test. Testing of hardware prototypes has traditionally involved both lab tests and field tests in various configurations, which are very expensive. With virtual prototyping, it is enough to create virtual equivalents of the lab tests and the field tests, and this reduces both time and cost.

To validate the virtual prototype, the physical and virtual models are tested identically, using the same testing and instrumentation procedures. The results are compared, and design sensitivity analyses are performed on the virtual model to identify design parameters that have great influence on the performance results that do not correspond.

Refining the virtual prototype involves the fidelity to the model. Replacing the rigid components with flexible counterparts or adding frictions can improve the fidelity of the virtual model relative to the physical (hardware) prototype.

The optimization of the virtual prototype is made in the following steps: parameterizing the model, defining the design variables, defining the design objective for optimization, performing parametric studies, and optimizing the model.

Usually, the parameterization of the mechanical systems is made by using the points that define the structural model, in fact the locations of the geometric constraints (i.e. the joints). In this way, relationships within the model are created, so that when a point is changed, any other objects that depend on it will be updated.

Design variables represent elements in the model that allow creating independent parameters and to link modeling objects to them. In our case, the design variables represent the locations for the design points. In the parametric studies, the design variables are stretched through a range of values for finding the sensitivity of the overall system to these design variations. As a result, parametric study allows identifying the main design variables, with great influence on the design objective.

Optimization problem is described as a problem to minimize or maximize a design objective over a selection of design variables, while satisfying various constraints on the design. Design objective is a numerical representation of the quality, efficiency, cost, or stability of the model. The optimum value of the design objective corresponds to the best design possible, which is achieved when the objective is minimized or maximized.

Part of the design process is to manipulate the unknowns (variables) in a design to arrive at a good design that satisfies all goals (objectives).

3. Case Study

The optimization based on virtual prototyping has become very important in various fields specific to automotive industry, aircraft industry, robotics, biomechanics, mechatronics and others.

To demonstrate the virtual prototyping capabilities, in the present paper, the virtual model of a complex mechanical system is developed and optimized using the MBS software ADAMS of MSC Software. Application is performed for the front wheel suspension mechanism of a Formula Student race car.

The suspension system contains two four-bar mechanisms (for the left and right wheels). There are 12 mobile bodies (Figure 1), as follows: 1 - chassis, 3/10 - left/right wheels, 4/9 - left/right uprights (wheel carriers), 2/11 - left/right upper control arms, 6/12 - left/right lower control arms, 5/8 - left/right tie rods, 7 - steering rack. Because the suspension system is symmetrically disposed relative to the longitudinal axis of the vehicle, this paper proposes to optimize only a half of the mechanism.
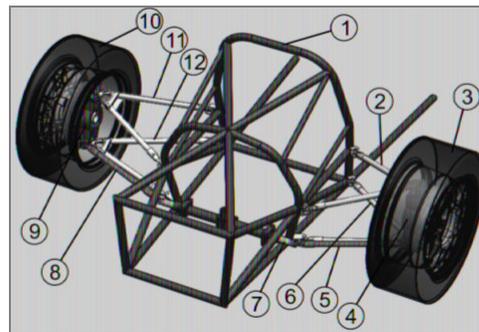

Fig. 1. *Suspension bodies*
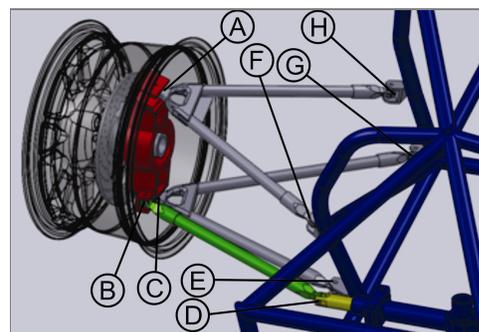
Fig. 2. *Suspension joints*

Under these terms, Figure 2 shows the connections (joints) between the bodies in the right wheel suspension mechanism, as follows: A - spherical joint (bodies 11-9), B - spherical joint (8-9), C - spherical joint (12-9), D - spherical joint (8-7), E & G - spherical joints (12-1), F & H - spherical joints (11-1). For the upper (11) and lower (12) control arms, the two spherical connections on car body define in fact revolute joints. So, the virtual model of the suspension mechanism uses 8 points that control the locations of the joints.

Considering that the locations of the joints on the upright (wheel carrier) are established exclusively on constructive criteria, only the locations of the joints to the chassis and steering rack will be considered for the optimization process. Thus, there are 5 design points, and consequently 15 design variables (the global coordinates X, Y, Z for each point):

$X_D \rightarrow DV\_1$, $Y_D \rightarrow DV\_2$, $Z_D \rightarrow DV\_3$;
$X_E \rightarrow DV\_4$, $Y_E \rightarrow DV\_5$, $Z_E \rightarrow DV\_6$;
$X_F \rightarrow DV\_7$, $Y_F \rightarrow DV\_8$, $Z_F \rightarrow DV\_9$;
$X_G \rightarrow DV\_10$, $Y_G \rightarrow DV\_11$, $Z_G \rightarrow DV\_12$;
$X_H \rightarrow DV\_13$, $Y_H \rightarrow DV\_14$, $Z_H \rightarrow DV\_15$.

The design variables allow to define independent parameters that can be linked to objects, and to organize the critical parameters of the design into a concise list of values that can be easily modified. In this way, a parametric model of the suspension mechanism has been created.

The optimization goal is to minimize the induced deflection, and the wheel track deviation. In the initial mechanism (before optimization) the time-history variations of these parameters are shown in Figures 3 and 4, with the following root mean squares (RMS): 1.2 deg - the induced deflection, and 9.1452 mm - the wheel track deviation. The optimization goal will be to minimize these values.

4. Results

The optimization study is performed with ADAMS/Insight, part of the ADAMS suite of software, which is a powerful design-of-experiments software.

ADAMS/Insight is a stand-alone product that also works with others products (including ADAMS/View - the general pre-processing interface, in which the MBS model of suspension mechanism was modelled). Within the ADAMS analysis environment, there are conduits between ADAMS/Insight and ADAMS/View, which streamline the process by taking advantage

of the inherent parametric strengths of the vertical application.
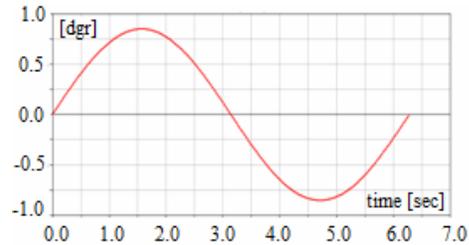

Fig. 3. *Initial induced deflection*
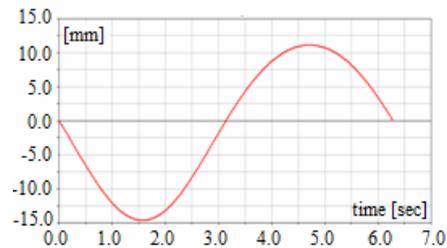
Fig. 4. *Initial wheel track deviation*

In order to run the optimization process in ADAMS/Insight (which has as purpose the minimization of the induced deflection and of the wheel track deviation, the ADAMS/View model of the suspension mechanism was exported as an experiment type file (*.xml) for ADAMS/Insight. Optimization process is performed in five steps: configuring the purpose of the experiment (the responses); setting the set of factors for the suspension mechanism that we are investigating (i.e. the design variables); planning a set of trials in which we vary the factor values from one trial to another; executing the runs and recording the performance of the suspension mechanism at each run; analyzing the changes in performance across the runs.

The runs are described by the design matrix, which has a column for each factor and a row for each run. The matrix entries are the levels for each factor per run. For each factor there were defined the nominal value and the variation field.

There are the following nominal values of the design variables (factors), in the initial mechanism - before optimization (in [mm]): DV_1 = −250, DV_2 = 104.75, DV_3 = −333.07; DV_4 = −253.69, DV_5 = 82.217, DV_6 = −390.92; DV_7 = −266.2, DV_8 = 224.94, DV_9 = −378.05, DV_10 = −257.71, DV_11 = 82.343, DV_12 = −755.27; DV_13 = −276.51, DV_14 = 229.45, DV_15 = −726.6. The variation field for each variable (factor) was set to [−5, +5] mm relative to the nominal value.

The investigation strategy used to create the design matrix is based on the DOE Screening technique, which allows identifying the factors and combinations of factors that most affect the behaviour of the suspension mechanism. The idea is to consider every factor that may potentially affect the response, and use a screening analysis to determine how much each contributes to the response [6]. Due to the relatively high number of factors included in the optimization process (15 factors/ design variables), it was chosen the Plackett-Burman technique [4], with 16 inputs in the design matrix.

The factors values combinations and the corresponding values of the design objectives (responses), which were obtained by successive analyses with the processing module ADAMS/Solver under the ADAMS/View interface, are presented in Table 1 (trials 1-5), Table 2 (trials 6-10) and Table 3 (trials 11-15). The so obtained design matrix is used to establish the relations between factors and responses.

The optimization problem is a multi-objective one, which involves reaching the minimum values for the considered responses (the root mean squares of the wheel track deviation - R_01, and induced deflection - R_02). During optimization, the factor values are adjusted so that the resulting responses come as closely as possible to the specified target values.

Table 1

The factors values combinations and the values of the design objectives (*trials 1-5*)

	T_1	T_2	T_3	T_4	T_5
DV_1	−271.5	−271.5	−271.5	−271.5	−281.5
DV_2	224.4	234.4	234.4	234.4	234.4
DV_3	−731.6	−731.6	−721.6	−721.6	−721.6
DV_4	−271.2	−271.2	−271.2	−261.2	−261.2
DV_5	229.9	219.9	219.9	219.9	229.9
DV_6	−383.1	−373.1	−383.1	−383.1	−383.1
DV_7	-262.7	−262.7	−252.7	−262.7	−262.7
DV_8	87.3	77.3	77.3	87.3	77.3
DV_9	−750.3	−750.3	−760.3	−760.3	−750.3
DV_10	−258.7	-248.7	−248.7	−258.7	−258.7
DV_11	87.2	77.2	87.2	87.2	77.2
DV_12	−395.9	−385.9	−395.9	−385.9	−385.9
DV_13	−245.0	−255.0	−245.0	−255.0	−245.0
DV_14	109.7	109.7	99.7	109.7	99.7
DV_15	−328.1	−328.1	−328.1	−338.1	−328.1
R_01	8.9	9.6	9.0	8.9	9.3
R_02	0.7	1.2	0.0	0.7	0.6

Table 2

The factors values combinations and the values of the design objectives (*trials 6-10*)

	T_6	T_7	T_8	T_9	T_10
DV_1	−271.5	−281.5	−271.5	−271.5	−281.5
DV_2	224.4	234.4	224.4	234.4	234.4
DV_3	−721.6	−731.6	−721.6	−731.6	−721.6
DV_4	−261.2	−261.2	−271.2	−261.2	−271.2
DV_5	229.9	229.9	229.9	219.9	229.9
DV_6	−373.1	−373.1	−373.1	−373.1	−383.1
DV_7	−262.7	−252.7	−252.7	−252.7	−252.7
DV_8	77.3	77.3	87.3	87.3	87.3
DV_9	−760.3	−760.3	−760.3	−750.3	−750.3
DV_10	−248.7	−258.7	−258.7	−258.7	−248.7
DV_11	77.2	87.2	77.2	77.2	77.2
DV_12	−395.9	−395.9	−385.9	−395.9	−395.9
DV_13	−245.0	−255.0	−255.0	−245.0	−255.0
DV_14	109.7	109.7	99.7	99.7	109.7
DV_15	−338.1	−328.1	−328.1	−338.1	−338.1
R_01	9.3	8.8	9.3	9.4	9.2
R_02	1.2	0.6	0.5	0.7	1.2

Table 3

The factors values combinations and the values of the design objectives (trials 11-16)

	T_11	T_12	T_13	T_14	T_15	T_16
DV_1	–281.5	–271.5	–281.5	–281.5	–281.5	–281.5
DV_2	224.4	224.4	234.4	224.4	224.4	224.4
DV_3	–721.6	–731.6	–731.6	–721.6	–731.6	–731.6
DV_4	–261.2	–261.2	–271.2	–271.2	–261.2	–271.2
DV_5	219.9	229.9	229.9	219.9	219.9	219.9
DV_6	–373.1	–383.1	–373.1	–373.1	–383.1	–383.1
DV_7	–262.7	–252.7	–262.7	–252.7	–252.7	–262.7
DV_8	87.3	77.3	87.3	77.3	87.3	77.3
DV_9	–750.3	–750.3	–760.3	–750.3	–760.3	–760.3
DV_10	–248.7	–248.7	–248.7	–258.7	–248.7	–258.7
DV_11	87.2	87.2	87.2	87.2	77.2	77.2
DV_12	–395.9	–385.9	–385.9	–385.9	–385.9	–395.9
DV_13	–255.0	–255.0	–245.0	–245.0	–245.0	–255.0
DV_14	99.7	99.7	99.7	109.7	109.7	99.7
DV_15	–328.1	–338.1	–338.1	–338.1	–328.1	–338.1
R_01	8.9	8.7	8.7	9.3	9.5	9.8
R_02	0.2	0.2	0.1	0.8	1.3	0.6

As ADAMS/Insight proceeds through the minimization, we will see the calculation converge; finally, the values of design variables will result in a simulation that meets the design requirements, as follows (Figures 5 and 6): R_01 = 8.4 mm (RMS of wheel track deviation), R_02 = 0.023 deg (RMS of induced deflection).
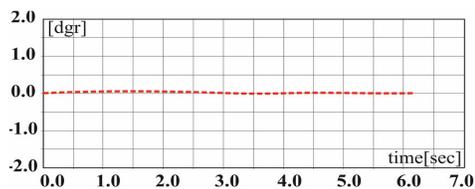

Fig. 5. *Optimized induced deflection*
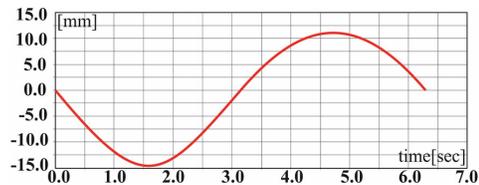
Fig. 6. *Optimized wheel track deviation*

5. Final Remarks

We can observe the substantial reduction of the induced deflection, and only a small decrease of the wheel track deviation (there are necessary larger variation fields of the design variables for obtaining a greater reduction of thes deviation). However, we can consider that the obtained variant is a good one, the variations being in the acceptable domains from the automotive industry [1].

The future researches in the field will be focused on the implementation of the above-described algorithm for the dynamic optimization of the suspension system.

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