FUNCTIONAL OPTIMIZATION OF WINDSHIELD WIPER MECHANISMS IN MBS (MULTI-BODY SYSTEM) CONCEPT

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Abstract: *In this paper, the functional optimization of windshield wiper mechanisms is performed, considering the wiper system of a domestic passenger car (tandem pattern double lever system) as an example. The optimization study is made by using a virtual model, which was realized with the MBS environment ADAMS of MSC Software. The following steps in optimizing the wiper mechanism in MBS concept will be described: parameterizing the model, defining the design variables, objectives and constraints, performing parametric studies to identify the main design variables, and optimizing the model by using the GRG algorithm from the OPTDES code.*

Key words: *windshield wiper mechanism, multi-body system, optimization.*

1. Introduction

Determining the real behaviour of the mechanical systems has been a priority in the design stage since the emergence of computer graphic simulation. Important publications reveal a growing interest in analysis methods for multi-body systems (MBS) that may facilitate the self-formulating algorithms, aiming at reducing the processing time in order to make real-time simulation possible [2-6]. These methods have been used to develop powerful modelling and simulation environments (MBS software products), which allow the designer to build and simulate a computer model for any mechanical system that includes moving parts.

In MBS concept, the mechanical system is treated as a constrained, multi-body, spatial mechanical system, in which body elements are connected through mechanical joints and force elements. The main difference between mechanical system dynamics and conventional structural system dynamics is the existence of a high degree of geometric nonlinearity associated with high values of rotational kinematics. The governing equations for conventional structural dynamics are linear differential, as compared to nonlinear differential equations, in the case of mechanical system dynamics, that are linked to nonlinear algebraic equations of kinematic constraints.

The increasingly growing demand for more performant vehicles imposes a new approach to both kinematic and dynamic analysis (the assembly, or the specific subsystems), by taking into consideration virtual models that are closer to the real physical models on the vehicle. In this way, the complexity of the theoretical model increases, thus leading to the necessity of using MBS analysis and simulation environments. There is a wide range of applications specific to the automotive

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industry in which MBS environments can be used, such as: suspension design, vehicle dynamics, engine design, power train engineering, body hardware engineering, predicting and avoiding acoustics problems, tire-roadway interaction, driver behaviour, controls design and simulation, safety systems. As far as body hardware engineering is concerned, an MBS approach can be used in the field of door, trunk and hood latch design, trunk and hood hinge linkage design, windshield wiper simulation and refinement, seat mechanism design, sun-roof and convertible mechanism design, window mechanism design and so on.

In this paper, the functional optimization of a windshield wiper mechanism in MBS concept is performed. The virtual model of the wiper system has been made using the MBS package ADAMS of MSC Software. The optimization of the virtual model consists in the following steps: parameterizing the prototype, defining the design variables, defining the objective function for optimization and performing parametric studies.

2. Virtual Model of the Wiper System

Windshield wiper mechanisms are vehicle-specific systems in which the wiping motion is transferred from the wiper motor to the pivot-shaft assemblies via linkages. A compact wiper system consists of the following components: wiper motor with thermo-switch, wiper gearing, motor crank, steel base-plate, crank linkage, pivot-shaft assembly with oscillating crank, and secondary pivot-shaft assembly with plate (for parallel wipe patterns). The linkage forces are supported by the sheet metal of the car body.

For present-day vehicles, the following wiper systems are frequently used [1]: single-lever systems with parallel wipe patterns, single-lever systems with sector wipe patterns, opposed-pattern double-lever systems with parallel wipe patterns, opposed-pattern double-lever systems with overlapping sector wipe patterns, tandem-pattern double-lever systems with overlapping sector wipe patterns, tandem-pattern three-lever systems with extra-wide overlapping sector wipe patterns.

For this paper, a tandem-pattern double-lever wiper mechanism (corresponding to a domestic passenger car - DACIA type) has been considered (Figure 1). The windshield wiper mechanism contains two planar four-bar linkages: ABDE - to command the right wiper arm & lamella, and ACFG - to command the left wiper arm & lamella. The connections between elements are made through revolute joints.

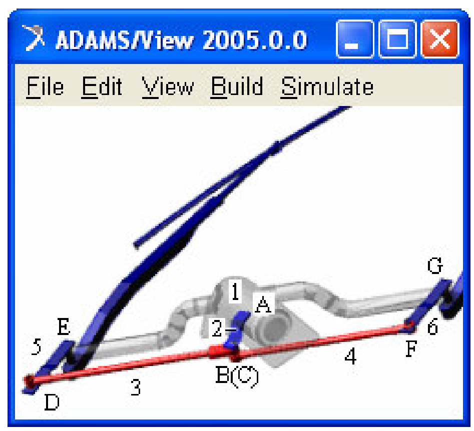


Fig. 1. *Tandem-pattern double-lever system*

The solid (geometric) model of the windshield wiper mechanism has been done using specialized CAD software (CATIA). The geometry was transferred to ADAMS using the STEP (Standard for the Exchange of Product Model Data) file format, through the specific transfer interface ADAMS/Exchange. The STEP format is used to describe the level of product through a specialized language (Express), which establishes the correspondence between the STEP file and the CAD model.

The windshield wiper mechanism has one degree of freedom, namely the rotation of the motor crank. For the kinematic model, a motion generator applied to the revolute joint of the motor crank controls this degree of freedom. Considering the input speed of the motor crank $n_2 = 60$ [rot/min], the kinematic constraint can be obtained: $\omega_2 = \pi n_2 /30 = 6.28 \rightarrow \varphi_2 = \omega_2 t = 6.28\ t$ [rad/sec]. For the dynamic model of the mechanism, the kinematic constraint is replaced with the torque applied to the motor crank; thus the dynamic model has one independent generalized coordinate, namely the position angle of the motor crank, φ_2.

The friction force that acts upon the wiper lamella (Figure 2) depends on the friction coefficient between rubber blade and windshield, as well as the normal force generated by the pressure spring mounted between the wiper arm and the oscillating crank (Figure 3). Considering a wet wiping regime, the magnitude of the friction force, which is applied at the connection point between arm and lamella, is $F_f = 1.5$ N, according to technical standards [1].

In ADAMS, these friction forces have been modelled by means of "Function Builder" [7], which is a versatile tool that allows the designer to create and modify functions, as well as to parameterize values for various entities. The direction of the friction force depends on the sign of wiper arm's velocity. The *SIGN* (*e*1, *e*2) function transfers the sign of one expression, representing a numerical value, to the magnitude of another expression, representing a numerical value. In our case, "*e*1" represents the friction force magnitude, and "*e*2" is the angular velocity of the wiper arm. In these terms, the run-time function that describes the time-history of the friction force has the value *SIGN* (1.5, *l/r_wiper_arm_velocity*), where "*l/r*_wiper_arm_velocity" is a measure which models the angular velocity of the wiper arm (left - *l*, or right - *r*).

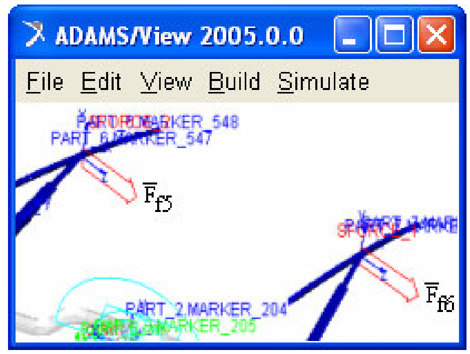


Fig. 2. *The friction forces on wiper arms*

Fig. 3. *The pressure spring model*

The positional analysis of the wiper mechanism is done with a view to determining the specific parameters that define the operating characteristics, as follows: parking position (the wiper arm's rest position on the windshield), wiping angle, and wipe-pattern size. The input data consist of the windshield size, the installation point for drive unit, and the clamping length (maximum thickness of the sheet steel to which the pivot-shaft assembly is fastened).

In the optimization process described in the next section, we considered wiping area (defined by the wiping angles of the left & right arms/ lamellas) as the main parameter in evaluating the functional behaviour of the windshield wiper mechanism.

3. Optimization Procedure

The functional optimization of the virtual model of a windshield wiper mechanism is done in the following sequence: the prototype is parameterized, design variables are defined, the design objective for optimization defined, parametric studies are performed, and the model is optimized on the basis of the main design variables.

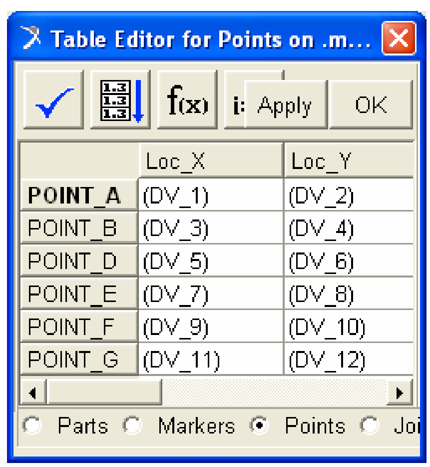
The parameterization of the windshield wiper mechanism is made by using the points that define the structural model, in fact the locations of the kinematic joints/geometric constraints (see Figure 1). Parameterization simplifies changes to the model because it helps to automatically resize, relocate and orient parts. In this way, specific relationships are established among the model's components, so that when a point is changed, any other objects (bodies, joints, forces) that depend on it will be updated.

Design variables represent elements in the model that allow the designer to create independent parameters and link modelling objects to them. In our case, design variables represent locations for the design points. A design variable allows it to run automatic simulations that vary the values of the variable over specified ranges in order to understand sensitivity to the variable or to find the optimum values.

In addition, by using design variables, parametric studies can be performed. These optimization techniques represent sets of simulations that help to adjust a parameter so as to measure its effect on the performance of the wiper system model. Parametric study describes the ability to select a design variable, allot the variable a range of values and then simulate the motion behaviour of various designs in order to understand the sensitivity of the overall system to these design variations. As a result, parametric study allows it to identify the main design variables, having a great influence on the operational performance of the windshield wiper mechanism.

Therefore, in the initial phase, the points that define the structural model of the windshield wiper mechanism were modelled in the global coordinate frame - an inertial frame attached to the car body (rigidly connected to the ground). Afterwards, the geometry of the bodies and the locations of the joints in the wiper mechanism were linked to the design points. Thus, whenever a global coordinate is modified, the objects depending on it will be changed accordingly.

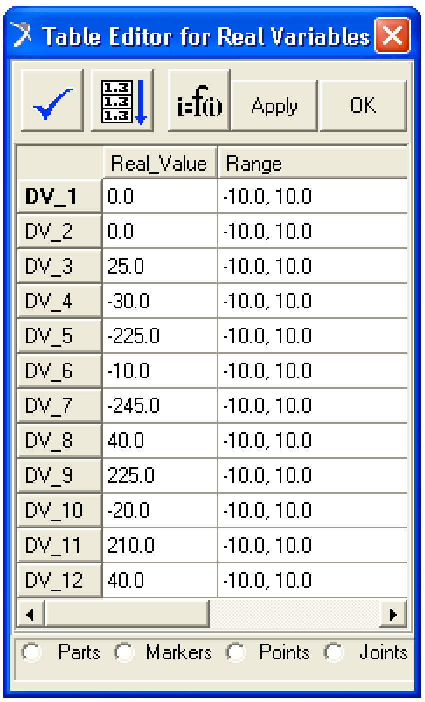
In the next step, the global coordinates of the points were transformed into design variables, with a view to controlling the virtual model in the optimization process. Each coordinate is a design variable; therefore, for the planar tandem-pattern double-lever mechanism presented above, 12 design variables will result, as follows (XY - motion plane): DV_1 → X_A, DV_2 → Y_A, DV_3 → X_B, DV_4 → Y_B and so on (Figure 4).



	Loc_X	Loc_Y
POINT_A	(DV_1)	(DV_2)
POINT_B	(DV_3)	(DV_4)
POINT_D	(DV_5)	(DV_6)
POINT_E	(DV_7)	(DV_8)
POINT_F	(DV_9)	(DV_10)
POINT_G	(DV_11)	(DV_12)

Fig. 4. *Table editor for design points*

To create design variables, one should select in the table editor for points the cell corresponding to the coordinate that is going to be parameterized, then right-click the Input text box, point to Parameterize, point to Create Design Variable, and then select Real. In this way, ADAMS creates a variable with the initial value, inserts an expression into the text box, and modifies the point to use the design variable as the coordinate value. The initial values (real values) and the variation fields (ranges) for the design variables, which are shown in Figure 5, can be modified in order to keep the windshield wiper mechanism within realistic constructive limits.



	Real_Value	Range
DV_1	0.0	-10.0, 10.0
DV_2	0.0	-10.0, 10.0
DV_3	25.0	-10.0, 10.0
DV_4	-30.0	-10.0, 10.0
DV_5	-225.0	-10.0, 10.0
DV_6	-10.0	-10.0, 10.0
DV_7	-245.0	-10.0, 10.0
DV_8	40.0	-10.0, 10.0
DV_9	225.0	-10.0, 10.0
DV_10	-20.0	-10.0, 10.0
DV_11	210.0	-10.0, 10.0
DV_12	40.0	-10.0, 10.0

Fig. 5. *Table editor for design variables*

In general, an optimization problem is described as a problem to minimize or maximize an objective function over a selection of design variables, while satisfying various constraints on the design and state variables of the system. Various algorithms are available to find a solution to an optimization problem. The objective function is a numerical representation of the quality, efficiency, cost, or stability of the mechanism (product). The optimum design is achieved when the objective function is either minimized or maximized. When minimized, the objective decreases with the design improvement. Conversely, when maximized, the objective increases with the design improvement.

As stated above, the maximization of the wiping area was defined as the optimization goal. For a start, measures that define the wiping angles for the left and right arms were modelled using the part's orientation by Euler angles (Figure 6), and then the design objectives were linked to these measures (Figure 7). In order to increase the wiping angles, the maximum absolute values during simulation were taken into account.

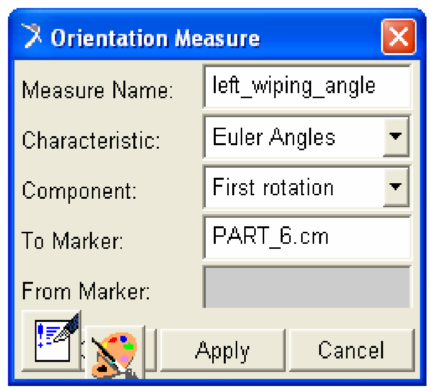


Fig. 6. *Modelling the orientation measure*

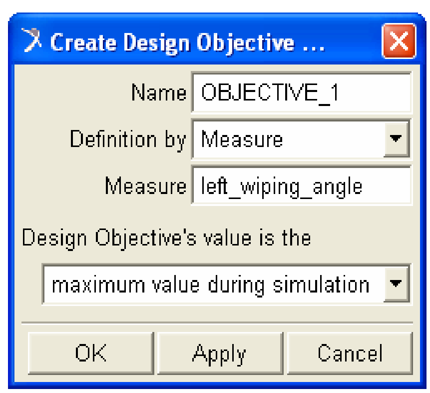
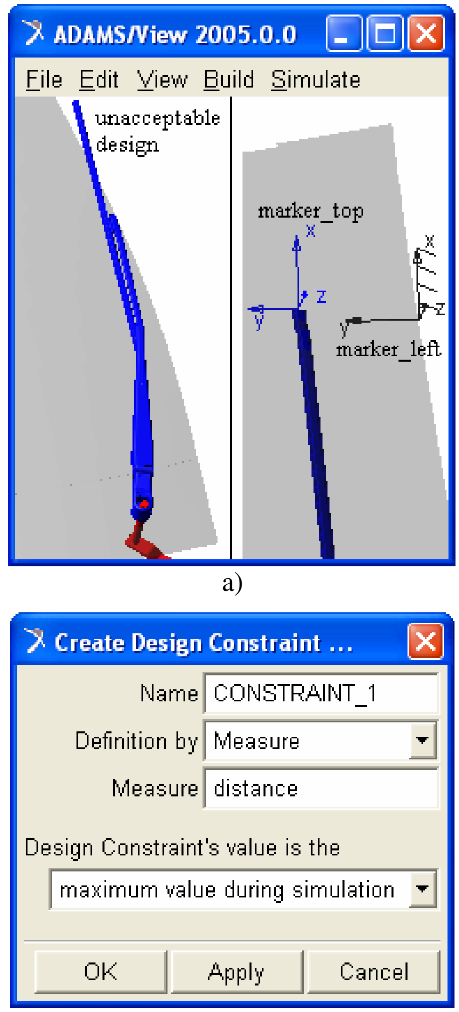


Fig. 7. *Modelling the design objective*

To avoid unacceptable results, design constraints for the optimization can be defined. The optimization study improves the objective as much as possible without violating the constraints. Constraints are boundaries that directly or indirectly eliminate unacceptable designs. Constraints often take the form of additional goals for the mechanism design. Each constraint object creates an inequality constraint. The optimization keeps the value of the constraint less than or equal to zero. In ADAMS optimization constraints, the sign of a measure (+ or −) has special meaning. For example, if an optimization constraint is positive, then it has been violated. If it is negative, it has not been violated and the design is considered acceptable.

For the optimization process of the windshield wiper mechanism, the constraint is to design the linkage so that the lamella never touches the outside part of the windshield (Figure 8a). The design constraint is based on a function measure that defines the Y-axis distance from a marker on the top of the lamella (marker_top) to a marker on the extremity of the windshield (marker_left). In ADAMS, this measure was created by using in Function Builder the predefined function "Distance along Y", with the following syntax: DY(To Marker, From Marker) [7]; in our case the distance function is: DY(marker_left, marker_top).

Because of the special meaning of the measure's sign, it is necessary to turn negative the DY function expression so that a positive value of the measure indicates that the lamella marker has interfered with the windshield's left surface. Conversely, if the measure stays negative throughout the operation cycle, it means that there is an acceptable mechanism design. Thus, the correct expression of the measure is: distance = −DY(marker_left, marker_top). The constraint was created using the maximum value of this measure (Figure 8b).



a)

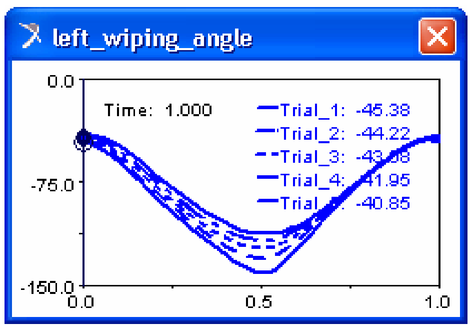
b)

Fig. 8. *Modelling the design constraint*

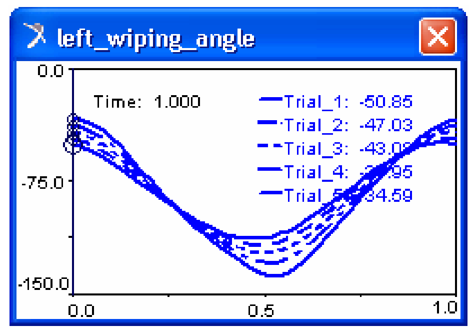
4. Results and Conclusions

With the above described design variables, objectives and constraints, the optimization study can be performed. In the first stage, the influence of design variables on the design objective is analyzed. Parametric studies have been successively conducted for each design variable, within their variation fields/ranges (see Figure 5). In this way, two types of design variables are obtained: main variables (with great influence on the design objectives), and secondary variables (with negligible influence). For example, the influence of several design variables on the left wiping angle is presented in Figure 9.

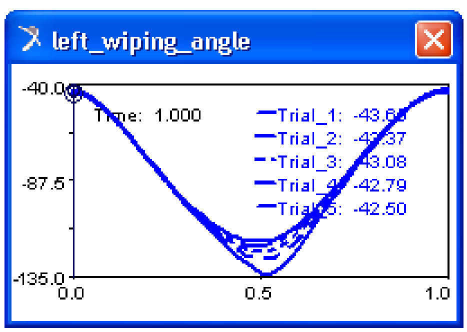
These results derive from individual design studies of each design variable, maintaining the rest of the variables constant at their nominal value. The results represent a summary of the sensitivity of the wiping angle to a given change in the geometric location, keeping all other locations fixed. By analyzing the graphs, the main design variables have been identified, as follows: DV_1, DV_2, DV_3, DV_5, DV_7, DV_9, and DV_11 (DV_9 and DV_11 only for OBJECTIVE_1 - the left wiping angle; DV_5 and DV_7 only for OBJECTIVE_2 - the right wiping angle).



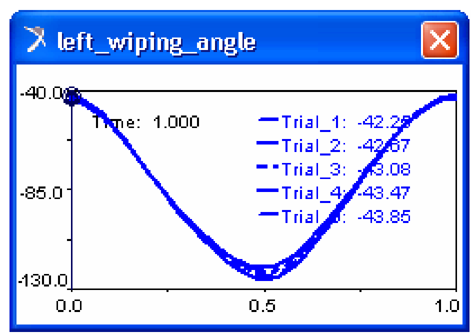
DV_1 (X_A)



DV_2 (Y_A)



DV_9 (X_F)



DV_10 (Y_F)

Fig. 9. *Parametric studies for the left angle*

Subsequently, the optimization study is performed considering the main design variables. However, because DV_1, DV_2, DV_7 and DV_11 are assigned to the fixed points on the car body (A, E, and G), only DV_3, DV_5, and DV_9 have been considered in optimizing the mechanism.

The optimization study is performed by using the GRG (Generalized Reduced Gradient) algorithm from the OPTDES code of Design Synthesis. This optimization algorithm imposes range limits on the design variables, since it works in scaled space. For example, the optimization result for the left wiping angle (OBJECTIVE_1) is shown in Figure 10. The optimized values of the specific design variables are: DV_3: 26.639, DV_9: 220.45 [mm], which correspond to the maximum absolute value of the design objective: 136.78° (the initial value being 122.9°). Similar results have been obtained for the right wiping angle. In addition, the optimization result regarding the design constraint is shown in Figure 11; the optimized mechanism observes the design constraint, the minimum value of the distance between markers (see Figure 8a) being −0.21 mm.

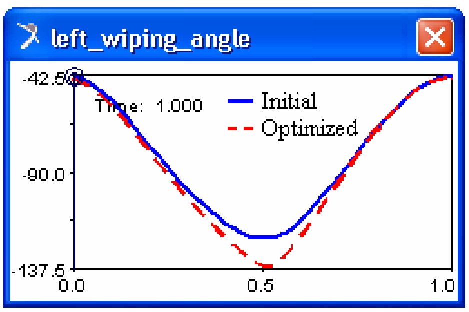


Fig. 10. *Optimization result for the left wiping angle (OBJECTIVE_1)*

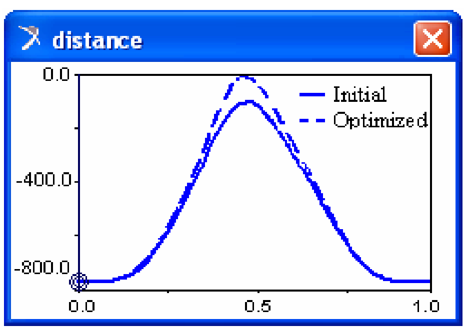


Fig. 11. *Optimization result for the design constraint (CONSTRAINT_1)*

Thus, the optimization leads to an efficient windshield wiper mechanism, without developing expensive hardware prototypes. 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 mechanical system and for any parameter. This is not always possible in real cases, due to lack of space for transducers placement, lack of appropriate transducers or high temperature.

In conclusion, the approach of vehicle subsystems in MBS concept brings important advantages: it reduces both time and cost of new product development, as well as product cycles; diminishes the number of physical prototypes and offers more design alternatives; enhances both quality and efficiency; and, finally, improves the product. MBS-based design tools allow the engineer to operate the projected reductions in cycles, while maintaining or increasing performance, safety, and reliability of vehicles.

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