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Mono-objective optimization with design constraints of the mechanical systems using ADAMS

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Abstract. The paper addresses the mono-objective optimization with design constraints of mechanical systems using the virtual prototyping software environment ADAMS. The optimization problem is formulated as follows: finding the optimal values of the independent design variables, defined by upper and lower bounds, in order to minimize or maximize, as appropriate, the objective function (also called design objective), which is subject to the state equations specific to the mechanical system and the design constraints, respectively. The application is developed for a single-axis tracking mechanism used to increase the efficiency of solar panels, by maximizing the degree of capture of incident solar radiation. The optimization goal actually consists of finding the optimal layout of the linear actuator used as motor source for generating the diurnal movement of the solar panel, and this in the circumstances in which the mechanism from which the initial solution was taken as a starting point proved to be inadmissible from a functional and constructive point of view.

1. Introduction

The development and implementation of automated analysis and optimization software tools is a continuing concern and challenge for research in the field of mechanical systems design. Relevant publications reveal a growing interest in analysis and optimization methods for multi-body systems (MBS), which can facilitate algorithms for the self-formulation of the specific equations of motion [1]–[6]. Such methods are extensively used to develop powerful software environments for virtual prototyping.

A typical virtual prototyping platform is schematically represented in Figure 1. The steps of creating a virtual prototype reflect the steps of creating a physical model [7]–[9], as follows: modeling (creation of bodies/parts, connections/joints, actuating elements and other force-generating elements), simulation (analysis/testing), validation (comparing the results obtained by simulation in a virtual environment with experimental results), refining (improving the fidelity of the virtual model compared to the physical one, for example by replacing rigid bodies with deformable/flexible parts, adding friction, modeling the control systems of the actuating elements), optimization (improving the behavior of the mechanical system, usually from a functional point of view). Physical (hardware) prototyping is a support activity for virtual (software) prototyping, providing the experimental results used in the validation stage of the virtual model [10]. The basic principle for a successful virtual prototyping process is based on the use of simplifying assumptions in order to reduce the complexity

of the virtual model, without affecting the accuracy of the virtual results relative to the experimental (real) results [11].

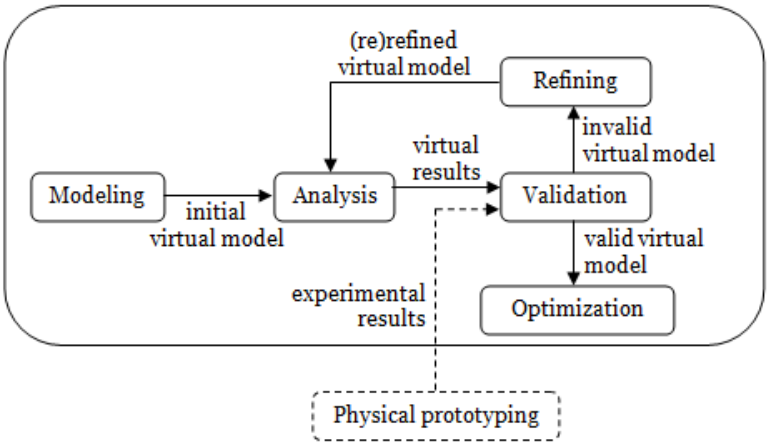

Figure 1. The stages of the virtual prototyping process.

The current paper focuses on the optimization stage of the virtual prototyping process. Thus, in the 2nd section of the paper, the optimization algorithm is generally presented, and then, in the 3rd section, the algorithm is implemented for the optimal design of a mechanical system, specifically the single-axis tracking mechanism of a solar panel. The optimization goal is to minimize the energy consumed in order to achieve the orientation of the solar panel along the diurnal movement axis, while satisfying a series of design constraints that refer to specific functional requirements over the entire range of movement of the mechanism. The virtual prototyping software environment ADAMS (Automatic Dynamic Analysis of Mechanical Systems) was used to model, analyze and optimize the mechanical system under study. The results and conclusions are discussed in the 4th and 5th sections of the work, with the aim of demonstrating the viability/usefulness of the optimization method here approached.

2. The optimization algorithm

In ADAMS, the mono-objective optimization of the mechanical systems is achieved by going through the following steps [12]: parameterizing the virtual model, modeling of design variables, modeling of design objective and design constraints, analysis of design sensitivities, and optimizing the model based on the main design variables. Typically, parameterization of mechanical systems is done using points that define the structural model, usually the locations of the connections (joints) between bodies. Parameterization simplifies changes to the model because it helps to automatically resize, reposition, and reorient the components of the mechanical system. In this way, relationships are created between the objects of the model, so that when one object is modified, all objects that depend on it will be automatically updated.

The design variables are elements that allow the creation of independent parameters for the optimization process, and the connection of other components in the model to them. The Cartesian coordinates of the design points are usually considered as design variables. Design variables allow the running of a set of automated analyses in which the values of the variable are changed (individually - Design Study, or combined - Design of Experiments) within specified intervals, with the aim of understanding the sensitivity of the design objective to changes in the design variables, respectively to find their optimal values. In this way, it is possible to group the design variables into two categories, main variables and secondary variables, respectively, which allows only the main variables to be included in the optimization itself, thus facilitating a faster process of searching for the optimal solution.

Generally, an optimization problem is described as a problem of minimizing or maximizing the objective function over a selection of design variables, while satisfying various constraints on the

design variables or on the behavior of the system. The objective function is a numerical representation of the quality, efficiency, cost, or stability of the mechanical system. The optimal design is obtained when the objective function is minimized or maximized, as appropriate. The optimal value of this function corresponds to the best possible design under the given conditions. To avoid functionally or structurally unacceptable configurations, design constraints can be defined for optimization. The optimization study improves the objective function as much as possible without violating the design constraints. Design constraints are boundaries that, directly or indirectly, eliminate unacceptable system variants, often taking the form of additional objectives for optimizing the mechanical system. In ADAMS, a constraint creates an inequality relationship, with optimization keeping the value of the constraint less than or equal to zero.

The optimization problem can be formulated in the following way:

- finding the optimal values of the design variables: $a^t = [a_1, a_2, a_3, ... a_n]^t$
- with the upper and lower bounds

$\Psi_{2+i} = a_i - (a_i)^H \leq 0, i = 1, \ldots, n$

$\Psi_{3+i} = (a_i)^L - a_i \leq 0, i = 1, \ldots, n$

where $(a_i)^H$ is the upper bound on the design variable "i", and $(a_i)^L$ - the lower bound on the design variable "i"

- to minimize or maximize, as appropriate, the objective function

$\Psi_0 = f(y, a, t)$

- subjected to
  a. equations of state specific to the mechanical system
     $g(y, a, t) = 0$
  b. design constraints
     b.1. equality constraints
        $\Psi c = h_c(y, a, t) = 0$
     b.2. inequality constraints
        $\Psi i = h_i(y, a, t) \leq 0$

where: t – time, y – the state vector of the system, g – the vector of equations governing the behavior of the mechanical system, h_c - the vector of functions defining equality constraints, h_i - the vector of functions defining inequality constraints [13].

3. Case study

The application developed in this work corresponds to a tracking mechanism used to increase the efficiency of the solar panels (by improving the degree of capture of incident solar radiation on the panel surface), the preliminary/simplified MBS (Multi-Body Systems) model of the mechanism, which was created with the ADAMS software solution, being the one shown in Figure 2. The tracking mechanism is one of single-axis type (with one degree of freedom), which is used to carry out the diurnal movement (from East to West) of the solar panel, the system being actuated by means of a linear actuator. The diurnal movement axis is horizontally positioned, such a system being in fact derived from the general dual-axis (with two degrees of freedom) pseudo-azimuthal tracking mechanism [10] by removing the elevation movement of the panel (the elevation angle of the panel is kept constant at the value corresponding to the spring-autumn equinox position).

The mechanism contains three mobile bodies, the solar panel (1) and the two components of the linear actuator - the cylinder (2) and the piston (3), the fixed part of the model being the support pillar (0). The connections between bodies are made by revolute joints. In the virtual model, there are 4 design points that control the locations of the joints, as follows (by indicating the pairs of adjacents bodies i/j): A – 2/0, B – 3/1, C – 2/3, D – 1/0). To these, an additional point is added, namely the point located in the cylinder head (E), which will be used to define one of the specific design constraints (as will be mentioned below).

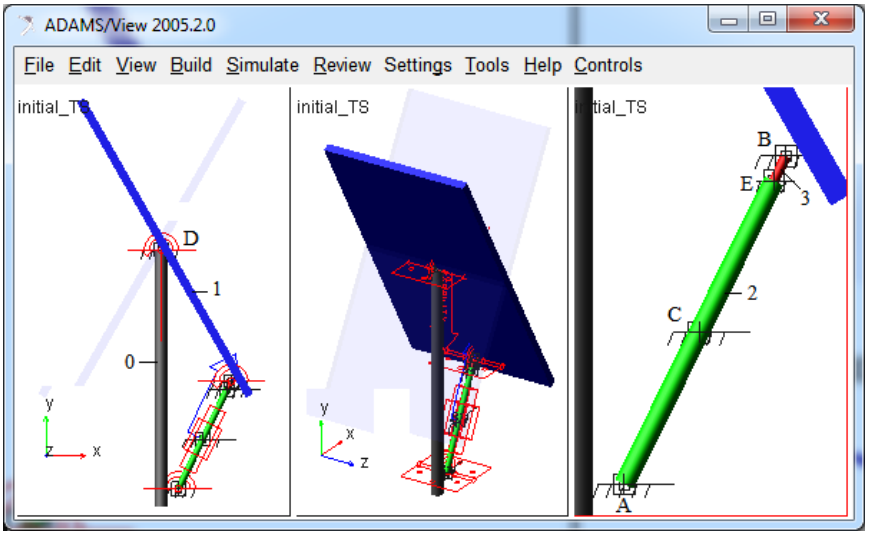

Figure 2. The MBS virtual model of the single-axis tracking mechanism.

Given that the location of point D (where the revolute joint between the solar panel and the fixed pillar is located) is established strictly on constructive aspects, and the locations of points C and E must be permanently on the AB axis (at predetermined distances from A or B), only two design points, A and B, will be available for the optimization process; the two points actually define the layout/arrangement of the linear actuator. Figure 3 shows the editor table for points in ADAMS, in which the global coordinates (X, Y, Z) of points A, B and D can be found, as well as the expressions by which C and E are parameterized relative to A and B, according to the previously specified. LOC_ALONG_LINE is a design-time function in ADAMS that returns an array of three numbers defining a location expressed in the global coordinate system (the location is a specified distance along the line from one coordinate system object to another).

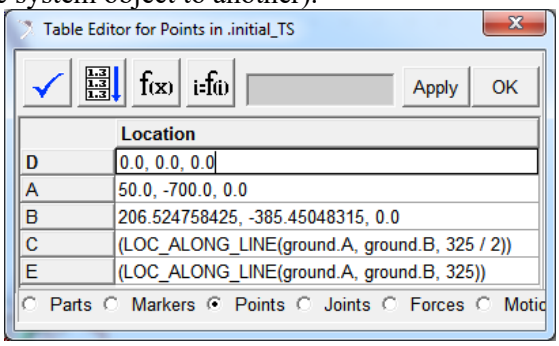

Figure 3. The coordinates / expressions of the design points in the initial mechanism.

In the initial model (before optimization), the linear actuator is arranged in the XY plane (so, the actuator ends A and B have the same coordinate on the Z axis). Starting from the requirement that in the final model (after optimization) the actuator remains in this plane, four design variables (DV) will be available for optimization, DV_1 → X_A, DV_2 → Y_A, DV_3 → X_B, DV_4 → Y_B, each of these variables being defined by the standard/real value (i.e. the initial value) and a range of variation, defined by the minimum and maximum values, which are established on constructive aspects, as shown in Figure 4. The optimization problem consists of determining the optimal values of the four design variables, hence the optimal arrangement of the linear actuator, so that the optimization objective is met and the design constraints are respected.

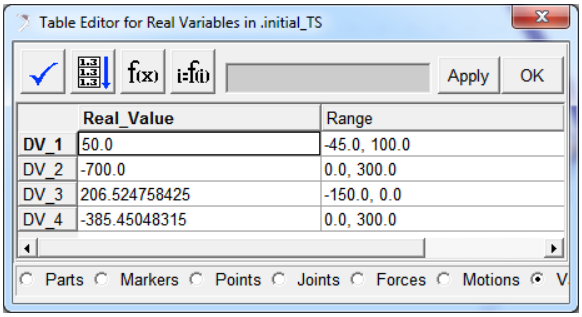

Figure 4. The design variables for optimization.

The objective function (called design objective in ADAMS) used in the optimization process refers to the driving/motor force developed by the linear actuator in order to achieve the diurnal movement of the solar panel. This force proportionally influences the required mechanical power, therefore the energy consumed by the linear actuator, the optimization goal being one of minimization. The motor force is measured along the axis of the translational joint between the two components of the linear actuator (piston and cylinder), this measure being then used for the modeling of the design objective, as shown in Figure 5.

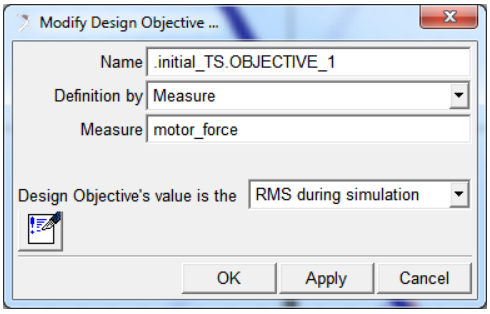

Figure 5. The modeling of the design objective.

Considering the variable nature of the driving force, which must balance in any position of the mechanism the system of resistance forces and torquesses that appear in the system, as well as the fact that depending on the current configuration of the mechanism the linear actuator can act either as a motor or as a brake, the root mean square (RMS) of the driving force will be monitored (and therefore minimized) during the otimization process.

The design constraints used in optimization are defined starting from the premise that the angular stroke specific to the diurnal movement of the solar panel must be achieved with a linear actuator having imposed sizes (minimum length – l, and maximum length – L). Specifically, a MecVel type actuator of the L02 class is used, having the following limit sizes: l = 350 mm (when the actuator is fully compressed), L = 600 mm (when the actuator is fully extended). Between the two extreme positions, the maximum stroke of the actuator is defined, $S_{max} = L - l = 250$ mm.

Under these conditions, the first two design constraints are defined such that the current length of the actuator d=|AB| over the entire simulation range is not less than the minimum length (l), respectively greater than the maximum length (L). Considering the way in which design constraints are defined/interpreted in ADAMS (according to those specified in the previous section of the paper), the two design constraints (DC) relating to the actuator length are defined based on measures expressed as follows: DC_1 $\rightarrow$ 350 – d, DC_2 $\rightarrow$ d – 600.

The third design constraint aims to keep the transmission angle in the tracking mechanism within acceptable limits, which ensures the operation of the mechanism over the entire required stroke without any risk of self-locking. The transmission angle (τ) in the tracking mechanism is defined as the angle between the actuator axis AB and the axis connecting the center of the revolute joints

between the piston and the panel (hence point B) with the center of the joint between the panel and the fixed pillar (hence point D), as shown in Figure 6. This angle is, in fact, the complement of the pressure angle, as the angle defined between the direction of the force applied by the actuator on the panel and the direction of the linear velocity on the panel at the point of force application (in the following, however, the use of the transmission angle is preferred, which is easier to measure in the virtual model in ADAMS).

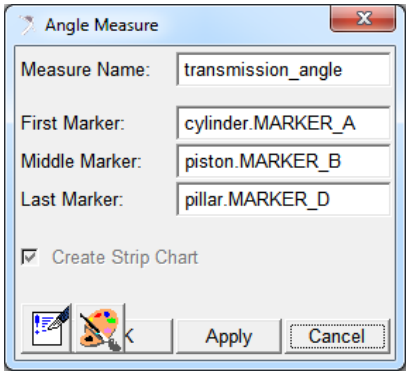

Figure 6. The modeling of the transmission angle.

Theoretically, self-locking of the mechanism occurs when the pressure angle becomes equal to 90°, so the transmission angle is either 0° or 180° (depending on the specific configuration of the mechanism). In practice, self-locking may occur at values earlier than those indicated, due to friction in the system, so a safety limit of 10° is considered, which means that in the optimization process it is not allowed to decrease the transmission angle below 10°, respectively increase it above 170°, as the case may be. For the considered configuration of the tracking mechanism (as shown in Figure 2), the risk to be avoided in the optimization process is that the transmission angle does not fall below the admissible value of 10°, so the design constraint is based on a measure defined as follows: DC_3 $\rightarrow$ 10 – τ.

The fourth constraint is to keep the upper end of the piston, to which the joint through which the piston connects to the panel frame is attached, outside the actuator cylinder. To define this design constraint, a measure based on the distance between points B and E is used, the value of this distance not being allowed to drop below 25 mm, which generates the following expression: DC_4 $\rightarrow$ 25 – d_{BE}.

The four design constraints have been modeled/defined in ADAMS by means of the following function measures (in the order in which the constraints were previously described): FUNCTION_MEA_1: DM(cylinder.MARKER_A, piston.MARKER_B)-600; FUNCTION_MEA_2: 350-DM(cylinder.MARKER_A, piston.MARKER_B); FUNCTION_MEA_3: 10-transmission_angle; FUNCTION_MEA_4: 25-DM(piston.MARKER_B, cylinder.MARKER_E). For each of these constraints, the maximum value during simulation is monitored. For instant, the modeling of the first design constraint (i.e. the one related to the maximum length of the actuator) is shown in Figure 7.

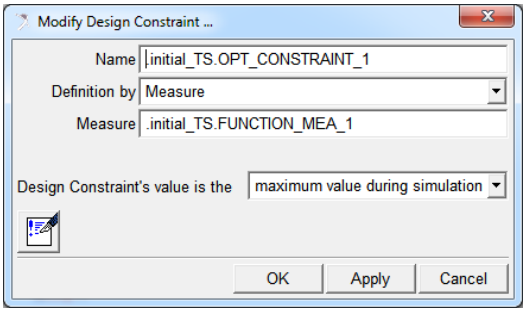

Figure 7. The modeling of the first design constraint.

4. Results

In the general case, the angular domain for the diurnal angle (β) of the solar panel is of 180°, from β = 90° facing East to β = -90° facing West, with null angle in solar noon position (considering the diurnal angle as positive in the morning and negative in the afternoon is just a convention). Previous researches have shown that for the Brașov geographical area, an angular range of 120° (β∈[60°, -60°]) is sufficient (in other words, the diurnal orientation in the ranges β∈[90°, 60°] and β∈[-60°, -90°] is not justified).

The configuration in which the system/panel is represented in Figure 2 corresponds to the morning position, in which β = 60°. In the initial position, the actuator is fully compressed. Once the simulation/analysis is launched, the actuator begins to extend so as to generate the 120° rotation of the panel, until the final (evening) position, in which β = -60°. To ensure automatic stopping of the analysis when the system reaches the evening configuration, a position sensor has been defined in the virtual model, the diurnal angle of the panel being measured at the level of the revolute joint between panel and pillar (in D). For the study carried out in this paper, it is not necessary to use a real-time variation law, considering that the linear actuator extends by 100 mm per time unit (second). A detailed study on how to design a real-time motion law for practical implementation is presented in ref. [14].

For the initial configuration (before optimization) of the tracking mechanism, defined by the standard values of the design variables (as shown in Figures 3 and 4, DV_1 = 50.0, DV_2 = -700.0, DV_3 = 206.524, DV_4 = -385.450 [mm]), the results obtained from the analysis carried out in ADAMS in 7.3534 seconds (at which point the system reaches the evening configuration, and the position sensor stops the simulation script) are rendered in Figure 8.

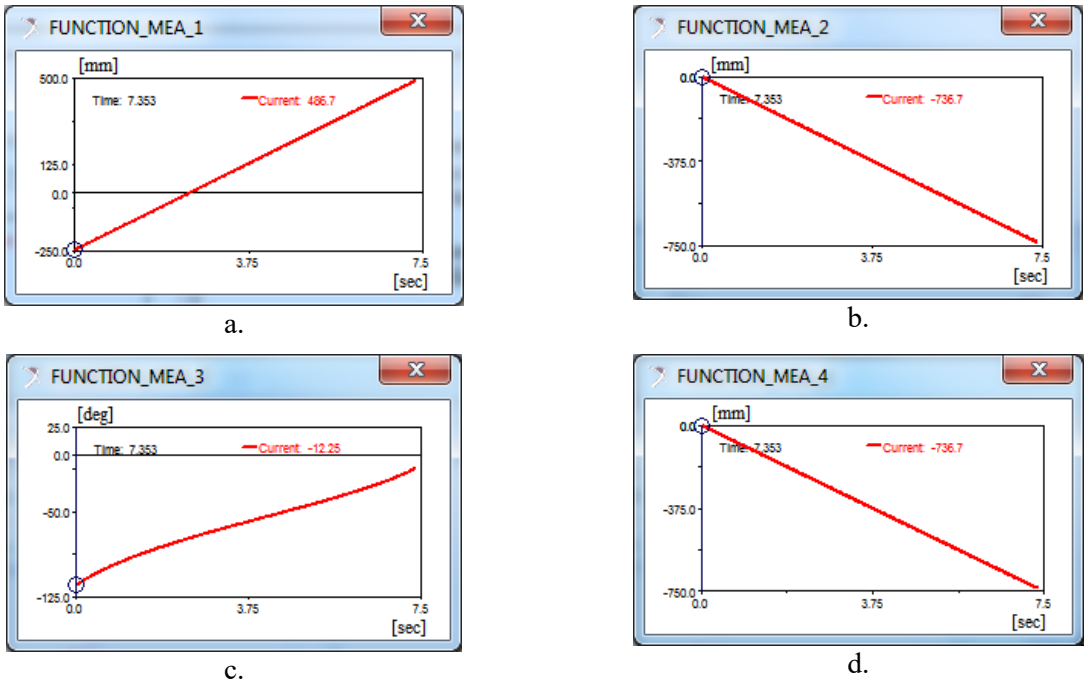

Figure 8. The variations of the design constraints in the initial mechanism.

As can be seen in Figure 8.a, the first design constraint (which is related to the maximum length of the actuator) is seriously violated, for most of the analysis interval the piston being actually out of the cylinder, which is obviously not possible in the real case. The maximum available length of the actuator (L = 600 mm) is reached at time t = 2.48 sec, when the corresponding diurnal angle of the panel is β ≈ 26° (in other words, the entire actuator stroke (of 250 mm) allows the panel to be rotated

by only 34°. Under these conditions, it is irrelevant that the other three design constraints are respected (that is, they have negative values throughout the entire simulation interval). Therefore, the initial configuration of the system is unacceptable from a functional point of view, it being necessary to obtain an adequate arrangement/layout of the linear actuator through the optimization process.

The algorithm used to perform the optimization is OptDes-GRG, which is integrated into ADAMS. This algorithm requires that the design variables have range boundaries (minimum and maximum values), since it operates in scaled space. The differentiation increment, which specifies the size of the increment to use when performing finite differentiation to calculate the gradients, is defined using the Forward method (the value is added to the nominal value of each design variable in successive runs).

Following the optimization process, the optimal configuration of the mechanism is reached, as shown in Figure 9. This configuration is characterized by the following values of the design variables (in mm): DV_1 = 61.120, DV_2 = -471.429, DV_3 = 75.571, DV_4 = -120.021.

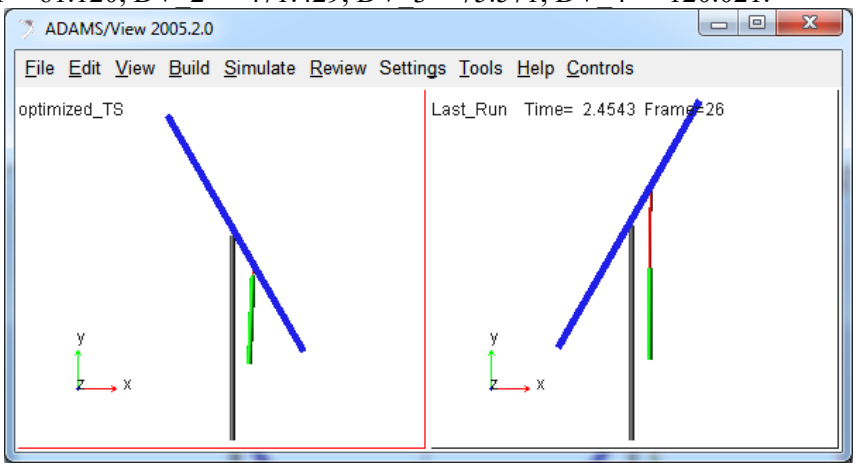

Figure 9. The optimal configuration of the tracking system (initial & final simulation frames).

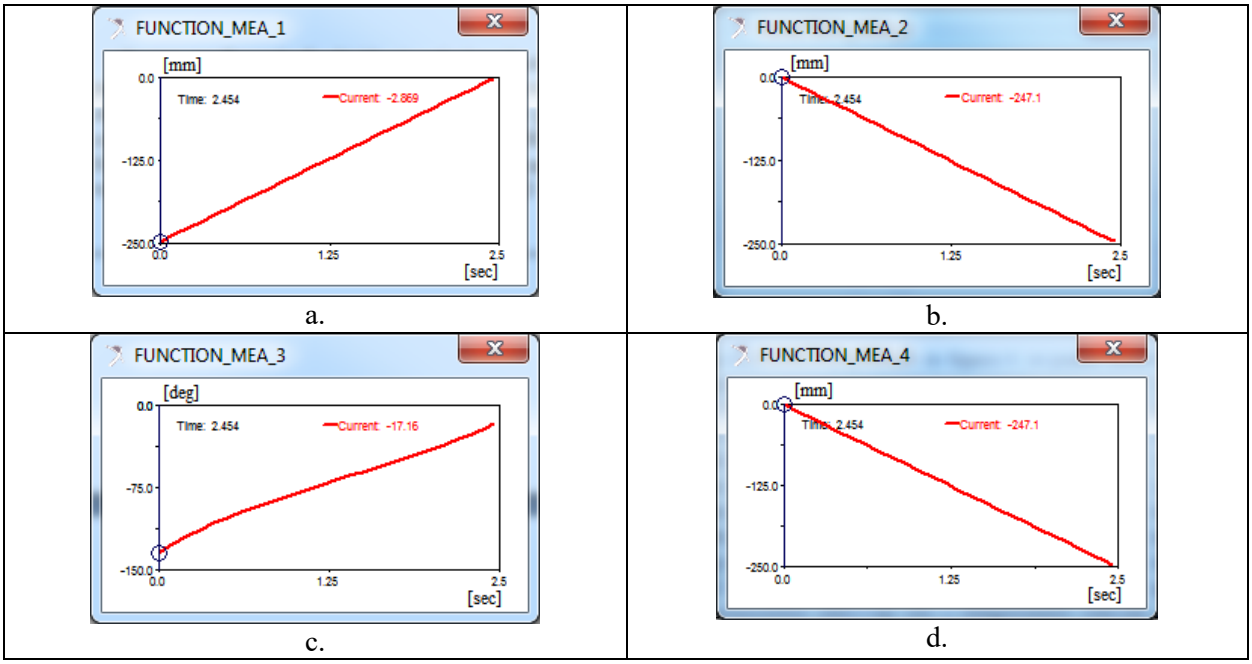

Figure 10. The variations of the design constraints in the optimized mechanism.

From the results presented in Figure 10, it can be seen that the tracking system resulting from the optimization complies with all the design constraints, therefore the optimization purpose is ensured. It

should be mentioned that in the case of the optimal mechanism, the evening position of the panel is reached after 2.452 seconds, for the same actuator motion law as in the initial mechanism (100 mm per time unit). Regarding the objective function for the optimization problem, namely the motor force developed by the linear actuator to rotate the panel within the angular range $\beta \in [60°, -60°]$, in the optimal variant of the tracking mechanism, the value of the root mean square during simulation is 28.297 N, which translates into reduced energy consumption to achieve the diurnal movement law imposed on the panel.

5. Final remarks

Among the facilities included in the ADAMS software package, there are available highly efficient optimization modules for both mono-objective optimization with or without design constraints (using the tools integrated in the general preprocessing module ADAMS/View), and multi-objective optimization (using a dedicated module, called ADAMS/Insight).

The study presented in this paper is focused on mono-objective optimization problems with design constraints. Practically, by using design constraints, the conditions of a multi-objective optimization can be replicated, without the need to use a separate software module such as ADAMS/Insight. Design constraints are a kind of additional objective functions through which unacceptable system designs (from a functional or constructive point of view) can be avoided. In this regard, the application presented in this paper (corresponding to a mono-axial tracking mechanism for solar panels) is a suggestive example of the facilities offered by ADAMS for optimizing more or less complex mechanical systems. The system under study is a relatively simple one, with a small number of bodies and connections, but which raises a series of problems, both functional and constructive, the optimization process carried out successfully solving all these issues.

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