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THE DYNAMIC OPTIMIZATION OF THE TRACKING MECHANISMS USED FOR INCREASING THE PHOTOVOLTAIC CONVERSION

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ABSTRACT
The purpose of the paper is to develop the optimization procedure for a photovoltaic tracking mechanism. The design objective is to minimize the motor forces for moving the panel, decreasing in this way the power consumption for orientation. The optimization strategy is possible by developing the dynamic model of the tracking mechanism, which is a multibody mechanical system (MBS). The tracking mechanism is parameterized using the points that define the structural model, in fact the locations of the geometric constraints between bodies. The dynamic optimization of the tracking mechanism is made by using the MBS environment ADAMS of MSC Software.
Keywords: PV panel, tracking mechanism, MBS model, dynamics, optimization.

1. PROBLEM STATEMENT
The solar energy conversion is one of the most addressed topics in the fields of renewable energy systems. The present-day techniques allow converting the solar radiation in two basic forms of energy: thermal and electric energy. The technical solution for converting the solar energy in electricity is well-known: the photovoltaic (PV) systems. The efficiency of these systems depends on the degree of use and conversion of the solar radiation. There are two ways for maximizing the rate of useful energy [1]: optimizing the conversion to the absorber level, and decreasing the losses by properly choosing the absorber materials; increasing the incident radiation rate by using mechanical tracking systems (the maximum degree of collecting is obtained when the incident radiation is normal on the active surface). Basically, the tracking systems are mechanical devices, driven by motors/actuators, which move the panel in order to follow the Sun path.

The key word for the design process of the tracking systems is the energetic efficiency: using the tracking system, the panel follows the Sun and increase the collected energy, but the driving actuators consume a part of this energy. The tracking system is efficient if the following condition is achieved: $\varepsilon = (E_{PT} - E_{PF}) - E_C >> 0$, in which E_{PT} is the quantity of electric energy produced by the PV panel with tracking, E_{PF} - the energy produced by the same panel without tracking (fixed), and E_C - the energy that is consumed for moving the system [3].

The energy consumption can be established by integrating the power consumption curve in absolute value, which depends on the motor force/torque that generates the prescribed motion law, and the angular/linear velocity of the input element (rotary motor and/or linear actuator). Consequently, the optimization strategy intends to minimize the actuating force/torque that is needed for tracking the sun movements. The optimization problem uses the dynamic model of the mechanical structure, and computes the geometrical parameters of the tracking mechanism. In paper, the application is made for a single-axis tracking mechanism, which tracks the daily motion of the Sun, facing East in the morning and West in the afternoon. The tilt angle of the revolute axis equals the latitude angle of the location because this axis is parallel with the polar axis. The numeric simulations are made by using the MBS (Multi-Body Systems) environment ADAMS of MSC Software.

2. OPTIMIZATION PROCEDURE

Generally, the optimization problem is described as a problem to minimize an objective function over a selection of design variables, while satisfying various constraints on the design and state variables of the system. In these terms, there are the following steps for optimizing a tracking system: parameterizing the virtual model, defining the design variables, defining the design objective and constraints for optimization, performing design studies for identifying the main design variables, and optimizing the model on the basis of these variables.

Usually, the parameterization of the tracking systems is made by using the points that define the structural model, in fact the locations of the geometric constraints (i.e. the joints). The parameterization simplifies changes to model because it helps to automatically resize, relocate and orient parts. In this way, relationships within the model are created, 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 creating independent parameters and to link modeling objects to them. In our case, the design variables represent the locations for the design points. Design variable allows running automated simulations that vary the values of the variable over specified ranges to understand the sensitivity to the variable or to find the optimum values.

In addition, using design variables, design studies 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 wiper system model. Design study describes the ability to select a design variable, sweep the variable through a range of values and then simulate the motion behavior of the various designs in order to understand the sensitivity of the overall system to these design variations. As a result, design study allows identifying the main design variables, with great influence on the tracking system behavior.

In addition, design of experiments can be performed for identifying the effects of varying several design variables simultaneously. This technique is 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 mechanical system.

The objective function is a numerical representation of the quality, efficiency, cost, or stability of the model. The designer decides whether the optimization chooses to find the minimum or maximum of the function. The optimum value of this function corresponds to the best design possible using that particular mathematical model. Examples of objective functions include execution time, energy required, and total material costs.

To avoid unacceptable results that violate the design, constraints for the optimization process can be defined. 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 mechanical system design. Each constraint creates an inequality constraint, the optimization keeping the value of the constraint less than or equal to zero. Constraints can involve the simulation results, or they can constrain overall size, weight, and other factors that depend only on model data. Concluding, the basic principle of the optimization process is to manipulate the unknowns (variables) in a design to arrive at a good design that satisfies all goals (objectives) and restrictions (constraints).

3. RESULTS AND CONCLUSIONS

For applying the above-described optimization procedure, we have considered a single-axis tracking system (fig. 1), at which the daily motion is driven by a linear actuator. The dynamic model of the tracking system includes the actuating motor, the bodies (with mass & inertia properties), the geometric constraints between parts, and the external & internal forces. The panel is mounted on a support, which rotates around a horizontal axis for the manually adjustment of the seasonal tilt angle. The daily motion is made by rotating the panel relative to the support, the linear actuator acting between the intermediary support and the panel.

The solution for system used in the study was selected from the multitude of the structural solution by using of the Multi Criteria Analysis. The evaluation criteria of the solutions were referring to the tracking precision, the amplitude of the motion, the complexity of the system, and easy manufacturing. The system will be implemented in the "Transilvania" University of Braşov, fact that will provide us a good opportunity to have a pertinent comparison between the real system performances and the results of the dynamic analysis developed on the virtual prototype.

In the virtual model of the tracking system, there are the following geometric constraints: panel to support - revolute joint (A-A'), cylinder to support - spherical joint (B), cylinder to piston - translational joint (C), piston to panel - spherical joint (D). The position of the revolute joint between panel and support is established on constructive criteria, and in this way there are 6 design variables that control the model in the optimization process, in fact the global coordinates of the points in which the linear actuator is connected to the adjacent elements, as follows: $X_B \rightarrow$ DV_1, $Y_B \rightarrow$ DV_2, $Z_B \rightarrow$ DV_3, $X_D \rightarrow$ DV_4, $Y_D \rightarrow$ DV_5, $Z_D \rightarrow$ DV_6.

In addition, for maintaining the relative location and orientation of the translational joint between cylinder and piston, the markers that define this joint have been parameterized using the following expressions: LOC_RELATIVE_TO ({0, 0, 0}, piston.point_C) - the function returns an array of three numbers representing the location; ORI_ALONG_AXIS (point_B, point_D, "Z") - the function returns the alignment of a specified axis from one coordinate system to another [4].

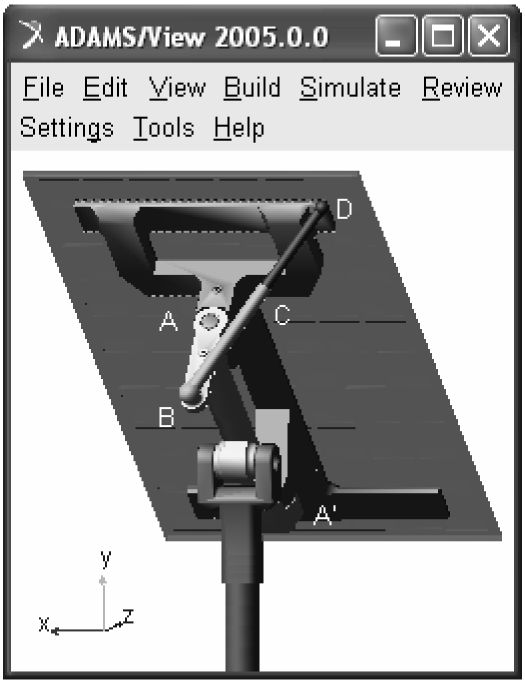

Figure 1. The virtual model of the PV system.

The energy consumption that is needed for tracking the Sun path is established by integrating the power consumption curve in absolute value. The power consumption depends on the motor force that is generated by the linear actuator, and the velocity between the actuator components. In these terms, the optimization strategy intends to minimize the power consumption for realizing the motion law.

The simulations have been made for the Braşov geographic area, which corresponds to the latitude of 45.5°, in the summer solstice day. The motion law of the panel has been established for maximizing the solar radiation absorption with minimum energy consumption [2], considering the correlation between the maximum amplitude of the motion and the operating time of the motor. In this way, the optimum angular field for the daily motion is $\beta^* \in [-60^\circ, +60^\circ]$, the motion being performed in 10.32 hours (the operating time of the motor), which corresponds to the local time interval $T \in [6.84, 17.16]$ (for the solar noon position of the panel, T=12.00, and $\beta^*=0^\circ$).

For identifying the influence of the design variables on the design objective, the design studies have been performed. In the design study, a design variable is defined by the initial value and the value range, which is established on constructive aspects. The results from figure 2, which represent the maximum absolute values of the power consumption during simulations, are from individual design studies of each design variable, keeping the rest of the variables fixed at their nominal value. We found sensitivities by using the plot statistics function and finding the slope of the design study curve for power consumption plotted against design variable value.

The effective optimization of the tracking system was made by using the GRG (Generalized Reduced Gradient) algorithm [4]. The optimization intends to minimize the design objective (i.e. the maximum absolute value of the power consumption), considering the main design variables. In this way, the final results for the optimum tracking mechanism are presented in figure 3 (the power consumption [Nm/h], and the energy/mechanical work consumption [J]), relative to the initial mechanism (before optimization), demonstrating the viability of the adopted optimization strategy.

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 tracking system and for any parameter. This is not always possible in the real cases due to the lack of space for transducers placement, lack of appropriate transducers or high temperature. This helps us to make quick decisions on any design changes without going through expensive prototype building and testing. In this way, the behavioral performance predictions are obtained much earlier in the design cycle of the tracking systems, thereby allowing more effective and cost efficient design changes.

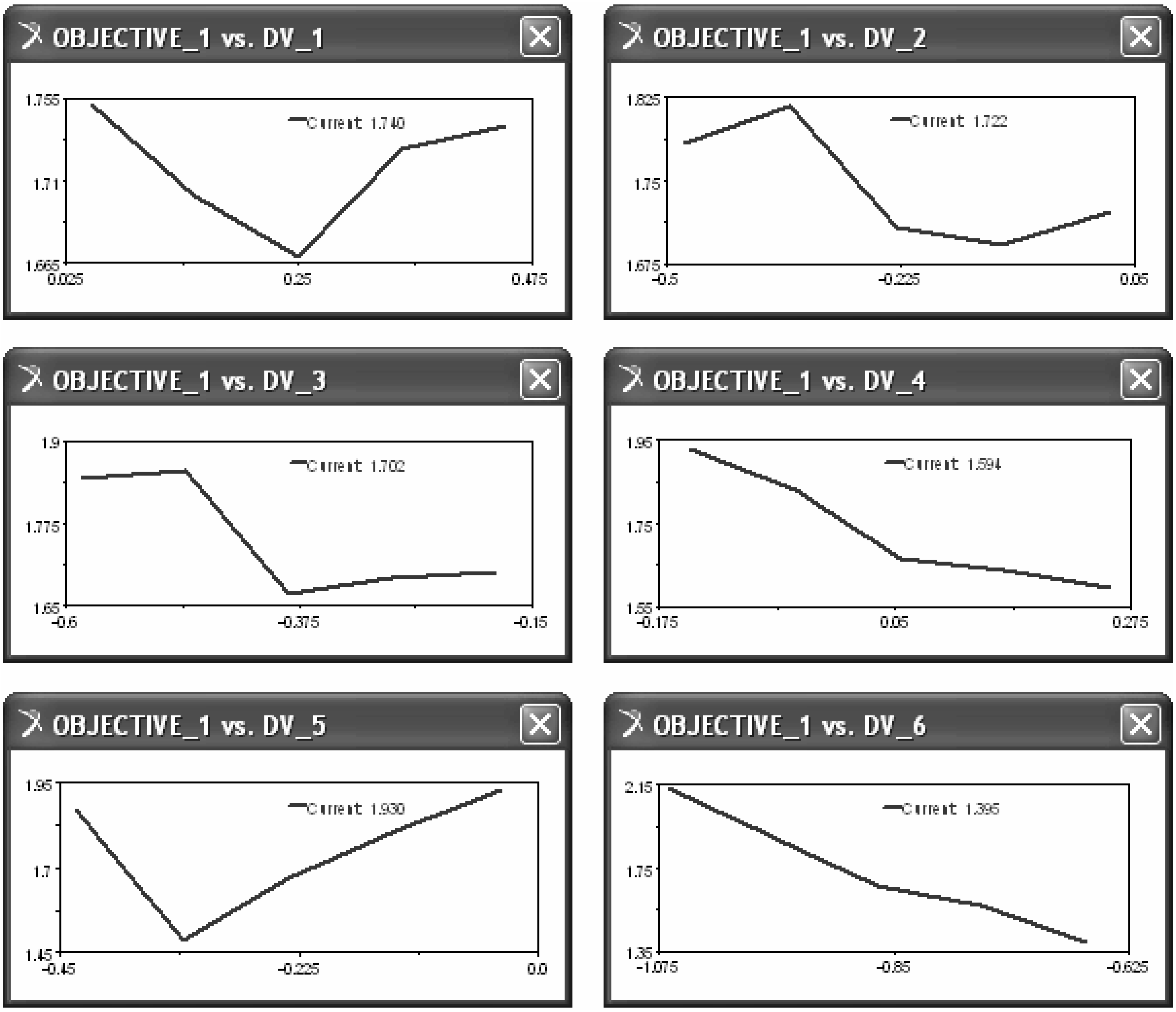

Figure 2. The results of the design studies (the sensitivity of the design objective).

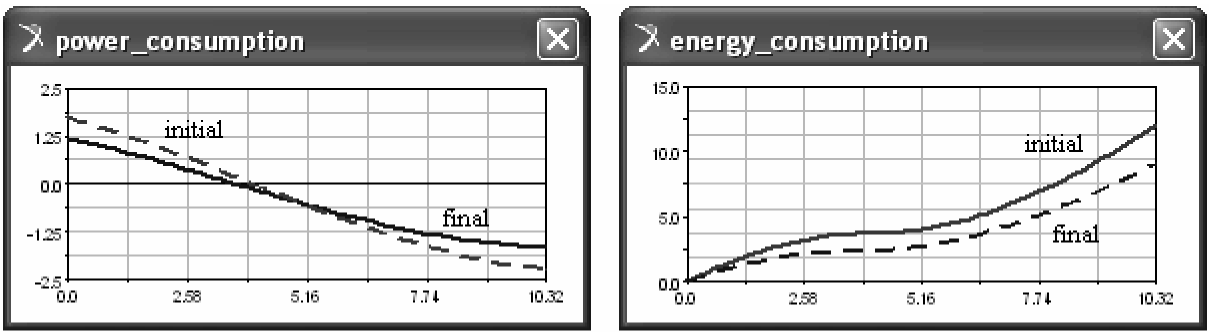

Figure 3. The power & energy (mechanical work) consumption.

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4. REFERENCES

[1] Abdallah, S., Nijmeh, S.: Two-Axis Sun Tracking with PLC Control, Energy Conversion and Management, no. 45, p. 31-39, 2004.
[2] Alexandru, C.: Strategy for Optimizing the Motion Law of the PV Tracking Systems Considering the Energy Balance, Proceedings of the 12th International Research/Expert Conference TMT, Istanbul, 2008.
[3] Canova, A., Giaccone, L., Spertino, F.: Sun Tracking for Capture Improvement, Proceedings of the 22nd European Photovoltaic Solar Energy Conference - EUPVSEC, Milano, p. 3053-3058, 2007.
[4] *** Getting Started Using ADAMS, MSC Software Publisher, Santa Ana, 2005.