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Review

Dynamic model of a parabolic trough solar concentrator with a water displacement mechanism

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ABSTRACT

This paper presents a three-dimensional mathematical model for determining the dynamic behavior of a parabolic trough solar concentrator of one degree of freedom, with a water displacement mechanism capable of minimize the angle of incidence (angle between the sun's rays irradiated on a surface and the line normal to this surface). This mathematical model allows the calculation of the angle of inclination of the collecting surface and the forces acting on the system. The validity of the proposed mathematical model is verified experimentally on two solar concentrators of different dimension.

1. Introduction

It is well-known that the simulation of mathematical models is very useful during the analysis of physical systems. In particular, mathematical models are especially required for the design, testing and validation of automatic control systems because they provide an approximation of the dynamic behavior of the physical system [2].

Different kinds of dynamic models and test methods of solar collectors have been developed since 1980s which can be distinguished by their particular mathematical models or tracking techniques as shown in Refs. [3–5].

At present, there are a limited number of investigations that are focused on outlining the dynamic model of parabolic trough solar concentrator, as in Refs. [5,6], where the dynamic behavior of parabolic cylinder concentrators installed in a plant of power for the generation of electric energy is considered, with the purpose of developing an adequate control approach. On the other hand, in Ref. [7] the authors propose numerical solutions of the mathematical transfer function model and test procedure were developed for dynamic solar collector, with the aim of making improvements in future designs. Also in Refs. [8–10], the authors propose some techniques to analyze and simulate the behavior of solar concentrators, such as a multi-linear regression method, a numerical integration algorithm and the multiple curved surface compound method were used to get collector parameters. However, all of them pay attention to the dynamics of the solar concentrator without considering the tracking mechanism in the analysis.

For that reason a three-dimensional mathematical model for determining the dynamic behavior of a parabolic trough solar concentrator with a tracking mechanism is showed in this paper. The most important feature of this model is that the tracking mechanism is included in the analysis. On the other hand, the angle of inclination of the solar concentrator and the forces of the system are known at all time. Therefore, the proposed model can be used to design control laws for positioning the surface of the solar collector perpendicular to the sun rays. Besides, this mathematical model can be easily adapted to solar concentrator of different sizes which include the water displacement mechanism.

2. Guidance and positioning mechanism

To rotate and position the surface of a parabolic trough solar concentrator was built and implemented a mechanism based on the displacement of water, Fig. 1a.

The main components of the proposed mechanism are two containers '1, 2′ half filled with water, connected by a flexible copper tube '6'. Each container is placed on the solar concentrator

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Nomenclature

a	acceleration [m^2/s]
A	area [m^2]
F_A	force on the bearing A [N]
F_B	force on the bearing B [N]
F_1	force on container 1 [N]
F_2	force on container 2 [N]
g	acceleration of gravity [m/s^2]
h_{10}	initial level of water [m]
h_1	level of water [m]
l	length of the center of mass of the solar concentrator and the origin “O” [m]
M	mass [kg]
M_{FA}	frictional moment on the bearing A [N m^2]
(d_{rec})	outer diameter of receiver [m]
M_{FB}	frictional moment on the bearing B [N m^2]
m_T	total mass of the water [kg]
q_i	water flow [m^3/s]
r_A	the distance between F_A and the origin “O” [m]
r_B	the distance between F_B and the origin “O” [m]
r_f	bearing diameter [m]
t	time [s]
α	angular acceleration [rad/s^2]
μ	friction coefficient
θ	angle of Inclination of the solar concentrator [Degree]
ρ	density of water [kg/m^3]
$\omega = \Omega$	angular velocity [rad/s]
I_{xx}, I_{yy}, I_{zz}	moment of inertia x,y,z of the system [N m^2]

framework and has a water pump ‘4’. Its operating principle is described as follows. Water pump of container 2 is turned on and it drains water from the container 2 to the container 1 when the rotation is in a counterclockwise direction. However, if the rotation is in a clockwise direction, water pump of container 1 has to be turned on. The water of the containers runs through the copper tube ‘6’.

The difference of water level generates a dynamic imbalance which is used to orient the collecting surface ‘5′ of the solar concentrator to where the sun is to heat water at high temperatures, (Figs. 1a and 4).

3. Dynamic model

Fig. 2 shows free-body diagram of parabolic trough solar concentrator with a water displacement mechanism. The $x-y$ coordinate system is established as shown in Fig. 2. The sum of the forces acting on the parabolic trough solar concentrator with a water displacement mechanism and the acceleration of its center of mass in terms of their components in a cartesian reference frame are:

$$\sum F_x\hat{i} + \sum F_y\hat{j} + \sum F_z\hat{k} = m\left(a_x\hat{i} + a_y\hat{j} + a_z\hat{k}\right) \quad (1)$$

$$\left(F_{A_x} + F_{B_x}\right)\hat{i} + \left(F_{A_y} + F_{B_y} - Mg - F_1 - F_2\right)\hat{j} = M\left(a_x\hat{i} + a_y\hat{j}\right) \quad (2)$$

The parabolic trough solar concentrator rotates about the spin axis “z ”, therefore sum of moments for this solar collector are:

It is important to mention that Eq. (3) is deduced based on Fig. 3.where F_A is the force on the bearing A, F_B is the force on the

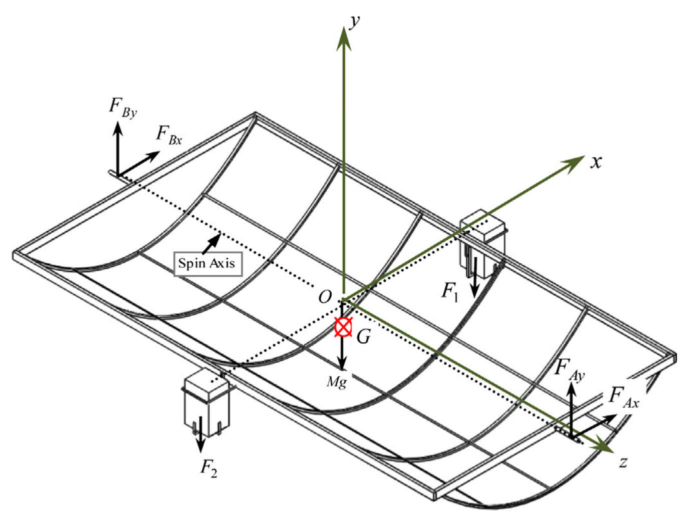

Fig. 2. Three-dimensional diagram of forces for the solar concentrator with parabolic channel.

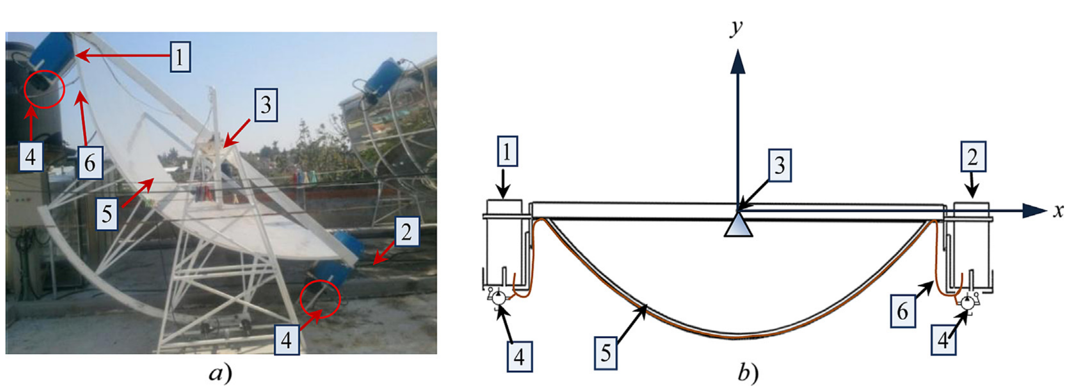

Fig. 1. Schematic diagram of the water displacement mechanism. 1-Container 2; 2-Container 1; 3-Bearings, 4-Water pump; 5-Collecting surface; 6-Cupper tube.