

# Sucker's reliability analysis of photovoltaic panel cleaning robot

Wang Jingshu<sup>1,\*</sup>, Xiao Xu<sup>1</sup>, Gong Hengxiang<sup>2</sup> and Zou Zheng<sup>1</sup>

<sup>1</sup> College of Mechanical Engineering, Chongqing University of Technology; Chongqing, 400054, China

<sup>2</sup> School of Science, Chongqing University of Technology; Chongqing, 400054, China

\*E-mail: donot@cqut.edu.cn

**Abstract.** The dust deposited on the surface makes a significant impact on the performance of photovoltaic modules. This paper mainly studies the sucker's reliability analysis of the photovoltaic panel cleaning robot. The research is carried from two aspects, the mechanical analysis and the finite element analysis. The reliability including anti-slipping, anti-overturning, and anti-twisting is researched based on the mechanical model, while the influence of the mechanical load is studied by the finite element model of the PV module. According to the constrain conditions, the sucker of the photovoltaic panel cleaning robot has been selected. Based on the prototype of PV cleaning robot, the reliability experiment is conducted to verify the sucker's reliability analysis.

## 1. Introduction

The dust deposition of microscopic particles in the outdoor environment affects the photoelectric conversion efficiency seriously [1, 2]. Many scholars had done out-door exposure tests in different areas. The results showed that the conversion efficiency reduced by 17% after 38 days exposure in Kuwait, while the reduction rate of efficiency is 40% after six months exposure in Sandi Arabia [3]. In Athens, the dust of the photovoltaic modules is 0.1-1g/m<sup>2</sup> after eight weeks exposure [4]. Therefore, it is necessary to clean the dust on the photovoltaic modules, especially for large solar power installation.

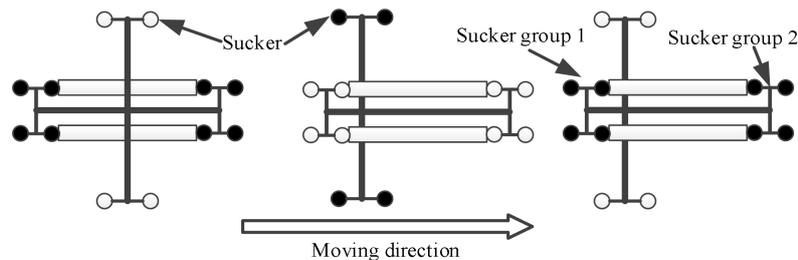
There are many types of mechanical devices aiming at cleaning the dust of PV modules, one of the fastest-growing devices is cleaning robot. In order to move on the angled surface, even vertical surface, the walking mechanisms applied by researchers include the tracked robot [5], the hybrid wheel-leg [6], and the magnetic absorption foot [7]. Nonetheless, the most widely used one is the sucker, which has advantages of simple structure, convenient control, and little influence on the surface [8, 9]. This paper focuses on the reliability analysis of the sucker of photovoltaic cleaning robot.

## 2. Suckers distribution of cleaning robot

The photovoltaic cleaning robot is capable of moving on the inclined surface of photovoltaic module. The dust will be cleaned when it reaches the destination. In our research, the walking mechanism of the cleaning robot is cruciform structure, while the suckers are installed on four terminals of the cruciform. The motion diagram of sucker based cleaning robot is shown in figure 1, in which the black sucker means it is attached to the surface, and the white sucker is not attached. Changing the statement of the suckers in figure 1 alternately, the cleaning robot can move along both the two directions of the cruciform.



The features of photovoltaic cleaning robot result in different absorbability requirements of the suckers on four terminals. When the cleaning mechanism works, the attached suckers need strong adsorption property. When the robot is moving, the cleaning mechanism is not running, the absorbability requirement of the attached suckers is relatively low. Therefore, both the two terminals along one line of cruciform have four suckers, marked as sucker group 1 and 2, while the number of suckers is two for the terminals along another line.

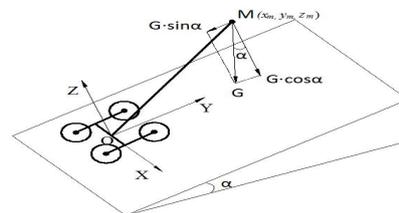


**Figure 1.** The motion diagram of sucker based cleaning robot.

Based on the suckers' distribution, the reliability analysis has been done from both theory and simulation aspects. Then, the prototype has also been made to verify the reliability.

### 3. Mechanical analysis of sucker reliability

For the cleaning robot should work on the slanting surface of PV module, the sucker reliability analysis is executed in three directions: anti-slipping, anti-overturning, and anti-twisting. The cleaning robot is described as a barycentre-sucker system shown in figure 2. In the simplified system, the centroid coordinate is  $(x_m, y_m, z_m)$  while the mass of the cleaning robot is denoted by  $m$ . The suckers are simplified as points in the system. The  $\alpha$  indicates the tilt angle of the PV module.



**Figure 2.** Analysis of mechanics force of robot.

#### 3.1. Analysis of anti-slipping

The pressure difference and the adsorption area of the  $i$ th sucker are expressed by  $\Delta P_i$  and  $S_i$ , respectively. When the cleaning robot works on the tilt surface without slippage, the maximum frictional force supported by the suckers should be greater than the gravity component. With the assumption that the friction coefficient of PV module is indicated by  $\eta$ , the anti-slipping constrain can be expressed as equation 1.

$$\eta \sum_{i=1}^n \Delta P_i \cdot S_i > G \cdot \sin \alpha, \quad i \geq 1 \tag{1}$$

#### 3.2. Analysis of anti-overturning

In general, the suckers are distributed as line-style or rectangle-style. It is assumed that the coordinates of the diagonal points are  $j(x_j, y_j)$  and  $k(x_k, y_k)$  for the rectangle-style. For the line-style distributed suckers, we can get a rectangle area based on the barycentre of sucker. Therefore, the overturn of the cleaning robot is the rotation around an edge or vertex of the rectangle.

The tendency of overturn is determined by the stress status and the centroid position of cleaning robot. Considering the equilibrium equations of forces and force moments, the anti-overturning constrains, including equations from (2) to (6), are listed in table 1.

**Table 1.** The anti-overturning constrains.

Equation number	Position of centroid	Stress status	Anti-overturning constrain
(2)	$x_m > x_k$	No constrain	$\sum_{i=1}^n \Delta P_i \cdot S_i \cdot  x_i - x_k  > G \cdot \cos \alpha \cdot z_m$
(3)	$x_m < x_j$	No constrain	$\sum_{i=1}^n \Delta P_i \cdot S_i \cdot  x_i - x_j  > G \cdot \cos \alpha \cdot z_m$
(4)	$y_m < y_k$	No constrain	$\sum_{i=1}^n \Delta P_i \cdot S_i \cdot  y_i - y_k  > G \cdot \sin \alpha \cdot z_m + G \cdot \cos \alpha \cdot  y_m - y_k $
(5)	$y_m > y_j$	$G \cdot \cos \alpha \cdot  y_m - y_k  < G \cdot \sin \alpha \cdot z_m$	$\sum_{i=1}^n \Delta P_i \cdot S_i \cdot  y_i - y_k  > G \cdot \sin \alpha \cdot z_m - G \cdot \cos \alpha \cdot  y_m - y_k $
(6)	$y_m > y_j$	$G \cdot \cos \alpha \cdot  y_m - y_j  > G \cdot \sin \alpha \cdot z_m$	$\sum_{i=1}^n \Delta P_i \cdot S_i \cdot  y_i - y_j  > G \cdot \cos \alpha \cdot  y_m - y_j  - G \cdot \sin \alpha \cdot z_m$

### 3.3. Analysis of anti-twisting

Based on the simplified barycentre-sucker system in figure 2, the force  $G \cdot \sin \alpha$  will drive robot to turn around Z-axis while the friction between suckers and surface will generate torque in opposite. Therefore, the anti-twisting constrain can be described as equation (7).

$$\eta \sum_{i=1}^n \Delta P_i \cdot S_i \cdot |x_i| > G \cdot \sin \alpha \cdot |x_m| \quad i \geq 1 \tag{7}$$

In conclusion, the results of theory analysis for sucker reliability are comprised of equations from (1) to (7) and cover constrains of anti-slipping, anti-overturning, and anti-twisting.

## 4. Simulation analysis of sucker reliability

The walking motion of the cleaning robot is realized by the adsorption of the suckers, which will influences the deformation of the PV modules. However, as the key component of PV module, the main failure mode of silicon cell is crack which is hard to find out in experiment with the sealed PV module. Therefore, the simulation analysis of sucker reliability considering the deformation has been executed.

Based on standards in GB/T9535, the maximum stress and maximum deflection of PV module with the static load being 2400pa are applied as the reliable bases. If the stress and deflection of PV module with the cleaning robot working are less, the suckers of the cleaning robot are approved reliable.

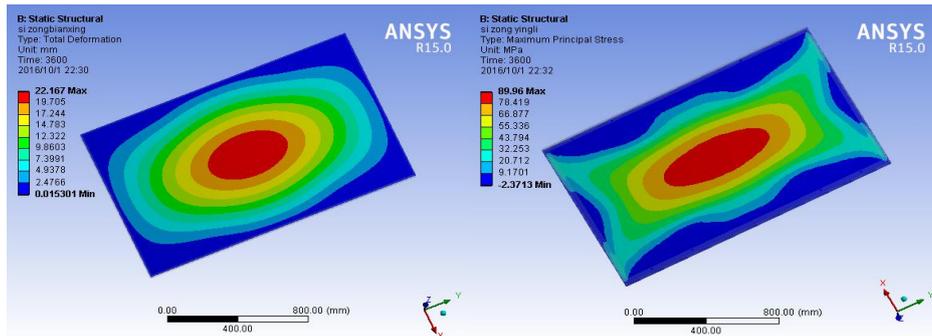
The simulation parameters are listed in table 2. The dimension of PV module refers to the EP260C-60 produced by Ningbo yipai.

**Table 2.** The model materials of PV module.

Material	E(Gpa)	Poisson ratio	Thickness (mm)
stalinite	73	0.22	3.2
EVA film	0.655	0.3	0.4

silicon cell	144	0.3	0.3
TPT film	1.5	0.24	0.225
aluminum alloy	71	0.3	1

ANSYS is employed to conduct finite element analysis. The deformation and stress nephogram of silicon cell with load being 2400pa are illustrated in figure 3.



(a) Deformation of silicon cell.

(b) Maximum stress nephogram of silicon cell.

**Figure 3.** Deformations of PV module subjected to load of 2400pa.

The simulation results present that the maximum stress of PV module is 109.01Mpa and the maximum deflection is 22.167mm. The values of silicon cell are 89.96Mpa and 22.167mm, respectively. According to figure 3, the maximum deformation occurs on the central area of PV module. The reason is that all the installation holes of PV module are distributed on the edges. Therefore, when validating the reliability of suckers, the values of maximum stress and deflection with the cleaning robot being working should less than the values of 89.96Mpa and 22.167mm, respectively.

### 5. Validation of sucker reliability

Before manufacturing the prototype of cleaning robot, the reliability validation of chosen suckers has been conducted. For practical purposes and economy reasons, the type of chosen sucker is FV50. The radius of sucker is 50mm while the radius of negative pressure chamber is 3mm. The type of matching vacuum pump is VBY7506, whose friction coefficient with PV surface is 0.6. Based on all the parameters of the sucker, the validation from both theory and simulation aspects are conducted as follow.

When only the sucker group 1 or sucker group 2 are absorbed on the PV panel, sucker failure and stress concentration may happen because the adsorption points are relatively centralized. Therefore, the validation is conducted for the situation when only the sucker group 1 or sucker group 2 are absorbed.

#### 5.1. Theory analysis validation

Due to the symmetry of sucker group 1 and group 2, we choose arbitrary group. According to the parameters of suckers and coordinate system in figure 2, the coordinates of the four suckers in sucker group 1 are (50, 105), (-50, 105), (-50, -15), and (50, -15). The coordinates of barycentre of cleaning robot is (42.8, 415.1, 88.3).

When the tilt angle of the PV module  $\alpha$  is  $60^\circ$ , the tendency to slip is the biggest. The force to slip and frictional force are calculated in equation (8).

$$\max F_{slip} = G \cdot \sin 60^\circ = 63.6N, \quad \max F_{friction} = \eta \sum_{i=1}^4 \Delta P_i \cdot S_i = 348.34N \quad (8)$$

When the tilt angle of the PV module  $\alpha$  is  $30^\circ$ , the tendency to overturn is the biggest. The coordinates of barycentre can match the condition of Equation (6), the reacting force of PV surface can be calculated by equation (9).

$$\sum_{i=1}^n (F_{N_i} - F_i) \cdot |y_i - y_j| = G \cdot \sin 30^\circ \cdot z_m - G \cdot \cos 30^\circ \cdot |y_m - y_j| \quad (9)$$

$$\Rightarrow F_{N1} + F_{N2} = 18.36N$$

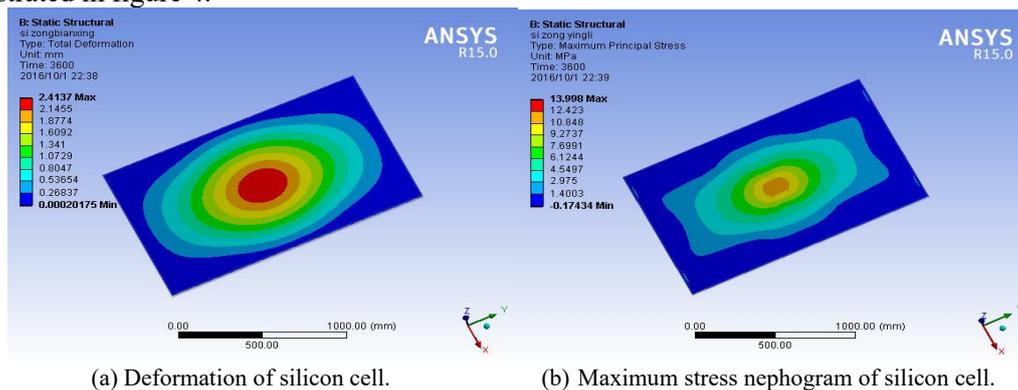
Based on the equation (7), the tendency to twist is the biggest when the tilt angle of the PV module  $\alpha$  is  $60^\circ$ . The maximum torques of twist and anti-twist are

$$\max M_{\text{twist}} = G \cdot \sin 60^\circ \cdot x_m = 2.72N \cdot m, \quad \max M_{\text{anti}} = \eta \sum_{i=1}^4 \Delta P_i \cdot S_i \cdot |x_i| = 17.42N \cdot m \quad (10)$$

The force to slip is less than the maximum frictional force supported by the suckers and the torque of anti-twist is bigger than the one of twist. The reacting force of PV surface is greater than zero. Therefore, the suckers are reliable from three aspects including anti-slipping, anti-overturning, and anti-twisting.

### 5.2. Simulation analysis validation

The finite element analysis of cleaning robot has been conducted with the condition that only sucker group 1 is absorbed. The weight of robot is supported by the four suckers. The results of simulation are illustrated in figure 4.



**Figure 4.** Simulation results of PV module with cleaning robot being working.

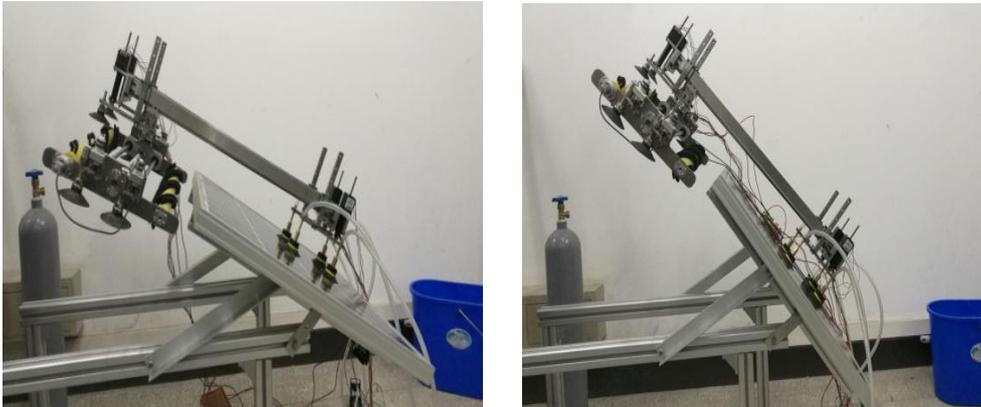
It is obvious that the maximum stress of silicon cell is 14Mpa, less than 89.96Mpa, while the maximum deflection is 2.41mm, less than 22.167mm. Therefore, the simulation results can prove that the selected suckers are reliable.

### 6. Prototype experiment of cleaning robot

Based on the suckers validated in above section, the prototype of cleaning robot has been developed. The robot adsorption experiments with tilt angle being  $30^\circ$  and  $60^\circ$  have been conducted as figure 5. The working state is maintained as long as one minute to observe whether the cleaning robot slips, overturns, or twists. In order to improve experiment effect, the whole cleaning device of cleaning robot is hung outside of the PV module.

The same adsorption experiments have been repeated for several times. The suckers are stable reliable. Therefore, the results of theory analysis of sucker reliability are verified to be practical and feasible.

The deformations of cleaning robot in the working state are measured by dial indicator. Deformations of three points in the central region have been measured five times. The maximum deformation measured is 2.39 mm. It is close to the value of 2.41mm, which is the simulation result of figure 4. The experiment result is in good agreement with simulation result.



**Figure 5.** Adsorption experiment of prototype with tilt angle being 30° and 60°.

## 7. Conclusion

This paper focuses on the reliability analysis of the sucker of photovoltaic cleaning robot. After the theory analysis and simulation analysis of sucker reliability, a series of constraints have been obtained. Based on the suckers selected according to the reliable constraint conditions, a prototype of PV cleaning robot has been developed. The experimental results of the prototype show that the proposed reliability analysis of sucker is practical. The analysis methods of reliability provide a helpful reference for other sucker based walking mechanisms.

## Acknowledgement

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