Modal analysis of trough solar collector
Qiong Zou, Zhengnong Li*, Honghua Wu

Key Laboratory of Building Safety and Energy Efficiency (Hunan University), Ministry of Education, 410082, China

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A B S T R A C T

Trough solar collectors exhibit a special structure: a thin mirror surface and a large windward surface. The mechanism of trough solar collectors results in stringent structural deformation requirements. Such requirements include wind load as an important control load whose dynamic effect must be considered in structural design. The natural frequency and mode shapes of a structure are important parameters in the study of dynamics. Therefore, simulation analysis should be performed before analyzing the structural dynamics of trough solar collectors to understand their natural vibration characteristics. In this study, the ANSYS software is first used to establish a finite element model of a trough solar collector for modal analysis. The goal in this step is to obtain the natural frequencies and the mode shapes of the solar collector structure at different pitch angles. Next, field measurements are performed on a prototype of the trough solar collector to obtain the natural dynamic characteristics of the collector. The measured data are then compared with the natural frequencies and mode shapes obtained from the finite element analysis to verify the applicability of the finite element model. A uniform design method is used in the selection of optimal measuring taps, and then this paper verifies the correlation of mode shapes between the finite element and the measurement. Results show that the natural frequencies of the trough solar collector are closely spaced, and the inherent dynamic characteristics measured under various pitch angle coincide with the results of the finite element simulations. Hence, the finite element model of trough solar collectors is applicable. The main contributions of this work include: (1) By means of the modal test in field measurements and the finite element modal analysis, the natural dynamic properties of the trough solar collector can be obtained. (2) Results of modal test could evaluate and improve the accuracy of finite element model, and the results of finite element modal analysis are compared with the field measured modal test results, which verifies the accuracy and the applicability of the finite element model of the channel condenser. (3) Based on the finite element model of the trough solar collector, the information obtained in this work can serve as a reference for subsequent analyses and calculations, such as wind-induced response dynamics analysis.

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1. Introduction

Trough solar collector systems (Fig. 1), which are concentrating systems with good commercial bases, are widely used in solar thermal power generation technology. Solar thermal power stations are usually distributed in open and flat areas, and wind serves as the control load of their structural design. Domestic and international research on the wind resistance of trough solar collector systems began in the 1970s. Anderson et al. (1975) investigated the working status of trough solar collectors under desert, strong wind, and other harsh conditions in 1975 and found that guaranteeing the working performance of some solar collectors is difficult. Peterka et al. (1990), Peterka and Derickson (1992) studied wind pressure distribution on the surface of trough solar collectors in boundary layer wind tunnel tests and presented a calculation method for the wind load on trough solar collectors. Naeenia and Yaghoubi (2007) studied trough solar collectors through numerical simulations and wind tunnel experiments to obtain the wind load under different angles and wind velocities. Randall et al. (1980) designed two groups of wind tunnel experiments for trough solar collector systems to simulate uniform flow and atmospheric boundary layer environment, respectively, and calculated the wind force of monomer and solar collector groups at work and rest; the results showed that wind force increases slightly with an increase in the length–width ratio of the mirror. Gong et al. (2012) studied the wind field characteristics of the boundary layer of trough solar collectors, as well as the characteristics of the surface wind load distribution, by taking field measurements. On the basis of the field measurement data of a heliostat, Zang et al. (2014) simulated the...
time history of wind pressure by using an AR(Auto Repressive) numerical model and incorporated it in a finite element model to perform the modal and transient analyses of heliostats and thereby determine the deformation and acceleration response of heliostat structures. Moya et al. (2014) presents modal tests of a heliostat located at the National Solar Thermal Test Facility (NSTTF) at Sandia National Labs in Albuquerque, New Mexico, and data acquisition software was developed to provide real-time monitoring of the wind velocity, heliostat strain, mode shapes, and natural frequencies which will be used to validate finite element models of the heliostat. Griffith et al. (2014, 2012) carried on modal test of a heliostat located at the NSTTF to measure its modes of vibration, strain and displacements under wind loading, modal tests were performed with artificial and natural wind excitation and the information gained from these tests could be used to evaluate and improve structural models that predict the motions/deformations of the heliostat due to gravitational and dynamic wind loadings.

In the application of a trough solar collector in practice, incident solar light must be projected to the target point exactly through reflection. However, most trough solar collector systems are located in wide, open desert or field areas, in which wind greatly affects solar collectors. Domestic and foreign scholars have made advances in the study of the collector wind pressure distribution and fluctuating characteristics of trough solar collector systems. However, the research on the modal analysis of trough solar collectors and wind-induced responses is limited. Mode is the natural vibration characteristic of a structure. Each mode has its own natural frequency, damping ratio, and unique mode shapes. Modal parameters can be obtained via modeling with finite element software or through experiments. As the modal parameters of structures are vital to dynamics studies, modal analysis is regarded as the starting point of further dynamic analysis, including spectral response analysis, transient dynamics analysis, and spectrum analysis. Verifying the applicability of the finite element model of a certain structure improves the persuasiveness of subsequent dynamic analyses.

The structure of trough solar collectors is unique. Changes in solar collector pitch angle may change the mass and stiffness distribution of the whole structure. Therefore, changes in vibration frequency and mode shape at different pitch angles should be considered when conducting modal analysis. In this study, we first establish a finite element model using ANSYS software and then conduct modal analysis on the model to obtain the natural dynamic properties of the solar collector. Thereafter, field measurements of a trough solar collector prototype located in Zhangjiagang City (Jiangsu Province, China) are taken to obtain the inherent dynamic characteristics of the collector, and a comparative analysis is performed on the mode shapes and natural frequencies obtained from the finite element analysis and field measurement. The conclusions may be used as calculation parameters and references for the subsequent dynamic analyses of trough solar collectors.

2. Finite element model and modal analysis

2.1. Brief introduction to the through solar collector prototype

A trough solar collector system mainly consists of mirrors, mirror support, main frame, trusses, condensing tube, tube support, elevation rotation device, and column pedestal. As can be seen from Fig. 1. In this work, the model combines two trough solar collectors through a connecting device. Each collector measures 6.2 m high and contains an opening that measures 5.958 m wide and 6.1 m long. Six small mirrors are distributed in the collector along its length and width. The size of each small mirror is 1 m × 1 m. The gap between the small mirrors measures 0.02 m along the length and 0.03 m along the width. The small mirrors are screwed onto the mirror support with four mirror pedestals. The main frame is a triprism steel structure composed of square tubes measuring 0.05 m × 0.05 m × 0.003 m; it is mainly used to fight torsion and bending. The end plate is a steel plate measuring 0.012 m thick. The mirror support is made of a square steel tube measuring 0.04 m × 0.04 m × 0.02 m. The section of the column pedestal measures 0.1 m × 0.1 m × 0.04 m.

2.2. Finite element model

The ANSYS Workbench platform is used to establish an accurate finite element model whose physical structure is reasonably simplified, especially in terms of the chamfer, fillet, and bolt. This simple structure ensures a short calculation time. The condensing tube and condensing support show low mass and stiffness and thus exert little influence on load distribution and solar collector stiffness. Therefore, they can be ignored in the model. A Shell63 shell unit is used for the mirror of the trough solar collector, whereas a Beam188 beam unit is used for the other components. Exactly 31,365 units and 42,802 nodes are obtained after meshing. For the bolt connection in the trough solar collector, a bond boundary condition is set, and column pedestals on both sides of the collectors are connected and fixed to the ground. Figs. 2 and 3 show the diagram of the finite element model of a trough solar collector at a pitch angle of 30°, with one working condition for rotating 10°
from 0° to 90°. A schematic diagram of the mirror angle is shown in Fig. 3.

2.3. Modal analysis of solar collector structure

The Lanczos method is adopted for the modal analysis of the trough solar collectors. Lanczos algorithm is the most effective method for the calculation of symmetric matrix eigenvalue problem. The algorithm is based on the basic Lanczos process which is a transformation of a symmetric matrix into three diagonal matrix. Lanczos process in the whole process of the calculation of the matrix remains unchanged, and just need add a little storage space, then it can be completed. Lanczos method adopts sparse matrix solver, and this solver is faster than any other solver when computing. Lanczos method is often applied to the entity or shell element model. This method is as accurate as the subspace method, but faster, so we choose Lanczos method for modal analysis of trough solar collectors. The dynamic characteristics of the trough solar collectors are calculated, including its natural frequency and mode shapes in various orders. Changes in the pitch angle of a trough solar collector causes the structural mass and stiffness distribution to vary. Thus, we present the natural frequency and mode shape under various pitch angles. Table 1 shows the natural frequencies of the first-ten mode at different pitch angles. The frequencies of a trough solar collector are closely spaced, and some frequency pairs, such as modes 1 and 2, modes 4 and 5, modes 6 and 7, have closely spaced modes. These characteristics can be explained by the fact that a trough solar collector is

![Fig. 2. Finite element model of trough solar collectors.](image1)

![Fig. 3. A schematic diagram of the mirror angle.](image2)
approximately symmetrical and that the modes 1–10 natural frequencies are in the range of 1.93–5.79. The pitch angle of the mirror does not exert a significant influence on various ordered frequencies. With an increase in pitch angle, the frequency changes very little, and the frequency value has a slight increase. Due to limited space, Figs. 4–7 only show the first 4 mode shapes at pitch angle of 0°, 30°, 60°, and 90°. At 0°, modes 1, 2, as well as modes 6, 7, mode shapes refer to the mirror of the collectors rotating around the X axis (X-axis refers to the span-wise direction, as shown in Fig. 2). The mode shapes 1, 2 refer to the mirror and the main frame rotating around the X axis, whereas the mode shapes 6, 7 refer to the mirror along the main frame that tighten inward and open outward. The mode shapes shows positive symmetrical and asymmetrical relationships. The mode shape 3 is the trough solar collector rotating along the X axis transversely. The mode shapes 4 and 5, as well as mode shape 8, mainly focus on the local rotation and deformation of the mirror. The mirror tightens (opens) inward (outward) at the four corners. The frequencies show positive symmetrical and asymmetrical relationships. Figs. 5–7 show that when the pitch angles of the collectors are 30°, 60°, and 90°, the mode shape of the collectors is similar to that at 0°; and modes shape 4 change slightly (at the local rotation of the mirror, the inward tightening and outward opening show certain variations). In general, when the pitch angle of a collector is changed, various modes frequencies increase slightly with pitch angle. At different pitch angle, the mode shapes in various modes are similar. Hence, the change in pitch angle of a trough solar collector exerts a small influence on the previous mode shapes and natural frequencies.

3. Modal test of trough solar collector

3.1. Modal testing procedure

The steps to carry out the modal testing usually include the following steps:

(1) Determination the position of measuring taps (the position of the sensors) and select the sensor

Reasonable layout of measuring taps (In this paper, measuring taps are the sensors.) can improve the precision of the modal parameter identification, and reduce the modal loss. Generally the principles of choosing the sensors are: the dynamic range and the working frequency band are both wide, the sensitivity and linearity are good, the anti-interference ability is strong.

Sensors should not to increase the weight of the structure, and should ensure that the actual measurement direction is consistent with the specified measurement direction.

(2) Choose the excitation method

Excitation methods include artificial excitation and natural excitation. The artificial excitation is suitable for some simple structure. The natural excitation, such as wind excitation, does not need any extra incentive equipment, and it is a good way of excitation. In this modal test, we choose the wind excitation method.

(3) Test execution

Firstly, the sensors are arranged on the measuring taps. Then the sensors are connected with the data acquisition instrument, and we use the data acquisition software on the computer to control the collection process. Finally we could get the results of data acquisition under different operating conditions.

(4) Identify modal parameters

The identification of modal parameters is a key step in the field measurement. The identification is based on the modal parameter model, the dynamic characteristics of the structure is reflected on the whole. It is one of the most important steps in the modal test.

(5) Validate modal parameters

The validation of modal parameters is to test the validity of the results of modal parameter identification. Usually the results of the modal test are compared with the results of finite element model simulation. By comparing the natural frequencies and the mode shapes to judge the correctness of the results of the identification of the modal parameters.

3.2. Modal testing equipment

The trough solar collector prototype for the field measurement is located in Leyu County, Zhangjiagang City (Figs. 1 and 8). Its component parameters are shown in Section 3.1. Data were obtained with UT3300 series data acquisition system produced by Wuhan Yutek Electronic Technology Co., Ltd. The highest sampling frequency is 204.8 kHz. The measured sampling frequency

| Table 1 | Natural frequency at different pitch angle (Hz). |
|---|---|---|---|---|---|---|---|---|---|---|
| Mode | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Pitch angle | 0° | 1.939 | 1.968 | 2.410 | 3.638 | 3.676 | 4.766 | 4.778 | 5.410 | 5.437 | 5.440 |
| 30° | 1.954 | 1.983 | 2.437 | 3.666 | 3.704 | 4.777 | 4.784 | 5.450 | 5.452 | 5.496 |
| 60° | 1.981 | 2.024 | 2.472 | 3.715 | 3.755 | 4.804 | 4.805 | 5.474 | 5.476 | 5.692 |
| 90° | 1.993 | 2.025 | 2.497 | 3.736 | 3.776 | 4.816 | 4.821 | 5.484 | 5.486 | 5.789 |

Fig. 4. The first 4 mode shapes of trough solar collectors (pitch angle = 0°).
is 128 Hz, which agrees with the Shannon sampling theorem. The sensor is a 4000-type accelerometer from the York Instrument Company. The uTekMa modal analysis software of Wuhan Yutek Electronic Technology Co., Ltd. is used to model and import the measured data. Through treatment and analysis, the modal parameters, mode chart of vibration, and damping ratio are obtained.

### 3.3. Sensors layout and working condition

The layout plan for the sensors on the trough solar collector is as follows (Li et al., 2009): one measuring point is selected as the reference point, and its sensor remains in place. The sensors in the other measuring taps are moved numerous times until the tests on all measuring taps are completed. One measuring point is placed at the center of 72 mirror plates. A test point is set on top of four column pedestals and the middle taps of both inclined columns. Hence, there are 84 measuring taps (84 sensors) in total. The measured excitation scheme of the trough solar collector is wind excitation. It is cost effective, it does not damage the structure, and it meets real boundary conditions. Wind excitation, as a natural form of excitation, involves fewer limitations than artificial excitation. It has been widely used in large projects. Wind speed and direction measurements are recorded by the anemometer during all of the tests. The height of the anemometer is about 3 m, and
locates about 10 m from the test trough solar collector. The wind speed and the wind direction are both varied in a certain range, and the wind load on the collectors is uncertainty. Wind excitation are performed for winds of 3.6–6.3 m/s. The wind direction is southeast, and the collector faces east. The horizontal wind direction is about 20°–30° (the schematic diagram of wind direction is shown in Fig. 3).

The measurement working conditions of a trough solar collector refer to pitch angles of 0°, 30°, 60°, and 90°, which correspond to the working conditions in Section 3.2. Under each working condition, the normal direction of the mirror and the horizontal surface of the column pedestal are tested. The testing time for each working condition is about 120 s.

4. Comparison of field measurement results of collector with finite element results

4.1. Comparison of frequency and mode shape

The uTekMa software is used to treat and analyze the measurement data from the trough solar collector. The functions include geometric modeling, model generation interactive editing system, constraint equation set up, model operation, parameter identification, model validation, animation display, etc. The uTekMa modal analysis software is used to model and import the measured data. Through treatment and analysis, the modal parameters, mode shapes of vibration, and damping ratio are obtained. The data processing window is shown in Fig. 9. The natural dynamic properties of the trough solar collector, including natural frequency, mode shape, etc., can be obtained. Table 2 shows the comparison of the natural frequency of trough solar collectors measured by the field measurement (short for FM) and simulated by the finite element model (short for FE) under various working conditions. Figs. 10–13 present the comparison of the mode shape of the trough solar collector measured by the FM and the mode shape simulated by the FE. Table 2 and Figs. 10–13 show that the mode shapes 1, 2 simulated by the FE correspond to the mode shape 1 measured by the FM, the mode shapes 4, 5 simulated by the FE correspond to the mode shape 2 measured by the FM, and the mode shapes 8, 9 simulated by the FE correspond to the mode shape 3 measured by the FM. The comparison chart shows that the mode shape simulated with the FE method is similar to that determined via FM. The frequencies of the trough solar collector are closely spaced, and as a result of the limited site measurement conditions, modal loss phenomena are observed. For example, the translation mode shape of the collector (the mode shape 3 of the FE simulation) and the mode shapes corresponding to the mode shapes 6, 7 simulated via the FE method, are not measured. Moreover, symmetrical and asymmetrical mode shapes are observed in the mode chart based on the FE simulation. By contrast, only a symmetrical mode shape is observed in the measured mode. Therefore, the asymmetrical mode shape may be lost in the measurement process. The main reasons for the modal loss are: (a) The model established in the finite element software is a three dimensional model, due to limited instrumentation DOF’s, the site measurement of the solar collector is performed in each direction in the field measurement, so certain complex modes are not tested accurately. (b) As wind excitation is used for field measurement and wind speed is only 4–6 m/s, some modes are not well-excited, or some modes with a weak vibration signal may not be identified due to the influence of surrounding vibration sources. (c) It is possible this mode could not be identified by the identification algorithm as it is a closely spaced mode.

The mode 1 of the trough solar collector measured in the FM and the modes 1, 2, 6, and 7 simulated with the FE method all rotate around the X axis. The modes 2, 3 measured in the FM and the modes 4, 5, 8, and 9 simulated with the FE method are local deformations. The results of the FM of the collectors show that with the increase in the pitch angle of the trough solar collector, the natural frequency of the structure is almost unchanged. Furthermore, the natural frequency calculated with the FE simulation also increases slightly with an increase in pitch angle. As pitch angle increases, the mode shapes from the measurements and sim-
Table 2
The comparison of the natural frequency of trough solar collectors measured by the FM and simulated by the FE under various working conditions (Hz).

<table>
<thead>
<tr>
<th>Pitch angle</th>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>FE</td>
<td>1.939</td>
<td>1.968</td>
<td>2.410</td>
<td>3.638</td>
<td>3.676</td>
<td>4.766</td>
<td>4.778</td>
<td>5.410</td>
<td>5.437</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>3.4%</td>
<td>4.9%</td>
<td>1.4%</td>
<td>0.3%</td>
<td>2.7%</td>
<td>2.3%</td>
<td>0.4%</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>FE</td>
<td>1.954</td>
<td>1.983</td>
<td>2.437</td>
<td>3.666</td>
<td>3.704</td>
<td>4.777</td>
<td>4.784</td>
<td>5.450</td>
<td>5.452</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>4.1%</td>
<td>5.8%</td>
<td>0.6%</td>
<td>0.4%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>0.4%</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>5.7%</td>
<td>7.3%</td>
<td>0.7%</td>
<td>1.8%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.4%</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>3.4%</td>
<td>4.9%</td>
<td>1.4%</td>
<td>0.3%</td>
<td>2.7%</td>
<td>2.3%</td>
<td>0.4%</td>
<td>0.3%</td>
<td></td>
</tr>
</tbody>
</table>

a. mode shape 1(FM)  b. mode shape 2 (FM)  c. mode shape 3(FM)
d. mode shape 1(FE)  e. mode shape 4(FE)  f. mode shape 8(FE)

Fig. 10. The comparison of the mode shapes of trough solar collectors measured by the FM and simulated by the FE (pitch angle = 0°).

a. mode shape 1(FM)  b. mode shape 2 (FM)  c. mode shape 3(FM)
d. mode shape 1(FE)  e. mode shape 4(FE)  f. mode shape 8(FE)

Fig. 11. The comparison of the mode shapes of trough solar collectors measured by the FM and simulated by the FE (pitch angle = 30°).
ulations show similarities. Hence, the change of pitch angle exerts minimal effect on the frequency and mode shape of the trough solar collector.

The comparative analysis of the measured and simulated results shows that the natural frequencies calculated with the two methods at different pitch angles show little relative error. The largest error is only 7.3%, and most errors are within 5%. The errors may be due to the accuracy of the measuring instrument or the simplification of some aspects during the FE simulation. The comparison of the natural frequencies of the trough solar collector at different pitch angles (Table 2) and the mode shapes in Figs. 10–13 reveals that the natural frequencies obtained with the two methods are similar with small relative errors. The mode shapes measured in the FM and the mode shapes obtained with the FE simulation are consistent. This result verifies the applicability of the finite element mode of trough solar collectors.

4.2. Mode correlation verification

This study aims to verify the correlation between modes obtained from the two methods by comparing the mode vectors from the FE and FM. The FM of the trough solar collector use 72 measuring taps (measurement locations of the sensors) on the mirror in its normal direction. In comparing the various mode vectors of the measuring taps at various pitch angles, the workload for verifying the mode correlation should be excellent. Therefore, this study adopts a uniform design (Fang, 1994) to optimize the measuring taps. This method significantly reduces the workload for comparison. The uniform design method distributes measuring taps in the test unit, particularly for those complex tests with large test scopes and high factor levels. This method offers unique advantages. In recent years, this method has been widely used in the military, chemical industry, medicine, and other fields in China, and it has achieved remarkable results. Recently, it has also been applied in the field of structural engineering (Xiao et al., 2006; Huang et al., 2006; Li and Wu, 2008) and has attracted the attention of the international mathematical community, gaining recognition and increasing use (Ning et al., 2011; Monnier, 2011).

4.2.1. Principle of uniform design

The uniform design method combines number theory methods with statistical test design. It was pioneered by Professor Fang Kai-
form design, Uniform design tables

design table comprises a code
form design tables and corresponding usage tables. Each uniform
greatly reduce the number of tests. Fang (1994) devised many uni-
design table to extract representative point of the test, thus it could
is fully represented. Uniform design method is use the uniform
tai and Academician Wang Yuan in China in 1978. Measuring taps
are uniformly distributed in the test scope such that each test point
is fully represented. Uniform design method is use the uniform
are uniformly distributed in the test scope such that each test point
through the modal assurance criteria (MAC) (Allemang and
Brown, 1982). The two mode vectors are \( \{\phi_a\} \) and \( \{\phi_e\} \). Similarity
is determined using the following formula:

\[
MAC(\{\phi_a\}, \{\phi_e\}) = \frac{(\{\phi_a\}^T \{\phi_e\})^2}{(\{\phi_a\}^T \{\phi_a\})(\{\phi_e\}^T \{\phi_e\})}
\]  (1)

The MAC values fall in the range of [0, 1]. If the MAC is 1, the
vectors, i.e. mode shapes are identical. If the MAC is equal to 0,
no similarity exists between the two vectors. In Eq. (1), \( \{\phi_a\} \) refers
to the mode vector obtained from the finite element analysis, and
\( \{\phi_e\} \) refers to the measured mode vector.

\[
\{\phi_a\} = \{\phi_{a1}, \phi_{a2}, \phi_{a3}, \ldots, \phi_{an}\}
\]  (2)

\[
\{\phi_e\} = \{\phi_{e1}, \phi_{e2}, \phi_{e3}, \ldots, \phi_{en}\}
\]  (3)

In Eqs. (2) and (3), \( n \) refers to the number of nodes. If the mode
from the finite element simulation is similar to the measured
mode, then the MAC values should be close to 1.

4.2.3. Uniform design application and comparison result

The uniform design method is used to optimize the measuring
taps (as the mirrors are symmetrical, we only need to compare
the mode vectors of the left mirror). In this work, we consider
two factors: the vertical coordinate (in X) and the horizontal coor-
dinate (in Y) of the mirror. The original point of the coordinate lies
in the lower left corner of the mirror. The changing range of X is
0.5–5.6 m, whereas the changing range of Y is 0.5–5.65 m. Six
levels are taken for X and Y, as shown in Table 4. When there are
2 factors, the test can be performed according to the codes of lines

![Fig. 14. The schematic diagram of the test point.](image)

Table 3
Uniform design tables \( U_q(6^4) \) and corresponding usage table.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>1</th>
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<th>3</th>
<th>4</th>
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<td>2</td>
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<tr>
<td>6</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>1</td>
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</tbody>
</table>

(b) \( U_q(6^4) \) usage table

<table>
<thead>
<tr>
<th>Factor S</th>
<th>Line</th>
<th>D</th>
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<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
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</table>

Table 4
Factors and levels.

<table>
<thead>
<tr>
<th>Level</th>
<th>X (m)</th>
<th>Y (m)</th>
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<tr>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
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<td>2</td>
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<tr>
<td>6</td>
<td>5.6</td>
<td>5.65</td>
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</table>

Table 5
The detailed test scheme of uniform design and MAC values at various pitch angles.

<table>
<thead>
<tr>
<th>X (m)</th>
<th>Y (m)</th>
<th>Measuring point</th>
<th>MAC (0°)</th>
<th>MAC (30°)</th>
<th>MAC (60°)</th>
<th>MAC (90°)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Mode 1</td>
<td>Mode 2</td>
<td>Mode 3</td>
<td>Mode 1</td>
<td>Mode 2</td>
</tr>
<tr>
<td>1</td>
<td>0.5(1)</td>
<td>2.56(3)</td>
<td>C6</td>
<td>0.996</td>
<td>0.997</td>
<td>0.965</td>
</tr>
<tr>
<td>2</td>
<td>1.52(2)</td>
<td>5.65(6)</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.54(3)</td>
<td>1.53(2)</td>
<td>B4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3.56(4)</td>
<td>4.62(5)</td>
<td>E3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.58(5)</td>
<td>3(1)</td>
<td>A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>5.6(6)</td>
<td>3.59(4)</td>
<td>D1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The number in brackets (2th, 3th line) correspond to the level number in Table 4.
1 and 3 at all levels in Table 3(a) on the basis of Table 3(b). The deviation is 0.1875. The detailed test scheme and results are shown in Table 5. As described in Section 4.1, the modes 1, 2, and 3 measured by FM correspond to the modes 1, 4 and 8 from the FE simulation. Fig. 14 shows the schematic diagram of the test point.

Table 5 shows that after using the uniform design method, only six measuring taps need to be compared: C6, F5, B4, E3, A2, and D1. This method greatly reduces the workload of correlation verification, and it is easy to use. Table 5 shows the MAC considering of the modes 1–3 (FM) under pitch angles of 0°, 30°, 60°, and 90°. The value of MAC is close to 1, which indicates that the mode shape of the through solar collectors obtained from the FE is similar to the mode shape measured by FM; hence, a proportional relationship is formed. In sum, the mode shape obtained from the FE coincides with the mode shape measured by FM.

5. Conclusion

The following conclusions are obtained after the modal analysis on the trough solar collector using the finite element software and field measurement, as well as a comparative analysis:

1. The natural frequency and mode shape of the collector are obtained through the modal analysis of the trough solar collector using the ANSYS Workbench platform. The frequencies of a trough solar collector are closely spaced, and some frequency pairs, such as modes 1 and 2, modes 4 and 5, modes 6 and 7, have closely spaced modes. Specifically, the modes 1, 2, as well as the modes 6, 7, rotate around the X axis; the mode 3 moves transversely along the X axis; and the modes 4, 5, as well as the mode 8, mainly focus on the local deformation of the mirror.

2. Increases in pitch angle do not significantly affect the collector frequency. The mode shapes corresponding to various modes are highly similar, thus indicating that the change in pitch angle exerts little influence on the frequency and mode shape of the trough solar collector.

3. After obtaining the field measurements of the trough solar collector, the natural dynamic properties of the trough solar collector can be obtained. The measured results are compared with the finite element simulation results. Modal loss phenomena are observed in the site measurement. Generally, the field measurement (FM) results at different pitch angles are consistent with the finite element (FE) simulation results, thereby indicating that the finite element model of trough solar collectors is applicable.

4. To verify the correlation between the finite element simulation and field measurement mode shapes of the trough solar collector, we adopt a uniform design method in the optimization of the measuring taps on the mirror. The number of measuring taps to be compared is reduced to six after optimization. This reduction minimizes the workload for verifying the correlation of mode shapes. This work presents the MAC values considering of the modes 1–3 under typical pitch angles. Table 5 shows that the values of MAC are close to 1, which indicates that the mode shape of the collector from the finite element analysis is similar to the field measurement mode shape. It also verifies the applicability of the finite element model.

5. The conclusions in this work can be applied to similar trough solar collectors of the same size and height. For solar collectors of vastly different heights and sizes, the results may be different, and further study would be required.

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References


