

The Numerical Model of Solar Radiation of Deployable Origami Structure

Chunxiao Lu, Dr.Mohamed Gadi

PhD Student, School of the Building Environment, The University of Nottingham, UK

Lecturer, School of the Building Environment, The University of Nottingham, UK

Abstract: This research seeks to exploit a novel building envelope by an investigation of integrating solar collectors into a specified deployable origami structure to improve the energy efficiency of building and its environmental controllability. Throughout a parametric study, a numerical model was developed to explore the relationship between the clear sky solar radiation received by the origami structure and its geometrical configuration in term of "compact ratio", "optimum slope". The application potential of this origami structure for radiation or thermal collecting also was discussed to facilitate it integrating into climatic responsive buildings.

Keywords: Deployable Origami Structure, Solar Radiation, Optimum Slop Angle,

NOMENCLATURE

a length of the shorter edge of the collector
 b length of the longer edge of the collector
 A altitude (km)
 G_0 horizontal extraterrestrial radiation (W/m^2)
 G_{on} extraterrestrial solar radiation on normal (W/m^2)
 G_{cb} horizontal beam radiation on clear days (W/m^2)
 G_{cd} horizontal diffuse radiation on clear days (W/m^2)
 G_c clear days total horizontal solar radiation (W/m^2)
 H_c the clear day's total solar radiation on a horizontal collector ($MJ/m^2 \cdot day$)
 H_{cb} the clear day's beam solar radiation on a horizontal collector ($MJ/m^2 \cdot day$)
 H_{cd} the clear day's diffuse solar radiation on a horizontal collector ($MJ/m^2 \cdot day$)
 $H_{c,T}$ the clear day's total solar radiation on a tilted collector ($MJ/m^2 \cdot day$)
 $H'_{c,T}$ the clear day's total solar radiation on a tilted collector of first row ($MJ/m^2 \cdot day$)
 f_i factor of the ratio of the area of the collector exposed to the beam radiation
 f_r factor of the ratio of the area of the reflecting plane surface exposed to beam radiation
 F_{c-s} view factor of diffuse radiation on the collector surface to sky
 F_{c-r} view factor of diffuse radiation on the collector surface to that the reflecting radiation come from
 F'_{c-s} view factor of diffuse radiation on the collector of first row surface to sky
 ρ_r reflectivity of the reflecting surface
 ρ_g reflectivity of ground, generally equal to 0.2
 n the nth day of the year
 N_x the number of unit of the origami structure in the X direction
 N_y the number of unit of the origami structure in the Y direction
 L_i the entire length of origami structure after folding
 W_i the entire width of origami structure after folding
 R_b the ratio of beam radiation on a tilted surface to that on the horizontal surface

$\bar{R}_b$ average ratio of beam radiation on tilted surface to that on the horizontal surface during a clear-day
 $\bar{R}_{br}$ average ratio of beam radiation on the reflecting surface to that on the horizontal surface during a clear day
 t_{ss} sunrise point
 t_{ss} sunset point
 S surface areas of collector (m^2)
 N_T daylight hour during azimuth restriction (hours)
 N_{eo} daylight hour on a horizontal surface (hours)
 $N_{eo,T}$ daylight hours on a tilted surface(hours)

Greek letters

δ solar declination ($^\circ$)
 α the acute angle between the two edges of the solar collector in the origami structure($^\circ$)
 ε angle of crease rotated in the symmetry plane ($^\circ$)
 α_s solar altitude angle($^\circ$)
 α_p profile angle of beam radiation($^\circ$)
 β slope, the angle between the collector in question and the horizontal($^\circ$)
 ϕ latitude ($^\circ$)
 θ angle of incidence between beam radiation and the normal of a tilted surface($^\circ$)
 θ_z solar zenith angle ($^\circ$)
 γ surface azimuth angle($^\circ$)
 γ_s solar azimuth angle($^\circ$)
 γ' the azimuth restriction to simplify the calculation
 τ_b atmospheric transmittance for beam radiation
 τ_d atmospheric transmittance for diffuse radiation
 ω_{sc} sunset angle on a horizontal surface($^\circ$)
 $\omega_{sc,T}$ sunset angle on a tilted surface($^\circ$)
 ω_T hour angle at the azimuth restriction
 ξ compact ratio of origami structure
 ϕ opening angle of origami structure($^\circ$)

Subscripts

f fold; x X-axis; y Y-axis; b beam; c clear; d diffuse; n normal; o outside space; rs sunrise; ss sunset; T tilted; c-s collector to sky; c-r collector to sky

1. INTRODUCTION

The widely accepted definition of origami is the making of folded paper models using straight line folds with no cuts and no glue in the way a great variety of shapes is produced. However, the folded and deployable origami is not only a recreational art, but also a scientific subject. Research indicates that folding phenomena occurs extensively in engineering and in nature.^[1]

In civil engineering applications, folding structure has been extensively adopted to construct long span buildings due to it can increase the stiffness of plates, as shown in Fig1. However, these projects only take the advantage of increasing rigidity of building by folded plate, and lack the consideration of environmental control.



Figure 1 Left, Van Wezel Performing Arts Hall, Sarasota Bay, Florida USA. Right, the Air Force Academy Chapel, Colorado, USA

On the other hand, many solar arrays, as shown in Fig2, usually with large ridged forms are analogous with origami structure. However, they are not a continuum form, which is difficult to be a part of the building envelope.

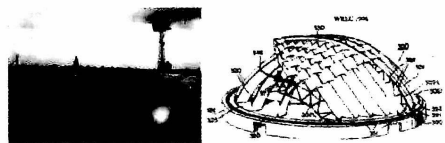


Figure 2 Left, PV array in Kent UK. Right, Solar-Voltaic Dome Power Station, Headrick, USA

In this paper, a novel building envelope integrating solar collectors into a typical origami structure, namely *Miura-Ori* pattern is explored by investigating the relationship between the quantities of solar radiation received by this origami structure and its geometrical configuration. The scope of this research does not include discussion of structural. Pertaining research can be found in the literature.^[2]

2. THE DEPLOYABLE ORIGAMI STRUCTURE

2.1 The advantages of deployable rigid origami structure for building application

1. Mobile or rapidly assembly. Origami structures can be compressed to be compact and flat. It could be assembled in the factory, then transported to the construction site, and deployed for erection. This could shorten the construction time.

2. Flexibility and adaptability. Origami structure is made of repeating homogeneous patterns that can be regarded as "cellular components". It provides a possibility to extend existing structure to any scale by a simple method: repeating itself like a cell proliferation in the corresponding direction. It could also be shaped into many kinds of forms, such as plan, vaulted, double surface and so on, by repeating different kinds of subassemblies and combination. So it could be adapted to for many architectural forms.

3. Transformability. This capacity provides the origami structure a possibility to control the environment by changing its geometry.

4. Movability, as one kind of deployable structure, origami system could be rapidly disassembled and moved to another site for a new application. This would greatly reduce the embodied energy in the construction process.

2.2 The *Miura-Ori* pattern

This origami pattern could be considered as the most basic origami form. It originates from the study of how to fold and deploy a map directly without complicated steps, and this technique, shown in Fig.3, was first proposed by Miura (1980) for a space solar array.



Figure 3 *Miura-Ori* Origami structure.

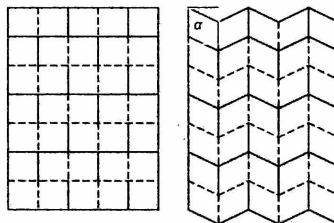


Figure 4 Left, the pattern of 'map folding'. Right, the pattern of 'Miura-Ori'. Dash line is the valley crease, solid line is crest crease.

2.3 The geometry of *Miura-Ori* pattern

2.4 It should be indicated that the *Miura-Ori* pattern has only a small difference compared with the map

fold pattern: the vertical fold creases are no longer straight but arranged along zigzag line at angles of $\pm\alpha$ to the horizontal, as shown in Fig.4. Although it is a small alteration, it changes the behaviour of the folding system and generates a radical difference in the deployment process: the map fold is a sequential process, but the *Miura-Ori* is synchronous [3].

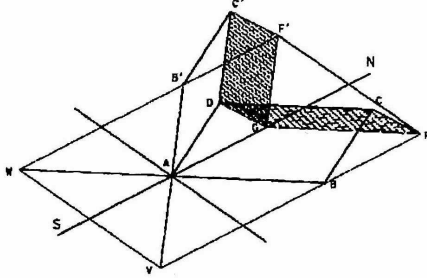


Figure 5 The basic geometry of the *Miura-Ori* unit.

To better understand the geometry behaviours of the origami system, the Cartesian coordinates are defined at the point o , shown in the Fig5, defining $BC=AD=a$, $AB=DC=b$, and the included angle $DAB=\alpha$.

Consequently, there are several important behaviours of the *Miura-Ori* pattern that should be indicated during the system deformation:

1. Whatever deformations the structure present, those parallelograms always maintain Z axial symmetry, namely, they are all symmetrical about the facet of ADG, shown in the figure 5 and 6 respectively.

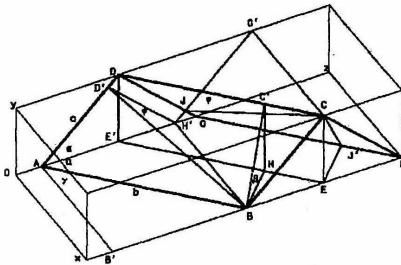


Figure 6 The geometrical parametric analysis of the half *Miura-Ori* unit

2. The facets of ADG and BCF are always vertical and they are always parallel to each others, in addition, the $\triangle ADG$ and $\triangle BCF$ are all isosceles triangles, and $\triangle ADG = \triangle BCF$.

3. If point A is assumed to be fixed on the Z-axis, the locus of point D is a partial circle in which the centre is point A, and the radius is equal a , and the plane of this circle is perpendicular to horizontal, $0 \leq \angle DAE \leq \alpha$. Obviously, the movement of point G is along the Z-axis, it is located at the intersection of the

Z-axis and the circle in which the control is point D, and the radius is also equal a , as shown in Fig.6.

To accurately describe the deformation, an independent variable should be defined, this research chose the opening angle, $\varphi = \angle BD'H'$, as shown in Fig.6, which is the dihedral angel between the parallelograms ABCD and vertical, also defining the $\angle BAB' = \gamma$. Therefore:

$$\begin{aligned} BD' &= b \sin \alpha \\ BH' &= b \sin \alpha \sin \varphi \\ \cos \gamma &= \sin \alpha \sin \varphi \end{aligned} \quad (2.1)$$

To determine the slope angle β , draw a perpendicular from B to C', and draw a line from C' perpendicular to the plane XZ on H, connect BH, then the angle $\angle C'BH = \beta$ is the slope angle of parallelograms ABCD.

Due to AB parallel E'E and GF, so the right-angled triangle $\triangle AB'B = \triangle BHE$, then $\angle HBE = \gamma$, therefore:

$$\begin{aligned} BC' &= a \sin \alpha \\ HB &= a \sin \alpha \cos \beta \\ C'H &= a \sin \alpha \sin \beta \\ BE &= a \sqrt{1 - \sin^2 \alpha \sin^2 \beta} \\ \cos \gamma &= \frac{\sin \alpha \cos \beta}{\sqrt{1 - \sin^2 \alpha \sin^2 \beta}} \end{aligned} \quad (2.2)$$

Substitution of Eq.(2.2) in Eq.(2.1) gives

$$\sin \beta = \frac{\cos \varphi}{\sqrt{1 - \sin^2 \varphi \sin^2 \alpha}} \quad (2.3)$$

$$\cos \beta = \frac{\sin \varphi \cos \alpha}{\sqrt{1 - \sin^2 \alpha \sin^2 \varphi}} \quad (2.4)$$

To determine the locus of point D, defining $\angle DAE' = \epsilon$, therefore:

$$\sin \epsilon = \frac{DE'}{AD} = \sin \alpha \sin \beta \quad (2.5)$$

Substitution of Eq.(2.3) in Eq. (2.5), gives

$$\sin \epsilon = \frac{\sin \alpha \cos \varphi}{\sqrt{1 - \sin^2 \alpha \sin^2 \varphi}} \quad (2.6)$$

Finally, science $\sin \varphi = \cos \gamma / \sin \alpha$, Eq. (2.6) becomes:

$$\sin \epsilon = \frac{\sqrt{\sin^2 \alpha - \cos^2 \gamma}}{\sin \gamma} \quad (2.7)$$

Regarding the plane CDFG, due to $\triangle BC'H' = \triangle CE'J'$, the value of its slope angle is the same with the plane ABCD's, obviously, they also have identical azimuths. Moreover, because of the right-angled triangle $\triangle BH'D' = \triangle CG'J'$, the angle between the plane CDFG and vertical is the same with the plane ABCD's. This result can be validated by the research of Kobayashi and Vincent's (1998) in which a vector analysis was applied. However, the slope angle and the locus of the origami system were not studied in their research^[4].

Regarding the surface angle, γ , those surface on the opposite side have the same value but they are negative, because the Z-axis is assumed southern.

$$\text{The length of entire structure } L_z = \frac{aN \cos \alpha}{\sqrt{1 - \sin^2 \alpha \sin^2 \varphi}}$$

The width of entire structure $W_t = b \sin \alpha \sin \phi \cdot N_y$

$$\text{The compact ratio } \xi = \frac{\cos \alpha \sin \alpha \sin \phi}{\sqrt{1 - \sin^2 \alpha \sin^2 \phi}} \quad (2.8)$$

In summary, it is obvious that the geometric behaviour of the deformation of the origami system does not depend on its dimension but is only relative to the angle α and the opening angle ϕ .

3. THE SOLAR PERFORMANCE ANALYSIS

3.1 The objective

In this paper, considering the origami system as a 'full-parameterized' multi tilted solar collectors system placed on a horizontal level playing the role of external enclosure. The schematic form is shown in the Fig.7.

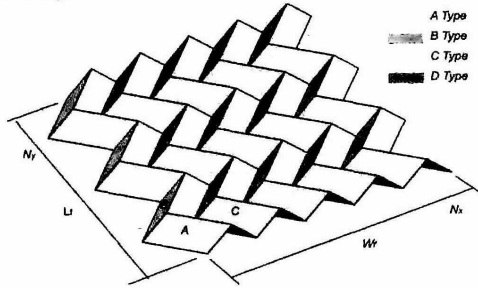


Figure 7 The isometric view of the deployable origami roof with a horizontal position. The facets toward left hand side are southern solar collectors, those northern are reflectors.

3.2 The numerical model

3.2.1 The clear sky instantaneous solar radiation in a single surface (Hottel Model)

The clear sky instantaneous beam solar radiation on horizontal surfaces can be expressed as:

$$G_{oh} = G_o r_o = G_{on} \cos \theta_z r_o \quad (3.1)$$

$$= G_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) \cos \theta_z \left[a_0 + a_1 \exp \left(-\frac{k}{\cos \theta_z} \right) \right]$$

The clear sky instantaneous diffuse solar radiation on horizontal surfaces can be expressed as:

$$G_{ow} = G_o r_o = G_{on} \cos \theta_z r_o \quad (3.2)$$

$$= G_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) \cos \theta_z$$

$$\times \left\{ 0.271 - 0.294 \left[a_0 + a_1 \exp \left(-\frac{k}{\cos \theta_z} \right) \right] \right\}$$

The clear sky instantaneous beam solar radiation on a tilted surface is

$$G_{o,T} = G_o r_o = G_{on} \cos \theta_z r_o \quad (3.3)$$

$$= G_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) \cos \theta \left[a_0 + a_1 \exp \left(-\frac{k}{\cos \theta} \right) \right]$$

Where

$$\cos \theta = \cos \theta_z \cos \beta + \sin \theta_z \sin \beta \cos (\gamma_s - \gamma) \quad (3.4)$$

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad (3.5)$$

$$\delta = 23.45^\circ \sin \left(\frac{360}{365} (284 + n) \right) \quad (3.6)$$

The constant a_0 , a_1 and k are for the standard atmosphere with 23km visibility and altitudes less than 2.5 km.

$$a_0 = r_o \left[0.4237 - 0.00821(6-A)^2 \right]$$

$$a_1 = r_1 \left[0.5055 + 0.00595(6.5 - A)^2 \right]$$

$$k = r_k \left[0.2711 + 0.01858(2.5 - A)^2 \right]$$

Where A is the altitude of the observer in kilometer, and the correction factors r_o , r_1 , r_k depend on the local climate and are given in table1.

The instantaneous geometric factor R_b is the ratio of instantaneous beam radiation on the tilted surface to that on a horizontal surface at any time:

$$R_b = \frac{G_{o,T}}{G_o} = \frac{G_{on} \cos \theta}{G_{on} \cos \theta_z} = \frac{\cos \theta}{\cos \theta_z} \quad (3.7)$$

Table 1 Correction factors for climate types

Climate	r_o	r_1	r_k
Tropical zones	0.95	0.98	1.02
Mid-latitude summer	0.97	0.99	1.02
Frigid summer	0.99	0.99	1.01
mid-latitude winter	1.03	1.01	1.00

3.2.2 The daily clear sky solar radiation in a single surface. (Integral method)

According to those instantaneous equations above, the corresponding formulas for a period of time can be obtained by integrating them over the period from sunrise to sunset:

The daily clear sky beam radiation on a horizontal surface:

$$H_{oh} = \int_{t_r}^{t_s} G_{oh} dt = \int_{t_r}^{t_s} G_{on} \cos \theta_z r_o dt \quad (3.8)$$

The daily clear sky diffuse solar radiation on a horizontal surface:

$$H_{ow} = \int_{t_r}^{t_s} G_{ow} dt = \int_{t_r}^{t_s} G_{on} \cos \theta_z r_o dt \quad (3.9)$$

The daily clear sky beam solar radiation on a title surface:

$$H_{o,T} = \int_{t_r}^{t_s} G_{o,T} dt = \int_{t_r}^{t_s} G_{on} \cos \theta r_o dt \quad (3.10)$$

The average ratio of beam radiation on a tilted surface to that on the horizontal surface in a clear day

$$\bar{R}_b = \frac{\int_{t_r}^{t_s} G_{on} \cos \theta r_o dt}{\int_{t_r}^{t_s} G_{on} \cos \theta_z r_o dt} \quad (3.11)$$

To evaluate these integrals, the daylight hours need to be calculated. Notices that the daylight hours on the horizontal is different to that on the tilted surface, when the incidence angle of the tilted surface equals 90°, the hour angle at this moment is the sunset angle. Defining the sunset angle of the tilted surface equals $\omega_{so,T}$,

$$\begin{aligned} \cos \theta &= \cos \frac{\pi}{2} = \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma \\ &+ \cos \delta \cos \phi \cos \beta \cos \omega_{so,T} + \cos \delta \sin \phi \sin \gamma \sin \omega_{so,T} \end{aligned}$$

$$+\cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega_{\text{sol},T}=0$$

The daylight hours on the tilted surface is

$$N_{\text{sol},T}=\frac{2}{15}\omega_{\text{sol},T} \quad (3.12)$$

For a horizontal surface, the daylight angle is

$$N_{\text{sol}}=\frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \quad (3.13)$$

Therefore, the total solar energy on a horizontal surface for a period of time is given by

$$H_c=H_{\text{cb}}+H_{\text{cd}} \quad (3.14)$$

$$=\int_{t_i}^{t_e} G_{\text{sol}}\cos\theta_{\text{r}}dt+\int_{t_i}^{t_e} G_{\text{sol}}\cos\theta_{\text{r}}\rho_{\text{g}}dt$$

Equation (3.14) can be used to calculate the total clear sky horizontal solar radiation for any period of time within a day by means of altering the t_{sr} and t_{se} to t_i and t_e , corresponding to initial time and end time respectively.

3.2.3 The daily clear sky solar radiation in multi tilted surface. (Isotropic sky)

Assuming the behaviour of the diffuse and reflected radiation is isotropic, the circumsolar diffuse and the horizon brightening will be ignored. Therefore, there are three main components to be evaluated as isotropic model: beam, isotropic diffuse and solar radiation diffusely reflected from the ground or the back plane in front of those solar collectors:

$$H_{\text{c},T}=H_{\text{cb}}\bar{R}_{\text{bf}}+H_{\text{cd}}F_{\text{c-s}}+H_{\text{r}}\rho_{\text{g}}F_{\text{c-r}}+H_{\text{c}}\rho_{\text{g}}F_{\text{c-g}} \quad (3.15)$$

Notice that the ground view factor $F_{\text{c-g}}$ of those collectors in the origami structure is 0 due to them cannot 'see' the ground, expect for those at the first row facing the south. It could be argue that those collectors at the both end side of west or east can 'see' the ground, however, the ground reflecting diffuses received by these collectors are very small comparing the beam, sky diffuses and those reflecting radiations from reflectors in front of them, so they could be ignored, the Eq.(3.15) becomes:

$$H_{\text{c},T}=H_{\text{cb}}\bar{R}_{\text{bf}}+H_{\text{cd}}F_{\text{c-s}}+H_{\text{r}}\rho_{\text{g}}F_{\text{c-r}} \quad (3.16)$$

Where the H_{r} is radiation receive by the reflector,

$$H_{\text{r}}=H_{\text{cb}}\bar{R}_{\text{bf}}+(1-F_{\text{r-c}})H_{\text{cd}} \quad (3.17)$$

Substitute (3.17) for (3.16), given:

$$H_{\text{c},T}=H_{\text{cb}}\bar{R}_{\text{bf}}+H_{\text{cd}}F_{\text{c-s}}+H_{\text{cb}}\bar{R}_{\text{bf}}\rho_{\text{g}}F_{\text{c-r}}+H_{\text{cd}}(1-F_{\text{r-c}})\rho_{\text{g}}F_{\text{c-r}} \quad (3.18)$$

notice $F_{\text{c-s}}+F_{\text{c-r}}=1$, and the area of collectors and reflects is the same, so the view factor $F_{\text{c-r}}=F_{\text{r-c}}$, Eq. (3.18) become

$$H_{\text{c},T}=H_{\text{cb}}\bar{R}_{\text{bf}}+H_{\text{cd}}(1-F_{\text{c-r}})+H_{\text{cb}}\bar{R}_{\text{bf}}\rho_{\text{g}}F_{\text{c-r}}+H_{\text{cd}}(1-F_{\text{c-r}})\rho_{\text{g}}F_{\text{c-r}} \quad (3.19)$$

The view factor $F_{\text{c-r}}$, defined as the ratio of diffuse radiation received by the collector that comes from the reflecting surface, should be considered. This theory could be express by the following equation:

$$F_{\text{c-r}}=\frac{1}{C_i}\int_{C_i}\int_{C_j}\frac{\cos\theta_i\cos\theta_j}{\pi S^2}dC_jdC_i \quad (3.20)$$

It has been calculated according to Siegel and Howell^[6]. It is only relative to the geometric configuration of the origami components.

The f_i is the factor of the ratio of the area of the collector exposed to the beam radiation. It describes the mutual shading which is generated by the arrangement of array of origami structure. Again, the f_{ir} is the factor of ratio of the area of the reflecting surface exposed to beam radiation.

Notice that when $|\gamma|\leq\pi/2-|\gamma_s|$, both plane ABCD and ADB'C' are exposed, shown in Fig.5. This is means when the azimuth alters within $\angle\text{VAW}$, without overlap between planes ABCD AND ADB'C'. To simply the calculation, only the period when the azimuth alters within this restriction would be considered to calculate the solar radiation. In case of finding out the optimum configuration geometry of origami structure by comparison, this assumption is acceptable.

According to this restriction, the duration of azimuth alteration within $\angle\text{VAW}$ can obtain by:

$$\tan\gamma'=\frac{\sin\omega_{\text{r}}}{\sin\delta\cos\omega_{\text{r}}-\cos\phi\tan\delta} \quad (3.21)$$

$$N_{\text{r}}=\frac{2}{15}\omega_{\text{r}} \quad (3.22)$$

where the $\gamma'=\pi/2+\gamma$, ω_{r} is the corresponding hour angle, N_{r} is the duration when solar azimuth alter from VA to WA as shown in Fig.5.

To determine f_i , f_{ir} , the profile angle of beam radiation α_{p} should be considered:

$$\alpha_{\text{p}}=\tan^{-1}\frac{\tan\alpha_{\text{s}}}{\cos(\gamma_{\text{s}}-\gamma)} \quad (3.23)$$

$$\text{when } \beta'\text{ is } \alpha_{\text{p}}, \pi-\beta', f_i=1, f_{\text{ir}}=1$$

$$\text{when } 0'\text{ is } \alpha_{\text{p}}, \beta', f_i=0, f_{\text{ir}}=0$$

$$f_i=\frac{\sin\alpha\sin\beta}{\sin\alpha\sin\beta+\tan\alpha\sqrt{\sin^2\alpha\cos^2\beta+\cos^2\alpha}} \quad (3.24)$$

where β' is the angle $\angle\text{CBE}$ shown in the Fig.7.

$\bar{R}_{\text{bf}}$ can be calculated from equations(3.11), (3.4)and (3.5), notices that the slop angle is negative.

Due to that first row collectors do not receive the reflected radiation form any other collector but from the ground, the solar radiation can calculate by:

$$H'_{\text{c},T}=H_{\text{cb}}\bar{R}_{\text{b}}+H_{\text{cd}}F'_{\text{c-s}}+H_{\text{r}}\rho_{\text{g}}F_{\text{c-g}} \quad (3.25)$$

$$H'_{\text{c},T}=H_{\text{cb}}\bar{R}_{\text{b}}+H_{\text{cd}}\left(\frac{1+\cos\beta}{2}\right)+H_{\text{r}}\rho_{\text{g}}\left(\frac{1-\cos\beta}{2}\right)$$

Where the $F'_{\text{c-s}}$ is the view factor of diffuse radiation of a tilted surface to the sky, $F_{\text{c-g}}$ is the view factor of diffuse radiation received by the collector from the part of ground reflecting diffuse radiation.^[6]

To calculate the entire solar energy received by an origami structure shown in the Fig7, which consists of $N_{\text{h}}N_{\text{y}}$ units. According to the possibility of emergence of mutual shading, this origami system can be considered as a combination of 4 types of independent solar arrays, with reference to the Fig7, they are:

The A type solar array, including the basic plane of ADBC, consists of N_{y} homogeneous planes in the first row toward south east. According to the restriction $|\gamma|\leq\pi/2-|\gamma_s|$, they are impossible shaded by others components, the solar energy of incidence

can be calculated by Eq.(3.25). Their slope angles are positive and given in Eq.(2.4). Their azimuths are negative, and can be obtained from Eq.(2.2), therefore, the entire daily clear sky solar energy of A type solar array is

$$H_A = S \sum_{i=1}^{N_A} H'_{c,T,i} \quad (3.26)$$

$$= S \sum_{i=1}^{N_A} \left[H_{cb} \bar{R}_b + H_{cd} \left(\frac{1 + \cos \beta}{2} \right) + H_{c\rho_i} \left(\frac{1 - \cos \beta}{2} \right) \right]$$

where the H_{cb} , H_{cd} , $H_{c\rho_i}$ are given by(3.9),(3.10),(3.14) The B type solar array, including the basic plane of $ADB'C'$, consisting of N_y homogeneous planes in the first row toward the south west, have the same slope angle and the same magnitude of azimuths as $ADBCs$, but their azimuths are negative.

$$H_B = S \sum_{i=1}^{N_B} H'_{c,T,-\lambda_i} \quad (3.27)$$

where $H'_{c,T,-\lambda}$ means using the same equation as $H'_{c,T}$, but different variable: $-\lambda_i$ in the $\bar{R}_b$, refer to (3.11),(3.4)

The C type solar array, with N_y ($N_x - 1$) homogeneous planes as unit ABCD except for those at the first row, orientating south east, have the same slope and azimuth angle as type A. However, they are possible shaded by those components located at the first row or receive reflected radiation from them, a different solution for this situation is given in Eq.(3.18)

$$H_C = S \sum_{i=1}^{N_C(N_x-1)} H_{c,T,i} \quad (3.28)$$

$$= S \sum_{i=1}^{N_C(N_x-1)} \left[H_{cb} \bar{R}_{b_i} + H_{cd} F_{c-g} + H_{cb} \bar{R}_{b_i} \rho_r F_{c-r} + H_{cd} (1 - F_{c-r}) \rho_r F_{c-r} \right]$$

The D type solar array, with N_y ($N_x - 1$) homogeneous planes as unit $ADB'C'$ except for those at the first row, have the same slope and azimuth angle as type B.

$$H_D = S \sum_{i=1}^{N_D(N_x-1)} H_{c,T,-\lambda_i} \quad (3.29)$$

where $H_{c,T,-\lambda}$ means using the same equation $H_{c,T,-\lambda}$, but the azimuth is negative.

For the entire daily clear sky solar energy of the origami structure,

$$H_{c,T,Entire} = H_A + H_B + H_C + H_D \quad (3.30)$$

For annual clear sky solar energy of the deployable origami structure, it can be expressed as:

$$\sum_{i=1}^{365} H_{c,T,Entire,i} = \sum_{i=1}^{365} [H_A + H_B + H_C + H_D]_i \quad (3.31)$$

4. THE DISCUSSIONS AND ANALYSIS

It is obvious that the most important advantages of the origami system integrated solar collector is this system provides a potential of tracking the sun:

In the case of Fig7 shown, the symmetric axis is on south-north direction. It means both the surface azimuth and slope angle of those collectors could alter from ± 90 , to 0 simultaneously. Approximately,

this is coincident with the alteration of solar azimuth in a day, which is from an angle close to ± 90 (at sunrise or sunset) to 0 (at noon).

Moreover, for maximize the received radiation flux, when the solar altitude close to sunset or sunrise is low, the collector needs to maintain a slope angle close to vertical, contrary, solar altitude at noon is highest of the whole day, which require collector posing a relative lower slope angle. This alteration is not inconsistent with the deformation of the origami system due to those collectors can maintain vertical at the sunrise sun sunset and horizontal at noon correspondingly.

This inherent character provides an ideal method to balance the absorption and storage of solar energy. This could be understood by the truth that solar (or thermal) collectors (such as PCM) would lose the heat by free ventilation or long-wave emission when the ambient temperature is lower than collectors (usually before sunrise, after sunset). However, deployable origami structure can entirely extend to maximize the heat absorption and be compressed to be compact to store the heat and reduce the surface areas exposed to the ambient.

5. CONCLUSIONS

A parametric model of origami structure has been explore to understand its geometric character and deformation behaviours, according to this model, the slope angle and azimuth of any components at any moment during the deformation process can be obtained, the model show that a larger configuration angle α can be fold more compactly.

A numerical model for calculating solar radiation of origami structure integrated multi solar collectors has been derived by mean of clear isotropic sky model. The instantaneous, diurnal, yearly solar radiation of this structure can be estimated for any period of time.

6. REFERENCES

- [1] Pellegrino, S., ed. *Deployable Structure, CISM Courses and Lecture Notes*. 2001, Springer, Wien.
- [2] V.A.Chelyshev, V.N.Z., V.E.Meshkovsky. *Development of folding aluminium sheet roof*. in *Third international conference on mobile and rapidly assembled structures*. 2000. Wessex Institute of Technology, Southampton UK: WIT Press.
- [3] Pellegrino, S., Julian F.V.Vincent, *How to fold a membrane*, in *Deployable Structures*, S. Pellegrino, Editor. 2001, Springer Wien NewYork. p. pp59-71.
- [4] Kobayashi, H., Kresling, B. and Vincent, J. F. V., *The geometry of unfolding tree leaves*. The Royal Society, 1998(B(1998)265): p. 147-154.
- [5] Siegel R, H.J., *Thermal Radiation Heat Transfer*. Vol. pp.189-241. 1992: Taylor & Francis.
- [6] Beckman, J.A.D.W.A., *Solar engineering of thermal processes*. 1980: John Wiley & Sons, Inc.