Springer

Journal of Mechanical Science and Technology 22 (2008) 1537~1543

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-xxxx-9

Study on the Light Receiving Characteristics of a Compact Solar Power Generation System with a Plant Shoot Shape†

Shinya Obara[1]

[1]*Department of Electrical and Electronic Engineering, Kitami Institute of Technology, 165 Kouen-cho, Kitami, Kokkaido 0908507, Japan*

(Manuscript Received March 6, 2009; Revised April 4, 2009; Accepted April 26, 2009)

Abstract

The distribution of solar cell modules is planned by referring to a plant shoot configuration. The object of this planning is to develop a solar power generation system with low directivity and a low installation space. In this study, the amount of insolation which reaches a plant shoot within an arbitrary period was investigated using the LAPS. The LAPS algorithm consists of the Genetic Algorithm and Monte-Carlo Method. In this analysis method, the optimal configuration of the shoot at the time of maximizing the amount of light received was clarified. The position of the light source in the representation day of mid-term to summertime has a wide movable range of the plant shoot configuration. Since the amount of light received of "the leaves arranged to the level surface" and "the plant shoot configuration optimized every month" is measured, light receiving characteristics of the Kenaf shoot model and coptophyllus shoot models were investigated.

Keywords: Solar energy; Solar power generation; Genetic algorithm; Leaf arrangement analysis

---

1. Introduction

Many plants are dependent on carbohydrates obtained by photosynthesis for energy [1, 2]. Therefore, in a forest with many competitors, it is thought that the leaf shape, as well as the arrangement and orientation of many plants, are designed so as to maximize the photosynthetic rate. In this study, the relation between various plant configurations and the amount of light received is investigated, and a solar power generation system with a small installation space and modest influence of solar position is developed. We developed LAPS ("Light received analysis algorithm of a plant shoot") in order to investigate the configuration of a leaf and its relation to photosynthetic rate [3, 4]. The Monte Carlo method and genetic algorithm (GA) are included in LAPS, and the characteristics of the light received by a plant shoot (the group of one stalk and leaves, composed of a stalk, a leaf branch, and leaves) are investigated. The result of the numerical simulations using LAPS showed that the leaf form has a significant influence on the photosynthetic rate.

It is thought that, in a forest, a plant with many competitors has a configuration that allows considerable light to be received in a narrow space. Therefore, the distribution system of a solar module in the form of a plant shoot (DSMS) is examined. In this paper, the relation between the configuration of a plant shoot and the amount of light received is investigated using LAPS.

2. The distribution system of a solar module with the form of a plant shoot (DSMS)

2.1 Amount of light received by a plant shoot

---

†This paper was presented at the 7th JSME-KSME Thermal and Fluids Engineering Conference, Sapporo, Japan, October 2008. This paper was recommended for publication in revised form by Associate Editor John Hamilton.

*Corresponding author. Tel.: +82 2 705 8635, Fax.: +82 2 712 0799.
E-mail address: erwin@sogang.ac.kr.

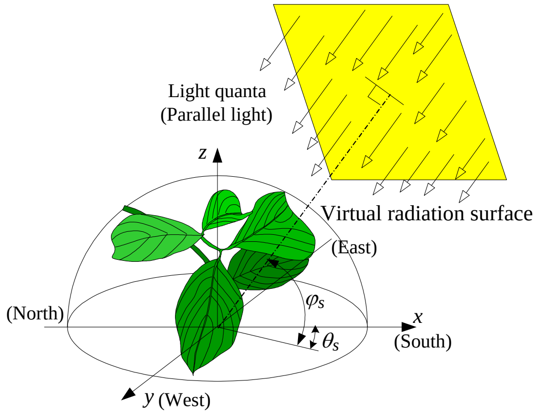


Fig. 1 Space coordinate of a virtual radiation surface

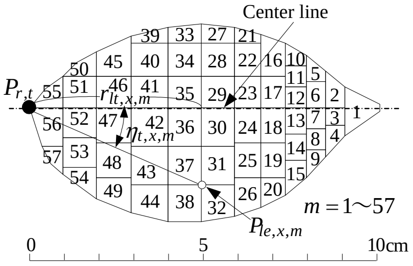


Fig. 2 Dogwood leaf model

A leaf is constructed of the shoot apex meristematic tissue of the stalk, and the leaf and stalk are joined by the leaf branch. In this paper, the unit of a plant shoot is considered to be composed of a stalk, a leaf branch, and leaves. Leaves are arranged on a stalk so as to maximize efficiency of photosynthesis. The space between a stalk and a leaf is also adjusted by the leaf branch.

In this paper, as shown in Fig. 1, the sun is simulated by defining the space coordinates of a virtual radiation surface. The positive direction of the x-coordinates indicates south. Solar radiation is simulated by emitting light perpendicular to the virtual radiation surface from a random position on the surface determined using the Monte Carlo method. The angle of elevation φ_s and the direction angle θ_s of this virtual radiation surface are changed for every sampling time. On the other hand, the plant shoot configuration is expressed with the direction angle θ_t, the elevation angle φ_t, the length of a leaf branch r_t, and the angle of rotation of the leaf β.

2.2 Directivity of the solar power generation system

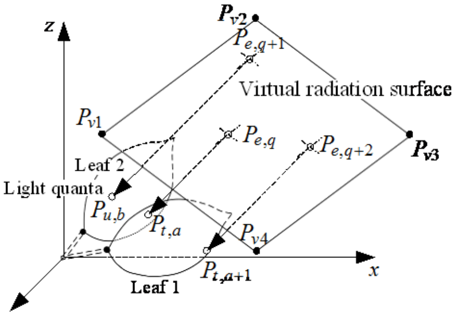


Fig. 3 Light source model

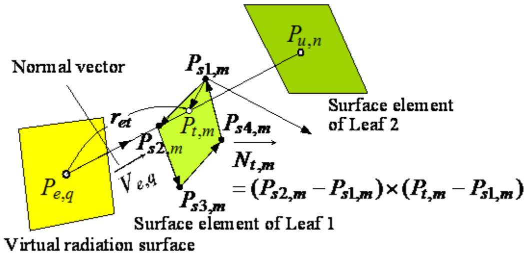


Fig. 4 Interrupt check of light quanta

If a weak-directive solar power generation system is realized, high power generation efficiency can be obtained, and is influenced by the solar radiation incidence angle. In this paper, DSMS with weak directivity is developed by optimizing the configuration of a plant shoot.

2.3 Installation space and production of electricity

When introducing a solar power generation system in a city area or residential block, the installation site is generally restricted to rooftops. Since many solar modules installed in homes to date have been of the flat plate type, the production of electricity is dependent on the installation area. If solar modules with a plant shoot configuration are distributed, the production of electricity is proportional to the magnitude of the installation space. It is predicted that it would be easy to introduce the configuration of a plant shoot into a city area or residential block.

3. Analysis method

3.1 Model

(1) The model of a plant shoot

The shoot configuration (the form of a leaf, direction and length of a leaf branch, etc.) are optimized by maximizing the amount of light received by a leaf and minimizing the overlap with other leaves. Although there are various types of plant shoots, a dogwood shoot is used as an example. Figure 2 shows the leaf model divided into 57 surface elements. Point $P_{r,t}$ is a corner point on the costa of a leaf. Subscript t expresses the number of leaves. Each apex coordinate $P_{le,x,m}$ of the surface element of a leaf is given by an angle $\eta_{t,x,m}$ and a length $r_{lt,x,m}$, as shown in Fig. 2. Subscript x is the apex number of a surface element, and m is the surface element number. The photosynthesis capability of the leaf of a plant depends on the environmental condition of the light [1].

(2) The model of the light source

Figure 3 shows the model of the virtual radiation surface with the emission of solar radiation. Solar radiation is emitted towards the leaves from a virtual radiation surface $P_{v,1}$ - $P_{v,2}$ - $P_{v,3}$ - $P_{v,4}$. Solar radiation is simulated with light quanta, and the photon flux density is calculated based on the number of light quanta arriving at each leaf using the Monte Carlo method. In this analysis, many light quanta are emitted to the leaves at right angles to the surface from the random point $P_{e,q}$ on the virtual radiation surface. The light quanta that directly reach Leaves 1 and 2 are expressed by $P_{t,a}$ and $P_{u,b}$, respectively. Subscripts a and b represent the numbers of the light quanta that reach Leaves 1 and 2 directly.

The number of light quanta $nq_{g,st}$ emitted during the sampling time st of the representative month g from the virtual radiation surface is calculated via the following equation, where, N_a is the total number of light quanta emitted in a day, $R_{g,st}$ is the rate of the number of light quanta emitted by st, and $e_{g,st}$ expresses the amount of level surface global solar radiation during the period st of the representative month g:

$$nq_{g,st} = N_a \cdot R_{g,st} = N_a \cdot \left(e_{g,st} \Big/ \sum_{st=0}^{Day} e_{g,st} \right) \qquad (1)$$

3.2 Shading check

Figure 4 shows the method of checking the interception of solar radiation. The light quantum emitted from point $P_{e,q}$ on the virtual radiation surface passes the surface element m on Leaf 1, and reaches the surface element n on Leaf 2. The normal line vector of the arbitrary point $P_{e,q}$ on the virtual radiation surface is expressed with $\overrightarrow{V_{e,q}}$. When the distance between $P_{e,q}$ and $P_{t,m}$ is expressed with r_{et}, the intersection coordinate $P_{t,m}$ on Leaf 1 will be calculated by Eq. (2).

$$P_{t,m} = P_{e,q} + r_{et} \cdot \overrightarrow{V_{e,q}} \qquad (2)$$

3.3 Amount of light received by a plant shoot

When the light quantum flux emitted from the virtual radiation surface reaches the surface element k on leaf w, the number of arrivals is calculated from Eq. (3). The number of arrivals to $\dot{q}_{d,w,k}$ is the 1st term within the right-hand side bracket of Eq. (3). After transmitting to other leaves, the number of arrivals to $\dot{q}'_{h,i,k}$ is the 2nd term within the right-hand side bracket of Eq. (3). The position of the virtual radiation surface changes for every sampling time.

$$E_{w,k} = \sum_{t=0}^{N_a} \left(\dot{q}_{d,w,k} + \sum_{i=1}^{J_l} \dot{q}'_{h,i,k} \right) \quad (i \neq w) \qquad (3)$$

3.4 Analysis method

(1) Chromosome model

The chromosome model introduced into the analysis of GA is shown in Fig. 5. The chromo-

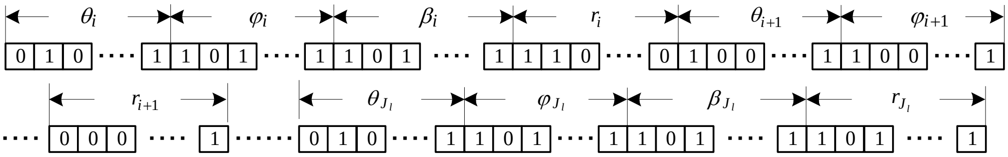
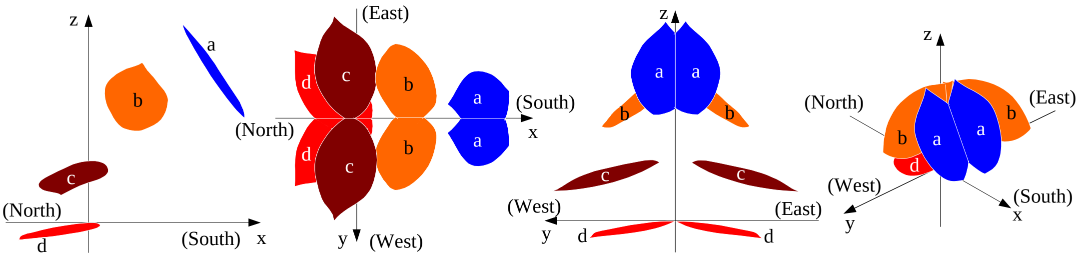
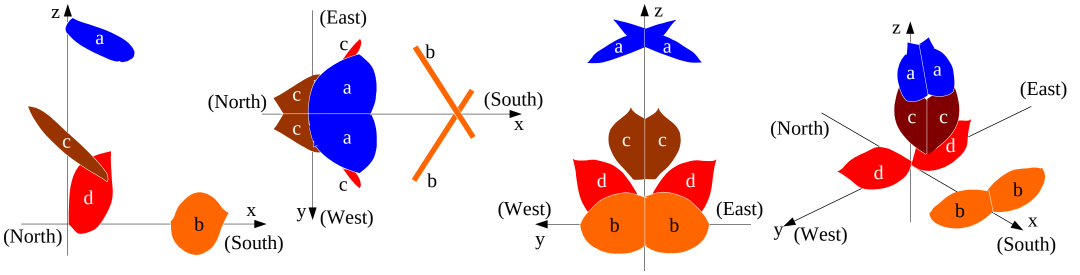


Fig. 5 Chromosome code



(a) x-z plane (b) x-y plane (c) y-z plane (d) Conformal map

Fig. 6 Result of the optimal arrangement of the leaf in July



(a) x-z plane (b) x-y plane (c) y-z plane (d) Conformal map

Fig. 7 Result of the optimal arrangement of the leaf in January

some model expresses θ_i , φ_i , β_i , and r_i with a 10-bit gene model of 0 and 1. When the real number is expressed with a 10-bit binary number, the analytical error is 1% or less. Here, subscript i expresses the leaf number of a plant shoot, and J_l is the total leaves in the shoot.

(2) Adaptive value

The adaptive value of the chromosome model is estimated to be high, meaning there are many light quanta arriving to each leaf. The adaptive value is calculated using Eq. (3). In the last generation's chromosome model, an individual with the highest adaptive value is considered the optimal solution. By decoding the gene of this model, the configuration of a shoot (θ_i , φ_i , β_i , r_i) is obtained.

4. Analysis results

4.1 Optimal configuration of shoot

Figures 6 and 7 show the results of the optimal arrangement of the leaves of the plant shoot in July and January. The direction of each axis is shown in these figures. The x-y plane is a horizon plane, and x-z plane and y-z plane are vertical planes to the x-y plane. During the summer season, the solar position significantly influences the elevation angle, and the surfaces of all leaves turn to a high position. However, in winter, the arrangement changes such that half the overall number of leaves (Leaves b and c in Fig. 7) may absorb solar radiation with a small angle of elevation.

4.2 Directivity

The optimal configuration of the monthly plant shoot and the result of having arranged the leaf in parallel with the x-y plane are shown in Fig. 8. The difference of the leaves arranged parallel with the x-y plane between March and September and the leaves of the optimal arrangement is small. However, significant greater volumes of

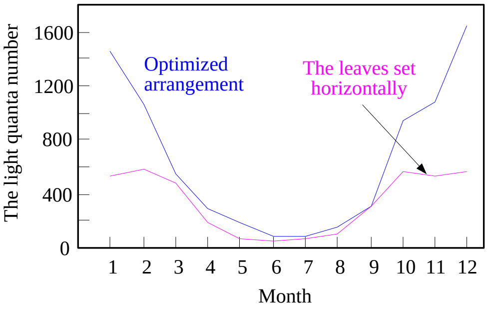
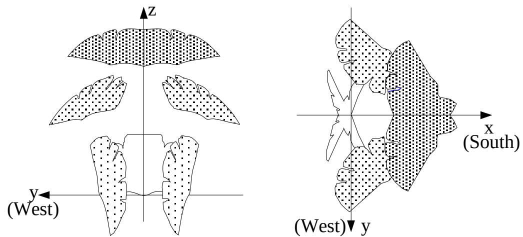
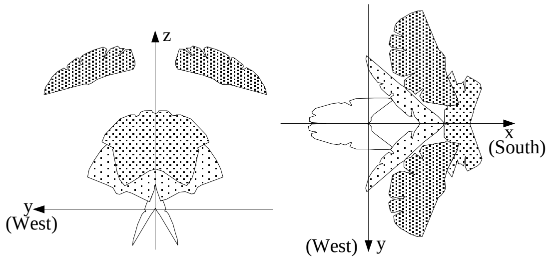


Fig. 8 Light quanta receiving number in every month

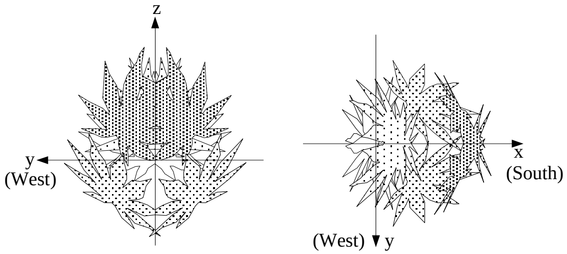


(a) Sapporo

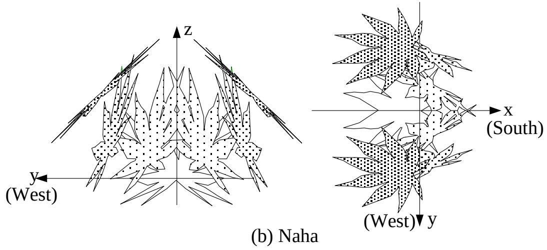


(b) Naha

Fig. 9 Arrangement result in January of the plant shoot model of a ginkgo biloba



(a) Sapporo



(b) Naha

Fig. 10 Arrangement result in January of the plant shoot model of an acer palmatum var. matsumurae

light are received with the optimal arrangement of leaves for five months; namely January, February, and October to December. During the summer period, the leaves are optimized in the solar position at 12:00 when there is a significant angle of elevation. Therefore, the difference in the amount of light received for the leaves arranged parallel with the x-y plane and the optimal arrangement is small. On the other hand, the optimal arrangement of the leaves in January, February, and October to December involves a considerable volume of light being received within a wide time period. Therefore, the arrangement of the leaves in this case has small directivity.

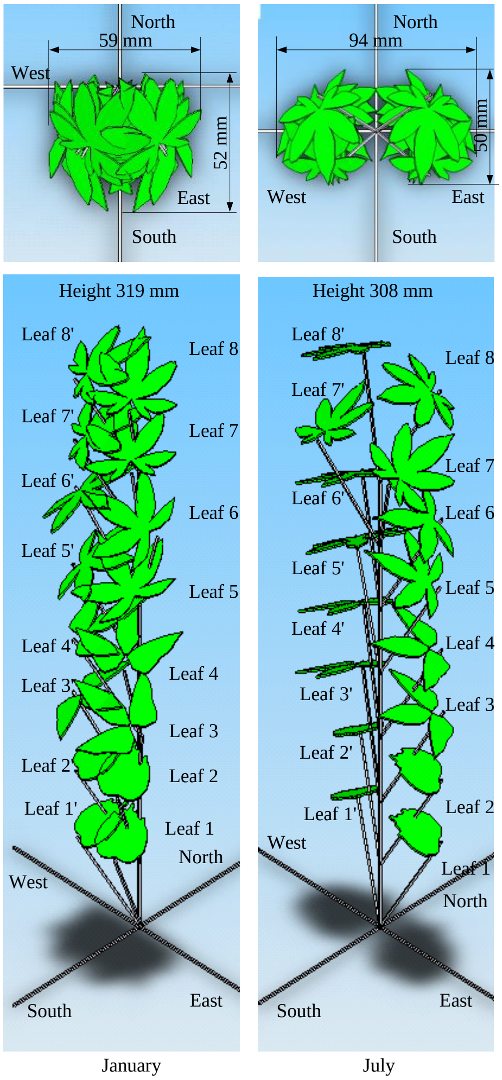


Fig. 11 Optimal configuration results of the individual model of a kenaf. (Space of a branch of a leaf position 35 mm)

4.3 Analysis results of coptophyllus shoot models

Figures 9 and 10 are the arrangement results of the leaves in January in Sapporo and Naha. In this paper, installation of the system in Sapporo and Naha is assumed. The difference in latitude of both cities is about 17 degrees. The solar positions (angle of direction and elevation angle) at each time in Sapporo and Naha differ. Furthermore, since the weather differs, the amount of solar radiation differs in each city. Figure 9 is a result of a ginkgo tree, and Fig. 10 shows an acer palmatum var. matsumurae. These projected areas are calculated using 3-dimensional CAD. However, many approximate solutions of the optimal solution appear in the search for the optimal shape of the plant shoot using LAPS. Although the shapes of a shoot differ greatly, solutions very near the optimal solution appear. Detail of the relations between the difference in a leaf configuration and the amount of light received was given to reference [5].

4.4 Analysis results of a kenaf shoot model

A kenaf has division leaves of two or more types, and the early growth is a characteristic. Thus, the relationship between the shoot configuration of a kenaf and the amount of light received was examined using numerical analysis, and the development of a compact light reception system was discussed. Figure 11 shows the results of the analysis of the optimal configuration of the individual model of a kenaf (Hibiscus cannabinus). The figures of the top are a figure which looked at the lower part from the top. Moreover, the figure of the bottom in Fig. 11 is the optimal shoot configuration of a kenaf model. The following conclusions have been obtained by this numerical simulation [6].

- In the shoot model of a kenaf, the amount of light received in the summer season is concentrated at the time zone of strong solar radiation. A light source position and the strength of solar radiation in each time affect the configuration of a shoot.
- Because the range of movement of the light source in the summer season is wide compared with winter, the light reception systems especially needs a design with low directivity in the summer season. It is necessary to improve the individual model of a kenaf examined in this paper, and to increase the amount of intercepted radiation in the summer season.
- One reason for the development to a divided leaf from a simple leaf is the increase in the overall amount of light received by the individual due to light access to lower leaves.

The shoot configuration design has a strong influence over light reception efficiency, and there is a suitable configuration in the shoot configuration.

5. Conclusions

The relation between the configuration a plant shoot and the amount of light received is investigated, and the distribution of solar modules using this configuration is planned. This study will facilitate a power generation system with a small installation space and weak directivity. With this in mind, the relation between the shoot configuration of some shoot models and the amount of light received was investigated using the light received analysis algorithm of a plant shoot (LAPS), via the Monte Carlo method and Genetic Algorithm.

Acknowledgment

This work was partially supported by a Grant-in-Aid for Scientific Research (C) from JSPS.KAKENHI (20560204).

References

[1] The Society for the Study of Species Biology, *Figures of Light, Water, and a Plant-Guide to Plant Physiological Ecology*, (2003), Bun-ichi Sogo Shyuppan, Tokyo.

[2] Hirose. T., Werger, M. J. A., Pons, T. L. and Rheenen, J. W. A., Canopy Structure and Leaf Nitrogen Distribution in a Stand of Lysimachia Vulgaris L. as Influenced by Stand Density, *Oecologia*, 77, (1988), 147-150.

[3] Shin'ya Obara and Itaru Tanno, Arrangement Analysis of Leaves Optimized on Photon Flux Density or Photosynthetic Rate, *Journal of Computational Science and Technology*, JSME, 2(1) (2008), 118-129.

[4] Shin'ya Obara, Itaru Tanno and Taichiro Shiratori, Study on Low Directivity Condensing Equipment for Solar Power Collection based on a Single Leaf Shoot Shape, *Journal of Thermal Science and Technology*, JSME, 3(3), (2008), 499-510.

[5] Shin'ya Obara, Itaru Tanno and Taichiro Shiratori, Light-receiving Characteristics of a Distributed Solar Module with a Plant Shoot Configuration, *Renewable Energy*, 34(5), (2009), 1210-1226.

[6] Shin'ya Obara, Characteristics of the Light Reception Systems Concerning a Kenaf Individual Model, 2008, *Journal of Thermal Science and Technology*, JSME, 3(3), (2008), 511-522.

Shin-ya Obara received his B.S. and M.S. degree in Mechanical Engineering from Nagaoka University of Technology, Japan, in 1987. He then received his Ph.D. degrees from Hokkaido University in 2000. Dr. Obara is currently a Professor at the Department of Electrical and Electronic Engineering at Kitami Institute of Technology in Hokkaido, Japan. Dr. Obara's research interests include fuel cell, renewable energy, power system and micro-grid. His major academic field is thermal engineering, power system and environmental engineering.