Control method for adaptive façades based on energy conservation and glare protection strategies

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Abstract. This study focuses on the control method of an adaptive façade based on the combination of energy conservation and glare protection strategies. Two evaluation methods are applied. The first method is to determine the appropriate range of the shading states which allow a minimum amount of solar heat gain and lighting energy requirements in the passive zone. The second method is to determine the appropriate range of the shading states which protect discomfort glare. Finally, the hourly optimal shading state can be determined through the two evaluation methods. In the application, the hourly shading state of a dynamic folding system, which can fully close and open in the two directions, is derived and evaluated. The results of the evaluation showed that the optimal control method suggested in this study can deliver effective energy performance while avoiding discomfort glare.

1. Introduction

Adaptive façade, also called ‘Kinetic façade’, is a double-skin façade where the dynamic shading device is installed on the exterior curtain wall [1,2]. Recent studies on a dynamic shading system have shown the significant improvement achieved in building energy conservation and visual comfort [3-8]. These shading devices continuously adjust their states to maintain an ideal indoor environment and reduce building energy load. In practice, the open-loop control system, which adjusts shading states based on control variables measured by the outdoor sensor, is commonly used for its low-cost maintenance advantage [1]. To avoid excessive solar heat gain during the cooling season, the control variables such as radiation/illuminance on the exterior vertical façade, indoor working plane, or indoor nearest façade are taken into consideration. Discomfort glare at an occupant position is also considered as a primary control variable during all seasons [5,7]. In the control system, shading devices operate independently based on threshold values (i.e., illuminance or radiation) without taking into consideration the building system efficiency concerning heating, cooling, and lighting. This control strategy may not be sufficient for energy conservation in certain heating and cooling conditions. Shading devices should be left in the open state when the lighting energy requirement is higher than the cooling system; on the other hand, if there is excessive cooling load, shading devices should be adjusted to close. A dynamic shading device affects zone cooling, heating, and lighting energy, and influences visual comfort. Therefore, an evaluation of thermal and lighting energy performance at each shading state is needed to determine the appropriate shading state.

The aim of this study was to propose a control method for adaptive façade systems based on energy conservation and glare protection strategies. Two methods were developed to evaluate thermal and lighting energy performance and discomfort glare protection of the adaptive façade. In both methods, step-by-step evaluation for all shading states was conducted to determine the appropriate range of the dynamic shading. Through the evaluations, the hourly optimal shading state that satisfied both high energy efficiency and glare protection was determined. In the application, evaluation of shading performance for a dynamic folding system, which can fully close and open in two directions, was carried...
out. The results of the evaluation showed that the optimal control method suggested in this study can deliver effective energy performance while avoiding discomfort glare.

2. Method for shade control

2.1 Evaluation of energy performance

An adaptive façade controls the solar radiation entering through windows by adjusting its shading state (including rotation and folding angle, retraction and sliding length, and the diameter of the aperture). The movement of the shading elements affects the solar heat gain and the lighting energy requirement. Existing methods are based on the calculation of the hourly solar heat gain [9] and lighting energy requirement [10,11] when using shading devices such as venetian blinds, horizontal, and vertical shading devices. In the above two calculation processes, there are four major factors of shading devices that represent its state (i.e., horizontal or vertical) and material properties. These shading factors are briefly summarized below:

- Unshaded fraction ($F_u$): a coefficient that indicates the proportion of direct solar incidence area to the total window area, a value between 0 and 1.
- Exterior solar attenuation coefficient (EAC): a coefficient showing the quantitative proportion of external solar radiation passing through a shading device, a value between 0 and 1.
- Light transmittance of shading ($\tau_{sh}$): a coefficient expressing the degree of light transmittance for the shading device, a value between 0 and 1.
- Obstruction index ($I_o$): a coefficient for expressing the degree of obstruction by a shading device for the diffuse illuminance, a value between 0 and 1.

Lee et al. [12,13] suggested the factor exposure coefficient that distinguishes the exposed and unexposed area of a window for diffuse solar radiation, a value between 0 and 1. This value can be applied to the calculation method regarding diffuse solar radiation. These five factors of shading devices differ according to the hourly sun position, façade orientation, the shading state, and the material properties. Equation 1 to 3 [13] shows the calculation methods of hourly solar heat gain ($q_{sol}$) and lighting energy requirement ($W_L$) according to the shading state $(n)$ at a given time $(t)$.

$$ q_{sol,t(n)} = A F_e \left[ I_{dir(\theta)} \left( F_{u,lt(n)} SHGC(\theta) + (1 - F_{u,lt(n)}) EAC_{dir(n)} \langle SHGC \rangle_D \right) + I_{dif} \left( C_{e(n)} \langle SHGC \rangle_D + (1 - C_{e(n)}) EAC_{dif(n)} \langle SHGC \rangle_D \right) \right] $$

$$ E_t(n) = E_s (4.13 + 20I_T + 1.36I_{De}) \tau_{win} \left\{ \tau_{sh} \left( 1 - C_e I_{0,(n)} \right) + C_e I_{0,(n)} \right\} $$

$$ W_{lt(n)} = LPD (A_p L + A_{KD}) $$

In the above equations, $A$ is the adaptive façade area and $F_e$ is the proportion of the glazing area in the façade. $I_{dir(\theta)}$ and $I_{dif}$ are direct and diffuse radiations on the façade, respectively. The solar heat gain coefficient for direct radiation is expressed as $SHGC(\theta)$, and that for diffuse radiation is $\langle SHGC \rangle_D$. $E_s$ is the exterior diffuse illuminance on the horizontal plane. $E$ and $E_{set}$ are the illuminance level on the task plane and the required illuminance level, respectively. $I_T$ and $I_{De}$ are transparency index and depth index, respectively. $A_p$ and $A_{KD}$ are daylit area and non-daylit area, respectively. The lighting energy requirement can be calculated by multiplying the lighting power density (LPD) and the floor area.

In the evaluation process, the solar heat gain and lighting energy requirement were converted to the equivalent primary energy ($P_E$) of identical resources to enable ease of comparison. The general control methods were based on the amount of measured illuminance or radiation. The major difference between the existing and proposed control methods is that the proposed method is based on the passive zone energy requirement. For calculating lighting energy requirement, the daylit area within the passive zone was set as the target lighting area.

The appropriate and desirable range of the shading states in the cooling mode is the range in which the total value of solar heat gain and lighting energy are the smallest among the shading states where there is no discomfort glare. However, during the heating period, the effective heat gain from solar
radiation has a positive effect on improving building energy performance. During the intermediate period, the solar heat gain is ignored, and the lighting energy requirement is regarded as the only energy requirement.

2.2 Evaluation of discomfort glare
Discomfort glare is regarded as a mandatory condition for adjusting shading state in most studies [3-8]. To avoid direct sun light, the cut-off angle method has been the preferred traditional method used and is still used as a firm basial shade control algorithm in the various studies [4,7,14]. This method is a fast and effective way to control venetian blinds or overhangs in protecting the occupants from direct sun light. However, Shen et al., from the literature review on previous simulation studies, reported that a cut-off angle method is not sufficient to avoid glare [5]. Moreover, in the case of adaptive façades, it is more difficult due to their varied shapes and movement directions.

In this study, a method to control the unshaded fraction defined above was applied to avoid discomfort glare. First, the presence or absence of direct solar radiation was evaluated based on solar altitude, azimuth, and building orientation. Then, the range of shading states that satisfied the conditions of the solar altitude being lower than 80º as well as the direct sun light being more than 50 $W/m^2$, was determined. If one of the conditions was not satisfied, it was assumed there was no discomfort glare.

2.3 Process for shade control
In the shading control method, two main information were used as input data, namely adaptive façade data and weather data (see Figure 2). The façade data comprised of passive zone model including heating, cooling, and lighting system efficiency, and the coefficient for primary energy consumptions. The depth of the passive zone was set as 2 times the façade height. The five factors were calculated using façade and weather data. In the evaluation process of each energy and glare, firstly the range of shading states that satisfy with glare protection is derived. Then through thermal and lighting energy evaluation, the optimal shading state that requires lowest energy is derived.

To calculate 8760 hourly shaded area generated on windows by adaptive facades, General Polygon-clipper (GPC) model has been adopted. Calculation tool for deriving hourly unshaded fraction for each shading states ($F_{u,t(n)}$) has been programmed using C. To evaluate energy and glare, Excel program is used. The evaluation algorithms of thermal, lighting energy and glare protection and the optimization algorithm has been programmed in Excel based on existing standards (ASHRAE, EN 13363–1, EN 15193) and the evaluation methods described in Section 2.1 and 2.2 [9-13].
3. Evaluation of shading control performance

3.1 Description of the adaptive façade system

For the application, an adaptive façade was designed with two dynamic folding elements which could fully close and open in two directions (see Figure 3). The façade was designed with a width of 2 m, a height of 4 m, and a zone depth of 8 m (south-oriented). The material properties of the shading elements and curtain wall system are shown in Table 1. The operational settings of the building used for the simulations included temperature settings of 26 °C for cooling mode and 21 °C for heating mode. The hours of building operation tested were established as 08:00 to 20:00. The light power density (LPD) for the lighting energy requirement calculation was 12 W/m², and the indoor illuminance was set at 300 lux. Artificial lighting control systems were set on on-off automatic control. The coefficient for primary energy conversion of the electric power used was set at 3.0, and that for the fuel used, was set at 1.1. For the cooling system of the building, an EHP (system air conditioner) having a COP (coefficient of performance) of 3 was used, and the efficiency of the boiler was set at 80%. The evaluation target area chosen was Seoul (Republic of Korea), and climate data were gathered through Meteonorm 7.

![Figure 2. The phased states of the dynamic folding system.](image)

| Shade state (1 to 11) |
|----------------------|
| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
| (90°) | (72°) | (54°) | (36°) | (18°) | (0°) | (18°) | (36°) | (54°) | (72°) | (90°) |

Table 1. Material properties of the adaptive façade

| Elements   | Physical properties |
|------------|---------------------|
| Shade      | Solar transmittance $\tau^H_s$, $R^H_s$: 0.00, $\langle R^H_s \rangle_D$: 0.66 |
| Light transmittance $\tau^V$: 0.00, $R^V_1$: 0.71, $R^V_2$: 0.71 |
| Glazing    | $U_{\text{win}}$: 2.088 W/m²K, $T_{\text{vis}}$: 0.623, $\langle SHGC \rangle_D$: 0.431 |

3.2 Evaluation results

The annual primary energy consumptions for solar heat gain and lighting energy requirement at each shading state were evaluated. Glare protection was the priority control variable to determine the appropriate range of the shading state for all seasons. Figure 4 shows the hourly shading state during the first three days of July. During non-working hours, the shading devices were set to be in the closed state (fully closed). Except for the second day, the shading devices were controlled to avoid discomfort glare but not to fully close as the shading devices were capable of adjusting their positions in two directions.
according to solar positions. The reduction rate for direct and diffuse radiation showed that the shading device allowed diffuse sunlight when there was no glare. Figure 5 shows the annual shading states. The vertical axis represents the hours of the day, and the horizontal axis represents the days. Global radiation on the south façade was high during the heating season but relatively lower during the cooling season. As south façade always faced the sun during daytime, reduction of direct radiation was high during both seasons for glare protection. The average reduction rates of the direct and diffuse elements of the radiation heat gain were 92% (89% for the heating season, 99% for the cooling season) and 77% (74% for the heating season, 85% for the cooling season), respectively. The results of the evaluation show that the adaptive façade can adjust its shading states to avoid discomfort glare but can allow positive heat gain during the heating season.

Figure 3. Hourly shading states on the south façade during 1st to 3rd of July.

Figure 4. The annual reduction rate of direct and diffuse elements of the solar radiation.
4. Conclusion
This study focused on a shading control method based on the combination of energy conservation and glare protection strategies. To reduce cooling and heating energy consumption, the window should be fully shaded during the summer but exposed as much as possible during the winter. However, in the case of the passive zone where can achieve effective daylight, shading devices should adjust appropriately during the summer. Therefore, this study proposed an evaluation method for the thermal and lighting energy performance of the dynamic shading devices to determine appropriate shading states. Through the evaluation, the appropriate range of the shading states was determined. In the shading control process, the glare protection was set as the priority control variable to determine the appropriate range of the shading states. In the application, an evaluation of shading performance for a dynamic folding system, which can fully close and open in two directions, was carried out. This application is performed in the limited simulation conditions without whole building. This study has been performed in the limited simulation environment focusing on determination of optimal shading state without a whole building simulation. The results of the study showed that the optimal control method suggested in this study could deliver effective energy performance while avoiding discomfort glare.

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