CONTROL OF ARTIFICIAL LIGHT FOR PLANTS

II. AUTOMATIC CONTROL OF LIGHT INTENSITY AND SPECTRAL COMPOSITION

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In a previous paper, we reported a new system of artificial light radiation, in which static control of light intensity and spectral composition was made possible in the wavelength range from 350 nm to 800 nm.

Present paper deals with a system of automatic control of light for plant growth and development in a growth cabinet. Feedback control of light intensity and feed-forward control of spectral composition were adopted with an on-line digital computer, and the variable-value control of light intensity and spectral composition was achieved. By this system, it was made possible to radiate plants with time series of both light intensity and spectral composition. Performances were as follows:

1) In a step response in light intensity control, the delay time was remarkably small, and the settling time was 5 min, where the proportional band, reset time and rate time were set at 85%, 1 min, and 0 min, respectively. 2) The fluctuation in the light intensity was made smaller in the feedback control than that in uncontrol. 3) In the feed-forward control, the response time was remarkably small. 4) The combined feedback and feed-forward control system made it possible to change the spectral composition in time series under keeping the optional light intensity constant. In this system, the integrated net area of spectral irradiance successfully conformed to the desired value of light intensity within the deviation of 0.5%.

In a previous paper,⁴⁾ we reported on an instrument for artificial light radiation in a growth cabinet. This instrument made it possible to give both optional intensity and spectral composition of light to plants. However, the variable-value control of both light intensity and spectral composition was impossible in the system.

The present paper deals with development of the system of automatic control of light for plants in a growth cabinet and with the analysis of its characteristics.

SYSTEM AND PERFORMANCES

Six kinds of lamps (10 blue, 10 blue-white, 10 yellow, 10 pink, and 5 red fluorescent lamps of 110 W extra-high-output, and 10 red beam lamps of 100 V-100 W) with individual spectral emissions were used as the light sources of the instrument as described in the previous paper. They were provided in the lamp

compartment of the growth cabinet.³⁾ The light output of individual lamp was independently controlled in the range from 0% to 100% of rated capacity, using SCR manipulators for varying the effective current through the lamps. Both light intensity and spectral composition at plant area in the growth cabinet were controlled by means of varying the light output of each lamp. The feedback and feed-forward controls were applied to this system.

Measurement methods. A radiometer (RMA-8, Japan Spectroscopic Co., Ltd.)⁴⁾ was used for detecting light intensity for using as the feedback signal. The time constant of the radiometer system, which is changeable, was selected at 10 sec in the present experiment with the notice of the matching to the process. The controlled variable of light intensity was monitored by a fast responding system, RMD-1 radiometer (JASCO) with the time constant of 0.025 sec. In this radiometer, the detector was made of a vacuum thermocouple of Schwartz type having equal response to wide range from 250 nm to 2,500 nm. In front of the thermocouple, a heat-absorbing glass (Heat Glass, Ohara Optical Glass Mfg. Co., Ltd.) was fixed in order to eliminate the long wavelength of light, so that this radiometer was able to measure the integrated power in the wavelength range from 300 nm to 800 nm. The light intensity was defined as the total irradiance by means of this integrated power in the present study.

Spectral composition was evaluated as the spectral irradiance. The spectroradiometer reported in the previous paper was improved and used for measurement of the spectral irradiance. Figure 1 shows the block diagram of the spec-

Fig. 1 Block diagram of the improved spectroradiometer.

troradiometer. Spectral response in the spectroradiometer was affected by spectral transmissions of integrating sphere (light receiver) and monochromator, and by spectral sensitivity of photomultiplier cathode. In this instrument, the detected value was automatically corrected with using of electronic components of a function generator (FT-3, Riken Denshi Co., Ltd.) and a multiplier. The drive of function generator was electronically synchronized to the wavelength scanning in the monochromator: The detected value was corrected by multiplying by the correction factor generated on the basis of the spectral response in this radiometer. Thus, the spectral irradiance was directly recorded without any manual correction. Sighting angle of the spectroradiometer was limited to about 40° with the shade attached to the entrance aperture of integrating sphere for adjusting cosine response to the radiometer. A heat-absorbing glass was also attached to the aperture in order to make similar spectral response of both radiometers.

Feedback control. Light intensity was controlled with using the total irradiance as the feedback element which was detected by the radiometer at a central position in the growth compartment. The total irradiance was evaluated as 0–10 mV/0–5 mW/cm², and used as the feedback signal led into a PID controller (EGC, Yokogawa Electric Works, Ltd.). The PID parameters were set at 85% (P_B), 1 min (T_I), and 0 min (T_D), respectively. A program generator (PGE-14, YEW) was connected with the PID controller.

Figure 2 shows the block diagram of the light control system. When switching onto the feedback circuit, the light output was compensated to satisfy the

Fig. 2 Block diagram of feedback and feed-forward control of light.

Fig. 3 Comparison of total irradiance between feedback control and uncontrol.

Fig. 4 Step response (0.5–3.0 mW/cm²) in feedback control of total irradiance.

desired value of the total irradiance. The light output of each lamp was controlled at the same ratio of the rated value. The light intensity was usually fluctuated under uncontrolled condition because of the changes of electric power and the other factors.¹⁾ Figure 3 shows the total irradiances in an uncontrol and in the feedback control. The fluctuation of the total irradiance was 10% of full scale in an uncontrol system, but it was reduced to 1% in the feedback control. A step response in feedback control of the total irradiance is shown in Fig. 4. In this step response, the overshoot was observed. The delay time was remarkably small, and the settling time was about 5 min. The variable-value control was made possible by setting the desired value of the total irradiance in the program generator. Figure 5 shows the ramp response as an example of the variable-value control. The response was successfully fitted to the desired value in time course.

Feed-forward control. An on-line digital computer system³⁾ was adopted for the feed-forward control. The desired value of light output was programmed

Fig. 5 Ramp response in feedback control of total irradiance.

Fig. 6 Feed-forward control of total irradiance with the desired value of $I=1.25 \sin 60T+2$, where I is total irradiance (mW/cm^2), and T is time (hr).

and put into CPU through either tele-typewriter or photoelectric tape reader. Computed value was converted into analog value through DA converters, and used as the manipulating signal. This system provided six DA converters corresponding to the six kinds of lamps. The light output of lamps to be controlled, was decided by messages in the program to select appropriate DA converters.

Figure 6 shows the feed-forward control of total irradiance, when the light outputs in the whole of lamps were controlled by the computer, with programming the desired value of $I=1.25 \sin 60T+2$, where I is total irradiance (mW/cm^2), and T is time (hr). The response was almost reliable. However, there was some fluctuation ($\pm 0.1 \text{ mW}/\text{cm}^2$) in a controlled variable because the feedback circuit was switched off in this case.

Combined feedback and feed-forward control system. As shown in Fig. 2, feed-

Fig. 7-a Total irradiance controlled at $2.5 \text{ mW}/\text{cm}^2$ by combined feedback and feed-forward control system; where variable-value controls of light outputs of both blue and blue-white fluorescent lamps were carried out with sine curve from the computer, and the others were controlled by feedback system.

Fig. 7-b Variable-value control of spectral irradiance with combined feedback and feed-forward control system; where control condition was the same as that in Fig. 7-a with the exception of mercury lines.

Fig. 7-c Changes of irradiance of mercury line in combined feedback and feed-forward controls.

back and feed-forward controls were combined in a system to control the spectral composition under keeping optional total irradiance. The feedback control was carried out by selecting switches onto each circuit, and the other light outputs were controlled by the computer system. Figure 7-a shows the total irradiance controlled at 2.5 mW/cm^2 by combined feedback and feed-forward control system; where variable-value controls of light outputs of both blue and blue-white fluorescent lamps were carried out with sine curve from the computer, and the others were controlled by feedback system. Variable-value control of the spectral composition was performed as shown in Fig. 7-b, where the spectral irradiance was measured at the intervals of 12 min. It is obvious that the irradiance in longer

wavelength region varied in inverse proportion to that in shorter region under the constant total irradiance. The value of area by means of integration of spectral irradiance from 300 nm to 800 nm was mostly equal to the desired value of total irradiance within the deviation of 0.5%. Thus, even if the spectral composition changed in time course, total irradiance was kept at the desired value of 2.5 mW/cm^2 with reliable condition as shown in Fig. 7-a. In this case, the irradiances of respective mercury lines were changed as shown in Fig. 7-c. Another example of combined feedback and feed-forward control is shown in Fig. 8,

Fig. 8-a Total irradiance controlled at 2.5 mW/cm^2 by combined feedback and feed-forward control system; where variable-value controls of light outputs of both yellow and pink fluorescent lamps were carried out with sine curve from the computer and the others were controlled by feedback system.

Fig. 8-b Variable-value control of spectral irradiance with combined feedback and feed-forward control system; where control condition was the same as that in Fig. 8-a with the exception of mercury lines.

where light outputs of both yellow and pink fluorescent lamps were controlled by the computer under constant total irradiance controlled by the feedback system.

Thus, the automatic control of total irradiance and spectral composition was carried out with optional desired values and made it possible to radiate plants with time series of those factors.

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<和文抄録>

植物に対する人工光の制御 II. 人工光の光強度とスペクトル組成の自動制御

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本研究は植物に照射する光の強度とスペクトル組成の自動制御系を確立することを目的としている。前報では光制御における操作および出力装置の試作をおこなった。その装置では、スペクトル放射分布の異なる6種のランプを用い、SCR調光装置により各ランプの光出力を制御する方式を採用した。この装置においては、各ランプの光出力をそれぞれに設定することにより、目標とした光強度とスペクトル組成を得ることが可能となった。この装置に本報ではフィードバックおよびフィードフォワード制御システムを加え、光強度とスペクトル組成の自動制御を試みた。フィードバック系では光強度(300~800nm波長域のエネルギー量)を熱電対放射計により検出し、それをフィードバック信号としたPID制御をおこなった。フィードフォワード制御系にはオンライン電算機を組み入れた。この電算機システムにより、6種のランプの光出力の目標値をそれぞれ個別に設定して制御することができ、また制御回路の選択によりこれら2種の制御系を組合せたフィードバック・フィードフォワード制御が可能となった。したがってこのフィードバック・フィードフォワード系では光強度を任意に設定した条件下で、スペクトル組成のプログラム制御が可能となった。この制御特性を解析した結果、次の点が明らかとなった。

1) 光強度のフィードバック制御では、ステップ応答における遅れ時間は著しく小さく、整定時間はおよそ5分であった。

2) フィードバック制御により光強度の制御精度は著しく向上、フルスケールの $\pm 1\%$ 以内であった。

3) フィードフォワード制御においては各ランプの光出力は良好な応答を示し、スペクトル組成の設定に十分な性能を示した。

4) フィードバック・フィードフォワード制御システムにおける分光放射照度の積分値は光強度の目標値に0.5%以内で一致した。この制御方式により、任意の光強度条件下で光スペクトルを時系列として植物への照射をおこなうことが可能となった。