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Development of a Non-contact Ultrasonic Pollination Device

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An ultrasonic pollination device was developed to achieve effective artificial pollination of strawberries in artificial light type plant factories. A phase array of hundreds of ultrasonic transducers was appropriately controlled and focused on one point in space, and it is possible to generate a force at any position in space. The force was modulated at 30 Hz which is the characteristic frequency of strawberry flower. The pollination experiment was conducted using the strawberry variety F1 Elan (*Fragaria*×*ananassa*). The total weight of the strawberries harvested over 22 days was 1.22 kg, and the average weights of individual strawberry fruits were 9.1 g.

Keywords : array, phase, production system, ultrasonic transducers

INTRODUCTION

In Japan, more than 95% of farmers who produce strawberries perform forcing using a variety of one-season harvests in a thermal insulation facility commonly known as “plastic house,” for the harvest season from around May to December (Mochizuki et al., 2009). Although summer cultivation using various four-season harvests has been achieved, temperature management in the thermal insulation facility is difficult, and the production volume is poor. As a result, imported fruits from California, USA are widely available in significant quantities (Takahashi, 2006). For farmers producing strawberries year round, the temperature management in summer and winter months as well as the need for virus-free seedlings and pesticides have become financial burdens.

Nevertheless, the influence of an external environment can be eliminated in an artificial plant factory and maintaining an optimum environment throughout the year is possible. When growing strawberries propagated by seeds, it is possible to realize safe and secure strawberry production without pesticides. Since the strawberry is a far more value-added agricultural product than leafy vegetables, the concept of strawberry production in artificial light type plant factories receives massive attention.

However, only certain wavelengths necessary for plant growth are included in artificial light sources such as fluorescent lamps and LEDs, used in artificial light type plant factories. The ultraviolet range of light, which is required for the pollination activity of bees, is not included in these light sources. In the absence of ultraviolet light, pollination through pollinating bees is inefficient because of a delay in flower-visiting activity and shortened lifespans due to a decrease in homing rate. Because no artificial pollination hormone for strawberries is currently available, an inefficient physical method using a brush is currently used.

Research on a technique where non-contact force is applied to a target, has already been reported. Air jet and magnetic force are practically used to generate the non-contact force. Lee et al. (2011) reported a three dimensional moving system where an object with a built-in magnet floated and moved by an electro-magnetic force mounted on the XY stage. As for the applied research on air jet, Suzuki and Kobayashi (2005) reported a haptic device to feel the air jet through the hemispherical tool, and Iwaki et al. (2011) addressed an object moving on a plane by pushing an air jet from the three dimensions.

In addition, an acoustic radiation pressure can also generate a non-contact force. This is a non-linear phenomenon where an acoustic wave pushes an object, and it acts without the material selection. A tactile display using acoustic radiation pressure has been developed (Iwamoto et al., 2008; Hoshi et al., 2010; Hasegawa et al., 2011), and a system for presenting haptic in a non-contact form have been developed (Ciglar, 2010; Alexander et al., 2011; Okunari et al., 2012).

The objective of this project was to develop an ultrasonic pollination device to achieve effective artificial pollination of strawberries in artificial light type plant factories, as well as to perform an initial feasibility study.

MATERIALS AND METHODS

Device description

Acoustic radiation pressure

When an object is blocking the progression of an ultrasonic wave, a stress is generated on the object’s surface in the propagation direction of the wave. This phenomenon is attributed to the non-linear acoustics of acoustic radiation

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pressure. Conventionally, the stress is called “pressure” however, it is a tensor rather than a scalar. When a plane wave is perpendicularly incident on an object, the acoustic radiation pressure P [Pa] generated on the object’s surface is expressed by the following equation.

$$P=\alpha E=\alpha\frac{I}{c}=\alpha\frac{P^2}{\rho c^2}$$

Here, E [J m^{-3}] is the acoustic energy density of the ultrasonic, I [W m^{-2}] is the acoustic intensity, c [m s^{-1}] is the sound velocity, p [Pa] is the acoustic pressure of the ultrasonic (effective value), ρ [kg m^{-3}] is the density of the medium, and α is a coefficient determined by the state of reflection, absorption, and transmission at the object’s surface ($\alpha=2$ for total reflection).

The above equation shows that any radiation pressure pattern P can be generated by controlling the spatiotemporal pattern of p.

Phased array

The acoustic radiation pressure generated from a single ultrasonic transducer is weak; therefore, hundreds of ultrasonic transducers were used to generate a force of several tens of mN. The phase of each transducer was appropriately controlled and focused on one point in space. This point can be shifted to any position in space by regulating the phase of each transducer. Hence, it is possible to generate a force at any position in space from a remote location. The phase θ_i [rad] of transducer i is calculated as follows.

$$\theta_i=\kappa l_i$$

Here, κ [rad m^{-1}] is the frequency of the ultrasonic and l_i [m] is the distance to the focal point from transducer i.

The above equation illustrates the need to advance the phase of a transducer located far from the focal point. When using a square transducer array, the sound pressure distribution of the ultrasonic waves generated in the focal plane has been theoretically derived as an approximation of the sinc function. The width of the main lobe in the direction parallel to the sides of the array (the focus diameter), ω [m], is provided in the following equation.

$$\omega=\frac{2\lambda R}{D}$$

Here, λ [m] is the wavelength of the ultrasonic wave, R [m] is the focal length, and D [m] is the side length of the square array.

The focal diameter determines the spatial resolution of this technique. The above equation clearly shows that there is a trade-off between the spatial resolution and array size.

Intensity control by Pulse Width Modulation (PWM)

The ultrasonic transducer was driven by a 40-kHz square wave obtained by amplifying the digital output of an FPGA using a driver. The intensity of the acoustic radiation pressure was controlled by applying a PWM to the square wave. Although in a typical PWM, the width of a pulse is proportional to the output, the intensity was controlled by the 40-kHz component here. 40 kHz was a resonance frequency because the transducer acted as a narrow band filter in this device. The PWM signal $V(t)$ [V] is shown in Fig. 1 and described by the following equation.

$$\begin{aligned}V(t)=&V_0\,(nT\leq t\leq nT+W)\\&0\,(nT+W\leq t\leq nT+T)\end{aligned}$$

Here, W [s] is the pulse width, T [s] is the duration of a cycle, and n is an integer.

The amplitude a_1 [V] of the 40-kHz component is the coefficient of the fundamental frequency of the Fourier series expansion of $V(t)$, as shown in the following equation.

$$a_1=\frac{2}{\pi}V_0\sin\left(\pi\frac{W}{T}\right)$$

This value is maximized with a 50% duty ratio. The ultrasonic wave emitted from the transducer is proportional to the voltage amplitude, and the acoustic radiation pressure is proportional to the square of the ultrasonic.

Implementation

The specifications of the developed device are shown in Table 1. The frequency of the ultrasonic was 40 kHz. The focal diameter was proportional to the focal length; for example, the focal diameter was 20 mm for a focal length of 20 cm. The focus could be moved by specifying spatial coordinates in 0.5-mm increments. The maximum force generated was 16 mN. The force could be varied in 624 levels by the PWM. Because the rise time of the ultrasonic transducer was 1 ms, the update rate of the apparatus was

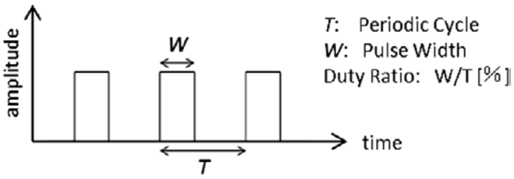
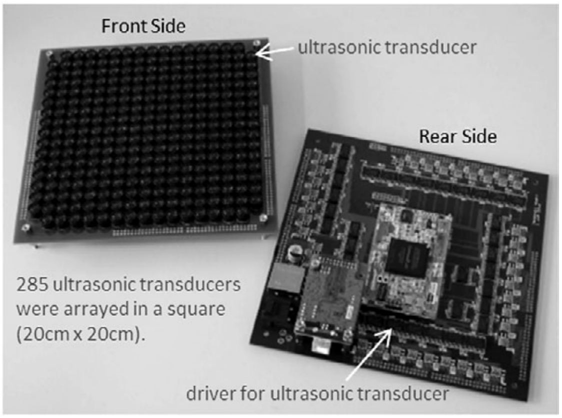


Fig. 1 PWM of 40-kHz rectangular wave.

Table 1 Specification of small ultrasonic focusing system.

Carrier wave	40 kHz ultrasonic
Diameter focal point	20 mm (Ar 20 cm focal length)
Position resolution	0.5 mm
Maximum acting force	16 mN (624 levels of PWM)
Amplitude modulation	DC and 1»1023 Hz square wave
Update rate	1 kHz



285 ultrasonic transducers were arrayed in a square (20cm x 20cm).

Fig. 2 Appearance of the developed device.

Table 2 Cultivation environment for strawberry.

Photoperiod	day/night＝12h/12h
Temperature	15 to 22°C
Humidity	60±10%
CO_2	800 ppm
Salution	EC: 0.9±0.1 dS m^{-1} pH: 7.5±0.1
Light	315 mmol m^{-2} s^{-1} fluorescent lamps

1 kHz. The appearance of the array substrate is shown in Fig. 2.

The side length of the array was $D=17$ cm, and 285 ultrasonic transducers (T4010A1, Nippon Ceramic Co., Ltd.; 40-kHz resonance frequency, 1-cm diameter) were arranged in the rectangular region. The FPGA communicated with the PC via USB. It calculated an appropriate phase for each transducer on the basis of the focus position and generated a drive signal. The drive signal was amplified to 24 $V_{p\text{-}p}$ by the driver IC and sent to the transducer after the DC component was cut by a high-pass filter.

Pollination experiment

The characteristic frequency of strawberry flower was measured and found approximately 30 Hz. Then the ultrasonic carrier frequency of 40 kHz was modulated with the natural frequency of 30 Hz.

The strawberry variety F1 Elan (*Fragaria*×*ananassa*; Syngenta Japan, Japan) was used in the experiment. Strawberry seeds were germinated and grown for 50 days in an artificially lighted plant factory. The seedlings were transplanted and grown in an environment described in Table 2. Pollination began 35 days after transplanting and strawberry fruits were harvested for 20 days, starting 55 days after transplanting. An NFT hydroponics system was employed, and the circulation rate of the nutrient solution was maintained at 15 liters per min throughout the day.

RESULTS AND DISCUSSION

The quantities of total flower buds, flowering buds, fruit-setting buds, and harvested fruits in the two experimental plots are shown in Fig. 3. The quantities of total flower buds and flowering buds were similar for both plots, indicating that there was no difference in the conditions of the two experimental plots. However, the difference in pollination method between the developed ultrasonic and the conventional contact vibration method significantly affected the amount of fruit-setting and harvested fruits. The number of fruit-setting buds was higher in the control group, but the number of strawberries harvested was greater in the ultrasonic pollination group.

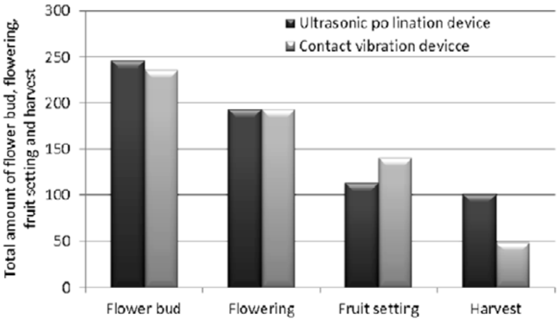


Fig. 3 Comparison of the amounts of total flower buds, flowering buds, fruit-setting, and harvested between plots.

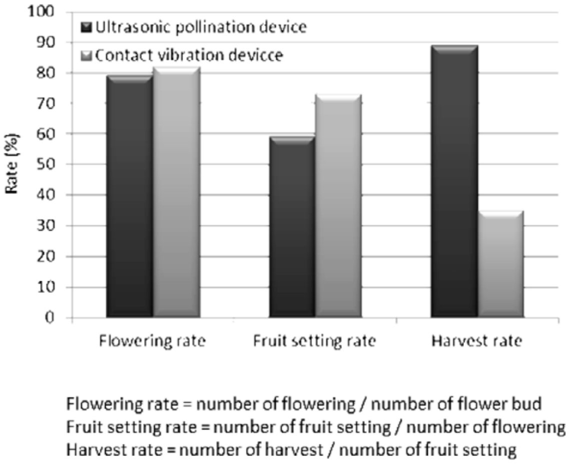


Fig. 4 Comparison of flowering rate, fruit-setting rate, and harvest rate between plots.

As shown in Fig. 4, the fruit-setting rate was lower in the ultrasonic pollination experiment than in the control experiment. We suspect the reason for this was the insufficient use of the ultrasonic pollination device in the early stages of the experiment. Although the fruit-setting rate in the ultrasonic pollination experiment was 59%, 89% of the fruits were harvested. In the control experiment, the fruit-setting rate was 73%, and 35% of the fruits were harvested; thus, the harvest rate was lower in the control experiment than in the ultrasonic pollination experiment. The number of strawberries not counted in the harvest number because of inadequate weight or quality was greater in the control experiment.

The total weight of the strawberries harvested over 22 days in the ultrasonic pollination experiment was 1.22 kg, which is approximately twice that in the control experiment. The average weights of individual strawberry fruits were 9.1 g and 9.7 g in the ultrasonic pollination group and the control group, respectively. A *t*-test ($p > 0.05$) showed no significant difference between the two experiments in the average weight of strawberry fruits. The newly developed ultrasonic pollination device compared favorably to the conventional contact vibration device with regard to the amount of fruit harvested and the harvest rate. The device shows promise for use in artificial light type plant factories.

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