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Staggered-Phase Spray Control: A Method for Eliminating the Inhomogeneity of Deposition in Low-Frequency Pulse-Width Modulation (PWM) Variable Spray

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Abstract: The pulse-width modulation (PWM) variable spray system is the most widely used variable spray system in the world at present, which has the characteristics of a fast response, large flow adjustment range, and good atomization. Recently, the pressure fluctuation and droplet deposition uniformity of the PWM variable spray system caused by the intermittent spray mode of the nozzle have attracted more and more attention. In this study, a method for eliminating the inhomogeneity of ground deposition in low-frequency PWM variable sprays based on a staggered-phase drive mode was proposed, and a PWM variable spray system was built. The experimental results indicated that the pressure fluctuation amplitude upstream of the nozzle of the PWM variable spray system with the staggered-phase drive was reduced by 40.91%, and the dispersion rate of the pressure fluctuation was reduced by 62.78% (the initial pressure was 0.3 MPa, solenoid valve frequency was 5 Hz, and duty cycle was 50%). The PWM control parameters had a significant effect on the upstream pressure fluctuation (initial pressure > duty cycle > frequency). The droplet spectrum relative span of the staggered phased PWM variable spray system decreased by 24.83%, the coefficient of variation of the droplet particle size decreased by 4.40%, the particle size was more uniform, and the atomization effect was improved. The average deposition of droplets in the forward direction driven by the staggered phase was 4.87% greater than that in the same phase, and the variation rate decreased by 20.87%. The average deposition amount increased, and the deposition became more uniform. Staggered-phase spray control could effectively reduce the inhomogeneity of deposition in low-frequency PWM intermittent spraying. This research provides strong technical support for a precision variable spraying effect and droplet drift prevention.

Keywords: precision spray; variable spray; PWM; deposition; duty cycle; frequency

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1. Introduction

At present, the control of weeds, pests, and diseases is still dominated by chemical pesticide spraying. However, conventional spray applications generally apply agrochemicals at a constant rate throughout the field, irrespective of pest/disease presence, planting system, crop density, or tree canopy characteristics; this type of spraying contributes to lower application efficiency. In vineyards, orchards and other fruits exhibit high variability within and between trees in terms of foliage density, canopy shape, and size, typically resulting in excessive pesticide application or insufficient local protection when using a constant application rate [1–5].

Precision agriculture is an information-based agricultural management system that optimizes the usage of water, fertilizer, seeds, pesticides, etc., to the maximum extent possible, according to the environmental conditions of each operating unit in the field and the temporal and spatial differences in crop yield, in order to achieve the highest yield and maximum economic benefits [6–8]. Precision pesticide application is an important component of precision agriculture.

The European Green Deal and the Farm to Fork Strategic Objective state that the overall use of pesticides will be reduced by 50% by 2030 [9] and that the European Commission will strengthen the implementation of integrated pest management. In addition to alternative control strategies, such as crop rotation and mechanical weeding, precision pesticide application technology is an important technical means to achieve this goal [10]. The core of precision pesticide application technology is to apply pesticides according to the needs of crops [11–14], and in the process of pesticide application, the control system adjusts the application speed according to the forward speed of the machine [15,16], the application prescription information [17], or the canopy information detected in real-time [18–21]; these can improve the spraying efficiency and reduce drift losses [22–24]. Among them, the spray flow regulation system based on PWM has attracted increasing attention from researchers due to its short reaction time, fast response speed, large flow adjustment range, good atomization quality, and spray characteristics that can be obtained by conventional nozzles [17,25–30].

Pulse-width modulation (PWM) variable spray control technology is an important technical means for precision spray. This method has the advantages of a short reaction time, fast response speed, and large flow adjustment range and is currently the most widely used variable spraying technology. PWM technology controls the nozzle flow rate by impulse control of the solenoid valve directly upstream of the nozzle. The flow rate is changed by controlling the relative proportion of time (duty cycle) for each solenoid valve to open. As a result, the system allows for a real-time change in the flow rate while maintaining the operating pressure [31–33]. Numerous studies have shown that the PWM flow control has a minimal effect on the droplet size and velocity, especially when compared to pressure-based systems [34–37]. Despite promising results, there are still questions about the pressure fluctuations in PWM systems [38–40], spray coverage accuracy, and uniformity [41,42] due to solenoid on/off delays in some systems and alternating on/off actions of adjacent nozzles. Hans measured and analyzed the pressure and flow fluctuations of a commercial variable PWM spraying system. The pressure fluctuation caused a nozzle in the system, and the flow fluctuated 0.5~2.2% during the period. Similarly, the variation in the spray flow rate between different sprinklers at different positions within one cycle reached as high as −15~12% [43]. Through laboratory-based simulations, Mangus determined that although each pulse emitted an accurate flow rate (regardless of the duty cycle and number of nozzles activated), the spray coverage accuracy decreased with a decreasing duty cycle [44]; thus, a lower duty cycle resulted in a lower percentage of areas receiving the target application rate, causing more under- or over-application. Pierce Robert et al. studied the deposition characteristics of PWM variable spray systems under different duty cycles and reported that the coefficient of variation of longitudinal deposition was 10% at a 100% duty cycle and 65% at a 25% duty cycle [45]. Their results indicated that changing the duty cycle affected the uniformity of spray deposition. Grella et al. reported that the switching effect of a pulse-width modulation system affected not only the change in spray coverage measured along the sprayer in the forward direction but also the change in spray coverage measured along the vertical spray profile. Even though the average spray coverage variability increased with increasing forward velocity, as the duty cycle decreased from 100% to 30%, the magnitude of the duty cycle effect in enhancing variability increased regardless of the forward velocity [11].

Li Longlong designed a pulse-width modulated variable spray system that could reach 20 Hz and studied the spraying characteristics of the pulse-width modulated variable nozzle of high-frequency solenoid valves; the results showed that the PWM frequency and duty cycle affected droplet deposition and that increasing the duty cycle and frequency could improve the uniformity of droplet deposition [46].

A review of numerous previous studies to aid in the determination of a method to improve the inhomogeneity of deposition for PWM variable spray systems showed that improving the working pressure, duty cycle, and frequency controlled by the solenoid valve, or reducing the operation speed, were the main parameters used for improvement [11,47]; however, for the actual operation process, the adjustment of the duty cycle and the adjustment of the operation speed depend on the decision-making information for the fertilization prescription, which cannot be changed at will. Moreover, the adjustment of the spray pressure will change the size of the droplet diameter and affect the droplet adhesion and plant protection effects. Recently, commercial variable spray systems in developed countries generally use 20–30 Hz high-frequency control (for example, Teejet Dynajet and Raven Hawkeye) to improve spray uniformity. Nevertheless, improving the control frequency of the solenoid valve can reduce the life of the solenoid valve and increase costs. Additionally, with increasing frequency, the effective duty cycle adjustment range of the solenoid valve becomes narrower, affecting the flow adjustment width of the variable spray. By the way, there are other ways to improve the uniformity of the spray, such as electrostatic spray technology, which can make droplets deposit quickly and evenly through electrostatic action. However, due to high maintenance costs, it is rarely used in field spraying [48,49].

The objective of this paper is to identify a method for controlling low frequencies and improving the uniformity of droplet deposition. To solve the problems of large droplet size variations and the uneven deposition of pesticides caused by turbulence and pressure impact due to the simultaneous opening and closing of a solenoid valve controlled by a same-phase spray, a low-frequency PWM variable spray ground deposition nonuniformity elimination method based on the dislocation drive mode is proposed, and a staggered-phase PWM variable spray system is constructed. The atomization characteristics and spray deposition characteristics are then examined. It is expected that through our research and efforts, we can promote the promotion and application of variable spray technology, especially in some developing countries.

2. Materials and Methods

PWM technology controls the nozzle's flow rate by pulsing an electronically actuated solenoid valve directly upstream of the nozzle. The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). The traditional PWM variable spray adopts the same-phase drive mode; specifically, all sprinklers open and close at the same time (the No. 1, No. 2, No. 3, and No. 4 nozzles open and close at the same time); this can cause serious fluctuations in the pipeline pressure, poor consistency of atomized droplet size, and inhomogeneity deposition in the direction of spraying. In this study, a variable spraying system was designed with a staggered-phase drive, and a schematic diagram of the working principle is shown in Figure 1; specifically, nozzles No. 1 and No. 3 are closed first and then opened, while nozzles No. 2 and No. 4 are opened first and then closed.

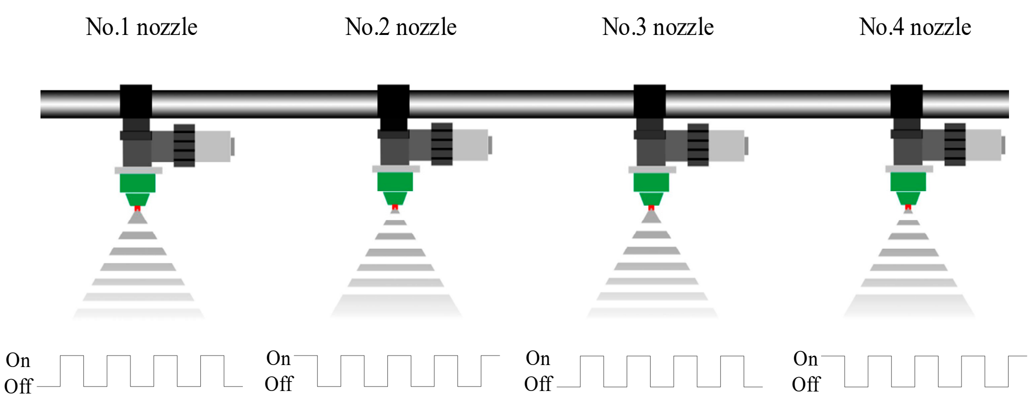


Figure 1. Schematic diagram of the working principle of the PWM staggered-phase variable spray system.

2.1. Staggered-Phase PWM Variable Spraying System Pressure Fluctuation Test

2.1.1. Test Bench Design

Figure 2 shows the pressure fluctuation characteristics of the staggered-phase-driven PWM variable spraying system. This system is composed of four parts as follows: a spray pressure control module, a variable spray module, a data acquisition module, and a host computer. The pipeline of the spray pressure control module was connected to the water tank, diaphragm pump (Taizhou Jiyi Co., Ltd., Taizhou, China), return proportional valve (Ningbo Licheng Agricultural Spray Technology Co., Ltd., Ningbo, China), spray boom, and nozzle (Teejet QJ17560A-1/2, nozzle 110VP03, Spraying Systems Co., Wheaton, IL, USA). The inverter motor (Shenzhen Wanchuan Technology Electronics Co., Ltd., Shenzhen, China) provided power to the system, drove the diaphragm pump to suck the liquid from the water tank, moved the flow into the return proportional valve, and then diverted the flow; part of the flow was transported to the spray bar to complete the effective spray, and the other part of the flow was transported back to the water tank. The system's pressure control mainly regulated the speed of the diaphragm pump by changing the frequency conversion motor frequency, changing the output of the diaphragm pump, and adjusting the output pressure of the system. The variable spray module was generated by a PWM signal generator (Fujian Yunlifang Electronic Technology Co., Ltd., Fujian, China) and two staggered PWM signals, with one signal controlling the No. 1 and No. 3 nozzles, and the other PWM signal controlling the solenoid valves connected to the No. 2 and No. 4 nozzles (Intelligent Equipment Technology Research Center of Beijing Academy of Agriculture and Forestry Sciences, Beijing, China). The module was controlled by the host computer through the RS485 signal to set the PWM signal duty cycle and frequency settings. In the main application of the data acquisition module (Beijing Zhongtai Yanchuang Technology Co., Ltd., Beijing, China), the high-frequency acquisition card collected the voltage values from the pressure sensors (Beijing Ao Sheng Automation Technology Co., Ltd., Beijing, China) upstream of the boom and the nozzle and communicated with the host computer through RS485 signals to achieve the real-time collection of pressure.

2.1.2. Nozzle Flow Test

To verify the performance of the PWM variable spraying system driven by the staggered phase, it was necessary to ensure that the adjustment function and adjustment multiple of the nozzle flow under the driving mode were not affected. Therefore, before the atomization and deposition tests, a flow test of a single nozzle needed to be performed under different duty cycles of the PWM variable spray system.

Tap water was used as the test liquid. The test began with an adjustment of the frequency of the inverter to control the speed of the inverter motor and the output flow of the diaphragm pump. The initial spray pressure of the pipeline system was adjusted to 0.2 MPa; that is, the continuous spray pressure of the nozzle. The return proportional valve was adjusted, and the return flow was set to 40%. The test was performed in two groups as follows: one group of same-phase tests, and one group of staggered-phase comparative tests. In the process of each group of tests, the duty cycles of the four nozzles were selected as follows: 10%, 20%, 30%, . . ., 100%. For the testing, the duty cycle was set, and the test started once the spray was stabilized; the droplets from the four nozzles were collected with a beaker, and the droplets were stopped for 30 s. The droplets were weighed with an electronic scale (Shenzhen Mobil Electronics Co., Ltd., Shenzhen, China). The single test was repeated three times, and the average flow rate from the four nozzles was calculated. Finally, the average flow rate of a single nozzle under different duty cycles during the spraying process of the same-phase and staggered-phase PWM variable sprays was obtained. The flow adjustment multiple was obtained according to Equation (1).

$$\mathrm{A} = \frac{q_{max} - q_{min}}{q_{min}} \tag{1}$$

where A is the flow adjustment multiple; q_{max} is the flow rate of the nozzle when adjusting the maximum duty cycle under the condition of good linearity, L/min; and q_{min} is the flow rate of the nozzle at the minimum duty cycle under the condition of good linearity, L/min.

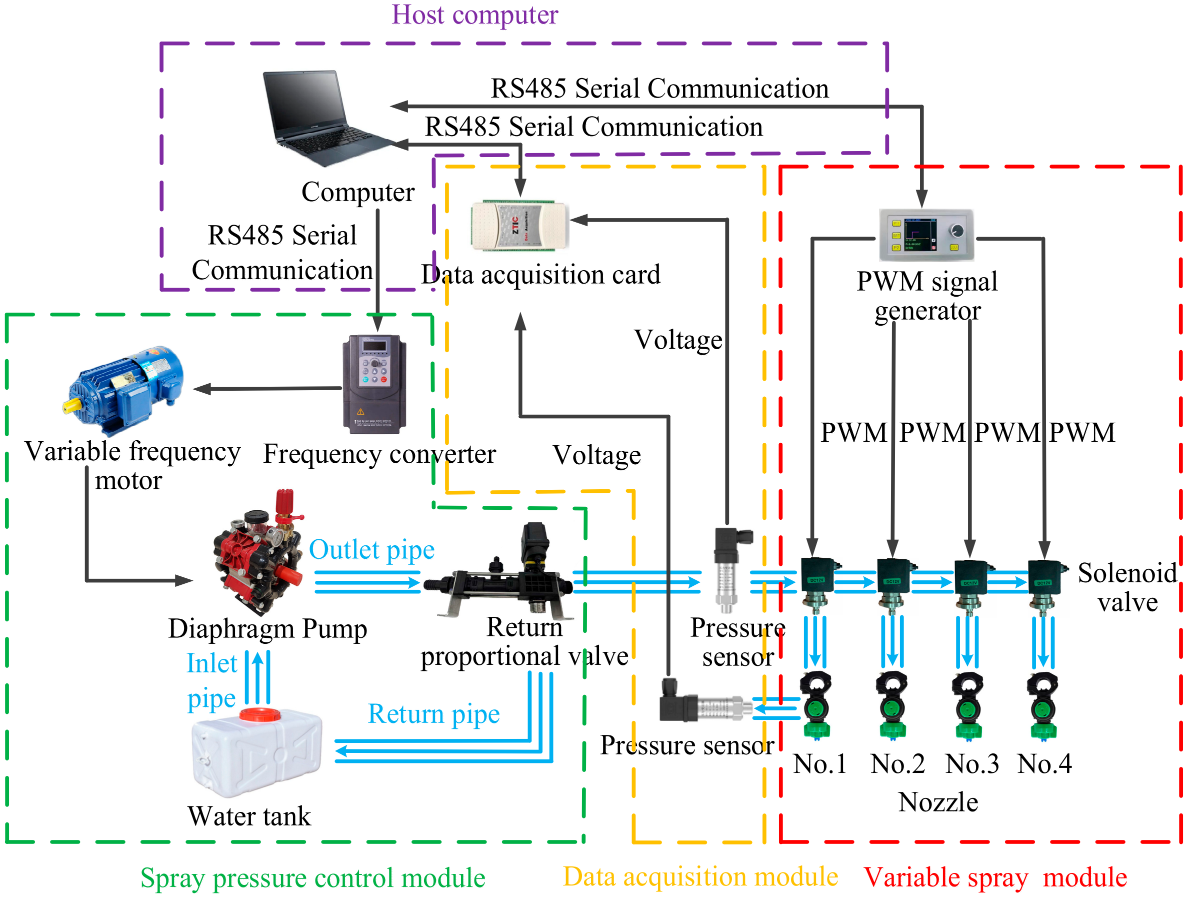


Figure 2. Schematic diagram of the composition of the staggered-phase PWM variable spraying pressure fluctuation test system.

As shown in Figure 3, the flow rate of the nozzle gradually increased with an increasing PWM duty cycle during the drive modes of the same and staggered phases. The flow adjustment multiple was 7.01 under the same-phase drive mode. Further analysis showed that the flow rate had a good linear relationship with the duty cycle and that the R^2 value was 0.9863. The flow rate was the lowest when the duty cycle was 10% under the staggered-phase drive, which was 0.132 L/min, and when the duty cycle reached 90%, the flow growth trend slowed to 0.936 L/min; this was basically the same as the flow rate when the duty cycle was 100%. The calculations showed that the flow adjustment multiple was 7.10 under the staggered-phase drive mode, the flow rate and duty cycle had a good linear relationship, and the R^2 value was 0.9976. The linear interval between the nozzle's flow and duty cycle was 10~90%. The difference between the flow adjustment times of the same phase and the staggered phase was minimal, which confirmed that the PWM spray system driven by the staggered phase had minimal influence on the variable spraying of the nozzle, and this aspect can be studied more thoroughly in the future.

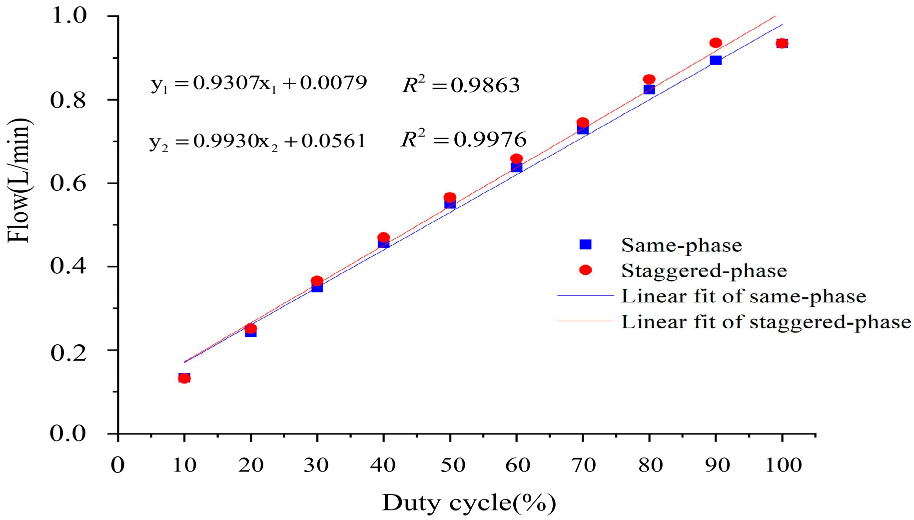


Figure 3. Nozzle's flow rate varies with PWM duty cycle.

2.1.3. Pressure Fluctuation Test of the Same-Phase or Staggered-Phase PWM Variable Spray System under Different Initial Pressures

The results of previous studies showed that the repeated opening and closing actions of the solenoid valves of the PWM variable system caused turbulence and pressure impact in the pipeline [46], which had undesirable effects on the flow rate of the nozzle, the particle size of the droplets, and the uniformity of the droplet deposition.

The test was carried out using the test platform built in Section 2.1.1, as shown in Figure 4. A pressure sensor was installed 20 cm in front of the No. 1 nozzle of the test nozzle for testing the upstream pressure valve of the nozzle. A pressure sensor was installed below the No. 1 nozzle, and the activation pressure of the nozzle was measured. To ensure the safety of the spraying system's pipeline during the test process, a return pipeline was arranged, and the system had a certain amount of return flow during the spraying process through the setting of the reflux valve.

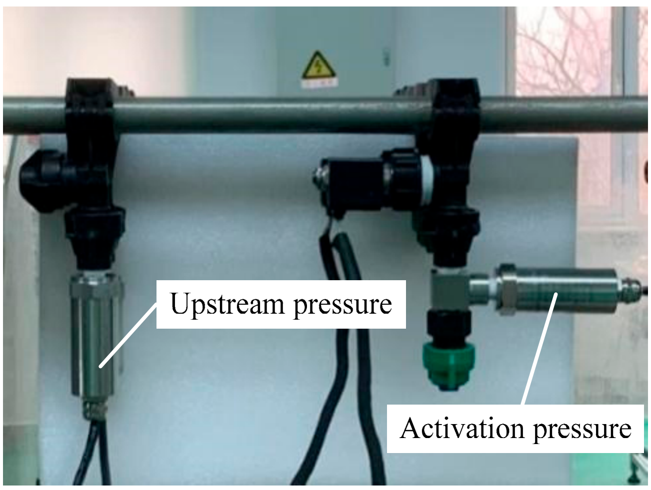


Figure 4. Pressure fluctuation test: pressure sensor installation's location diagram.

During the test, tap water was used instead of pesticide, and the test was performed in three groups as follows: the same-phase test, the staggered-phase test, and the blank control test (CK). Each group of tests was repeated three times. Table 1 shows the specific parameter settings for each test group. The initial pressure of the system was set to 0.2 MPa, 0.3 MPa, and 0.4 MPa. In particular, the initial pressure is not the working pressure; it is the spray boom pressure when the duty cycle is set at 100% before the test starts. When the duty cycle changes, the working pressure will rise. The frequency of the inverter was set by changing the input value of the inverter. The reflux ratio, which is the proportion of the flow in the reflux pipeline to the total output flow of the diaphragm pump, was set to 40%. The data acquisition card was used to collect the two pressure values at the same time: the acquisition time was 10 s, and the pressure monitoring time interval was set to 0.006 s.

Table 1. Test parameter settings.

	Same-Phase Test	Staggered-Phase Test	CK
Initial pressure (MPa)	0.2, 0.3, 0.4	0.2, 0.3, 0.4	0.2, 0.3, 0.4
Reflow ratio (%)	40	40	40
Frequency (Hz)	5	5	5
Duty cycle (%)	50	50	100

After the data collection was completed, the average pressure (P_{mean}), pressure fluctuation amplitude (P_F), and pressure fluctuation dispersion rate (root mean square error) (δ_P) of the three groups of tests were calculated according to Equations (2), (3), and (4), respectively.

$$P_{mean} = \frac{\sum_{i=1}^{N} P_i}{N} \quad (2)$$

$$P_F = P_{max} - P_{min} \quad (3)$$

$$\delta_P = \sqrt{\frac{\sum_{i=1}^{N} (P_i - P_{mean})^2}{N}} \quad (4)$$

where P_i is the pressure of each sampling point in the boom, P_{max} is the maximum pressure, P_{min} is the minimum pressure, P_{mean} is the average pressure, and N is the number of pressure samples.

2.1.4. Pressure Fluctuation Test of the Same-Phase or Staggered-Phase PWM Variable Spray System under Different Duty Cycles

In the same 2.1.3 test process, the reflux ratio of the system was 40%. The test was performed in two groups as follows: one group was in the same phase, and the other was in the staggered-phase comparison test. The initial pressure of the system was set to 0.3 MPa, the PWM frequency was set to 5 Hz, and the duty cycles were set to 10%, 20%, 30%, . . ., 90%. The acquisition time was 10 s, and the pressure monitoring time interval was set to 0.006 s. Each test was repeated three times, the upstream pressure of the nozzle under the corresponding test conditions was obtained, and the pressure fluctuation's discrete rates from the two groups of comparative tests were calculated according to Equation (4).

2.1.5. Pressure Fluctuation Test of the Same-Phase or Staggered-Phase PWM Variable Spray System at Different Frequencies

In the same 2.1.3 test process, the reflux ratio of the system was 40%. The test was performed in two groups as follows: one group was in the same-phase test, and the other group was in the staggered-phase comparison test. The initial pressure of the system was set to 0.3 MPa, and the PWM duty cycle was set to 50%. The frequency was selected to be 3 Hz, 5 Hz, 7 Hz, 9 Hz, and 11 Hz. Each group of tests was carried out at 5 different frequencies, and the data were collected three times for each test to obtain the upstream pressure value of the nozzle under the corresponding test conditions. The acquisition time was 10 s, and the pressure monitoring time interval was set to 0.006 s. The dispersion rates of the pressure fluctuation in the two groups from the comparative tests were calculated according to Equation (4).

With the results from the comparative test results of the initial pressure, duty cycle, and frequency of the three variables on the pressure impact of the PWM variable spray system, a t-test was used to evaluate the influence of the same-phase and staggered-phase driving modes on the pressure fluctuations in the system. Multiple regression was used to analyze the significance of the influence of the three factors on pressure fluctuations.

2.2. Atomization Test of Staggered-Phase PWM Variable Spraying System

To test the atomization characteristics of the staggered-phase-driven PWM variable spray system compared with those of the conventional same-phase PWM system, an atomization test was carried out in the spraying laboratory of the National Precision Agriculture Research Base at a temperature of 20.3 °C and humidity of 39.6%. As shown in Figure 5, the PWM variable spray system's atomization test platform was composed of a variable spray system, a spray boom, nozzles and solenoid valves, a controller, and a computer, as described in Section 2.1. The spray system supplied pesticide to the spray boom; the spray boom was fixed on the bench, and 4 nozzles spaced 50 cm apart were installed on it. An Oxford laser VisiSize P15 laser analyzer (British, OXFORD LASERS Ltd., Didcot, UK) was placed 50 cm directly below the No. 2 nozzle.

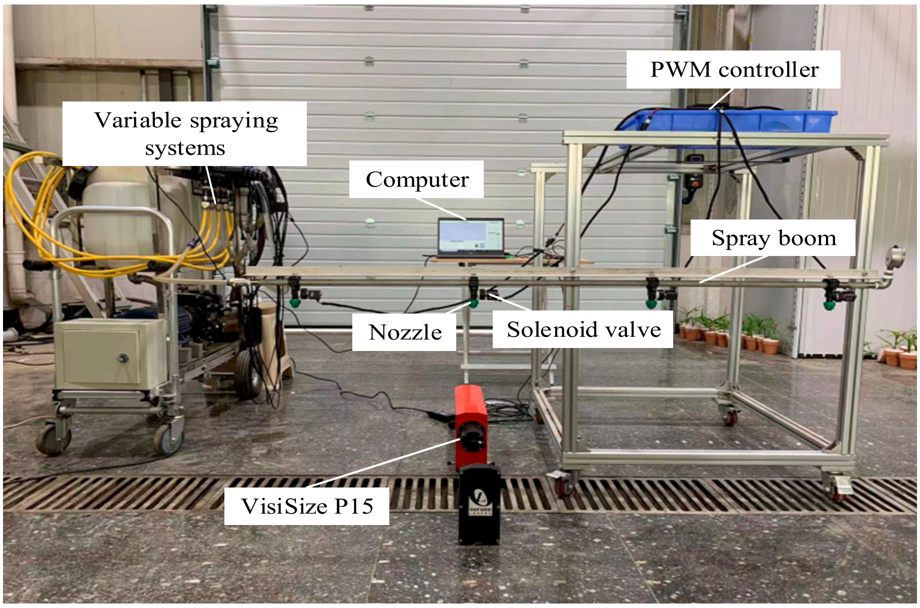


Figure 5. Schematic diagram of the layout of the atomization test bench.

Tap water was used as the test liquid. The initial spray pressure of the test setting system was set to 0.3 MPa, the frequency of the PWM parameters was set to 5 Hz, and the duty cycle was set as follows: 10%, 20%, 30%, . . ., 90%. The test was performed in two groups as follows: one group of same-phase tests, and the other group was of staggered-phase comparative tests. Each group of tests was repeated three times, with an interval of 5 s, and 10,000 particles were collected for each test. The main parameters for the analysis and evaluation of the atomization performance of the nozzles were $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, and *velocity*, the relative span of the droplet spectrum (*RS*), and the coefficient of variation of the droplet size. Among them, $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ indicated that the volume of all droplets increased in order from small to large during the spraying process, and the cumulative value was equal to a particle size of 10%, 50%, and 90% of the total volume of the sampled droplets, $D_{v0.5}$ is also called volume median diameter (VMD). The divergence of the droplet size values was also an important indicator of the relative span of the droplet spectrum (*RS*). According to the American Society of Agricultural and Biological Engineering (ASABE) and the American National Bureau of Standards (ANSI) 572.1 [50] standards, the droplet spectrum distribution of agricultural sprinkler spray is evaluated by the droplet distribution span; a smaller RS correlates to a narrower droplet size distribution, higher consistency of the atomized droplet size, and the RS calculation formula is as follows:

$$RS = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (5)$$

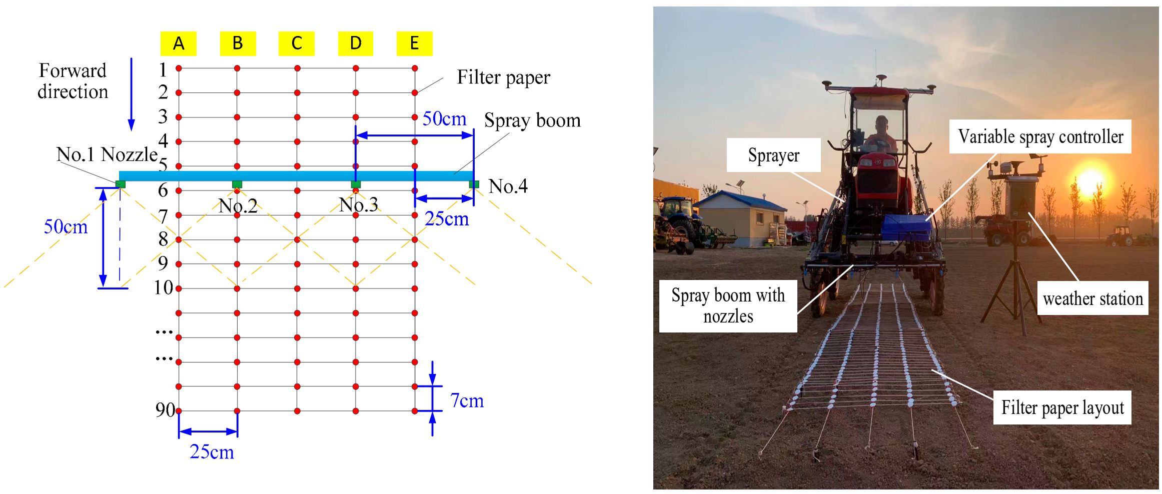
The coefficient of variation of the droplet particle size ($C.V_{droplet}$) is used to evaluate the degree of dispersion of the droplet particle diameter, and a lower coefficient of variation correlates to a lower degree of droplet particle size dispersion. The calculation formula is as follows:

$$C.V_{droplet} = \frac{Droplet_{SD}}{Droplet_{mean}} \times 100\% \quad (6)$$

where $Droplet_{SD}$ is the standard deviation of the droplet particle size, µm, and $Droplet_{mean}$ is the average droplet particle size, µm.

2.3. Staggered-Phase PWM Variable Spraying System Droplet Deposition Test

To test the degree of uniformity of the deposition of the staggered-phase-driven PWM variable spray system compared with that of the conventional same-phase system, a deposition test was carried out at the National Precision Agriculture Research Base in Xiaotangshan Town, Changping District, Beijing, China, Base, at a temperature of 29.5 °C, a humidity of 39.4%, and a southeasterly wind speed of 0.75 m/s. As shown in Figure 6, the test was completed with a 3WSH-500 self-propelled boom sprayer (Shandong Yongjia Power Co., Ltd., Shandong, China). The PWM variable spraying control system designed in Section 2.1 was installed, the spray boom was installed with 4 nozzles, and each nozzle was adjacent to 50 cm. The test droplets were collected with filter paper with a diameter of 3.5 cm. The nozzle was placed 50 cm above the filter paper, and the arrangement of the filter paper is shown in Figure 6. The travel speed was set 2 m/s to ensure a travel distance of 40 cm for each control cycle (200 ms) with at least 6 filter papers to display changes in the uniformity of droplet coverage; a distance of 7 cm was set for each filter paper. The spacing between the five columns (A–E) of filter paper was 25 cm, 90 filter papers were evenly arranged in each column, nozzles No. 2 and No. 3 were placed directly above columns B and D, and the total test length was 6.23 m.



(**a**) Label placement (**b**) Spray testing

Figure 6. Schematic diagram of test label's layout and spray test.

A total of 25 g of tracer (rhodamine B, Tianjin Kemiou Chemical Reagent Co., Ltd., Tianjin, China) was used for the experiment; the tracker was dissolved in 10 L of distilled water, and the dissolved mother liquor was poured into 90 L of pesticide tank water. A small amount of tank solution was taken back to the laboratory for dilution, the relationship between the rhodamine solution concentration and absorbance was calibrated with a fluorescence analyzer (Turner Designs, Inc., San Jose, CA, USA), and the recovery rate from the filter paper was measured. At the beginning of the experiment, the spraying pressure was set to 0.3 MPa, which was selected based on the research by Butts T, who suggested that a spray pressure greater than or equal to 276 kPa and a PWM duty cycle greater than or equal to 40% are needed to ensure the normal operation of a PWM [31]. The test was carried out in two groups as follows: one group was in the same-phase test, and the other group was in the staggered-phase drive. After the spray test was completed, the filter paper was collected in a black lightproof bag and transported to the laboratory for data analysis. The filter paper was washed with 25 mL of distilled water, shaken with an MMI-2500 multitube vortex mixer (Hangzhou Qiwei Instrument Co., Ltd., Hangzhou, China), and placed in a cuvette to measure its absorbance. The tracer (rhodamine) deposition per unit area of filter paper was calculated by Equation (7):

$$Deposition = \frac{C_{paper} \times V}{C_{tank} S_{paper} \times R} \tag{7}$$

where $Deposition$ is the standard deviation of the tracer deposition per unit area of all rows, mL/m^2; C_{paper} is the average amount of the tracer deposition per unit area of all rows, mg/mL; V is the volume of distilled water, mL; C_{tank} is the concentration of the solution in the pesticide tank, mL/m^2; S_{paper} is the area of the filter paper, m^2; and R is the recovery rate. The recovery rate was 95.27%.

The coefficient of variation ($C.V_{deposition}$) of the sedimentation amount in the forward direction was calculated by substituting the average amount of deposition per unit area of 5 filter papers in each row into Equation (8).

$$C.V_{deposition} = \frac{Deposition_{SD}}{Deposition_{mean}} \times 100\% \tag{8}$$

where $Deposition_{SD}$ is the standard deviation of the tracer deposition per unit area for all rows, mL/m^2; and $Deposition_{mean}$ is the average amount of the tracer deposition per unit area across all rows, mL/m^2.

3. Test Results and Analysis

3.1. Pressure Fluctuation Test Results and Analysis

A pressure fluctuation test was carried out in the spraying laboratory of the National Precision Agriculture Research based on a temperature of 19.8 °C and a humidity of 37.4%.

3.1.1. Different Initial Pressures

Through a real-time collection of the pressure values of the spray system with the same-phase and staggered-phase PWM variables under different initial pressures and calculations according to Equations (2) and (4), the dispersion rate of the pressure fluctuations in the three groups of tests is shown in Figure 7. The dispersion rate of the pressure fluctuations in the spray system under the same-phase-driven mode was 0.017134; this value was 171.84% greater than that of the control group. Additionally, the dispersion rate of the pressure fluctuations in the spray system was 0.006377; this value was 1.18% greater than that of the control group. These results showed that, in this case, the pressure fluctuations in the system were basically eliminated. At this time, the dispersion rate of the dislocation pressure fluctuation was reduced by 62.78% compared with that of the same phase.

According to the above results for the discrete rate of pressure fluctuation, the pressure fluctuation elimination effect of the dislocation driving mode was most evident at 0.3 MPa. Then, the pressure fluctuation amplitude of the three groups of tests was further calculated by applying Equation (3). These results are shown in Figure 8. When the frequency was 5 Hz, and the duty cycle was 50%, the amplitude of the upstream pressure fluctuation of the staggered-phase PWM spray system was significantly lower than that of the same-phase spray system. The pressure fluctuation amplitude of the control group (continuous spraying of the nozzle) was 0.038 MPa, the pressure fluctuation amplitude of the dislocation was 0.052 MPa, the pressure fluctuation amplitude of the same phase was 0.088 MPa, the pressure fluctuation amplitude of the same phase increased by 131.58% compared with that of the control group, and the pressure fluctuation amplitude of the staggered phase increased by 36.84% compared with that of the control group (these small pressure fluctuations mostly come from the pump directly). But, obviously, the average pressure of the CK group was lower than that of the two phase groups because the duty cycle of the CK group was 100%. The larger the duty cycle, the lower the average pressure of the system [32]. In general, the PWM intermittent spray caused an increase in the system's pressure fluctuation; however, compared with that in the same-phase driving mode, the dislocation greatly reduced the pressure fluctuation's amplitude in the system. Moreover, compared with the pressure fluctuation amplitude in the same phase, the dislocation pressure's fluctuation amplitude was reduced by 40.91%. Normally, those small fluctuations in red and blue signals also come directly from the pump and the vibration of the test bench.

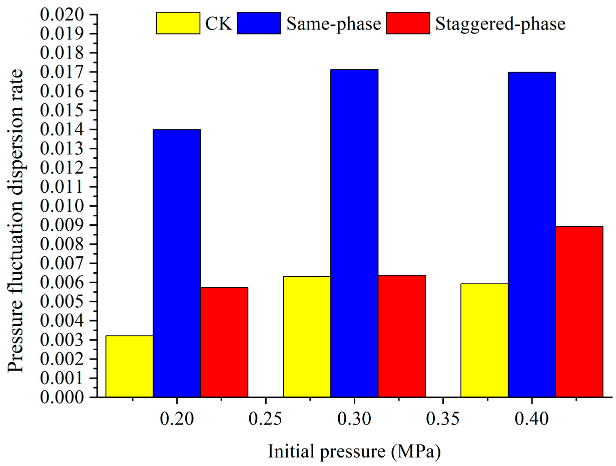


Figure 7. Comparison of the pressure fluctuation rate of PWM variable spray system under different initial pressures and different driving modes.

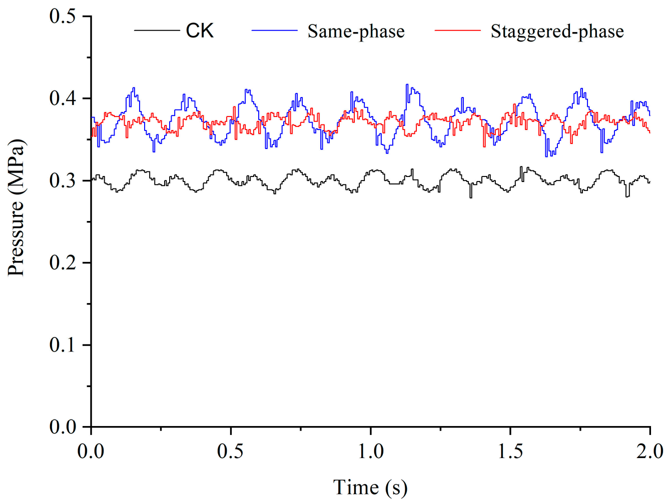


Figure 8. Upstream pressure shock fluctuations.

As shown in Figure 9, when the initial pressure of the system was 0.3 MPa, the frequency was 5 Hz, and the duty cycle was 0.5. A comparison of the nozzle's activation pressure of the staggered-phase and same-phase PWM variable spray systems showed that the pressure of the nozzle caused by PWM intermittent spraying was distributed in a square wave. Compared with that of the same-phase-driven mode, the activation pressure of the nozzle under the staggered-phase drive was reached more quickly after the nozzle was turned on, and the fluctuation was smaller and more stable.

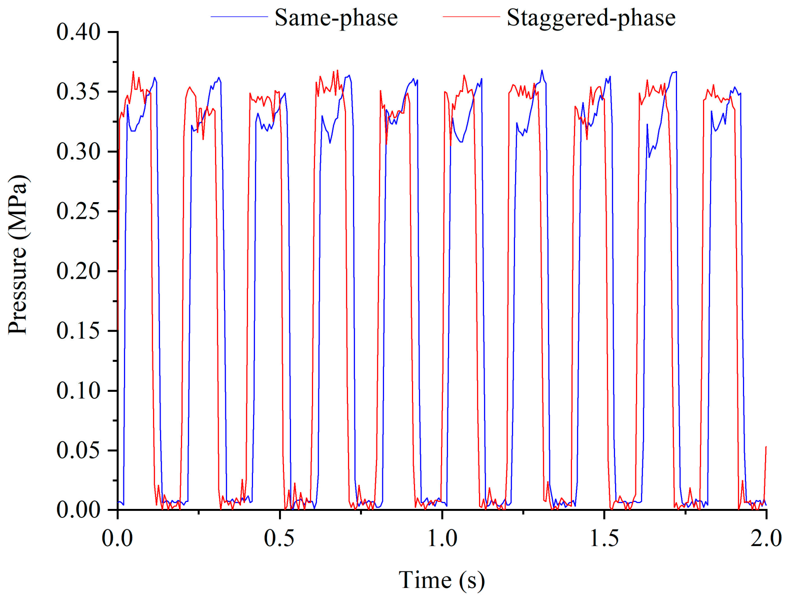


Figure 9. Nozzle's activation pressure fluctuations.

3.1.2. Different Duty Cycles

According to Equations (2) and (4), the pressure fluctuation rate of the spray system with the same-phase and staggered-phase PWM variable spray systems was calculated under different duty cycles. As shown in Figure 10, a larger number of duty cycles of the same-phase-driven PWM spray system correlated to a decrease in the fluctuation dispersion rate of the pressure shock generated by the spray system. With a larger number of duty cycles of the staggered-phase-driven PWM spray system, the fluctuation dispersion rate of the pressure impact generated by the spray system initially decreased and then increased. Clearly, the dispersion rate of the pressure fluctuations in the system was the lowest when the duty cycle was 50%.

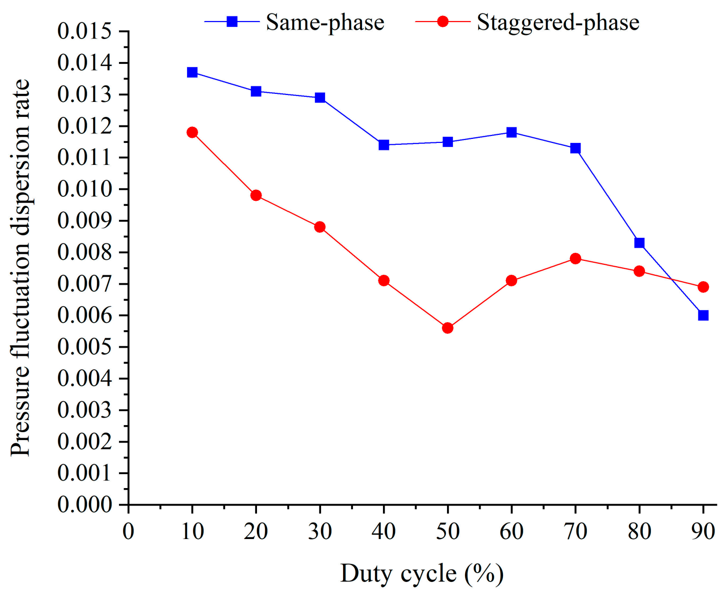


Figure 10. Discrete rates of the pressure fluctuation in the same- and staggered-phase test groups under different duty cycles.

3.1.3. Different Frequencies

According to Equations (2) and (4), the dispersion rate of the pressure fluctuation of the spray system with the same-phase and staggered-phase PWM variables at different frequencies was calculated, as shown in Figure 11. The same-phase- and staggered-phase-driven PWM spray systems both exhibited fluctuating fluctuations in the pressure impact generated by the spray system at a greater frequency, and the dispersion rate initially increased and then decreased. In the 3–7 Hz range, the dispersion rate of pressure fluctuations in the pipeline was greater in the same-phase method than in the staggered-phase method. However, in the 7–11 Hz range, the dispersion rate of pressure fluctuations in the pipeline was greater in the staggered-phase method than in the same-phase driving method. Under the same-phase driving mode, the pressure fluctuation dispersion rate of the system reached its maximum at a frequency of 7 Hz, while under the staggered-phase driving mode, the pressure fluctuation dispersion rate of the system reached its maximum at a frequency of 9 Hz. Therefore, the resonance frequency of the system was different under the different driving modes. Therefore, the spray system needs to be designed to avoid the resonance frequency of the system to reduce the pressure impact of the pipeline.

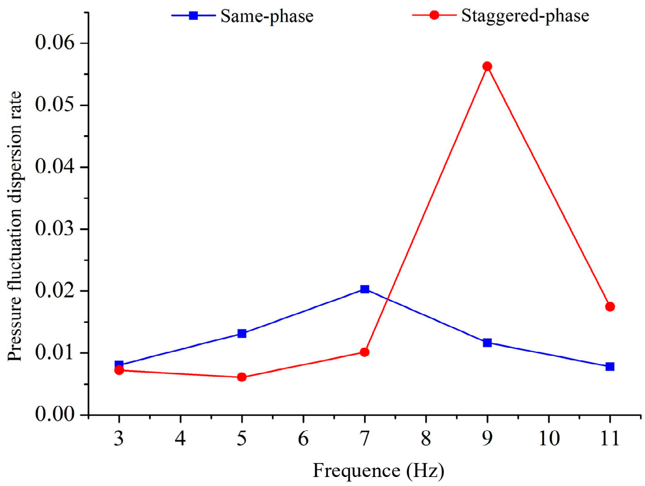


Figure 11. Discretization rates of the pressure fluctuations in the same and staggered phases at different frequencies.

Figures 9–11 show the effects of three variables of the initial pressure, duty cycle, and frequency on the dispersion rate of the pressure fluctuations in the PWM variable spray system. Clearly, the pressure fluctuations in most staggered phases were smaller than the pressure fluctuations in the same-phase-driven system. When the frequency was in the same phase at 7 Hz and in the staggered phase at 9 Hz, a large fluctuation point appeared, which was the resonance point of the system.

To verify whether the staggered-phase drive method could eliminate the pressure fluctuations of the PWM spray system. We used the t-test method to determine whether there was a significant difference between the two sets of data (excluding abnormal data at frequencies of 7 Hz and 9 Hz under system resonance) and proposed the following hypothesis:

H0: *There was no significant difference between the pressure fluctuations in the staggered phase and those in the same phase.*

H1: *There was a significant difference between the pressure fluctuations in the staggered phase and those in the same phase. The pressure fluctuations in the staggered phase were smaller than those in the same phase.*

The analysis results are shown in Table 2. The mean same-phase fluctuation was 0.0126379, which was greater than the staggered-phase fluctuation of 0.0077807. P (T = t) = 0000, P (T > t) = 0000. At a significance level of 0.05, we rejected the null hypothesis. There was a significant difference between the same-phase and the staggered-phase driving modes, and the pressure fluctuations in the staggered-phase driving mode were smaller than those in the same phase.

Table 2. The dispersion rates of the pressure fluctuations in the PWM variable spray system under different initial pressures and different driving modes.

Variables	Obs	Mean	Std.Err.	Std.Dev.	[95% Conf. Interval]	
Same-phase	15	0.0126379	0.000952	0.0036872	0.010596	0.0146798
Staggered-phase	15	0.0077807	0.0004588	0.0017771	0.0067966	0.0087648
diff	15	0.0048572	0.0008984	0.0034797	0.0029302	0.0067841

Mean (diff) = mean (Same phase—Staggered phase)		t = 5.4062
Ho:mean (diff) = 0		degrees of freedom = 14
Ha: mean(diff) < 0	Ha:mean (dift) ! = 0	Ha:mean (diff) > 0
Pr(T < t) = 1.0000	Pr (| T | > | t |) = 0.0001	Pr (T > t) = 0.0000

Note: Obs is the number of observations; Mean is average; Std.Err. is the standard error; Std.Dev. is the standard deviation; [95% Conf. Interval] is the 95% confidence interval.

To verify that the initial pressure, duty cycle, and frequency of the three variables had significant effects on the pressure fluctuations in the PWM variable spray system, multiple regression analysis was applied to analyze the significance levels of the three factors on the pressure fluctuations. The results are provided in Table 3. The initial pressure had the greatest impact on the pressure fluctuations, with coefficients of 1.211 and 1.212, and the *p*-value was highly significant, with a positive impact on the pressure. The duty cycle had a significant negative impact on both the same-phase and staggered-phase situations, with coefficients of −0.00123 and −0.00128, respectively. The impact of frequency on the pressure fluctuations was relatively small, with coefficients of 0.000653 and 0.00235 for the same-phase and staggered-phase situations, respectively. In contrast, the frequency of the staggered-phase-driven systems had a more significant impact on the pressure fluctuations.

Table 3. Linear regression analysis results for the different duty cycles, frequencies, and initial pressures.

Variables	Same-Phase	Same-Phase	Same-Phase	Same-Phase	Staggered-Phase
Duty cycle	−0.00123 ** (0.000)			−0.00123 ** (0.000)	−0.00128 ** (0.000)
Frequency		0.000653 (0.747)		0.000653 (0.626)	−0.00235 * (0.086)
Initial pressure	(0.000)	(0.000)	1.211 ** (0.000)	1.211 ** (0.000)	1.212 ** (0.000)
Constant	0.344 ** (0.000)	0.279 ** (0.000)	−0.0811 ** (0.000)	−0.0228 ** (0.003)	−0.0141 * (0.070)
Observations	11,481	11,481	11,481	11,481	11,481

Note: The values in parentheses are *p*-values; ** indicates high significance ($p < 0.01$); * indicates significance ($0.01 \leq p < 0.05$).

3.2. Atomization Test Results and Analysis

The comparison of the atomization test results suggested that minimal differences were observed between the droplets' sizes and velocity in the PWM variable spray systems based on different modes. The staggered-phase driving method could slightly increase the average velocity of the droplets. The correlation between size and velocity under two driving modes with a duty cycle of 50% is shown in Figure 12. When the duty cycle was 50%, the average droplet velocity of the variable spray system based on the same-phase and staggered-phase methods was 2.30 m/s and 2.37 m/s, respectively.

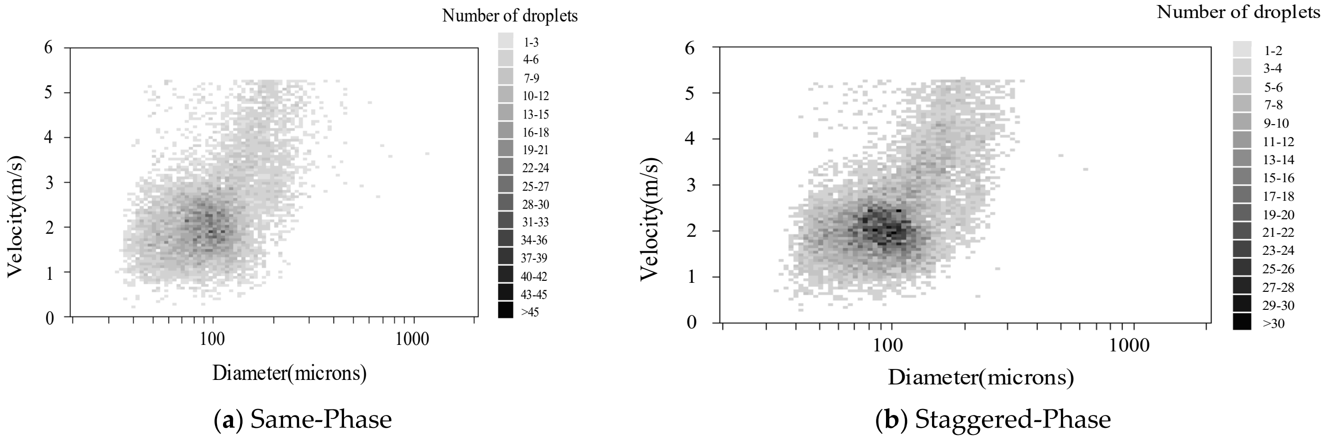


Figure 12. Comparison of velocity–size correlation in same–phase and staggered–phase atomization tests.

As shown in Table 4, minimal differences were observed between the PWM variable spray droplets of $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$. Compared to the atomization test results of the PWM variable spray system of the two driving modes, as shown in Table 4, it suggested that the droplet particle size increased with the increase in the duty cycle in the PWM variable spray system. Both $D_{v0.1}$ and $D_{v0.5}$ of the staggered-phase system were slightly larger than those of the same-phase system, while $D_{v0.9}$ showed an opposite trend. This resulted in a large difference in the RSs between the two systems, which is an important index for evaluating droplet particle size uniformity. As shown in Figure 13, the RSs of the same-phase and staggered-phase variable spray systems were calculated based on Formula (5) under different duty cycles. The test results showed that the RS value of the variable spray system driven by the same-phase method fluctuated greatly under different duty cycles. In the range of 10–50%, the RS value first decreased and then obviously increased. When the duty cycle was 30%, the minimum RS value was 1.30, and when the duty cycle was 50%, the maximum RS value reached 1.49. When the duty cycle was greater than 50%, the RS value showed a gradually decreasing trend. The RS value of the staggered-phase variable spray system with a different duty cycle changed more smoothly than that of the same-phase system. The minimum RS value was 1.12 at a 50% duty cycle, which was 24.83% lower than that of the same-phase system. These results potentially occurred because the activation pressure of the nozzle could reach the threshold faster than it could in the same phase; thus, this caused relatively smaller particle sizes, more uniform and consistent particle sizes of the atomized droplets, and a decreased RS.

Table 4. $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ of PWM variable spray system based on two driving modes under different duty cycles.

Duty Cycle (%)	Same-Phase			Staggered-Phase		
	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$(μm)
10	70.50	141.50	271.90	73.10	143.80	250.50
20	72.53	136.50	263.60	75.23	155.33	257.17
30	73.40	141.57	257.63	76.93	142.10	249.77
40	75.00	142.70	268.60	84.13	150.07	258.60
50	81.63	146.77	300.77	82.87	145.13	246.10
60	82.73	154.60	286.83	88.40	160.47	275.90
70	85.30	156.53	282.83	91.93	163.20	282.03
80	88.63	159.17	278.47	93.70	168.40	289.13
90	91.10	161.37	282.10	94.67	170.23	297.37

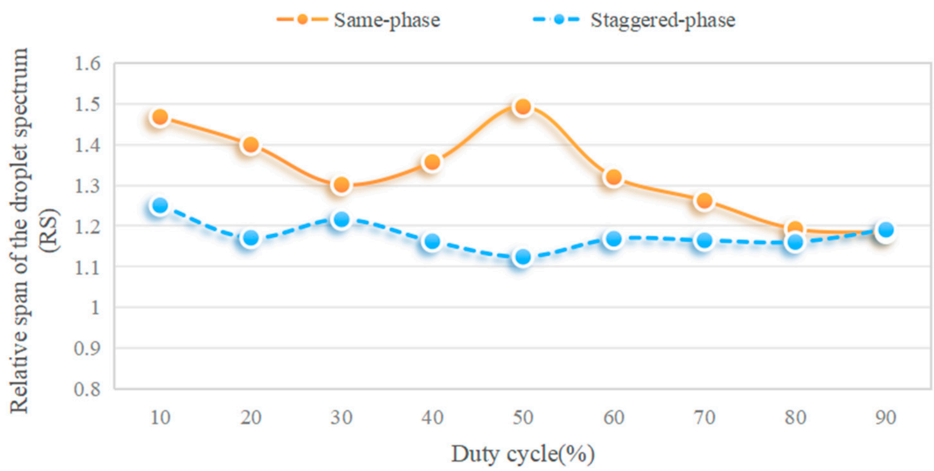


Figure 13. RS of the same-phase and staggered-phase variable spray systems under different duty cycles.

According to the coefficient of variation Formula (6), the coefficient of variation (C.V) of the droplets of the same-phase mode driving the PWM variable spray system could be obtained, with a C.V of 48.40%; however, the C.V. of the staggered phase was 44.00%, showing a decrease of 4.40%. These results indicated that the staggered-phase driving mode had better atomization characteristics and a more uniform and consistent droplet size.

3.3. Spray Deposition Test Results

Section 2.3's fluorescence analyzer was used to measure the absorbance via the substitution Formula (7) for the calculation of the unit tracer deposition on each filter paper sample; an average was recorded for each row of filter paper deposition, and the final average from the filter paper deposition per line in the forward direction is shown in Figure 14. Both the same-phase and staggered-phase PWM variable spray systems showed periodic changes in the tracer deposition in the travel direction, which is in accordance with the square wave periodicity change trend of the PWM signal. Compared with the same-phase periodic change, the staggered-phase periodic change was the result of the superposition of two opposite waves, and the amplitude of the periodic fluctuation was significantly lower than that of the same phase. As observed from the test data in Table 5, the $Deposition_{mean}$ of the staggered-phase PWM variable spray system was 13.79, which was 4.87% greater than the same-phase deposition amount of 13.15; moreover, the $C.V_{deposition}$ was used to determine the uniformity of droplet deposition, calculated according to Formula (8), and decreased from 32.48% to 11.61%, representing a 20.87% reduction. This system greatly reduced the inhomogeneity of deposition.

The deposition amount on each filter paper was calculated according to Formula (7), and the average was determined. According to Formula (8), the $C.V_{deposition}$ of the PWM variable spray system driven by the staggered phase was 12.88%, an increase of 2.79% compared with 10.09% in the same phase. This difference was potentially caused by changes in the wind speed and direction during the experiment, which resulted in slight changes in the uniformity of sedimentation in the direction of the spray boom in both experiments; however, the $C.V_{deposition}$ values did not exceed 15%. Therefore, our system met the national standard GB/T24677 1-2009 [51] Technical Conditions for Spray Bar Spray, which states this value should be lower than 20%.

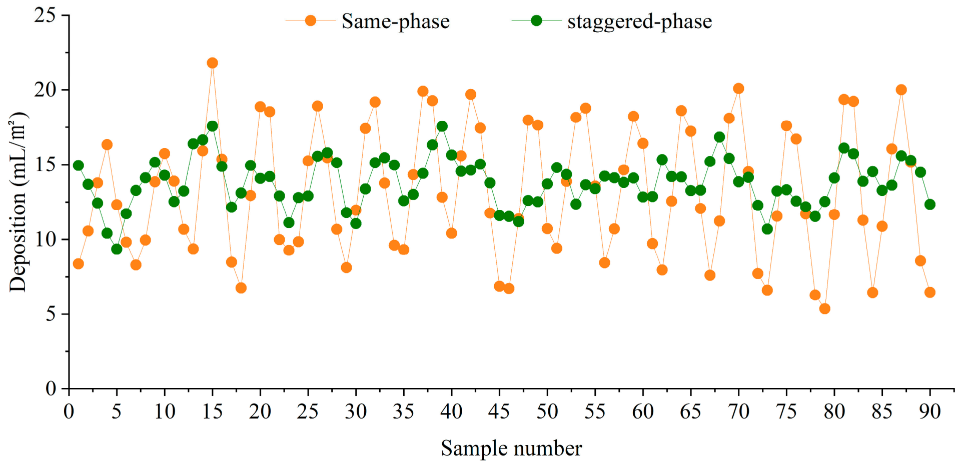


Figure 14. Deposition amount of droplets in the same-phase or staggered-phase variable spray system of the forward direction.

Table 5. Spray deposition test results.

	Same-Phase	Staggered-Phase
$Deposition_{mean}$ (mL/m^2)	13.15	13.79
$C.V_{deposition}$ (%)	32.48	11.61

4. Discussion

1. At present, most pieces of literature showed that the main way to improve application accuracy is through flow control, turn compensation, and high-resolution overlap control by pulsing an electronically actuated solenoid valve [38–41]. Literature [46] showed that by increasing the frequency of the solenoid valve from 15 Hz to 30 Hz, the coefficient of variation of the different nozzles could be reduced by 6.07–18.31%. This will reduce most of the nonuniform deposition. But at the same time, the high cost of high-frequency solenoid valves and narrow flow regulation have brought some concerns. This paper focuses on the research of variable spray systems with low-frequency control, which is one of the effective methods that provides consideration to the cost, ensures the flow adjustment width, and plays a positive role in promoting the popularization of variable spray systems in the world.
2. The deposition test results in this study showed that the variable spray system (duty cycle 50%, initial pressure 0.3 MPa) with staggered driving mode had a deposition variation coefficient of 12.88% in the spray bar direction, which was far less than the standard 20%. The forward direction deposition uniformity variation coefficient was 11.61%, which was very close to the literature. Pierre Robert et al. conducted a study on the deposition characteristics of a PWM variable spray system under different duty cycles; their results showed that the longitudinal deposition variation coefficient was 10% at a 100% duty cycle [45], and the forward direction deposition variation coefficient of the spray boom of continuous spray was 10%. This method basically eliminated the inhomogeneity deposition caused by frequent switching of the nozzle based on the PWM variable spray.
3. The phase-shifting driving method used in this study is a completely opposite signal-shifting method for odd- and even-numbered nozzles. The experimental results showed that the uniformity of droplet deposition was significantly improved, and many ways could be used to achieve phase shifting. In the future, further research can be conducted on other shifting methods to provide a theoretical basis for the development of variable spraying systems and precision spraying equipment.

5. Conclusions

1. To address the problems of pipeline pressure fluctuations and poor forward direction deposition uniformity, which is caused by the simultaneous opening and closing of nozzles in the same-phase-driven PWM variable spray system, a staggered-phase driving method for odd- and even-numbered nozzles was proposed, and a variable spray system based on staggered-phase driving was developed. By building a series of test platforms for the study of pressure fluctuation characteristics, atomization characteristics, and deposition characteristics, the relevant characteristics of the PWM variable spray system driven by the same and staggered phases were analyzed, and the significance of the relevant influencing factors was analyzed.
2. The experimental results from the pressure fluctuation characteristics of the staggered-phase-driven PWM variable spray system under different initial pressures showed that the dispersion rate of the pressure fluctuation of the staggered-phase-driven system decreased by 62.78%, and the fluctuation amplitude of the upstream pressure decreased by 40.91%. The nozzle's activation pressure was quickly reached, and the fluctuations decreased and became more stable. Under different duty ratios, the dispersion rate of the pressure fluctuations in the same-phase-driven PWM variable spray system decreased with increasing duty cycle, and the dispersion rate of pressure fluctuations in the staggered-phase-driven PWM spray system initially decreased and then increased with an increasing duty cycle. When the duty cycle was 50%, the dispersion rate of the pressure fluctuation of the system was the lowest. Under different frequencies, the dispersion rate of the pressure fluctuation of the same-phase-driven and staggered-phase PWM spray systems initially increased and then decreased with increasing frequency. The maximum corresponding frequency values of the pressure fluctuation rates for the same-phase and staggered-phase systems were 7 Hz and 9 Hz, respectively. The PWM control parameters had a significant impact on the upstream pressure fluctuations with the following trend as follows: initial pressure > duty cycle > frequency. The test results can provide a basis for the subsequent choice of operating parameters for the sprayer.
3. The experimental results of the atomization characteristics research showed that there was a minimal difference between the PWM variable spray droplets of $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, but the RS of the PWM variable spray system (driven by the staggered phase) decreased by 24.83% compared with the same phase, and the $C.V_{deposition}$ of the droplet size decreased by 4.40% compared with the same phase. These results indicated that the staggered-phase driving mode had better atomization characteristics in the tests with different duty cycles, and the droplet size was more uniform and consistent.
4. The experimental results of the deposition characteristics research showed that the longitudinal average deposition amount in the forward direction of the staggered PWM variable spray system was 13.79, an increase of 4.87% compared with the deposition amount in the same phase of 13.15. Additionally, the $C.V_{deposition}$ was used to determine the droplet deposition uniformity and decreased from 32.48% to 11.61%; this represents an overall decrease of 20.87%. The inhomogeneity sedimentation was significantly reduced. The $C.V_{deposition}$ of the transverse deposition in the spray's forward direction of the PWM variable spray system (driven by the staggered phase) was 12.88%; this value represented an increase of 2.79% compared with 10.09% in the same phase, and the deposition uniformity in the spray's forward direction was slightly reduced but remained within the allowable range.
5. In this study, the PWM variable spray system was driven by odd- and even-numbered spray heads with completely opposite signal staggering (a phase difference of 180°). The results showed that the uniformity of droplet deposition significantly improved. In the future, the effect of the stagger-phase difference on the pressure fluctuations in variable spray systems could be studied, which could provide a theoretical basis for the development of variable spray systems and precise spray equipment.

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