Using variable spray angle fan nozzle on long spray booms

Hamid Reza Ghasemzadeh[1*], Daniel D. Humburg[2]

(1 Biosystems Engineering Department, University of Tabriz, P. O. Box 51666- 14776, Tabriz, 51666, I. R. Iran;
2 Agricultural and Biosystems Engineering Department, P. O. Box 2120, Brookings, SD 57007, USA)

Abstract: A new-concept of using variable spray angle fan spray nozzle in conjunction with pulse width modulation technique was proposed for compensation of the effects of spray boom vibration on chemical application rate and pattern. A review of literature regarding techniques used to diminish the effects of long spray booms dynamic behavior on uniformity of spray application reveals that the research work so far has mostly involved boom positioning, vibration analysis, mathematical modeling and monitoring of boom dynamic behavior, in the hope of finding the ways to attenuate vibration through improving the design of boom structure, suspension, and control systems. The present article puts forward the idea of using Variable Spray Angle Fan Spray Nozzle (VSAFSN) along with pulse width modulation (PWM) technique to maintain constant spray coverage, hence, uniformity of spray application. TEEJET-XR11002 Nozzle was used and preliminary experiments were carried out to study the feasibility of the proposed concept. Spray pressure range of 55 kPa to 490 kPa, was used to vary spray angle from 78 to 160 degrees. Results showed that the spray maintained its almost normal distribution pattern within full range of spray angle. Relationships between spray angle (y) and operating pressure (x) was found as y=0.1495x-90.851, R^2=0.7953, and, between nozzle flow rate (y) and spray angle (x) was found as y=8.3824x-387.13, R^2=0.8712.

Keywords: dynamic, nozzle, pulse width modulation, uniformity

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1 Introduction

Apart from huge costs associated with the use of chemicals in the farms, there are some evidences that long term exposure to pesticides may cause neurodegenerative diseases such as dementia; Alzheimer’s in particular, and Parkinson (Streenland et al., 2014; Thany et al., 2013). On the other hand, ever increasing demands by farmers for better machinery (Chaplin and Wu, 1989), including longer spray booms have made manufacturers to build giant booms to help farmers in terms of increasing their working rates to overcome timeliness problems.

Application of minimum amount of liquid chemicals efficiently and maintaining a uniformity of spray coverage, has long been a challenging issue in crop protection operations. On the other hand, the sizes of the machines that deal with spraying chemicals over the large areas of the land have been increased tremendously and sprayers with 46 m long booms are not uncommon (Anon, 1997).

Boom moment of inertia increases as boom length increases and the vertical movement of the boom results in non-uniform spray coverage (Nalavade et al., 2008). This non-uniformity may range from 0 to 800% (Anthonis et al., 2005).

Apart from excessive vertical boom movements, the operator may need to reposition either sides of the boom, when the machine is travelling on slopes, in such a way that they may not be aligned (Bjørnsson et al., 2013) and this may require some additional precision which increases the work load of an operator.

Despite of tremendous efforts by researchers around the world to implement a kind of active spray boom position control system (Sartori et al., 2002), owing to high inertial forces involved, non-uniformity of the spray

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***Corresponding author: Hamid Reza Ghasemzadeh,** University of Tabriz, Biosystems Engineering Department, Tabriz 51666-14776, Iran, ghassemzadeh@tabrizu.ac.ir. Phone: +98 914 313 5277.

coverage have not yet been overcome. It seems that in the long run Altek carbon fiber booms (Vogt, 2013) can be a better solution in terms of reducing the time of response of the boom to control commands due to their light weight hence lower inertia. Another approache, i. e., isolation of the sprayer boom from the chassis vibration in the hope of controlling the violent dynamic behavior of boom has received more attention (Chaplin and Wu, 1989). Chaplin and Wu (1989) developed a computer model to simulate the movement of a sprayer boom and investigated the effect of tank liquid volume and tire inflation pressure on dynamic behavior of a spray boom. They concluded that spray distribution tends to be more uneven when the amount of liquid in the tank decreases.

Most of the research carried out during the last decade regarding relationship between spray boom dynamics and spray distribution uniformity was concentrated on analyzing and modeling the dynamic behavior of the long spray booms and their relation with spray pattern, and the validation of models through either workshop or field experiments (Clijmans et al.,1996; Clijmans et al., 2000a; Clijmans et al., 2000b; Clijmans et al., 2001; Jeon et al., 2003; Langenakcns et al., 1993).

The core idea during these works was to develop some techniques to better understand system behavior and identify those parameters that have the most control on the system dynamic behavior with the aim of establishing well defined standards for laboratory testing of the machines and avoiding the laborious field experiments.

The amount of works faded out by the early years of current decade as far as the literature of the subject is concerned, since these methods seemed to have become sufficiently mature (Parloo et al., 2003; Jeon et al., 2004). Instead, interests were shifted towards optimization and redesigning of the components as well as developing better, and in some cases smart control systems for spray boom behavior control (Anthonis et al., 2005; Bjørnsson et al., 2013).

On the other hand, research works are underway to study the key parameters of nozzles affecting the droplet size distribution (Cock et al., 2014) and to develop the nozzles with the capability of variable rate application (Womac and Bui, 2002; Lang, 2013).

The common goal of all works presented above was to apply the minimum amount of liquids uniformly with appropriate size of droplets necessary to destroy pests, in the meantime, avoiding undesirable skips and/or overlaps. This article attempts to develop an idea of using variable spray angle fan spray nozzle (VSAFSN) with modulated pulse width (PWM) to overcome the problems imposed by vibration of long spray booms resulting in non-uniform spray pattern while employing variable rate technology (VRT).

2 Materials and methods

To maintain the uniformity of spray while the spray boom is oscillating, two possibilities may be considered: first, real time controlling of the angle of angled flat fan nozzles (AFFN) that can be directed forward or backwards, and second, using a real time controlled variable spray angle fan spray nozzles (VSAFSN). It might not be necessary to control all the nozzles along the boom, but those nozzles that contribute to spray non-uniformity at either ends of the boom.

2.1 Geometrical considerations

The geometry as well as the equations for calculating the spray distribution was proposed by Chaplin and Wu (1989) as follows:

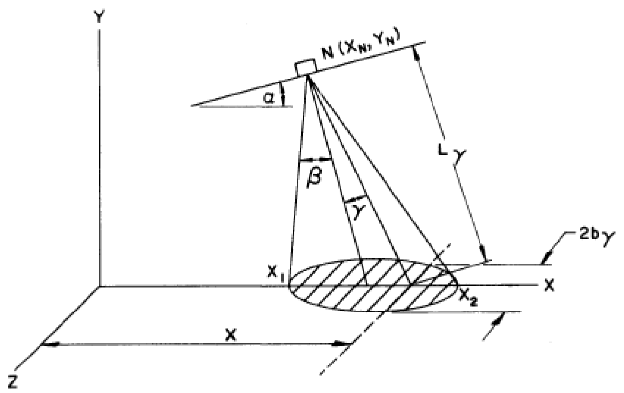

Figure1 Geometry of spray distribution (Chaplin and Wu, 1989)

$$X_1 = X_N + Y_N tan(\alpha - \beta) \quad (1)$$

$$X_2 = X_N + Y_N tan(\alpha + \beta) \quad (2)$$

Where:

X_1 and X_2 $= Intercept\ of\ spray\ pattern\ with\ X\ axis, m,$

X_N and $Y_N = Nozzle\ coordinates, m,$

$\alpha = Boome\ angle, deg,$

$\beta = Half\ cone\ angle, deg.$

2.1.1 he effect of boom inclination on transversal shift of the spray coverage (TSSC)

Nozzles with 80 and 110 degrees of spray angles are the most common that are used in farming practices. Suggested minimum spray heights for aforementioned nozzles are 0.8 and 0.6 m respectively for nozzle spacing of 75 cm (Anon, 2015). If the length of the boom considered to be within the range of 27 to 51 m, and the range of boom tip vertical displacement to be within the range of -0.45 to +0.45m from its horizontal position while operating on the smooth track (Jeon et al., 2003a), then, the range of boom angle can be calculated as follows:

For 27m boom:

$$\tan^{-1}\frac{-0.45}{13.50} \le \alpha \le \tan^{-1}\frac{0.45}{13.50},\ i.e.,\ -1.9 \le \alpha \le +1.9\ deg \quad (3a)$$

Similarly, for 51m boom:

$$\tan^{-1}\frac{-0.45}{25.50} \le \alpha \le \tan^{-1}\frac{0.45}{25.50},\ i.e.,\ -1 \le \alpha \le +1\ deg \quad (3b)$$

For 80 degrees spray angle nozzle at 0.8m spray height on 27 m long boom, the range of variation for X_1 and X_2 for outermost nozzle due to boom tip vertical displacement can be calculated from Equations (1) and (2) as follows:

For X_1:

$$X_N + (0.8 - 0.45)\tan(1.9 - 40) \ge X_1 \ge X_N + (0.8 + 0.45)\tan(-1.9 - 40)$$

i.e.

$$X_N - 0.27 \ge X_1 \ge X_N - 1.12\text{m} \quad (4)$$

And, for X_2

$$X_N + (0.8 - 0.45)\tan(1.9 + 40) \le X_2 \le X_N + (0.8 + 0.45)\tan(-1.9 + 40)$$

i.e.

$$X_N + 0.31 \le X_2 \le X_N + 0.98\text{m} \quad (5)$$

From Equations (4) and (5), a transversal shift for X_1 and X_2 (TSSC_{80}) can be found as:

For X_1:

$$\text{TSSC}_{80} = -0.27 - (-1.12) = 0.85\text{m} \quad (6)$$

For X_2: $\text{TSSC}_{80} = 0.98 - 0.31 = 0.67\text{m}$ (7)

Similarly, for 110 degree spray angle nozzle at 0.6m spray height on 27 m long boom the range of variation for X_1 and X_2 for outermost nozzle due to boom tip vertical displacement can be calculated from Equations (1) and (2) as follows:

$$X_N + (0.6 - 0.45)\tan(1.9 - 55) \ge X_1 \ge X_N + (0.6 + 0.45)\tan(-1.9 - 55)$$

i.e.

$$X_N - 0.20 \ge X_1 \ge X_N - 1.61\text{m} \quad (8)$$

And, for X_2

$$X_N + (0.6 - 0.45)\tan(1.9 + 55) \le X_2 \le X_N + (0.6 + 0.55)\tan(-1.9 + 55)$$

i.e.

$$X_N + 0.23 \le X_2 \le X_N + 1.39\text{m} \quad (9)$$

From Equations (8) and (9), a transversal shift for X_1 and X_2 for110 degree spray angle nozzle at 0.6m spray height on 27 m long boom (TSSC_{110}) can be found as:

For X_1:

$$\text{TSSC}_{110} = -0.20 - (-1.61) = 1.41\text{m} \quad (10)$$

For X_2: $\text{TSSC}_{110} = 1.39 - 0.23 = 1.16\text{m}$ (11)

2.1.2 The effect of boom end height variation on the spray coverage

Under the same conditions mentioned already for the boom, the normal spray coverage (NSC) for the nozzles at suggested height can be written as:

$$\text{NSC}_{80} = 2 \times 0.8 \tan 40° = 1.34m \quad (12)$$

$$\text{NSC}_{110} = 2 \times 0.6 \tan 55° = 1.71m \quad (13)$$

For 80 degree nozzle, range of spray coverage variations (RSCV_{80}) due to boom oscillation can be calculated from Equations (4) and (5) as follows:

$$0.31-(-0.27) \leq \mathrm{RSCV}_{80} \leq 0.98-(-1.12)$$

i.e.

$$0.58m \leq \mathrm{RSCV}_{80} \leq 2.10m \qquad (14)$$

This means that the spray coverage for 80 degrees nozzle would vary from 0.58m to 2.10m, if boom tip vertical displacement varies from -0.45m to +0.45m.

For 110 degree nozzle, the range of spray coverage variations (RSCV_{110}) due to boom oscillation can be calculated from Equation (8) and (9) as follows:

$$0.23-(-0.20) \leq \mathrm{RSCV}_{110} \leq 1.39-(-1.66)$$

i.e.

$$0.43m \leq \mathrm{RSCV}_{110} \leq 2.99m \qquad (15)$$

This means that the spray coverage for 110 degree nozzle would vary from 0.43m to 2.99m if boom tip vertical displacement varies from -0.45m to +0.45m.

The deviation of spray coverage (DSC) from normal spray coverage due to boom vertical oscillations for the 80 degrees nozzle can be deduced from Equations (14) as below:

$$\mathrm{DSC}_{80}=\left[\frac{2.10-0.58}{2}\right]=0.76m \qquad (16)$$

Similarly, the deviation of spray coverage (DSC) from normal spray coverage due to boom vertical oscillations for the 110 degrees nozzle can be deduced from Equation (15) as below:

$$\mathrm{DSC}_{110}=\left[\frac{2.99-0.43}{2}\right]=1.28m \qquad (17)$$

To correct this situation, i.e. to keep the spray coverage constant during boom vertical oscillations, two approaches may be envisaged: a) varying the angle of nozzle forward or backward from its vertical position, or, b) varying the angle of spray. The implications of these approaches are discussed below.

a) he range of the angular variation of the AFFN forward (or backward) from its vertical position (RAV) if the spray coverage is to be kept constant while boom is oscillating:

$$\mathrm{RAV}_{80}=\cos^{-1}\frac{0.8-0.45}{\mathrm{NSC}_{80}}=\cos^{-1}\frac{0.8-0.45}{1.34}=74 \qquad (18)$$

$$\mathrm{RAV}_{110}=\cos^{-1}\frac{0.6-0.45}{\mathrm{NSC}_{110}}=\cos^{-1}\frac{0.6-0.45}{1.71}=84\ \mathrm{deg} \qquad (19)$$

b) he range of spray angle variation (RSAV) required in VSAFSN if the spray coverage is to be kept constant while boom is oscillating:

$$2\times\tan^{-1}\frac{1.34}{2(0.8+0.45)} \leq \mathrm{RSAV}_{80} \leq 2\times tan^{-1}\frac{1.34}{2(0.8-0.45)}$$

i.e.

$$56\mathrm{deg} \leq \mathrm{RSAV}_{80} \leq 125\mathrm{deg} \qquad (20)$$

And

$$2\times\tan^{-1}\frac{1.71}{2(0.6+0.45)} \leq \mathrm{RSAV}_{110} \leq 2\times\tan^{-1}\frac{1.71}{2(0.6-0.45)}$$

i.e.

$$78\mathrm{deg} \leq \mathrm{RSAV}_{110} \leq 160\mathrm{deg} \qquad (21)$$

As one can easily conclude from Equations (18) and (19), approach (a) is one-sided approach, i.e., it might only be effective when the boom preset height decreases; it could not accommodate the increase in boom preset height. Therefore, the rest of this article would discuss the technical requirements and implications that may arise from the deployment of approach (b).

2.2 The architecture and operation of the VSAFSN control system

Figures 2 and 3 show the architecture of the proposed system and the changing trends of the dependent variables with nozzle height respectively. As can be seen in Figure 2, an ultrasonic transducer monitors the height of the nozzle from crop canopy. The amplitude of the output signal from the transducer which is input to controller varies in proportion with the nozzle height. The controller sends two input signals; one to pressure regulator to adjust the liquid pressure, and the other to Pulse Width Modulator (PWM) to adjust the duty cycle of the spray solenoid valve. This means that the spray pressure, hence, spray angle, would change simultaneously while maintaining the desired spray volume and coverage on crop canopy.

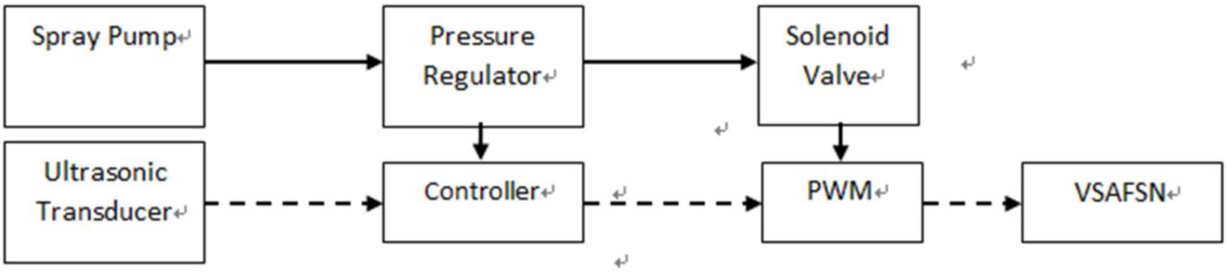

Figure 2 The architecture of the VSAFSN control

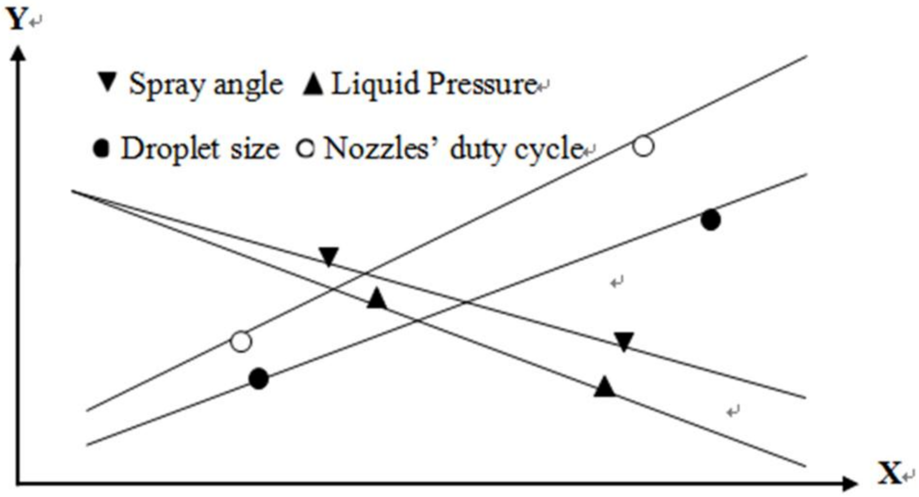

Figure 3 Anticipated variation of dependent variables(Y) as a function of spray nozzle height (X)

Figure 3 shows the anticipated changing trends of the spray angle, liquid pressure, droplet size, and nozzle duty cycle with nozzle height. As the height of the nozzle increases/decreases, the spray pressure, hence spray angle decreases/increases. Decrease/increase in spray pressure results in increase/decrease in droplet size (Grisso et al., 2013). Since the spray rate (GPM) is also dependent on spray pressure, the duty cycle of the nozzle increases/decreases to compensate for the change in rate of spray.

2.3 Experiments

To find out how the outcome of the idea might look like some preliminary experiments were carried out. TEEJET-XR11002 nozzle was examined using Sprayer Nozzle Testing and Calibration facility based in Agricultural and Biosystems Engineering department workshop of South Dakota State University as shown in Figure 4 Shown in the figure are

Note: Shown in the figure are collectors mounted on a swing table, test nozzles, and pressure gauge

Figure 4 Sprayer nozzle testing and calibration facility

To cover the spray angle range of 78 to 160 degrees (see Equation 13), the spray pressure was varied from 55 to 490 kPa. Spray angle was read directly from properly waterproofed paper protractor as shown in Figure 5.

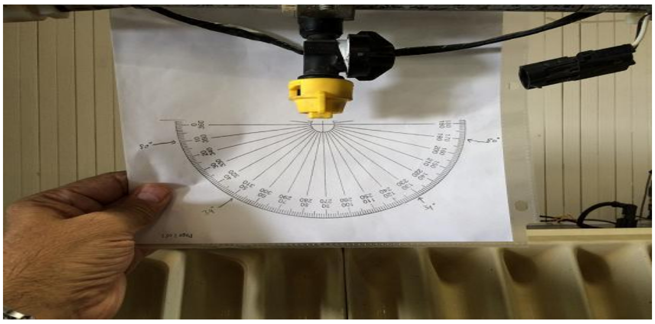

Figure 5 Waterproof paper protractor

3 Results and discussion

As mentioned in section 2.3 to provide spray distribution pattern for spray angles of interest, namely, 80, 110, 130, and 160 degrees, spray pump was switched on and spray pressure was set in such a way that a desired spray angle was achieved. The collectors mounted on the test table were then exposed to water spray until the middle collectors were almost full. The height of the water in each collector was read. As is shown in Figure 6 below, the spray maintained its almost normal distribution pattern within full range of spray angle.

Table 1 Spray distribution data: showing the height of water in each collector for different spray angles

Spray angle(deg)	Collector number																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
80	0.2	0.2	0.2	0.2	0.5	1	3	5.8	5.2	5	2	7.2	9	11	12	11.8	10	8	6.5	3.2	5	5.8	2.2	0.5	1	0.5	0	0.5	0.5	0.5
110	0.0	0.2	0.2	0.0	1.2	3	4.1	4.8	5.5	5.8	2	8	10	11	11	10.8	10.5	9	7	4	5.5	5	3.2	1	1	1	0.5	0.5	0.5	0.5
130	0.5	0.5	0.5	0.2	3	4.8	4	5	6	7	4	10	11	11.8	11.2	11.2	11	10.5	9	5.5	6.2	5.5	3.5	1	3.8	2	1	0.5	0.5	0.5
160	1	1.5	2.2	2	3.2	3.5	4	5.5	6.4	7.5	6	10.5	11.8	11.8	11.8	11.2	11	11.2	9.5	6.8	7	6	4	1.5	4	3	3	3.8	0.2	0.2

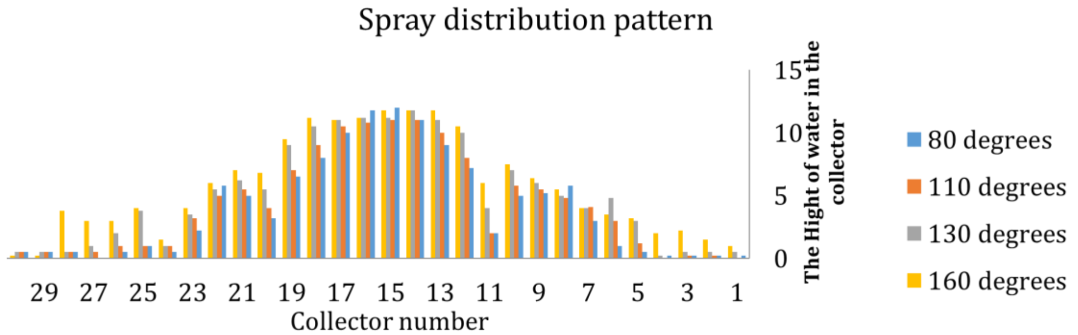

Figure 6 Distribution pattern within full range of spray angle used

The amount of water sprayed at different spray angles were collected for 20 seconds followed by the calculation of flow rates (Table 2 and Figure 7). Data from Table 2 were used to find "spray angle/operating pressure", and "spray angle/nozzle flow rate" relationships.

Table 2 Nozzle flow rates at different operating pressures and spray angles

Operating Pressure (x)*, kPa	Spray Angle (y* or x**), deg	Flow rate (y**), mL/min
55	80	375
83	110	450
152	130	600
490	160	1050

Note: *Relationship between spray angle (y) and operating pressure (x): $y = 0.1495x - 90.851, R^2 = 0.7953$

**Relationship between nozzle flow rate (y) and spray angle (x) was found as $y = 8.3824x - 387.13, R^2 = 0.8712$

Figure 7 Nozzle flow rate measurement

To examine the adequacy of the VSAFSN system it is necessary to conduct extensive lab tests in the first place including step response, frequency response, droplet size distribution, and uniformity of spray coverage before implementation of large scale field tests.

It is anticipated that maintaining uniform spray coverage at different nozzle heights by varying spray angle, increase in droplet size will result due to lower spray pressure (see Figure 3), reducing susceptibility of spray to wind drift.

As can be seen in Table 2, the flow rate of the spray decreased as spray angle decreased; this was in agreement with the results obtained by other researchers (Martin, 2013). Therefore, it can be expected that the amount of sprayed chemical would vary at different nozzle heights. This can be overcome through PWM; increasing the duty cycle of a nozzle (percentage of time that a solenoid operated nozzle would remain open during one cycle of operation or duty) as its height increases (see Figures 2 and 3). The main obstacles that must be overcome are the operational pressure/spray angle, spray angle/spray coverage, and operational pressure/spray flow rate non-linear relationships. This may require a software to send appropriate commands to pressure control valve as well as PWM to compensate the nonlinearity.

It may also be possible to limit the normal range of PWM duty cycle within say 25% to 75% in such a way that at lowest height duty cycle be set for 25% while at highest nozzle position the duty cycle of the nozzle be set for 75%; this would allow for incorporating Variable Rate Application (Lang, 2013) within full range of PWM cycles, i.e. 0 to 100%.

The limitations that may encounter in practice can include time of response of the valves and nozzles as well as the performance of the system at high travel speeds.

4 Conclusions

- rends towards achieving higher work rates, hence, longer spray booms and precision continues in chemical application operations and mechanical complexity of the systems increases.
- Simulation methods and modelling of dynamic behavior of the long spray booms seem to have well been developed by researchers.
- Optimization and redesigning of the components as well as designing smart control systems for spray boom behavior control are the aim of most research activities at the present time.
- The VSAFSN system proposed in this article proved to be a promising alternative in terms of improving the uniformity of spray in long spray booms susceptible to vertical oscillations.
- The proposed system may take advantage of VRT through using PWM.
- Commercially available nozzles can accommodate a range of pressure required to produce desired angles of spray.

5 Further research requirements to implement this concept

- Spray boom equipped with adequate number of spray nozzles is necessary for further study.
- Appropriate instrumentation system should be provided for precise and real time monitoring of important parameters such as spray operating pressure, spray angle and flow rate.
- A necessary circuitry and control system have to be designed to process signals from different distance measuring devices, including ultrasonic transducers within acceptable period of time.

- Dynamic response measuring system is needed to find out if the control system is fast enough to produce an appropriate operating pressure, hence spray angle.
- Detailed lab tests including step response, frequency response, droplet size distribution, and uniformity of spray coverage should be carried out prior to large scale field experiments.
- Some kinds of software are required to compensate the nonlinearities in the system.
- PWM controller must be provided for maintaining constant flow rate as well as obtaining desired variable rate of application (VRA).

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