REAL-TIME PRESSURE AND FLOW DYNAMICS DUE TO BOOM SECTION AND INDIVIDUAL NOZZLE CONTROL ON AGRICULTURAL SPRAYERS

A. Sharda, J. P. Fulton, T. P. McDonald, W. C. Zech, M. J. Darr, C. J. Brodbeck

ABSTRACT. *Most modern spray controllers when coupled with a differential global positioning system (DGPS) receiver can provide automatic section or swath (boom section or nozzle) control capabilities that minimize overlap and application into undesirable areas. This technology can improve application accuracy of pesticides and fertilizers, thereby reducing the number of inputs while promoting environmental stewardship. However, dynamic system response for sprayer boom operation, which includes cycling or using auto-swath technology, has not been investigated. Therefore, a study was conducted to develop a methodology and subsequently perform experiments to evaluate tip pressure and system flow variations on a typical agricultural sprayer equipped with a controller that provided both boom section and nozzle control. To quantify flow dynamics during boom section or nozzle control, a testing protocol was established that included three simulation patterns under both flow compensation and no-compensation modes achieved via the spray controller. Overall system flow rate and nozzle tip pressure at ten boom locations were recorded and analyzed to quantify pressure and flow variations. Results indicated that the test methodology generated sufficient data to analyze nozzle tip pressure and system flow rate changes. The tip pressure for the compensated section control tests varied between 6.7% and 20.0%, which equated to an increase of 3.7% to 10.6% in tip flow rate. The pressure stabilization time when turning boom sections and nozzles off approached 25.2 s but only approached 15.6 s when turning them back on for the flow compensation tests. Although extended periods were required for the tip pressure to stabilize, the system flow rate typically stabilized in less than 7 s. The tip flow rate was consistently higher (up to 10.6%) than the target flow rate, indicating that system flow did not truly represent tip flow during section control. The no-compensation tests exhibited tip pressure increases up to 35.7% during boom and nozzle control, which equated to an 18.2% increase in tip flow. Therefore, flow compensation over no-compensation had better control of tip flow rate. A consistent difference existed in dynamic pressure response between boom section and nozzle control. Increased tip pressure and delayed pressure stabilization times indicated that application variability can occur when manually turning sections on and off or implementing auto-swath technology, but further testing is needed to better understand the effect on application accuracy of agricultural sprayers.*

***Keywords.** Distribution, Liquid application, Precision agriculture, Swath control, Variable-rate technology.*

Pesticide and nutrient transport via runoff or leaching from agricultural land to surrounding surface and ground water bodies poses a potential environmental and public health concern. In 2007, U.S. farmers spent \$10.5 billion on pesticide application (USDA, 2008). With environmental stewardship becoming an increasingly sensitive issue, on-farm pesticide and nutrient application needs to be performed accurately to ensure that only a prescribed amount is applied. However, over- and under-application can commonly occur when applying these crop inputs. Further, calibration and proper maintenance can impact the performance of sprayers. Grisso et al. (1989) conducted a field survey of 103 private herbicide applicators in Nebraska and reported that only 30% were applying herbicide within 5% of the intended application rate. Based on these results, they estimated an additional cost of \$3.11 ha^{-1} due to over-application of herbicides equating to a \$4.26 million loss for the state of Nebraska. Sprayer application errors are typically due to worn nozzle tips, inaccurate calibration, or inability to maintain the required flow rate in the system during spraying (Grisso et al. 1989; Hofman and Solseng, 2004). Equipment operators can also impact the application performance by deviating from the desired swath, causing double coverage or no coverage in areas. Overlap generally occurs at headland turns, when operating within point rows, and between adjacent passes.

Today, most large self-propelled sprayers control application rate based on required system flow. The controller uses

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The authors are **Ajay Sharda, ASABE Member Engineer,** Graduate Student, **John P. Fulton, ASABE Member Engineer,** Associate Professor, and **Timothy P. McDonald, ASABE Member Engineer,** Associate Professor, Department of Biosystems Engineering, Auburn University, Auburn, Alabama; **Wesley C. Zech,** Engineer and Associate Professor, Department of Civil Engineering, Auburn University, Auburn, Alabama; **Matthew J. Darr, ASABE Member Engineer,** Assistant Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa; and **Christian J. Brodbeck, ASABE Member Engineer,** Research Engineer, Department of Biosystems Engineering, Auburn University, Auburn, Alabama. **Corresponding author:** John P. Fulton, Department of Biosystems Engineering, Auburn University, 200 Corley Bldg., Auburn, AL 36849; phone 334-844-3541; fax 334-844-3530; e-mail: fultojp@auburn.edu.

a flowmeter for closed-loop control and then either controls an in-line valve or the pump speed to maintain an established target rate in the controller regardless of ground speed changes or width changes (turning boom sections on or off). Therefore, this closed-loop approached minimizes application errors by adjusting the system flow to meet the required target rate. Al-Gaadi and Ayers (1994) reported that a spray controller reduced application errors to within -7% to 1% compared to a ground driven system, which produced a larger range of errors between -18% and 5%. Ayers et al. (1990) reported that a Dickey-John SC 1000 pressure-based sprayer control system maintained an application error of less than 5% with ground speeds varying between 3.2 and 9.7 km h^{-1}.

Over the past couple of decades, rate controllers have also evolved to implement variable-rate application (VRA) of inputs such as nutrients and pesticides. Past research on the response and accuracy of rate controllers has been conducted on variable-rate technology (VRT). Prior experiments on VRT have shown that real-time response of the controller was influenced by the type of rate controller, control hardware selection, and ground speeds (Ayers et al., 1990). The response time includes delays between when the control signal was conveyed and when the application rate was actually attained (Fulton et al., 2005a). Rockwell and Ayers (1996) designed and constructed a variable-rate direct nozzle injection field sprayer and concluded that the system took 3.8 s to go from 10% to 90% of the step input. The reaction time for the control system in response to the differential global positioning system (DGPS) receiver can be as high as 2.2 s while maintaining a horizontal accuracy of 1 m (Al-Gaadi and Ayers, 1999). Another study indicated that application errors for direct injection systems were estimated to be as high as 40% for mistreated areas of the field with the chemical rate change at the nozzles occurring as much as 80 m past the desired step change location (Qiu et al., 1998). Another issue when using direct injection systems is how product introduced into the spray plumbing, upstream of the nozzles and boom valves, gets delivered across the boom. Lateral location of nozzles along the boom also affected the application accuracy of boom injection sprayers (Miller and Smith, 1992). However, Vogel et al. (2005) indicated that rate changes for a variable-rate sprayer usually consisted of a smooth increase or decrease in herbicide rates, except that application rate spikes occurred when transitioning from off (areas requiring no input) to back on. The use of “fast” control valves produced flow rate spikes that reached as high as 450 L ha^{-1} between old and new target rates. A sprayer with a control system can provide accurate application rates within 2.3% of the desired rate but could have lag times ranging from 15 to 55 s (Anglund and Ayers, 2003).

More recently, a precision agriculture (PA) technology referred to as “automatic section control” or “auto-swath” turns on and off sections or individual control mechanisms, like boom valves, nozzle solenoids, or planting row clutches to reduce the over-application of crop inputs. Auto-swath technology was initially implemented on sprayers to enhance the application of liquid pesticides, fungicides, and nutrients. This technology utilizes a global positioning system (GPS) or Global Navigation Satellite System (GNSS) receiver along with application software to record areas that have already been sprayed or have been mapped as no-spray regions. If the boom section or nozzle starts to apply in these areas, the spray controller will respond by turning the boom sections or nozzles off accordingly. The use of auto-swath technology can potentially result in 15.2% to 17.5% reduction in sprayed area by way of efficiently managing boom sections (Luck et al., 2010).Therefore, overlap at headlands and within point rows is reduced, thereby providing product savings.

Rate control systems inherently have response time delays that can be classified into two types: (1) control system response and lag time, and (2) dynamic stabilization time due to spray system configuration (Fulton et al., 2005b). Intermittently turning nozzles on and off on one side can increase operating pressure on the other side of the sprayer (Salyani, 1999). Although concerns regarding control system response have been reported by many researchers, boom dynamics that may cause off-target application have not been reported for sprayers equipped with auto-swath systems. The fundamental understanding of boom dynamics is important to understand in order to develop (1) control systems and new technology and (2) the associated mechanical design (e.g., boom plumbing and related hardware) of agricultural sprayers. This understanding becomes even more pertinent as the size of agricultural sprayers increases and as we try to reduce the control aspect down to an individual nozzle. Real-time pressure differences during automatic boom section and nozzle control need to be investigated to understand their impact on application efficacy. Therefore, the objectives of this study were (1) to evaluate real-time system flow rate and tip pressure variations across the boom for a typical agricultural sprayer using various boom section and nozzle control experiments, and (2) to compare and contrast flow dynamics for a controller providing feedback flow compensation to no-compensation during boom section and nozzle control tests.

Materials and Methods

Sprayer and Data Acquisition System

All experiments were conducted using a three-point hitch mounted 18.3 m agricultural sprayer (Schaben Industries, Columbus, Neb.). The sprayer boom was divided into three sections: left (1), center (2), and right (3). There were a total of 37 nozzles spaced at 50.8 cm across the boom. Boom sections 1 and 3 were 6.1 m wide having 12 nozzles each, while section 2 had 13 nozzles and was 6.6 m wide. The sprayer was plumbed using a 2.54 cm inner diameter (ID) hose from the boom valves to each of the three boom sections. A 1.91 cm ID hose was used to connect nozzle bodies along each boom section. The length of the hose from the boom valve manifold to each boom section was 7.62 m for sections 1 and 3 but 2.44 m for section 2. Teejet 11003 extended-range flat spray tips were selected as nozzles (Spraying Systems Co., Wheaton, Ill.). Each nozzle was equipped with a 12 VDC solenoid valve (Capstan Ag Systems, Inc., Topeka, Kans.) in order to turn individual nozzles on and off. The sprayer utilized a hydraulically driven centrifugal pump (FMC-150-HYD-206, ACE Pumps Corp., Memphis, Tenn.). A commercially available spray controller was used for all tests. This system used a turbine-type flowmeter (model RFM-60P, Raven Ind., Sioux Falls, S.D.) and a 2.54 cm butterfly-type control valve (model 063-0171-120, Raven Ind., Sioux Falls, S.D.) to regulate the overall system flow rate. The calibration numbers used for the control valve and flowmeter were 2123 and 700, respectively, as suggested by the manufacturer’s literature. For the control valve number of 2123, the first digit (2) repre-

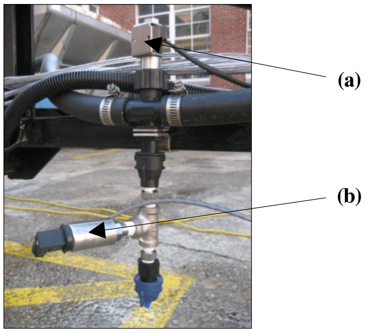


Figure 1. Illustration of nozzle body setup equipped with (a) Capstan solenoid body and (b) pressure transducer.

sents the valve backlash digit, which controls the time of the first correction pulse after detecting a change in correction direction of the valve. Backlash values range from 1 (short pulse) to 9 (long pulse). The second digit (1) controls the response time of the control valve motor with a range of 0 (fast response) to 9 (slow response). The third digit (2) is the valve brake point digit, or the point at which the control valve starts to turn at a slower rate to avoid overshoot when adjusting to the target rate. The values of the break point range from 0 to 9, where 0 corresponds to 5%, 1 to 10% 2 to 20%, and on up to 9 for 90% of the target rate. The fourth digit (3) represents the dead band, which sets the allowable difference between the target rate and the actual application rate. For the control valve used, the dead band can be set between 1 and 9, with 1 representing an allowable 1% difference and 9 corresponding to an allowable 9% difference. The flowmeter calibration number indicated 70 pulses per 37.85 L. The rate control system provided flow compensation (C) when programmed to the automatic control mode and no-compensation (NC) in the manual mode. During the compensation tests, the controller attempted to maintain the set target rate (L ha^{-1}) with any changes in application width (nozzles or boom section turned on and off) and/or ground speed. The rate controller was set to simulate a 56.8 L min^{-1} flow rate at a ground speed of 9.7 km h^{-1}.

To measure nozzle tip pressure (fig. 1), thin-film pressure transducers (model 1502 B81 EZ 100 PSI G, PCB Piezotronics, Inc., Depew, N.Y.) were used at ten nozzle locations. Nozzles were numbered from 1 to 37 starting from the left side, with transducers mounted on nozzles 1, 8 12, 17, 20, 22, 25, 29, 35, and 37 (fig. 2). The pressure transducers had a measurement range of 0 to 689.5 kPa with reported accuracy of $\leq$0.25% full scale and a response time of $\leq$1 ms. Another pressure transducer was mounted at the boom valve manifold to monitor the overall system pressure at the same location where the analog pressure sensor providing feedback to the operator was plumbed by the sprayer manufacturer. The input signal to the boom valves was used to decide the on and off status of the boom valves based on high (13 VDC) and low (0 VDC) voltage. The analog signals from the pressure transducers and the three boom valves were sampled using two National Instruments (NI) 9221 analog input modules. System flow rate was measured using the existing in-line flowmeter connected to a Measurement Computing (MC) USB-4303 counter/timer board. A program in LabVIEW (version 8.6, National Instruments Corp., Austin, Tex.) was written to read the analog signals, and the frequency from the MC board. The developed LabVIEW program also converted the analog signals from the various transducers to a pressure and converted the flowmeter frequency to the system flow rate. All data were time-stamped and written at 50 Hz to a *.txt file for analyses.

EXPERIMENTAL DESIGN

A total of ten tests were conducted and replicated three times to evaluate real-time system flow and tip pressure (fig. 2). The testing procedure was comprised of two boom section (B) and three nozzle control (N) tests. During each test, boom sections or nozzles with stable system pressure were turned off and then switched back on, allowing system pressure to stabilize each time between off and on. For each test, the sprayer was allowed to run for 60 s to attain stable system pressure before turning boom sections or nozzles off (fig. 3). Locations for installing ten pressure transducers were established with the intent to record pressure changes at varying distances from the point of liquid entry at each boom section. During the two boom control tests (B1 and B2), either one or two consecutive boom sections were turned off and then back on, respectively. Nozzle control tests N1 and N2 were similar to boom section tests B1 and B2 with the point of on/off control (nozzle versus boom valve) being the difference (fig. 2) for comparison. The third nozzle control test (N3) consisted of turning 31 nozzles off and then back on to evaluate conditions when only a few nozzles remained on. The boom section and nozzle tests represent unique operating conditions when using auto-swath technology. The real-time tip pressure directly reflects the extent to which the control system is successful in maintaining constant application rates during auto-swath engagement and disengagement. These tests also quantify the stabilization time for tip pressure and system flow rate during these engagements and disengagements, thus providing insight on control system response time and boom plumbing dynamics. Comparison of flow compensation (C) and no-compensation (NC) tests will ascertain the controller's ability to regulate and maintain system flow rate for the set target rate. Therefore, abbreviations will be used to indicate the various tests (e.g. B1-C indicates

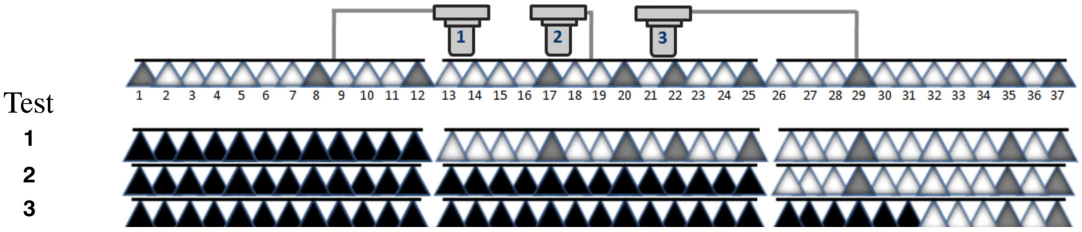


Figure 2. Sprayer plumbing configuration from the three boom valves to each boom section (number assignment between 1 and 37 from left to right for each nozzle). Gray triangles represents nozzles equipped with pressure transducers, while black triangles indicate nozzles turned off for the various tests.

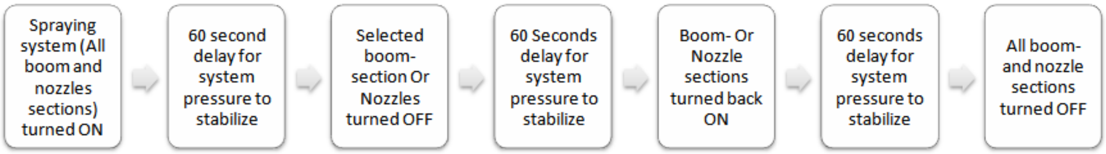


Figure 3. Data collection procedure used for all tests.

boom section control, test 1, with flow compensation, whereas N1-NC represents nozzle control, test 1, with no-compensation).

The test and data collection procedures for the boom and nozzle control tests were identical (fig. 3). The data were collected for two boom-section control tests with compensation (B1-C and B2-C), two boom-section tests with no-compensation (B1-NC and B2-NC), three nozzle control tests with compensation (N1-C through N3-C), and three nozzle control tests with no-compensation (N1-NC through N3-NC). The data for all ten tests were analyzed separately for the part of the experiment when sections were turned off and subsequently back on.

A program in MATLAB (R2008a, The MathWorks, Inc., Natick, Mass.) was written to compute the initial nozzle pressure before initiating a test, final settling pressure (FP), settling time (ST), percent overshoot (OS), lag time, boom valve input signal (or off/on) time, flow rate stabilization time, and pressure stabilization time. A boom valve input signal of 13 VDC was considered on, and 0 VDC was considered off. The flowmeter calibration number corresponds to the number of pulses for every 37.8 L of fluid passing through the flowmeter; therefore, system flow rate was calculated using the following equation:

$$FR = \frac{10 \times f \times 227.12}{MCN} \tag{1}$$

where

FR = system flow rate (L min^{-1})
MCN = meter calibration number for flowmeter
227.12 = constant to convert gallons per second to L min^{-1}
f = flowmeter frequency (Hz).

The settling time (ST) represented the difference between the time of observation of ±5% change in tip pressure from the initial system pressure to the time when the tip pressure finally reached and stayed within ±5% of the final pressure after the boom section was turned off. The data tables present the average values of final pressure, percent change in pressure, pressure settling, and stabilization times considering only the boom sections or nozzles that are on. In addition to pressure and system flow rate, the boom input signal to each boom valve was recorded to estimate pressure and flow rate stabilization times. Pressure stabilization time (PST) was defined as the difference between the time the input signal actuated a boom valve to the time when the pressure settled and remained within 5% of the final value. The lag time was computed by taking the time difference between when the first nozzle on the section exhibited a pressure change compared to when the other nine nozzles exhibited an initial pressure change. Therefore, the PST is the sum of the settling time and lag time. The flow rate stabilization time (FST) represents the difference between the time when the boom valve was turned off to the time when the system flow rate settled and remained within 5% of the final value. For presentation purposes, only one pressure sensor from each of the boom sections was selected and presented along with the system flow rate. In the figures, a black dotted line is used to separate when boom valves or nozzles were turned off (left side of line) and when they were turned back on (right side of line).

An analysis of variance (ANOVA) was conducted using the General Linear Model (GLM) procedure in SAS (SAS Institute, Inc., Cary, N.C.) to ascertain if statistical differences existed between tip pressure, PST, and FST based on the mean values of these parameters during different tests. Means and standard deviations for different parameters were also calculated using the GLM procedure. A two-sample t-test was used to obtain statistical differences between initial and final tip pressures for each test. Multiple comparisons of tip pressures for all tests were conducted using the Tukey-Kramer procedure. The tip pressure coefficient of variation (CV) was computed across the boom and signified the tip spray uniformity for any point in time. All statistical analyses were conducted using a 95% confidence interval. A second-order polynomial regression line ($y = -2 \times 10^{-5} x^2 + 0.0059x + 0.1003$, where y is the tip flow rate and x is the measured tip pressure, $r^2 = 0.999$) was fitted to the manufacturer's tip pressure versus flow rate data to estimate tip flow rate (Teejet, 2008).

RESULTS AND DISCUSSION

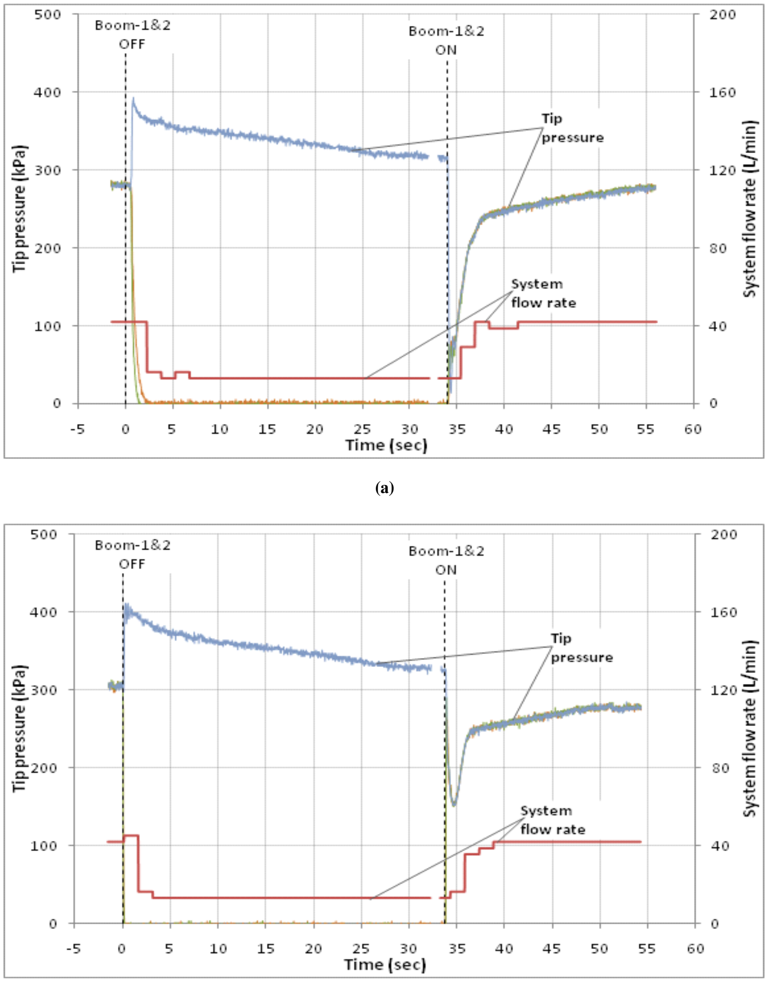
FLOW COMPENSATION TESTS

The increase in tip pressure ranged from 6.7% to 20% during flow-compensated tests (table 1) when turning boom sections or nozzle off. Boom control tests (B1-C and B2-C) demonstrated tip pressure increases between 9.4% and 14.1% while tip pressure increases between 6.7% and 20.0% were observed during nozzle control tests (N1-C, N2-C, and N3-C). The highest tip pressure increase (20.0%) occurred during the N3-C test when 31 out of 37 nozzles were turned off. The increase in nozzle tip pressure from 6.7% to 20.0% during various tests was equivalent to 3.7% to 10.6% increase in the tip flow rate. Figure 4 depicts the nozzle tip pressure variation during the B2-C and N2-C tests, respectively. It can be determined from figure 4 that once sections 1 and 2 were turned off, the final tip pressure could not stabilize to the initial pressure conditions even for the flow compensation tests. This increase in tip pressure could be due to the fact that the controller adjusted the system flow rate based on feedback from the flowmeter and did not take into account the tip pressure or boom flow dynamics when sections were turned off. Controller response based only on flow rate feedback also resulted in second-order dampening and delayed stabilization of tip pressure during section control. This result is illustrated in figure 4 where the tip response did not correspond to the upstream flowmeter (closed-loop feedback for controller) response, which may be an important consideration for spray control systems or when designing

Table 1. Summary of tip pressure and flow rate results (means presented with standard deviation provided in parenthesis) for both flow compensation and no-compensation when sections were turned off.[a]

Test	IP (kPa)	% Change in Tip Pressure	% Increase in Tip Flow Rate	OS (%)	ST (s)	FST (s)	PST (s)
Compensation							
B1-C	278.7 (0.1)	9.4 ef (0.1)	5.1 (0.0)	6.5 d (0.3)	0.3 (0.1)	2.9 ab (0.6)	1.0 d (0.1)
N1-C	296.2 (0.4)	6.7 f (1.0)	3.7 (0.5)	12.3 c (0.7)	11.3 (1.6)	4.7 a (2.4)	11.4 c (1.1)
B2-C	277.5 (0.1)	14.1 cde (0.9)	7.3 (0.5)	23.0 a (1.5)	23.7 (3.3)	3.9 ab (0.8)	24.4 a (3.3)
N2-C	294.0 (1.6)	11.8 efd (4.7)	6.3 (2.7)	25.1 a (2.9)	25.1 (2.2)	3.5 ab (0.3)	25.2 a (2.2)
N3-C	304.9 (1.1)	20.0 b (2.4)	10.6 (1.2)	19.1 b (1.0)	17.9 (1.5)	2.7 b (0.0)	18.0 b (1.5)
No-Compensation							
B1-NC	285.9 (0.1)	17.2 bc (0.2)	9.3 (0.1)	1.7 e (0.2)	0.1 (0.0)	2.5 ab (0.2)	0.7 d (0.0)
N1-NC	293.0 (0.4)	16.0 bcd (0.6)	8.8 (0.4)	3.4 ed (0.3)	0.1 (0.0)	1.9 b (0.4)	0.1 d (0.0)
B2-NC	284.9 (0.2)	35.3 a (0.6)	18.1 (0.3)	4.0 ed (0.9)	0.1 (0.0)	3.0 ab (0.7)	0.7 d (0.0)
N2-NC	292.3 (0.4)	34.1 a (1.5)	17.8 (0.7)	3.7 ed (0.4)	0.1 (0.0)	4.3 ab (0.2)	0.1 d (0.0)
N3-NC	301.3 (0.3)	35.7 a (0.9)	18.2 (0.4)	6.1 d (0.8)	0.2 (0.0)	2.4 ab (0.4)	0.3 d (0.0)

[a] IP = initial pressure, OS = overshoot, ST = settling time, FST = flow stabilization time, and PST = pressure stabilization time. Within columns, means followed by the same letter are not statistically different at the 95% confidence level.



(a)

(b)

Figure 4. Tip pressure, system flow rate, and control input signal for flow compensation tests (a) B2-C and (b) N2-C.

the mechanical aspects for sprayers (e.g., plumbing, hose length, valve locations, etc.). This consideration would minimize application errors when these conditions are encountered under field operation. However, additional research is required to more fully understand the responses measured, determine the primary causes, and determine how to reduce this effect in order to minimize potential application errors.

System response was found to be different while turning boom sections off (table 1) versus turning them back on (table 2). The boom system pressure stabilization took longer than expected during compensated section control tests. The

Table 2. Summary of tip pressure and flow rate results (means with standard deviations in parentheses) for both flow compensation and no-compensation when sections were turned back on.[a]

Test	US (%)	ST (s)	FST (s)	PST (s)	FP (kPa)
Compensation					
B1-C	-52.5 d	10.7	4.8 ab	10.9 b	275.1
	(0.0)	(0.2)	(4.6)	(0.2)	(0.3)
N1-C	-9.2 f	3.0	3.0 b	3.0 c	278.6
	(0.2)	(0.4)	(0.8)	(0.4)	(0.3)
B2-C	-99.3 a	15.3	6.4 ab	15.6 a	277.2
	(0.0)	(1.6)	(4.5)	(1.5)	(0.1)
N2-C	-46.4 e	11.8	5.9 ab	14.0 ab	278.6
	(0.0)	(0.6)	(2.0)	(3.4)	(0.1)
N3-C	-59.7 c	14.4	10.7 a	14.4 a	276.5
	(0.0)	(0.8)	(1.3)	(0.8)	(0.0)
No-Compensation					
B1-NC	-42.8 e	1.6	3.1 b	0.9 c	284.1
	(0.0)	(1.7)	(2.1)	(0.1)	(0.1)
N1-NC	-4.1 g	0.2	3.0 b	0.2 c	289.6
	(0.0)	(0.0)	(1.6)	(0.0)	(0.2)
B2-NC	-71.4 b	1.0	4.7 ab	1.2 c	285.5
	(0.0)	(0.1)	(1.2)	(0.1)	(0.1)
N2-NC	-3.5 g	0.2	4.0 b	0.3 c	291.7
	(0.0)	(0.0)	(1.1)	(0.0)	(0.1)
N3-NC	-3.8 g	0.2	2.3 b	0.2 c	297.9
	(0.2)	(0.1)	(0.3)	(0.0)	(0.1)

[a] US = undershoot, ST = settling time, FST = flow stabilization time, PST = pressure stabilization time, and FP = final pressure. Within columns, means followed by the same letter are not statistically different at the 95% confidence level.

PST varied between 1.0 and 25.2 s (table 1) when turning sections off and between 3.0 to 15.6 s after a section was turned back on (table 2). The tip pressure exhibited a second-order under-damped system response, with gradual decrease in tip pressure before stabilization, when boom sections were turned off (fig. 4), whereas the tip pressure gradually increased and exhibited a second-order over-dampened response when sections were turned back on (fig. 4). Tip pressure stabilization times for the B2-C (fig. 4a) and N2-C (fig. 4b) tests were 24.4 and 25.2 s, respectively, when sections were turned off, while stabilization times were 15.6 and 11.9 s, respectively, when sections were turned back on. A similar trend can be seen between the B1-C and N1-C tests involving one boom section. The flowmeter and flow control valve response time largely contributes toward the PST. The higher PSTs when turning the sections off could be due to the slow response of the flow control valve while adjusting the system flow to the target rate. During nozzle control, the liquid within the hoses between the boom valves and nozzles remained pressurized. Therefore, when the sections were turned back on, nozzle control demonstrated lower pressure stabilization times as compared to the boom section tests.

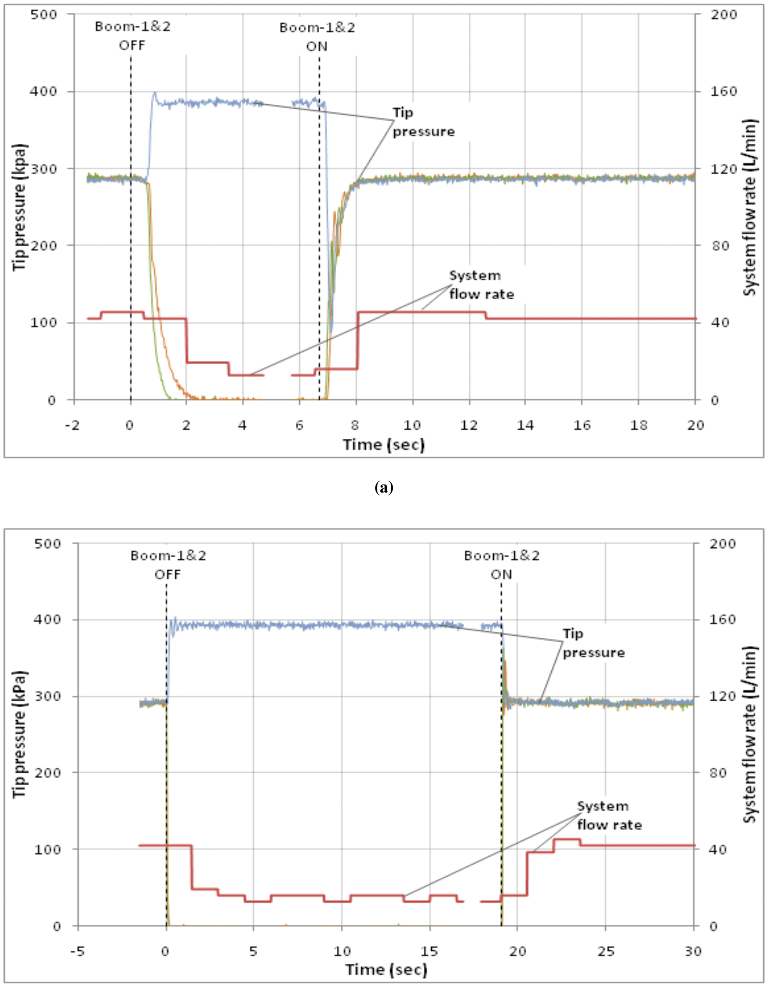
The percentage overshoot in tip pressure for the flow compensation tests varied from 6.5% to 25.1% (table 1), which was proportional to the pressure settling times (0.3 to 25.1 s) with the exception of B1-C. The tip pressure demonstrated 46.4% to 99.3% undershoot when the sections were turned back on. The lower undershoot and PST during nozzle control tests signified that nozzle control provided lower tip pressure variations across the boom and faster pressure stabilization when turning sections back on. There was little difference between the settling and pressure stabilization times, demonstrating negligible lag time for all flow compensation tests. Therefore, a 3.7% to 10.6% increase in final tip flow rate with a pressure stabilization time between 1.0 and 25.2 s can result in off-target application when boom sections or nozzles are turned off. The over-damped system response accompanied by PSTs between 3.0 and 15.6 s when turning boom sections back on will essentially contribute to under-application even when implementing flow compensation.

For the boom section tests, the PST within the boom sections turned off was up to 1.6 s. This delay in tip pressure reaching zero could be attributed to the fact that the nozzles continued to spray for a short time until the residual pressure in the boom section equaled the pressure drop across the nozzles. During both the boom section and nozzle control tests, the tip pressure responded almost instantaneously (<260 ms) and coincided with the input signal (dotted black line; fig. 4a) to the boom valve or nozzle solenoids while turning off or on.

The system flow rate stabilized between 2.7 and 4.7 s (table 1) when boom sections were turned off. Flow rate stabilization took between 3.0 and 10.7 s (table 2) when turning boom sections back on. The FST was longer when a section was turned back on compared to turning it off. It was also observed that the system flow rate was sensitive to the number of boom sections initially turned off before turning the entire boom back on. Of interest, these results did not indicate a trend between the flow rate stabilization times and the number of boom sections or the percentage of the boom turned off. The longer flow stabilization time for B2-C compared to B1-C was expected since B2-C required a larger adjustment by the control valve. It was also interesting to note that the system flow rate stabilized to the target rate value within 7.0 s, while the tip PST lasted as long as 25.1 s with tip pressures remaining 20% more than the initial pressure. The sample standard deviation between the replications for tip pressure, percent change tip flow rate, OS, FST, and PST was found to be low except for the FST when turning sections back on (tables 1 and 2). Thus, these results suggested that the system flow does not directly correspond to the tip flow rate response during these stabilization periods. The difference in the PST and FST also implied the need for a secondary, real-time feedback mechanism to provide information to the spray controller to manage boom dynamics. This feedback mechanism could use both tip pressure and system flow rate as a means to either implement a look-ahead time to make adjustments in a timely manner or adjust settings to minimize application errors.

NO-COMPENSATION TESTS

The no-compensation tests demonstrated tip pressure increases between 16.0% and 35.7% (table 1) when boom sections were turned off. This range equated to a respective increase of 8.8% to 18.2% in tip flow rate. There was a two-fold increase in tip pressure for B2-NC (two boom sections off) compared to B1-NC (one boom section turned off). The trends for the increase in tip pressure were also similar to the compensating tests. Tip pressure for the no-compensation tests increased by two times as compared to the flow-compensated tests. The final tip pressure after the sections were turned back on stabilized close to the initial conditions (table 2).



(a)

(b)

Figure 5. Tip pressure, system flow rate, and control input signal for tests (a) B2-NC and (b) N2-NC.

The PST was less than 1.2 s for all no-compensation tests whether turning boom sections off or on (fig. 5). System response when turning boom sections off versus turning them back on was similar to the compensating tests. Overshoot in tip pressure for the non-compensating tests was between 1.7% and 6.1%, which was lower than the compensating tests (6.1% to 25.1%). The system FST varied between 2.0 to 6.9 s and was comparable to the flow-compensated tests when boom sections were turned off. Similar trends in PST and FST were observed when boom sections were turned back on. The system flow rate deviated by 24.6% (B2-NC) and tip flow rate increased up to 18.2% during the no-compensation tests. It is expected that no-compensation would have resulted in redistribution of energy in the hoses, thereby increasing the tip flow rate during different tests. This redistribution of energy and increased tip flow rate could be the predominant reason for nearly equal system flow rates even during the no-compensation tests. The unit frequency on the flowmeter represented 3.2 L min^{-1} with a response time of 1.5 s; therefore, a flowmeter with better resolution and faster response will help further understand system flow rate behavior. Tip pressure response during the no-compensation boom section and nozzle control tests was similar to that during the compensation tests. The computed standard deviations were considered small for all the no-compensation data (tables 1 and 2).

Faster response during the no-compensation tests should not be interpreted as an advantage over compensation when using auto-swath technology. The quick response during no-compensation is due to the rapid redistribution of energy in

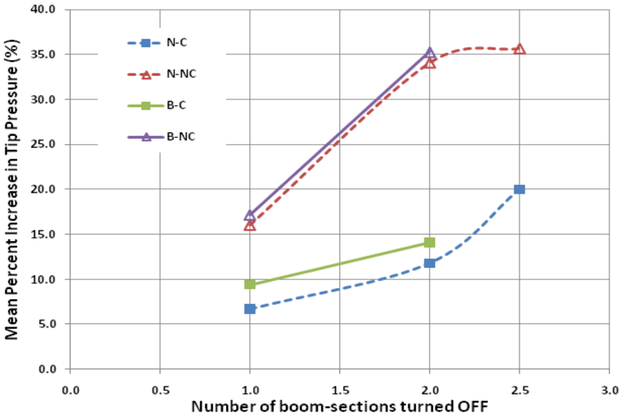


Figure 6. Mean percentage increase in tip pressure for those nozzles which remain on versus the number of boom sections turned off for the various boom-section (B) and individual nozzle (N) tests.

Table 3. ANOVA results for mean tip pressure, PST, and FST during different section control tests.

Source	Degrees of Freedom	Sum of Squares	p Value
Tip pressure sections turned off	10	901.0	<0.0001
PST sections turned off	9	2978.1	<0.0001
FST sections turned off	9	21.41	0.0155
PST sections back on	9	1221.3	<0.0001
FST sections back on	9	169.8	0.0095

the hoses to those nozzles still on since the controller has no feedback from the flowmeter. Therefore, flow compensation is a tradeoff between having tip pressure increases between 6.7% and 20% with some settling time to achieve the target system flow rate as opposed to a 35.7% increase during the N3-NC test.

The tip pressure increase was greater during the boom control tests and was roughly proportional to the percentage or number of boom sections or nozzles turned off (fig. 6). This tip pressure increase could be the result of the net decrease in pressure drop across the control system hardware, but it requires further investigation. Tip pressure increase resulted in a statistically different and proportional increase in tip flow rate, which can increase application errors, as the number of sections turned off increases. The unequal increase in tip pressure during comparative boom and nozzle control tests could be largely due to the location point of turning the liquid on and off. For a given system flow rate, there will be dissimilar pressure drop across boom valves and nozzles, which might be the cause of different effective tip pressures during boom section and nozzle control tests. The final nozzle tip pressure when the boom sections or nozzles were turned back on stabilized close to the initial tip pressure (table 2).

The ANOVA procedure demonstrated that mean tip pressure during all the boom and nozzle control tests was significantly different from the initial and final tip pressures (table 3). The PST with sections turned off and the PST and FST after sections were turned back on were also significantly for different tests. Multiple comparisons of all tests using the Tukey-Kramer procedure indicated that the PSTs when turning sections on/off and the FSTs when turning sections back on were significantly different for the flow compensation tests, whereas the PSTs and FSTs were not significantly different for the no-compensation boom and nozzle control tests.

The tip pressure (fig. 7) along the boom had a CV of up to 70% for a short duration (<600 ms) during PST, whereas it was less than 1.5% otherwise. The boom control tests had tip pressure CVs over 7% for approximately 1.8s (figs. 7a and 7b) when turning sections back on. In general, nozzle control offered faster tip pressure response when turning sections on and off, resulting in lower CVs. The results also indicated that the magnitude in tip pressure increase depended on the number of boom sections or nozzles turned off (fig. 6). The control point for turning boom valves or nozzle solenoids on and off impacted boom system flow dynamics. Nevertheless, auto-swath control generated complex and unique flow

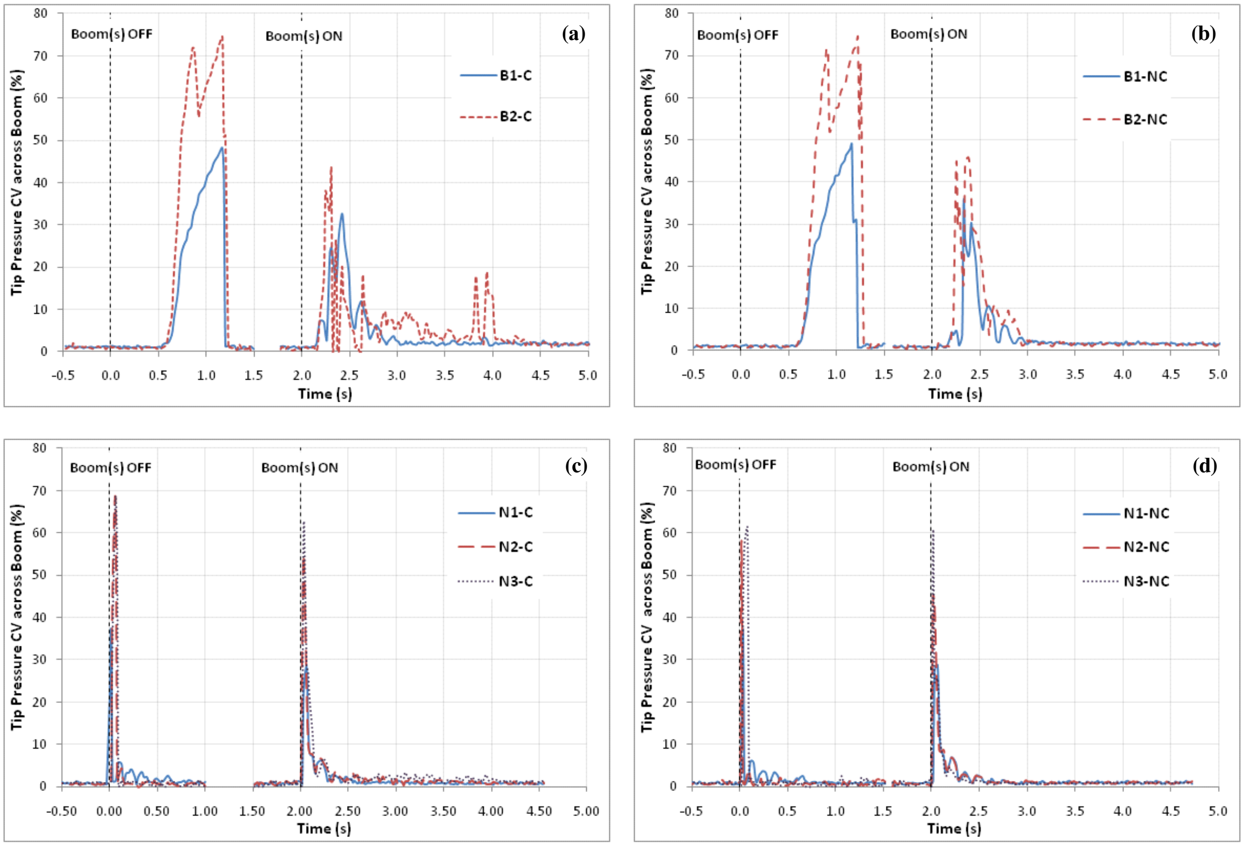


Figure 7. Tip pressure CVs across the spray boom during the boom section (a) flow compensation and (b) no-compensation tests along with the nozzle (c) flow compensation and (d) no-compensation tests.

dynamics affecting tip pressure and system flow rate. Considerations on how to improve the PST beyond 10 s is needed to minimize application errors. However, further testing, both in the lab and in the field, is needed to fully understand flow dynamics while using automatic section control technology. The tip pressure and PST between turning sections on and off was consistently different for the various tests, which indicated a need to reassess rate controller strategies during on and off routines. The comparison between compensation and no-compensation showed that although auto-swath technology did control the pressure and flow rate, it could not maintain constant tip pressure and flow rate to match the application rate during section control. In general, pressure stabilization times and elevated tip pressures during and after system flow rate stabilization suggested that off-target application errors can occur when using automatic section control technology. The tests selected for the purpose of evaluating boom fluid dynamics provided a preliminary understanding of the control system behavior when turning boom sections or nozzle solenoids on and off.

CONCLUSIONS

The following conclusions were drawn from this study:

- Tip pressure varied between 6.7% and 20.0% from the initial tip pressure, which was equivalent to an increase of 3.7% to 10.6% in tip flow rate during the flow compensation tests. The tip pressure increase was approximately proportional to the percentage of boom sections turned off during all boom section and nozzle control tests.
- The tip PST, when turning sections off and back on, was up to 25.2 and 15.6 s, respectively, for the compensating tests. Conversely, the system FST was typically less than 7 s during the compensation and no-compensation section control tests. Therefore, these results highlighted that a difference can exist between the control measurement point (flowmeter) and actual point of application (the nozzle) when using auto-swath technology. However, additional research is needed to better understand this difference.
- Nozzle control tests showed an instantaneous response (<140 ms) in tip pressure, demonstrating negligible lag time. The point of control (boom valve versus nozzle) contributes significantly towards boom flow dynamics during section control.
- Nozzle tip flow rate was always higher (4% to 11%) than the flow rate measured by the flowmeter. Therefore, system flow rate did not represent tip flow rate during section control.
- Flow-compensated boom and nozzle control tests exhibited 20.0% increase in tip pressure but successfully managed system flow rate to match the target application rate. The no-compensation tests demonstrated up to 24.6% variation in system flow rate and 35.7% increase in tip pressure during boom and nozzle control tests.

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