Ground Speed Control of a Direct Injection Sprayer

Y.M. Koo, Assistant Professor
Department of Agricultural Machinery
Kyungpook National University
Taegu, 702-701, Korea
and
H.R. Sumner, Research Agricultural Engineer
USDA-ARS, IBPMRL
Tifton 31793 GA, USA

ABSTRACT

A direct injection-mixing total-flow-control sprayer was developed and evaluated. The system provided precise application rates and minimized operator exposure to chemicals as well as providing a possibility for recycling containers of unused chemicals that can cause environmental contamination. Chemicals were metered and injected proportionally to the diluent flow rate to provide constant concentrations. The main diluent flow was varied in response to changes in travel speed.

Experimental variables of the sprayer were the control interval, the sensitivity of flow regulating valve, the tolerance of control object and the sensitivity of the injection pump system. The optimal performance of the flow control system was with an average response time of 8.5 sec at an absolute steady-state error of 0.067 L/min (0.8% of flow rate). The average response time of the injection rate was -0.53 sec and the coefficient of variation (CV) of concentration was 3.2%.

Keywords: Direct injection sprayer, Ground speed control, Spray controller, Applicator safety, Recycling pesticide containers.

INTRODUCTION

Agrichemicals are applied by sprayers to add plant nutrients and to control weeds, diseases, and insects. Chemicals must be applied at the correct rate to achieve satisfactory results and maintain crop yields. Deviations from the desired application rate cause inefficient pest control in under-applications, while over-applications increased production cost and may leave illegal residue on crops. The guideline for commercial applicators by U.S. Department of Agriculture and Environmental Protection Agency states that application errors should be within 5 percent of the recommended rate (Cupery, 1988; Grisso et al., 1989). Major causes of application error are calibration, malfunction of equipment, inadequate hardware and inaccurate sprayer travel speed.

Environmental contamination and occupational exposure to hazardous chemicals have become concerns for all of society. Agricultural workers involved in chemical applications are vulnerable to possible chronic exposure to chemicals by spills, released vapors, or fine particles produced during mixing, loading and applying (Brazelton, 1988). The development of ground-based chemical application methods that provide precise control and minimize operator contact with chemicals has stimulated research on spray control systems, nozzle design, and application techniques to solve current problems (Ayers et al., 1990; Loussaert, 1992; Koo and Kuhlman, 1993; Ghate and Perry, 1994; Rockwell and Ayers, 1994).

Two control principles necessary to achieve a constant pesticide application rate, independent of travel speed, are: (1) to vary the total flow rate based on travel speed and maintain constant chemical concentration; (2) to vary the chemical concentration in the diluent flow based on travel speed and maintain a constant total flow rate. The second concept has become known as the 'injection metering' or the 'direct injection' system. The injection system has many potential advantages. The most obvious advantages would be the significant reductions of exposure and leftover spray mixtures, including recycling chemical containers and multi-chemical injection applications. However, when chemicals are injected into a spray boom, a definite period of time is required for a change in concentration to become fully established at the spray nozzles. The time delay results in a transient error in application rate (Koo et al., 1987; Budwig et al., 1988; Tompkins et al., 1990).

The concept of injection mixing provides a potential advantage of protection from hazardous chemicals without the transient error when used with the first concept of total flow control. In the injection-mixing total-flow-control system, chemicals are metered and injected proportionally to the diluent flow rate, so `that the concentrations are kept constant while the main diluent flow is varied in response to changes in travel speed.

The objective of this research was to develop and evaluate an injection-mixing total-flow-control spray system. The system would provide precise application rates, and minimize operator exposure to chemicals, as well as provide the possibility of recycling containers of leftover pesticides that could cause environmental contamination.

MATERIALS AND METHODS

Test Apparatus and Sensors

The injection sprayer test apparatus used in the test consisted of a diluent flow system, a concentrate injection system, spray booms, and a console for output adjustment (Fig. 1). The main flow system of the sprayer was built with a water tank (T, 200 L) and a regenerative turbine pump (Youjin Company 101, 30-40 L/min at 500-600 kPa) driven by the tractor PTO (Daedong L2202-4WD). An electro-mechanical butterfly valve (R, 244A-3/4, Spraying Systems Co.) was installed at the bypass line for regulating pressure and liquid flow rate to booms selected with a solenoid valve (S, 144A, Spraying Systems Co.). The response time of the regulating valve was 14 seconds for a quarter turn, fully closed to open. A sine curve characterized the behavior of pressure change during the valve turn.

A flow circuit was constructed with 25 mm dia hoses for inlet and outlet to the main pump, 20 mm PVC pipes for main and bypass lines, and 16 mm PVC pipes for the booms after the solenoid valve. Ten extended pressure range nozzles (N, XR8002, Spraying Systems Co.) were installed at 50 cm spacing along a 6-m boom. The concentrate injection system was a reciprocating piston pump (I: FMI, CSC-Q1) with a variable DC motor (M, FMI-QV, 1/27HP, 0.41A). A 3-L pesticide tank(Q) was connected to the pump suction with a quick-dry lock disconnector. The concentrate material was injected into an injection port(A) against an inline check valve.

The following sensors measured and controlled physical quantities used in the sprayer. The details of CPU and interface are presented in Fig. 2. A pressure transducer (P, Omega, PX181, 170.72Pa/digit) and a dial gauge(J) were installed at the mainline. A turbine flowmeter (F, Omega, FTB603, K=3100 pulses/L) was located 15 cm downstream of the boom solenoid valve to meter diluent flow rate to the boom. A proximity sensor (V, GoldStar Electronics, ZVF-C12-4DNO) was used to measure sprayer speed. The proximity sensor was near a toothed plate (60 teeth, 0.16 kph/pulse) and installed on the inside of the rear wheel. A slippage adjustment was required and applied to the control program. An rpm encoder (E, GoldStar Electronics, MS50-0060BO) was synchronized with the injection motor to estimate the injection rate of concentrate. The concentration was measured with a conductivity sensor (C, Omega, CDE-344).

A programmable logic controller (PLC)(GoldStar Electronics, G5) was used to control the sprayer with the interface of digital input/output (D/I, D/O), analog-to-digital converter (A/D), digital-to-analog converter

(D/A) and counter (H/C). The D/I was optically isolated(K) for use with the main and reset switches. The digital input was used to count the low frequency signal of the proximity sensor to obtain travel speed. The D/O was used to drive 12 volt DC relays, which played a major role for pressure and flow controls by forward- and backward-rotating of the regulating valve. The A/D (1mV resolution) was used to measure analog signals from the pressure transducer(P) and battery supply voltage(B). Pulse signals from the flowmeter(F) and RPM encoder(E) were counted using H/C (20 kHz) for research purpose; however, the frequency signal could be converted to analog voltage signal using a frequency to voltage (F-V) converter(G) for realistic application. The DC drive motor to the injection pump has a converter-fed variable drive (D: FMI, V200) to control the injection rate of concentrate using an analog signal (4-20mA) generated by a control program through the D/A (4μA, resolution). The PLC was able to independently control the system; however, a personal computer was linked to the system for the data acquisition and monitoring sequence.

Test Procedure and Variables

A step input of 8 to 12 km/h for the tractor travel speed was applied to analyze the dynamic characteristics of the sprayer control. The control interval of 2.0, 1.0, and 0.2 sec; the tolerance (k4) of 2(±0.5%), 9(±2.25%), and 18(±4.5%); and the sensitivity (k3) of 3(slow), 4(mid), and 5(fast) for the flow regulating valve; and the sensitivity (k2) of 1(slow), 2(mid), and 3(fast) for injection pump motor were selected for the independent variables of the experiment. Dependent variables of the tests were the response time(RSPT), the absolute steady-state error(ASSE), the coefficient of variation(CV), overshoot(OS) for the control analysis; and the diluent flow rate(Qw), concentrate injection rate(Qp) and concentration(C) for the performance analysis.

The RSPT was defined as the time lag between a desired target value and an actual steady-state response. The ASSE was defined as the absolute value of the deviation between a target value and an actual response over the steady-state period. The input of tractor speed was not ideal but real and unsteady, so that the relative CV and the relative OS were used for the stability analysis of the control system. The relative CV was determined by dividing the CV of response(output) with the CV of target(input). The relative OS was also found as the OS of response(output) with respect to the target(input) OS. Duncan's multiple range test was used to compare the means.

Operating Control Program

Two manual switches, main and reset, were located at a control box (X of Fig 2). The moment of spraying was decided by the operator by manually opening the main switch that controlled the boom solenoid valve for normal spraying. The reset switch, slaved on the main switch, was also manually operated for nozzle calibration and system reset to maintain a system pressure of 300 kPa. The injection of concentrate did not take place without the main switch on. Also, the injection of concentrate should never occur for tractor and/or PTO pausings.

A flow chart of the sprayer control in Fig.3 shows the sequence of flow and injection controls. During the very first seconds, the system was initialized by setting variables. The input variables were the desired application rate (F, L/ha), swath (W, m), slippage (Sf, %), target concentration (C) for the spraying operation, and the adjustment of injection pump (k1), the sensitivity of injection pump (k2), the sensitivity of flow regulating valve (k3), the tolerance of flow control (k4). The control interval was selected by setting the clock, and the measurements of the system pressure (PRS), tractor speed (SPD), flow rate of diluent (FLW, Qw), injection pump speed (RPM) and supply voltage (Volt). The target flow rate (Tflw, TQw) was calculated using SPD and a constant(A).

For normal spraying, the flow regulating valve was forward- or backward-rotated to pursue the target flow rate after the program determined whether the main switch was on, main pump was on and tractor was traveling. The injection rate (Qp) was controlled proportional to the actual diluent flow rate (Qw). Thus, the concentration (C) was intended to be consistent. The flow control was established by determining the duration time (TIMER) of valve rotation using the sensitivity (k3) and difference (ΔFLW) between the target and actual flow rates. The injection rate was determined from the target (Trpm) output of the injection pump using diluent flow rate (FLW, Qw) and adjustment of injection pump (k1). The difference between the target and actual rpm's (ΔRPM) and its sensitivity (k2) was used to calculate the D/A output signal for controlling injection rate through the DC motor drive.

For the nozzle flow calibration and reset process, the sprayer control was set at the target pressure of 300 kPa using a fixed TIMER of 200ms within ±1% of tolerance. The upper and lower pressure limits of 420 and 100 kPa, respectively, prevented malfunctioning of the system. During the reset process, the injection of concentrate was locked at null.

RESULTS AND DISCUSSION

A typical response of the control system to tractor speed change from 8 to 12 km/h is presented in Fig. 4. The comparison of tractor speed (SPD) and actual flow rate (Qw) revealed a finite lag in response time. The response of the injection rate (Qp) and concentration (C) to the diluent flow rate (Qw) are also presented. Under-application occurred during the increase of tractor speed because the flow regulating valve responded slow to the tractor speed change and vise versa. The concentration of mixture should be maintained constant to minimize the lag time error.

A pretest was conducted to find a proper control interval for stable responses of the diluent flow and concentrate injection rates. As the result of pretest, the control interval of 1.0 sec was the most appropriate selection in terms of the prompt response time and stable control performance.

Table 1 shows the test results for the variables of the tolerance, the injection pump sensitivity and the sensitivity of the regulating valve with a control interval of 1.0 sec. The response time of flow rate was mainly affected by the tolerance of control error (k4) and the sensitivity of valve (k3). As those variables increased, the response time of flow rate increased. The response time of injection rate was dependent on the injection pump sensitivity (k2). The response times of injection rate were -0.17, 0.09 and 1.58 sec with the descending sensitivities of fast(3), medium(2) and slow(1), respectively. The value below zero meant that the system overshot at the fast sensitivity. The optimum response time of injection pump was at the medium sensitivity (k2=2).

The control tolerance affected the absolute steady-state error. Errors were 0.9, 1.0 and 2.1% of flow or 0.074, 0.083 and 0.164 L/min with increasing tolerances of 0.5, 2.25 and 4.5% of flow, respectively. The expected errors were half of the program values for the test tolerance variable. However, the control activation was oscillated over the thresholds of tolerance at a narrow tolerance (k4=0.5%), and the error did not decrease.

The CV of concentration during a test period of 180 sec was minimal at the mid-sensitivity of injection pump (k2=2). However, the CV increased due to unstable fluctuation at the fast-sensitivity (k2=3) and the slow response to the change of diluent flow at the slow-sensitivity (k2=1). At the fast control interval, the resolution of flow meter through the counter (H/C) could decrease and cause the system instability, therefore, a frequency-to-analog converter was necessary for field application.

The relative CV's for the diluent flow rate and injection rate were indicators for stability of the control system. The relative CV of flow rate was less than 1.0 (meaning stable) at all sensitivity settings of the flow regulating valve. The relative CV of injection rate depended on the sensitivity of injection rate and the stability (CV) of diluent flow response. The relative CV's of injection rate were 0.598, 0.717 and 1.272 with increasing sensitivity (k2) of 1, 2, and 3, respectively. The control system became unstable (the relative CV > 1.0) at the fast-sensitivity (k2=3) of the injection pump.

The relative OS established the initial stability of control system. The relative OS was stable at less than 1.0, and resulted in similar trends with the relative CV. The sensitivity of injection pump directly affected the relative OS. The fast-sensitivity of injection pump increased the relative OS greater than 1.0, revealing unstable initial response. However, the effect of diluent flow response was not noticeable.

The CV and OS of the diluent flow were less than those of injection rate indicating that the flow regulating valve was overdamped and injection pump was underdamped for the overshooting input from the tractor speed input.

CONCLUSIONS

Optimal conditions and variables for the direct injection sprayer were summarized. The proper control interval was 1.0 sec, performing faster response time than 2.0 sec and more stable dynamic characteristics than 0.2 sec. The flow regulating valve was overdamped, so that the system behaved stable at the fast-sensitivity of the flow valve. The medium tolerance (k4=9) of ±2.25% error showed the actual test error about ±1.0%. Lower tolerance did not enhance the actual error. The fast-sensitivity of injection pump resulted in responds too early and an unstable system. The CV of concentration was minimal at the medium (k2=2) sensitivity of the injection system. Therefore, the optimal sensitivity of the injection pump was medium.

The performance of the optimal control system was summarized as follows. The average response time of the flow rate was 8.5 sec at the absolute steady-state error of 0.067 L/min. The average response time of the injection rate was -0.53 sec (meaning overshoot) and the CV for concentration was 3.15%.

To improve the system, the rotating speed of the diluent regulating valve should be increased in response to changes in tractor speed. An enhanced control system could be constructed using a reliable speed sensor with high resolution or wheel-slip adjustment. This integrated system with controlled application and recycling container capabilities should minimize human exposure to chemicals and enhance environmental conservation as well as provide economic advantages.

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Table 1. Test results of the average response time of flow rate (RSPT of Qw), the response time of injection rate (RSPT of Qp), the absolute steady state error of flow rate (ASSE of Qw), the overall C.V. of concentration (CV of C), the relative C.V. of flow rate (Rel CV of Qw), the relative CV of injection rate (Rel CV of Qp), the relative overshoot of flow rate (Rel OS of Qw) and the relative overshoot of injection rate (Rel OS of Qp) for the independent test variables at the control interval of 1.0 sec.

Independent Variables		Dependent Variables							
Control	Value	RSPT Qw (sec)	RSPT Qp (sec)	ASSE Qw (L/min)	C.V. C (%)	Rel CV Qw	Rel CV Qp	Rel OS Qw	Rel OS Qp
Sensitivity of injection pump k2	1 (slow)	8.04b	1.58a	0.114a	4.37a	0.576a	0.598b	0.577a	0.559b
	2 (mid)	9.28a	0.09b	0.097a	2.59b	0.501a	0.717b	0.297a	0.665ab
	3 (fast)	9.06a	-0.17b	0.110a	3.72a	0.563a	1.272a	0.394a	1.054a
Sensitivity of flow reg valve k3	5 (fast)	8.32b	0.47a	0.115a	3.85a	0.669a	1.039a	0.431a	0.794a
	4 (mid)	8.74ab	0.49a	0.094a	3.62a	0.458b	0.741a	0.337a	0.596a
	3 (slow)	9.29a	0.56a	0.113a	3.29a	0.516ab	0.795a	0.497a	0.889a
Tolerance k4 (%, wrt 8.0lpm)	2 (0.5)	9.70a	0.50a	0.074b	3.66a	0.505a	0.926a	0.352a	0.664a
	9 (2.25)	8.68b	0.68a	0.083b	3.56a	0.591a	0.859a	0.444a	0.857a
	18(4.5)	7.98c	0.34a	0.164a	3.54a	0.546a	0.792a	0.475a	0.756a
Replication	1	9.15a	0.35a	0.092a	-	0.604a	0.928a	0.287a	0.604a
	2	8.83ab	0.69a	0.125a	-	0.514a	0.687a	0.482a	0.751a
	3	8.37b	0.48a	0.104a	-	0.525a	1.002a	0.503a	0.936a

* Means of variable effects followed by the same letter are not significantly different (Duncan's multiple range test at α=0.05).

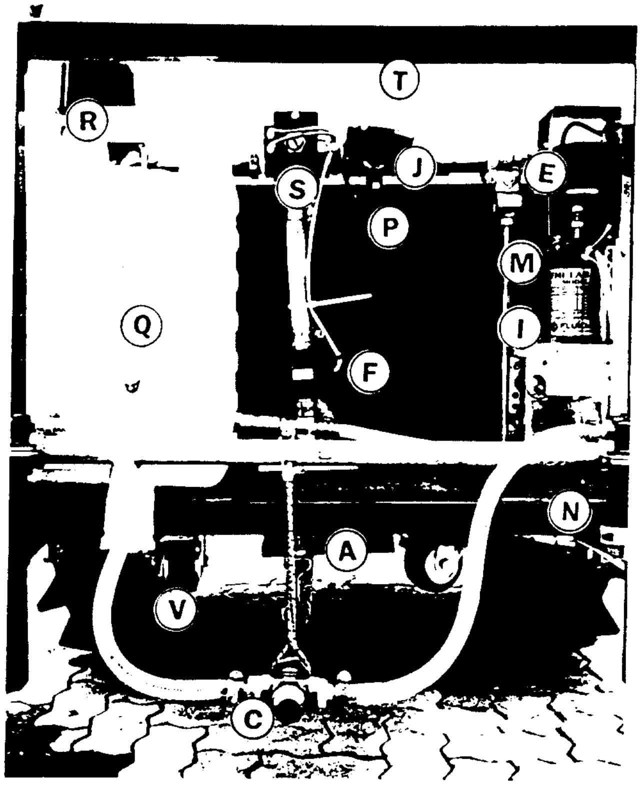

Fig.1. Rear view of the direct injection boom sprayer.
A: Injection port, C: concentration sensor, E: RPM encoder, F: turbine flowmeter, I: injection metering pump, J: dial gauge, M: DC motor, N: nozzles, P; pressure transducer, Q: concentrate tank, R: electric flow regulating valve, S: Solenoid boom valve, T: diluent(water) tank, V: vehicle speed sensor.

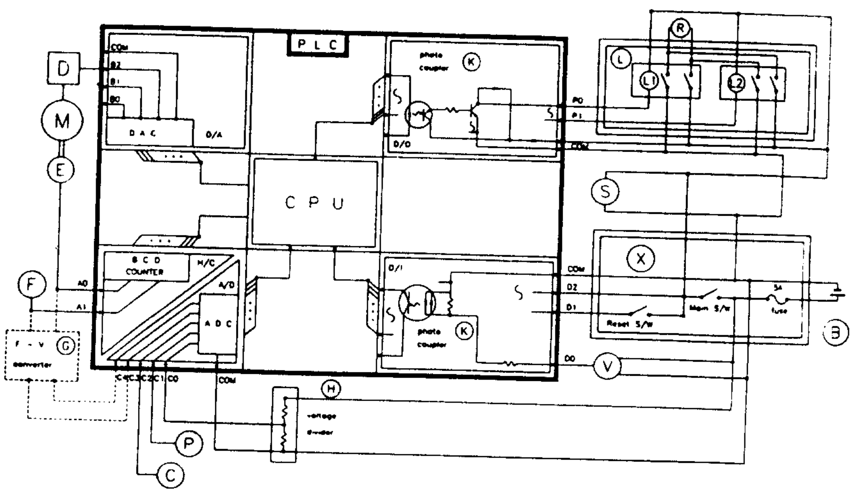

Fig.2. Interface and adjacent circuitry for spray controller.
B: tractor battery (power supply), D: DC motor drive, E: RPM encoder, F: Turbine flowmeter, G: Frequency-to-voltage converter, H: Voltage divider, K: Photo coupler, L: Forward(L1)-reverse(L2) control relays, M: DC motor, P: Pressure transducer, R: Electric flow regulating valve, S: Solenoid boom valve, V: Vehicle speed sensor, X: Switch box.

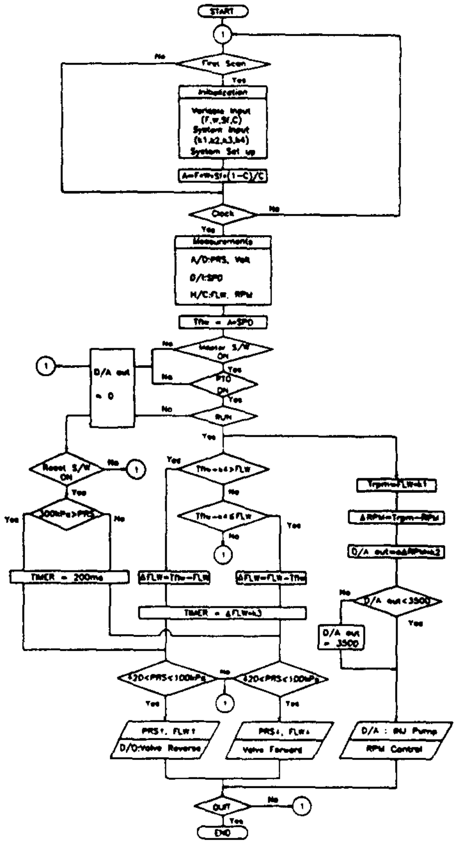

Fig.3. Control flow chart of the direct injection sprayer.

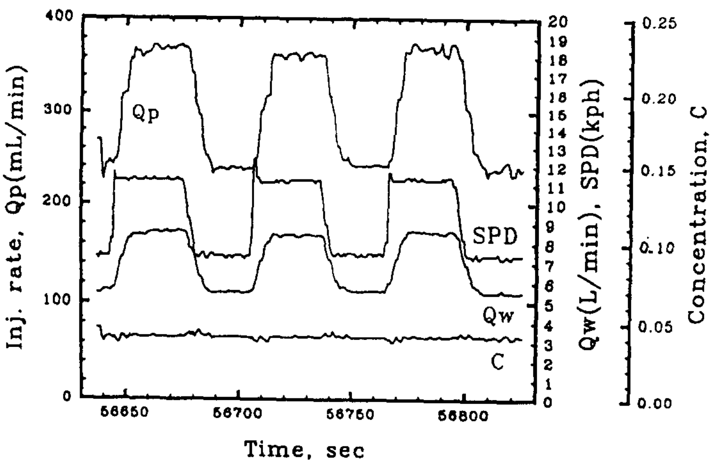

Fig.4. Typical behaviors of injection spray system were illustrated for the variables of 0.1 sec control interval, fast flow regulating valve (k3=5) and mid injection pump sensitivities (k2=2), and 2.25% tolerance (k4=9). Responses of the water (Qw) and concentrate florets(Qp) to the tractor speed change(SPD) were presented. The concentration(C) during the spray control was illustrated to assess the spray controller.