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Improving flow response of a variable-rate aerial application system by interactive refinement

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A B S T R A C T

Experiments were conducted to evaluate response of a variable-rate aerial application controller to changing flow rates and to improve its response at correspondingly varying system pressures. System improvements have been made by refinement of the control algorithms over time in collaboration with the system manufacturer, Houma Avionics, Houma, LA, USA. The variable-rate application system consists of Differential Global Positioning System (DGPS)-based guidance, AutoCal II automatic flow controller, and hydraulically controlled spray pump. The AutoCal II was evaluated for its ability to track desired flow rates set by the pilot. The system was then evaluated over several field trials to quantify its response to rapidly changing flow requirements and to determine the effect of the latest control algorithm improvements on response characteristics. System responses were analyzed while operating the AutoCal II in automatic mode over a pre-set field prescription containing four management zones (28, 47, 56, and 37 L ha^{-1} each 81 m long). To evaluate the effect of control algorithm improvements, areas under the flowrate-time curves were integrated and percentage differences in areas between those response curves and target flow rate curves were determined. Results for south–north runs indicated reduction of average error from 6.9% before control algorithm modification to 1.8% after algorithm modification. Benefits of a new flow monitor with capabilities for improved data acquisition resolution were illustrated by examining data from both 2005 and 2008 prescription runs. For the 2005 data, integration times per run matched expected values based on ground speed when using either the new flowmeter monitor or conventional monitoring via the AutoCal II with its irregular data integration intervals. The 2008 data showed inconsistencies in total integration time per run when reading flowmeter data via the AutoCal II; these intervals varied between 1.2 and 1.66 s. Integration timing intervals matched expected results when using the new flowmeter monitor instead of the AutoCal II to read and output data. Inconsistencies in AutoCal II timing were attributed to possible modifications in loop-timing portions of the AutoCal II control algorithm since the 2005 run was conducted. These results further support the value of the new flowmeter monitor in providing consistent results regardless of changes the manufacturer might make to the AutoCal II data acquisition and control program. The experiments served to illustrate an example of how iterative refinement of control algorithms in collaboration with the control system manufacturer could improve system response characteristics. System evaluation techniques described should also apply to aircraft that use propeller-driven spray pumps as well as hydraulically controlled spray pumps.

1. Introduction

Agricultural aircraft are used to apply chemical and biological pest-control agents, harvesting aids, and nutrients to assure a high-yielding and economically viable crop. Only recently have agricultural aircraft been equipped to implement variable-rate application to match site-specific needs of the crop. Variable-rate aerial application systems have seen limited use only within the past six years or so, and very little information has been presented on the accuracy of these systems for placement of chemical and response of these systems to changing rate requirements.

In addition to variable-rate application, aerial flow control systems must adjust flow properly to accommodate changes in ground speed. This assures that the same rate of material is applied per unit field area. Kirk and Tom (1996) evaluated an early version of the Satloc automatic flow control system (Hemisphere GPS, Cal-

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gary, AB, Canada) over 1600 m runs. Performance was evaluated from data logged during the flight describing performance of the controller relative to the information received from the flow sensor and GPS receiver. Several aircraft runs were made upwind and downwind at four different wind speed levels. Spray rate errors ranged from 0 to 4.4% over the eight treatments with flow control switched on. Without the flow controller, errors ranged from 6.4 to 14.3%. Smith (2001) evaluated two early versions of the AutoCal flow controller (Houma Avionics, Houma, LA, USA) in terms of their ability to make corrections in boom flow rate and to compensate for changes in ground speed. The Air Tractor 402B spray plane used a propeller-driven pump, whose flow output was proportional to airspeed. One version of the flow controller used a servo-driven linear actuator to adjust a ball valve in the spray line to the spray booms. The other flow controller utilized a bypass line to divert a proportion of flow back to the tank when flow changes were required. The AutoCal I had a maximum error of 1.55% while applying 37.4 L ha^{-1} (4 gal $acre^{-1}$) under controlled conditions. Experimental error was not significantly affected by application rate in either system.

Martin et al. (2004) evaluated a variable-rate system mounted in an agricultural aircraft that used a propeller-driven spray pump on an Ayers Thrush aircraft, similar to the pump used by Smith (2001). However, instead of controlling a ball valve or bypass return valve, a servo-controlled actuator was connected directly to the pump propeller to achieve variable fluid rates. Propeller pitch was controlled by the AutoCal I flow controller, and a Trimble AgGPS® TrimFlight™ 3 was used for guidance and position georeferencing. A 1 mm cotton string was placed in parallel with the spray path to determine where spray with a fluorescent dye tracer started or stopped relative to a target positions measured on the ground. Preliminary tests showed that on–off control could be achieved within 16 m of the target. A follow-up study evaluated the system's ability to vary flow rate in-flight. The aircraft was flown through six application rate zones of 0, 44.9, 0, 33.6, 22.5 and 0 L ha^{-1} in sequence, and water sensitive paper (WSP) cards were used to collect deposition samples in each of the zones. Results indicated a delayed response of the system to the input requests and an overall inability of the system to achieve the desired application rates. This was attributed to the turbulent fluid dynamics of the system using a conventional hydraulic nozzle, where a doubling of the flow rate required a quadrupling of the pressure in the system.

Thomson et al. (2009) evaluated the AutoCal II flow controller set in an Air Tractor 402B aircraft operating in automatic mode over a field prescription of four pre-set rates. The AutoCal II was set to control a hydraulically operated spray pump and was integrated with Satloc Airstar M3 guidance GPS set to update position every 0.2 s. A key objective was to evaluate positioning accuracy of rate changes (in this case on–off) at precisely georeferenced field boundaries. WSP cards were placed every 2 m along the flight path, and visual observation was used to determine where rate changes were made over several runs. A lead time of 0.5 s was used to trigger rate changes with respect to the system boundary to account for response lags inherent in the aircraft plumbing. Observations of WSP showed that average spray deposition position error magnitude was 5.0 m when traveling east to west and 5.2 m when traveling north to south. Statistical analysis indicated that direction of travel had a non-significant effect on the magnitude of spray deposition position error. Placement variability over all runs was rather high for some runs (standard deviations ranging from 2.3 to 6.9 m), and this was attributed to limitations in the GPS updating interval. An updating interval of 0.2 s (5 Hz) translates into about 14 m at 70 m s^{-1} ground speed, which is probably a realistic grid size for variable-rate changes using the Satloc M3 guidance system and 0.2 s position updating. Spraying system response for a single set of spray runs was also illustrated by Thomson et al. (2009), and responses tended to vary from overdamped to slightly underdamped depending on rate change levels. Potential improvements to the control algorithms and hydraulic system modifications were proposed.

2. Objectives

The objectives of this study were:

1. To evaluate the hydraulically operated flow controller for its ability to track flow rates corresponding to changes in system pressure set by the pilot.
2. To quantify improvements to AutoCal II system response as a result of changes made by the manufacturer to the variable-rate control algorithms.
3. Compare flow responses obtained using a new high resolution flowmeter monitor with responses obtained using the AutoCal II only.

3. Materials and methods

An Air Tractor 402B turbine aircraft was used to implement variable-rate control. The setup was described in Thomson et al. (2009) and is also summarized here. A Satloc Airstar M3 swath guidance system used a GPS receiver at a 5 Hz update rate to determine the current position and ground speed of the spray plane. Speed and required rate (set manually or from a prescription file) is communicated to the flow controller, which computes the required boom flow rate and adjusts actual flow to match the required rate. The GPS receiver is used to guide the pilot along the proper spray swath, monitor ground speed, and identify management zone boundaries where application rates should change. The Satloc M3 runs AirTrac software to implement variable-rate application, and uses the Wide Area Augmentation System (WAAS) for differential correction. The AutoCal II automatic flow controller received ground speed and application rate from the Satloc system and adjusted the spray pump output to deliver the required flow to the boom based on speed, rate, and swath width. Flow data from the AutoCal II were logged using Hyperterminal on a notebook computer mounted in the airplane as described in Thomson et al. (2009). The AutoCal II control program in its present form generates data records (serial output) at different time intervals depending on which of two control loops is running within the controller software. A status flag in the AutoCal II output data file indicates which of the two loops is running, so the number of readings of target flow rate (received by the Satloc and logged by the AutoCal II) can be counted within each timeframe and matched one-to-one to actual flow rate obtained directly from the flowmeter at 10 Hz for comparison.

A flowmeter monitor was also developed to allow readings of actual flow rate at regular 0.1 s intervals. Readings by the newly developed monitor were based on the measurement of elapsed time between consecutive turbine-wheel blade passes through the magnetic field of the flowmeter proximity sensor. This time was measured by gating a 250 kHz signal generated by a crystal-controlled oscillator to a counter during this period. Simulating the flowmeter signal with equivalent output from a signal generator demonstrated that the circuit was accurate within 1 period of the 250 kHz signal; therefore, the interval between blade passes was measured with an accuracy of 4 μs. The time required for one blade pass could be converted to gallons per minute by using the calibration constant of 45.47 blade passes per gallon. A Basic Stamp micro-controller (BS2p-24, Parallax, Inc., Rocklin, Cal.) was used to read the flowmeter and real-time-clock. The raw data were converted to desired units and then output through a serial port at a 10 Hz rate for capture by an HP IPAQ HX-4700 Pocket-PC. The flow rate monitor produced records at 0.1 s intervals that

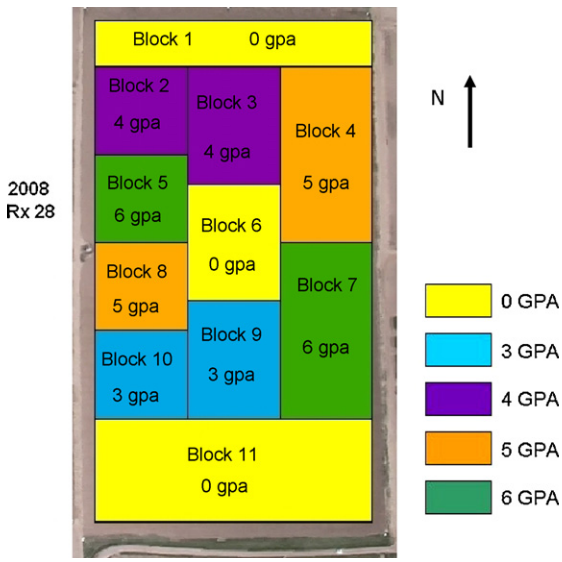

Fig. 1. Field prescription for testing the AutoCal II automatic flow controller. Blocks were set to English units of gal acre^{-1} (gpa) in the field (1 gal acre^{-1} = 9.35395623 L ha^{-1}).

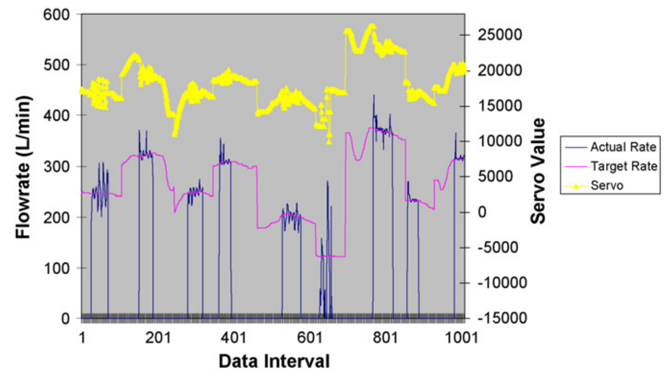

Fig. 2. Flow rate tracking as the AutoCal II was manually set by the pilot to track flow changes. Servo position to accomplish adjustments is illustrated by the yellow line. Sensitivity setting 58; ground speed 60 m s^{-1} (134 mph). Test was conducted 05 January 2008. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

included the current time and flow rate to the boom, and this output was captured with the Pocket-PC using ZTERM CE software (http://www.tsreader.com/legacy/). The apparatus is illustrated in Thomson et al. (2009) and circuit diagrams for the flowmeter monitor are available from the first author by request.

Fifty-seven CP-09 deflector spray nozzles with 0.078 orifices (CP Products Inc., Tempe, AZ, USA) were set up on spray booms. The spray system was customized by installing a Kawak Aviation hydraulic power pack (Kawak Aviation Technologies, Bend, OR, USA) that featured an engine-driven hydraulic pump, a hydraulic motor for driving the spray pump, and a hydraulic cylinder to actuate the spray valve. Hydraulic power to the spray pump was controlled with an electrically operated hydraulic servo valve from signals generated by the flow controller. The spray valve was also operated electrically with a toggle switch mounted on the aircraft control stick. Variable-rate operation requires the development of a prescription file specifying areas of the field to receive different application rates.

To test the variable-rate system, a test field prescription layout was developed (Fig. 1). Details of how this field layout was georeferenced and how the prescription was generated using ArcGIS software can be found in Bright et al. (2009). The west side of the field was used to test system response to changing rates on 05 January 2008, 20 March 2008, and 18 August 2008. For the tests of 05 January 2008 and 20 March 2008, the AutoCal II was operated manually, that is, it was switched on when desired flow set-point was set by the pilot. Several flights were made, and the ability of the AutoCal II flow controller to attain the set-points was verified.

Three sets of flights over the field prescription were then made on 18 August 2008 in both south–north and north–south directions with the AutoCal II set to automatic mode. Flow responses by the AutoCal II to changing rates were observed and quantified. To make comparisons between desired and actual flow rates, data from the AutoCal II output file were analyzed for each spray run. The AutoCal II control program changes its flow sampling interval based on rate-of-change of flow readings, and flowmeter readings are averaged over those intervals. System responses indicated herein use those variable intervals as output by the AutoCal II.

Field-applied application rates illustrated in Fig. 1 correspond to system flow rates in English Units by the following relationships (Gardisser and Kuhlman, 1993):

$$\text{acre min}^{-1} = (0.00202)(\text{swath width})(\text{speed}) \quad (1)$$

$$\text{gal min}^{-1} = (\text{acre min}^{-1})(\text{application rate}) \quad (2)$$

The Satloc guidance GPS also logs data in English units, so conversion to L min^{-1} flow rate is accomplished subsequently. For our experiments, swath width was set to 18 m (60 ft). Application amount (acre min^{-1}) was obtained from the Satloc output log file and calculated by Eq. (1) using GPS-derived ground speed data. Flow rates (calculated by Eq. (2) in gal min^{-1}) corresponding to application rates shown in Fig. 1 are then calculated and tracked by the AutoCal II. Flow rate in L min^{-1} can then be calculated by the relationship 1 L min^{-1} = 0.2642 gal min^{-1}.

4. Results and discussion

4.1. Tracking of manually set target rates

The AutoCal's ability to attain desired flow rate as the system was switched to track flow rates manually set by the pilot is illustrated in Fig. 2. The figure indicates flow response from zero flow to the target rate. The AutoCal II was able to instantly track preset flow rates at most settings, but slight oscillations around the set-point are indicated for this set of runs. Observation of the output data file indicated a higher-than-normal sensitivity setting for the AutoCal II (Graves, 2008), which may have caused these oscillations. The pilot indicated trouble changing the initial sensitivity setting on this date, as the system would reset automatically. This problem has since been corrected by the manufacturer in an updated control algorithm. The figure shows that the lowest flow rate (sixth setting in the graph) was not tracked properly due to pressure being too low for the chosen nozzle complement.

Fig. 3 illustrates flow rate tracking similar to the plot shown in Fig. 2, except that the AutoCal II was switched on the instant a desired rate was selected by the pilot. The figure indicates a more pronounced effect of a sensitivity setting set too high causing overshoot as a single event. Another likely cause of this overshoot could have been the presence of air in the flow pipe, causing the flowmeter to spin fast until fluid filled the pipe, although we have taken steps to assure a water-tight system before flight. To account for any condition in control that causes overshoot of this magnitude, the manufacturer has set the program to ignore initial wide swings if rate changes are desired within that window. Otherwise, unbounded oscillation could occur. Fig. 3 illustrates implementation of this safety feature, as control settles quickly after the initial overshoot.

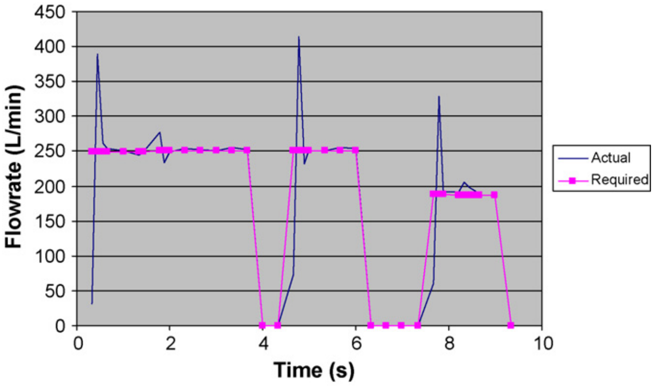

Fig. 3. System response (manual activation mode) illustrating overshoot on initial activation of flow control program. Sensitivity setting 73; ground speed 62 m s^{-1} (138 mph). Test was conducted 20 March 2008.

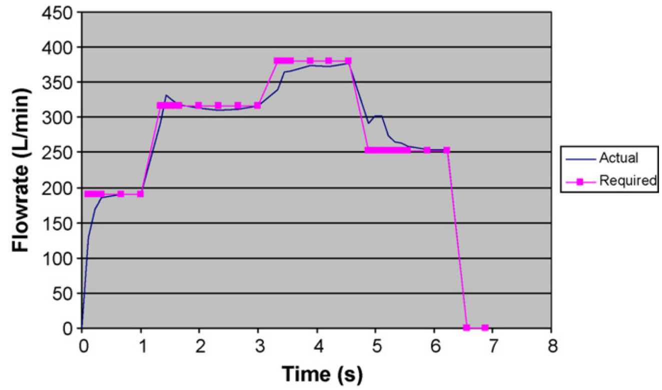

Fig. 4. Typical response of actual boom flow rate to step changes in required rate before control program modification. These data were captured by the AutoCal II while spraying a series of four management zones in the west lane of the prescription area (Fig. 1) from south to north. Sensitivity setting 46; ground speed 62 m s^{-1} (139 mph). Test was conducted 18 August 2008.

4.2. Automatic tracking of the field prescription

AutoCal II responses to four different flow rates set by the field prescription (Fig. 1) were determined as the aircraft flew over the west side of the field. To help quantify improvements to the algorithms, areas under the flow rate-time curves were determined for each rate under the prescription and compared with each other before and after changes to the control algorithms were made by the manufacturer. Changes in the algorithm were meant to smooth out responses and provide tighter control over a wide range of operating pressures (Graves, 2008). Although the control aspects are proprietary, it appears that some type of Proportional-Integral (PI) control method is implemented. Three runs were made in each travel direction and results indicate average values of these three runs per direction.

Percentage differences between actual and desired flow rate areas were consistently lower after program modification, and this can be illustrated by a typical controller response (Figs. 4 and 5) and integrated areas (Table 1). There was also more variability between Actual Flow Rate Area before program modification than after modification (as illustrated by the standard deviations in Table 1). Any ground speed differences between runs in the same direction would influence the calculated areas, but speed differences for all runs in the same direction were very small (maximum difference = 2.2%).

Results were mixed for runs in the reverse flight direction (north–south). The upper limit of system capacity was reached for

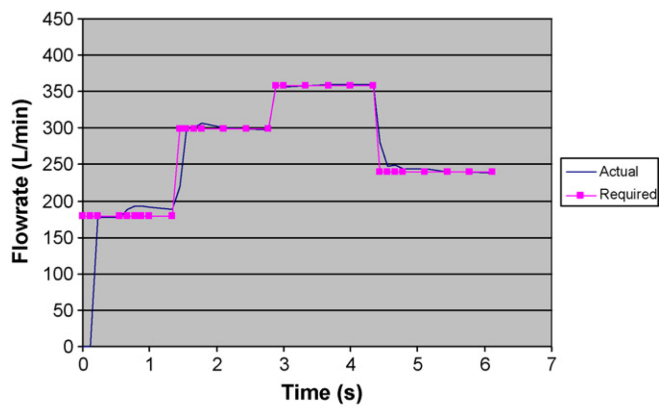

Fig. 5. Typical system response to changing rates (south–north runs) after control program modification. Sensitivity setting 48; ground speed 59 m s^{-1} (131 mph). Test was conducted 18 August 2008.

5 out of 12 total runs as indicated by example in Figs. 6 and 7. So, the highest flow rate programmed for the second prescription zone could not be achieved for a conventional nozzle complement of 57 CP nozzles with 0.078 orifices. The pilot was instructed to maintain a ground speed low enough to avoid overly high operating

Table 1
Area under flow rate vs. time curves comparing accuracy of flow controller response to step changes in required flow rate as defined by the variable-rate system for three south–north spray runs over the four prescription management zones (each 81 m in length) with application rates of 28, 47, 56, and 37 L ha^{-1}. Area values represent the average response for each pass and were computed by numerical integration techniques over timing intervals used by the flow control program in the AutoCal II.

Prescription zone	Actual flow rate area [L min^{-1} s]	Required flow rate area [L min^{-1} s]	Percent error (%)	Standard deviation of actual flow rate area [L min^{-1} s] – three runs
Before program modification				
1	158	190	−16.7	5.13
2	522	527	−0.9	5.86
3	449	463	−3.1	9.50
4	360	337	6.7	15.95
|Average|			6.9	9.11
After program modification				
1	164	160	2.5	4.73
2	325	332	−2.2	6.03
3	439	439	0.0	5.51
4	355	346	2.5	5.20
|Average|			1.8	5.36

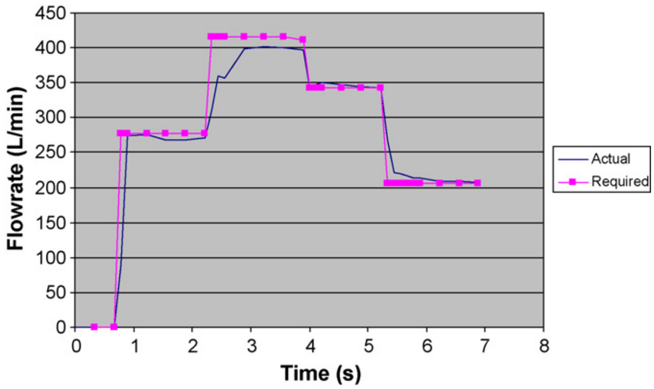

Fig. 6. Typical system response to changing rates (north–south runs) before control program modification. Sensitivity 43; ground speed 68 m s^{-1} (152 mph). Test was conducted 18 August 2008.

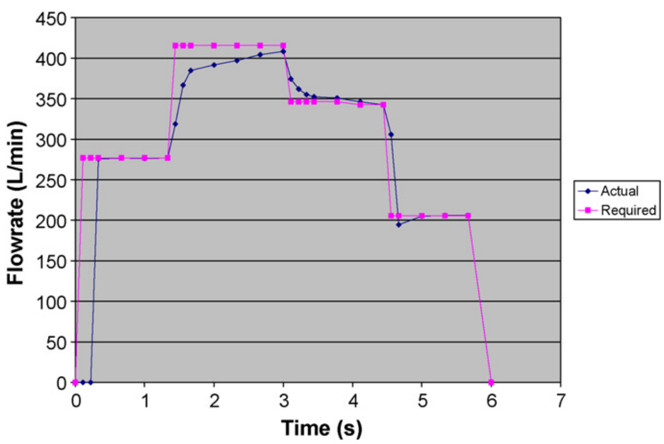

Fig. 7. Typical system response to changing rates (north–south runs) after control program modification. Sensitivity 45; ground speed 67 m s^{-1} (150 mph). Test was conducted 18 August 2008.

pressures at the highest flow rates dictated by the field prescription, but ground speed was influenced by a high tailwind from the north. Boom pressure was not logged, but calculations for a swath width of 18 m (60 ft) and a ground speed of 68 m s^{-1} (152 mph) indicate nominal system pressure exceeded 434 kPa (63 psi). This is above the recommended operating range for the nozzle orifice used (CP Products, 2009). Mainly due to these pressure limitations,

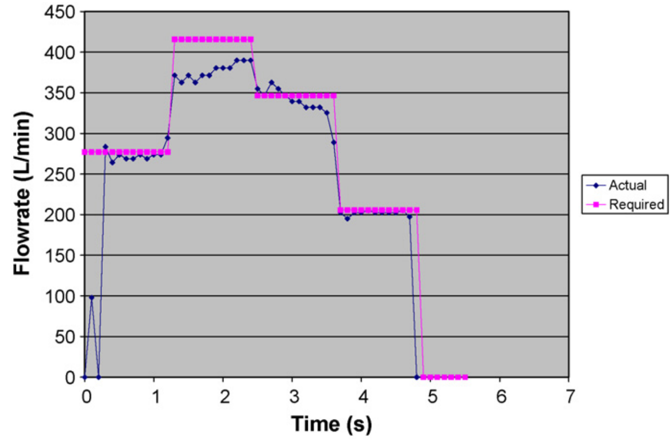

Fig. 8. Typical system response to changing rates (north–south runs) after control program modification. Sensitivity 45; ground speed 67 m s^{-1} (150 mph). Test was conducted 18 August 2008. Flow rates were logged by the flow monitor.

percentage differences in integrated areas were 7.2 and 6.6% below the highest rate dictated by prescription zone 2 for runs before and after algorithm modification, respectively (Table 2). The first prescription zone for the post-modification run (Fig. 7) showed a −11.6% difference, primarily due to control initiation delay for the first prescription zone entered by the aircraft. Fig. 7 also illustrates a delayed (and steep) response from the third flow rate to the fourth and final flow rate. The fourth integration interval captured the first value of flow rate on steep decline of the response curve, biasing the integrated value higher for that prescription zone. The result was a +11.4% difference (actual vs. desired area). It is not clear why response delays occurred for these runs, but the responses themselves tracked smoothly. Considering that the controller operated under a wide range of pressures customary with a fixed nozzle arrangement, tracking ability in response to changing flow rates was excellent.

4.3. Data acquisition using the flowmeter monitor

Fig. 8 illustrates flow responses for the same run as illustrated in Fig. 7 but using the new flowmeter monitor. Data resolution is higher than that illustrated in Fig. 7, and integration intervals for actual flow rates were quite consistent. Calculated timing for the entire run based on ground speed was about 4.8 s, and data rep-

Table 2
Area under flow rate vs. time curves comparing accuracy of flow controller response to step changes in required flow rate as defined by the variable-rate system for three north–south spray runs over the four prescription management zones (each 81 m in length) with application rates of 28, 47, 56, and 37 L ha^{-1}. Area values represent the average response for each pass and were computed by numerical integration techniques over timing intervals used by the flow control program of the AutoCal II.

Prescription zone	Actual flow rate area [L min^{-1} s]	Required flow rate area [L min^{-1} s]	Percent error (%)	Standard deviation of actual flow rate area [L min^{-1} s] – three runs
Before program modification				
1	311	339	−8.4	7.51
2	515	554	−7.2	8.50
3	346	343	0.9	4.73
4	289	274	5.6	7.00
|Average|			5.5	6.93
After program modification				
1	245	277	−11.6	9.29
2	517	553	−6.6	5.86
3	393	385	2.0	7.09
4	254	228	11.4	7.21
|Average|			7.9	7.36

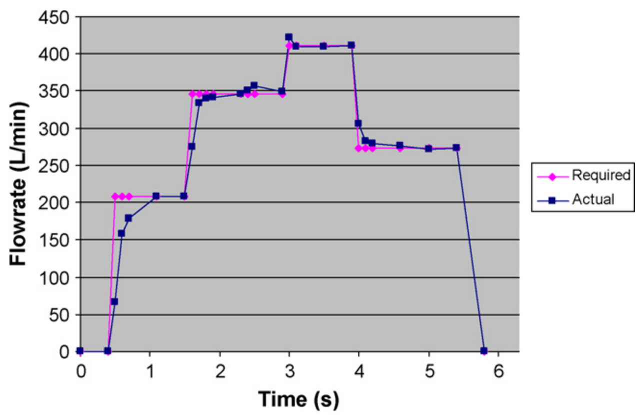

Fig. 9. Typical system response to changing rates (south–north runs). Sensitivity 45; ground speed 68 m s^{-1} (152 mph). Test was conducted 30 November 2005.

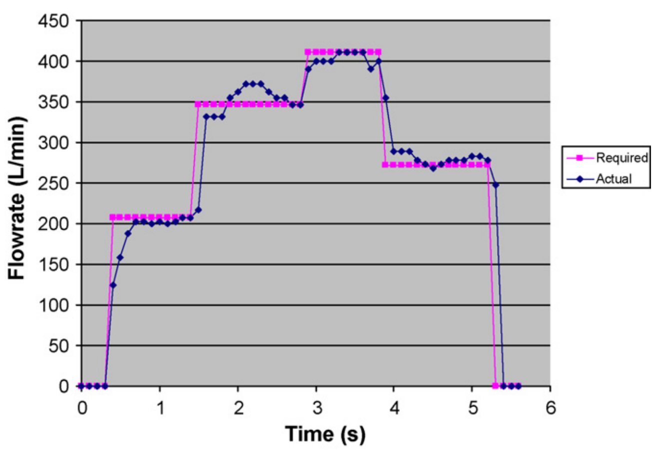

Fig. 10. Typical system response to changing rates (south–north runs). Sensitivity 45; ground speed 68 m s^{-1} (152 mph). Test was conducted 30 November 2005. Flow rates were logged by the flow monitor.

resented by Fig. 8 were very close to that value. This was not the case when using irregular timing intervals generated by the AutoCal II (Fig. 7). Time intervals for individual flow rates varied between 1.2 and 1.66 s and total time for the entire run of Fig. 7 was represented as about 5.6 s, or 0.9 s greater than that represented in Fig. 8. Timing intervals did not change in actuality; they were simply misrepresented in Fig. 7.

Data from 2005 runs (Figs. 9 and 10) might help illustrate reasons for differences between the two flow counting methods. In these cases, both the AutoCal II and flowmeter monitor represented integration times properly as timing for both matched expected values based on ground speed. Thus, inconsistencies in AutoCal II timing (Fig. 7) might be attributable to modifications to loop-timing portions of the AutoCal II control algorithm by the system manufacturer since the 2005 runs were conducted. These results further support the utility of the flowmeter monitor in providing consistent results regardless of possible changes to the AutoCal II data acquisition and control program. Integrated flow rate areas might also be more accurate because of the higher temporal resolution in acquiring flow data.

4.4. General considerations

It should be noted that spray nozzles must be operated within optimal pressure operating ranges to produce desired droplet size characteristics. Some flow rates programmed for the field prescription operated the nozzles outside their optimal operating ranges for optimal application efficacy and spray drift reduction. The CP Products website (CP Products, 2009) indicates nozzle tip combinations on the boom to extend usable operating ranges, and Thomson et al. (2009) used such a nozzle complement for a positioning accuracy experiment. Users should be cognizant of the minimum and maximum flow rates required for a variable-rate prescription before selecting a nozzle set. Not all pressure ranges can be accommodated properly with a fixed nozzle arrangement. The possibility of increased off-target drift (too many fine droplets) or reduced efficacy of application within the target crop canopy (too-large droplets) can exist when nozzles are used outside their target operating pressures. Pressure monitoring requirements and the need for operational diagnostics have prompted us to develop a miniature boom pressure logger. This monitor is self-contained and is based on a Logomatic v2 single board logging computer (SparkFun Electronics, Boulder, CO) connected to a Kavlico pressure transducer (Kavlico, Inc., Moorpark, CA) to monitor boom pressure. Operation and verification of this system will be reported on in a future study.

Disclaimer

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the U.S. Department of Agriculture and does not imply approval of the product to the exclusion of others that may be available.

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