

REDUCING PROCESS VARIABILITY BY USING FASTER RESPONDING FLOWMETERS IN FLOW CONTROL

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Abstract

The dynamic response characteristics of flowmeters are often not considered when selecting a flowmeter for use in flow control applications. It is generally assumed that slow controller sample rates make flowmeter response a moot issue. This assumption is shown to be incorrect. It is demonstrated that the use of faster responding flowmeters will always result in reduced process variability, regardless of the controller sample rate.

Introduction

The overall purpose of a control system is to minimize the deviations of the controlled process variable from a desired value. The choice of control strategy, selection of control instrumentation and tuning of the control loop are all key elements of achieving the desired end – a reduction in process variability. It is often the case that most of the emphasis in reducing the process variability is placed on the selection of the control algorithm. While the control algorithm obviously plays an important role in reducing the process variability, it is also important to pay careful attention to the dynamic performance of the control instrumentation. It is often incorrectly assumed that the speed of response of flowmeters is unimportant in flow control applications, especially when digital control systems with relatively slow sample rates are used. Experimental and theoretical analysis have shown that the use of faster responding flowmeters always results in reduced process variability, even when using slow sample rates with digital controllers.

Flow Control System

A simple flow control system is shown schematically in Figure 1. It consists of a recirculating loop with water as the flowing medium. A 2-inch x 3-inch centrifugal pump driven by a variable speed drive supplied the flow through the 3-inch piping system. A control flowmeter measured the process variable and provided input to a proportional-plus integral digital controller. A fast responding monitoring flowmeter consisting of the mechanical parts of a turbine meter and a fast Frequency-Voltage converter served as a monitoring flowmeter to give as true a representation of the flow rate as possible. Two

identical 3-inch globe-style valves with positioners were installed downstream of the flowmeters. One valve served as the control valve and the other was used to apply load changes to the system. The valves were the fastest available industrial control valves. The input and output of the controller were 4-20 mA analog signals. A LabView data acquisition system was used to send signals to the load valve and record the data from the loop. The variables measured included the stem position of both valves, the output of the control flowmeter, the output of the monitoring flowmeter and the water temperature. Additional details about the experimental loop are published elsewhere [2, 3, 4].

The block diagram of the flow control system is shown in Figure 2. In analyzing the overall performance of the control system with the aim of reducing process variability, the dynamic performance of all four main elements must be considered. The dynamics of the process itself contribute to the overall performance of the loop but generally cannot be altered significantly. The dynamic characteristics of the controller are usually considered to have the largest impact as the controller parameters are adjusted during the tuning process. The dynamic characteristics of the other two elements of the instrumentation, the flowmeter and the valve/actuator, also play important roles in determining the level of process variability but are often neglected. The results presented here will show the effects of the dynamic performance of the flowmeter. Similar effects can be expected when the actuator/valve dynamics are considered [1].

Experimental Test Results

The loop described above was used to evaluate the closed loop control performance when three differential pressure/orifice flowmeters were used as the control flowmeters. The beta ratio of the orifice meter was 0.67. The transfer functions for all of the elements in the loop are given in equations 1 – 4.

Flowmeter:
$$TF_f = \frac{K_f e^{-\tau_{df}}}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (1)$$

Actuator/Valve:
$$TF_{A/V} = \frac{K_A K_V e^{-\tau_{dA/V}}}{(\tau_3 s + 1) \left[\frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1 \right]} \quad (2)$$

Process:
$$TF_p = \frac{1}{(\tau_p s + 1)} \quad (3)$$

All of the parameters associated with the dynamic response of the various elements (i.e., the τ values of the first order lags, the ω_n and ζ values of the second order lag and the dead times) were determined using the frequency response test method [2, 4]. The parameters K_f , K_A and K_V are the static gains of the flowmeter, the actuator and the valve. The transfer function of a proportional plus integral controller is:

Controller:
$$TF_C = K e^{-\tau_{dc} s} \left(1 + \frac{1}{\tau_i s} \right). \quad (4)$$

The proportional gain, K , and the integral time constant, τ_i , are adjustable parameters in controllers. The controller dead time, τ_{dc} , is determined by the digital sample rate of the controller. The controller sample rate for the tests was 0.03 sec.

The three differential pressure meter used in the experiments were DP2A, DP1A and DP 4A [2, 4]. Meter DP2A was chosen as the reference case since it was the fastest available flowmeter when the initial experimental work was done. The control loop was tuned with the reference meter using the auto-tuning feature of the controller. The controller tuning parameters for the other two flowmeters were set to maintain the same gain and phase margins observed with the reference meter. Using the same gain and phase margins allowed the results for all three meters to be fairly compared. The transfer function parameters are tabulated in Table 1. The damping for all three flowmeters was set to the minimum available value. The controller tuning parameters, gain margins and phase margins for the three cases are tabulated in Table 2. It should be noted that because of the fast process dynamics for this relatively small flow loop and the limitation of the integral time constant for the controller used (minimum integral time was 1.0 sec), the resulting tuning was not very aggressive. This can be seen most clearly in the phase margin values.

For the experiments the controller was tuned to the appropriate values of K and τ_i for the meter being tested. A sinusoidally varying signal was sent to the load valve causing the flow rate to vary in the loop. The data were first recorded in an open loop mode where the controller was placed in manual. After a period of time sufficient to capture several periods of the variation in the flow rate, the controller was returned to the automatic mode. An example of the test results for the reference case flowmeter at a load disturbance frequency of 0.07 Hz is shown in Figure 3. The nominal flow rate was 120 GPM with a load disturbance amplitude of 5.4%. The left half of the graph shows the open loop part of the test. The control valve position is a flat line indicating that the controller was in manual. In the right hand half of the graph the control valve position is seen to vary, indicating that the controller was in automatic and was trying to correct for the variations in the flow rate caused by the load valve. The flow rate was measured using the fast monitoring flowmeter to get as true a representation of the actual flow rate as possible. The closed loop gain of the system is determined by taking the ratio of the closed loop amplitude of the flow variations and the open loop amplitude. This procedure was repeated for a number of load disturbance frequencies for all three flowmeters. The results of the experiments for flowmeters DP2A and DP1A are shown in Figure 4. The symbols show the experimental results obtained at ten different frequencies. The theoretical results were calculated using the transfer function parameters in Tables 1 and 2 and the software application *Mathematica*[®] with the add-on package *Control System Professional*[®]. System limitations [2, 4] prohibited the verification of the transfer function at frequencies greater than 2 Hz so the theoretical curves are truncated. The results for flowmeter DP2A and DP4A are shown in Figure 5. From both Figure 4 and 5 it is seen that there is excellent agreement between the experimental data and the results predicted by the theoretical models. The rest of this paper will make use of this excellent agreement between experimental and theoretical results to evaluate the effects of flowmeter dynamic performance on process variability.

Dynamic Effects on Flowmeter Accuracy

Before considering the effects of flowmeter dynamic performance on the process variability it is instructive to look at what happens to the output of a flowmeter when it is subjected to time varying inputs. The results of frequency response tests [2, 4] show that all devices, including flowmeters, experience both an attenuation and a time delay of their output as they are subjected to time varying inputs. The Bode plot [2, 4] is a useful way of displaying these effects in the frequency domain that lends itself well to analyzing control systems. However, good insights can also be gained by looking at things in the time domain.

Figure 6 shows the first half cycle response of three different differential pressure/orifice meters (DP2B, DP1A and DP4A) to a 0.1 Hz sinusoidal input. It should be noted that this and all subsequent analyses are done using flowmeter DP2B [2, 4] as the reference flowmeter rather than DP2A. DP2B became available after the initial experimental work described above was performed and was found to be slightly faster than DP2A. Using the same nomenclature as in Table 1, the transfer function parameters for meter DP2B were $\tau_1 = 0.010$ sec, $\tau_2 = 0.031$ sec and $\tau_{df} = 0.070$ sec. It is seen that the flowmeter output is attenuated and lags behind the input. At this frequency the three flowmeters underestimate the magnitude of the transient by -0.037% , -1.81% and -1.98% , respectively. Figure 7 shows the underestimation of the flow rate as a function of frequency for the same three flowmeters. One of the performance parameters used in the selection of flowmeters is the uncertainty of the flowmeter. The uncertainty is always measured in the laboratory at steady flow rates. As these results indicate, the uncertainty in real-world flow applications when flow transients occur is always compromised. As the frequency of the transients increases the effective uncertainty of the flowmeter can significantly be compromised. It should be noted that this effect is due to the dynamic response of the devices and will be exhibited by all flowmeter technologies. It should also be noted that this increase in flowmeter uncertainty means that the process variability is generally worse than what is observed by looking at the flow rate indicated by the controlling flowmeter.

The Effect of Flowmeter Response on Process Variability

The analysis of the effects of flowmeter response on process variability was done using transfer function models and *Mathematica*[®] to simulate the control loop. As stated above, the reference flowmeter was chosen to be DP2B, the fastest available flowmeter. For this analysis the decision was made to tune the loop more aggressively. It is the recommendation of some experts that a properly tuned loop should have a gain margin between 4.6 dB and 6 dB and a phase margin between 30° and 45° [5]. For this analysis the loop tuning parameters were chosen such that the gain and phase margins were 7.11 dB and 53.5° , respectively. It was deemed impractical to reduce the phase margin to below 45° . The tuning parameters used in the simulations are shown in Table 3.

Assuming sinusoidal process variations, the process variability can be defined by equation 5:

$$\varepsilon = \frac{2X}{\sqrt{2}Q_{mean}} \times 100 \quad (5)$$

where: ε = process variability in %
 X = amplitude of the process variations
 Q_{mean} = mean flow rate.

A mean flow rate of 120 GPM and a disturbance amplitude of 5% were used in the analysis. The initial analysis was done using a controller sample rate of 0.030 sec.

The closed loop transfer functions for the three cases are shown in Figure 8. The shape of each of the curves in Figure 8 is characteristic of closed loop control. The peak occurs at the system critical frequency. At all other frequencies, particularly those below the critical frequency, the control system attenuates the transients. It is important to note that one of the most significant parameters in the

flowmeter transfer function is the dead time. Longer dead time values result in significantly more phase shift reducing the loop critical frequency.

Using the values from Figure 8 and equation 5, the process variability values were calculated. Figure 8 shows that a constant percentage reduction in process variability would be expected at frequencies below the critical frequency when a faster flowmeter is used. The use of flowmeter DP2B results in a reduction in process variability of approximately 39.9% and 56.7% compared to when flowmeter DP2A and DP4A were used. The reduction of the closed loop gain as the frequency is reduced means that the actual magnitude of the process variability becomes smaller as the frequency is reduced. This is clearly shown in Figure 9. However, it is still the case that the use of faster flowmeters will always result in reduced process variability.

It is often assumed that the use of a slow controller sample rate obviates the need for faster flowmeters. To evaluate the validity of this assumption the analysis was done with several slower controller sample rates. The additional sample rates evaluated were 0.1, 0.2, 0.3, 0.5 and 1.0 seconds. Figures 10 and 11 show the closed loop gain and the process variability for the control loop when flowmeter DP2B is used at slower sample rates. The gain margin and phase margin were held constant at 7.11 dB and 53.5°, respectively. It can be seen from Figure 10 that using slower controller sample rates results in poorer control. The additional phase shift from the increased dead time lowers the critical frequency and shifts the closed loop gain curve to the left. The result is higher gain values at frequencies below the original critical frequency. As Figure 11 shows, this results in higher process variability at any given frequency.

Figure 12 shows the closed loop gain for all three flowmeters when the controller sample rate is set at 1.0 seconds. It is clear that the same trend seen at faster sample rates holds true. The use of faster flowmeters continues to result in a reduction in the closed loop gain values at a given frequency. This again means reduced process variability at all frequencies below the critical frequency. Table 4 shows the process variability values for a disturbance amplitude of 5% at a frequency of 0.08 Hz. It also shows the reduction in process variability that could be realized if the faster flowmeter is used. A key feature of Figure 12 and Table 4 is that as the controller sample rate is slowed the percentage reduction in process variability may go down but the actual magnitude of the reduction in process variability increases. This is due to the fact that, as shown in Figure 10 and 11, slower controller sample rates compromise the overall performance of the loop resulting in larger process variability. The smaller percentage reduction in these larger values actually results in larger magnitude reductions in process variability. The benefits from using faster flowmeters continue to be realized even at slower controller sample rates.

While it is difficult to generalize the benefits that can be realized by using faster flowmeters, the following example will serve to help quantify the benefits of reducing the process variability. Assume that the fluid being controlled is an additive in a mixing process where a minimum value of the additive is required to ensure the proper quality of the mixture. Reducing the process variability means that the set point of the control loop can be lowered and still maintain the overall product quality. If the nominal flow rate of the additive is 10 gpm and the reduction in the process variability is taken as the maximum values from Table 4, the resulting savings are shown in Table 5. The benefits from using faster flowmeters can clearly be significant.

Conclusions

The results presented support the following conclusions. The dynamic response characteristics of flowmeters play an important role in the performance of flow control loops. One of the key performance

parameters of flowmeters is the dead time. Smaller dead time values when combined with shorter time constants will always result in improved control loop performance as the process variability is reduced. This reduction in process variability is realized regardless of the controller sample rate. Despite the fact that longer controller sample rates will always result in poorer overall control loop performance, users will still benefit from using faster flowmeters.

References

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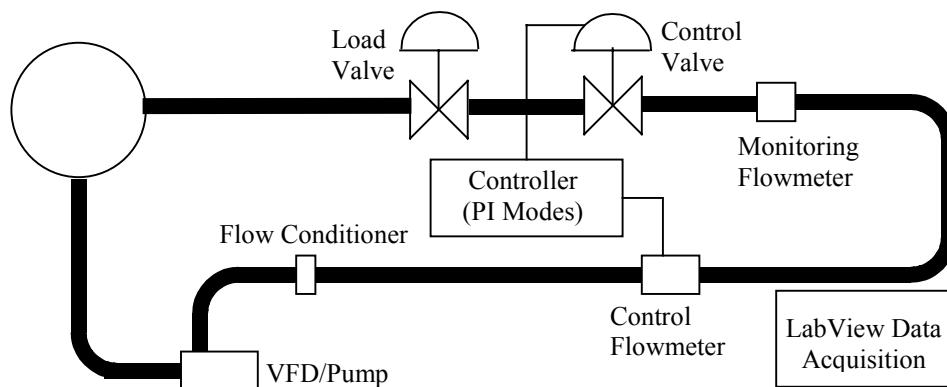


Figure 1. TEST RIG FOR FLOW CONTROL ANALYSIS.

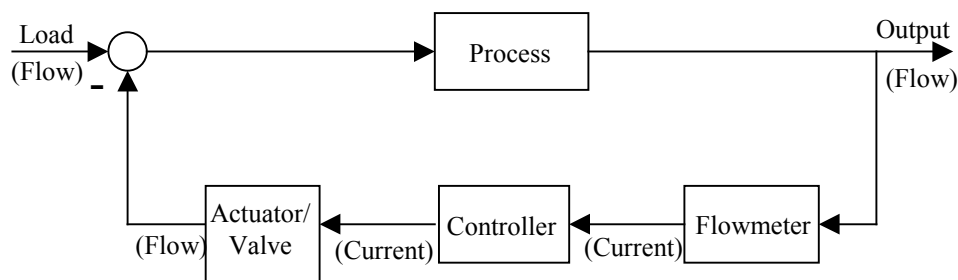


Figure 2. BLOCK DIAGRAM OF FLOW CONTROL LOOP.

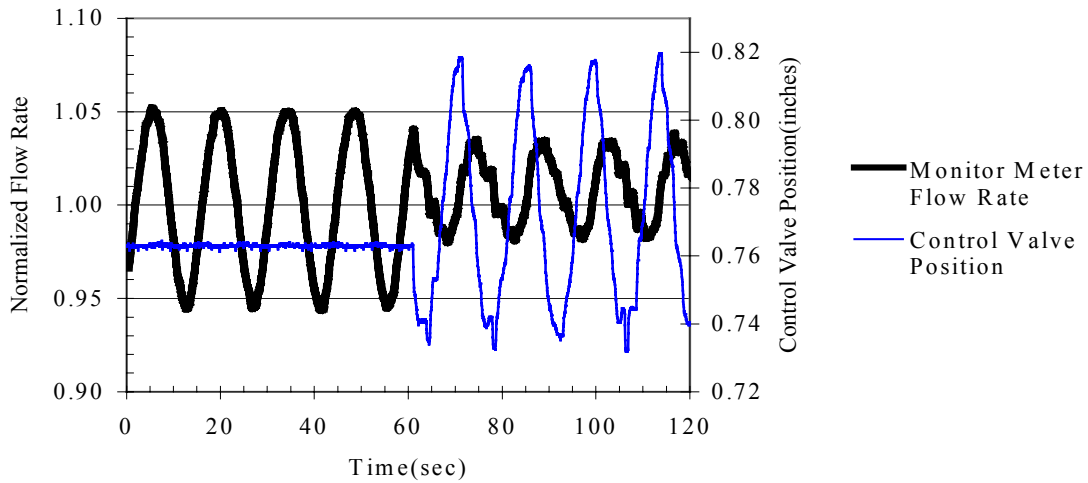


Figure 3. OPEN LOOP AND CLOSED LOOP FLOW TESTS WITH REFERENCE FLOWMETER DP2A AS THE CONTROL FLOWMETER.

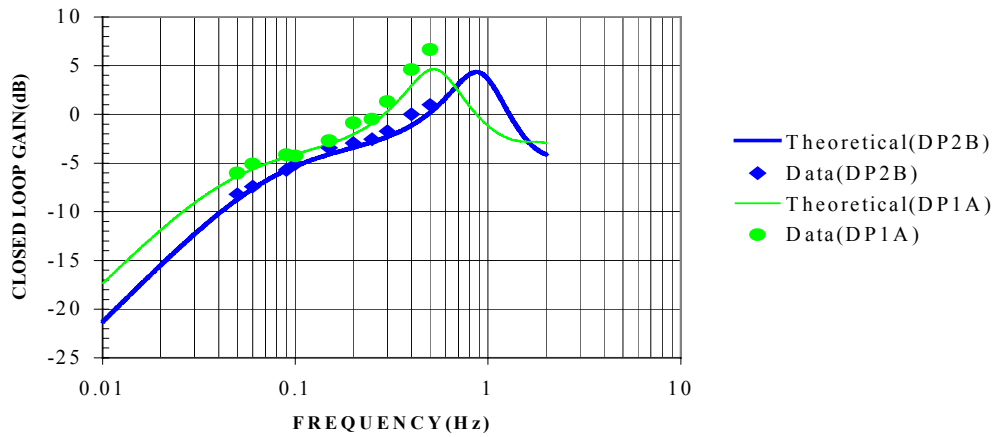


Figure 4. EXPERIMENTAL AND THEORETICAL CLOSED LOOP GAIN FOR DP2A AND DP1A AS THE CONTROL FLOWMETER.

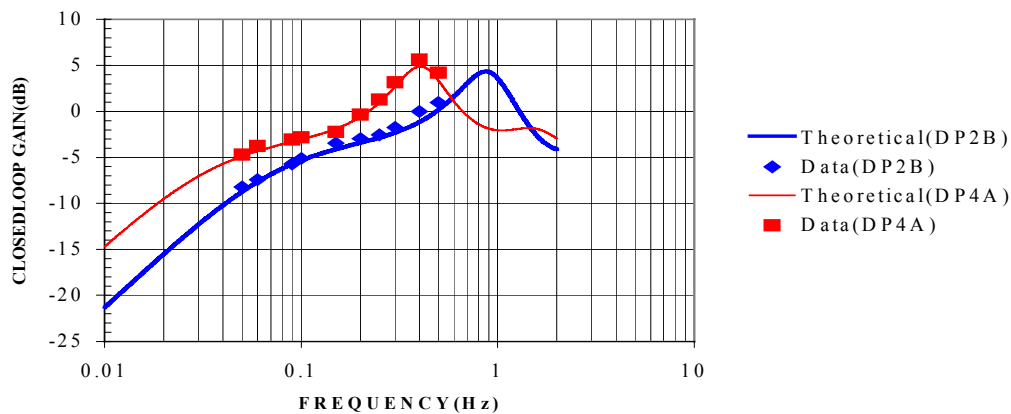


Figure 5. EXPERIMENTAL AND THEORETICAL CLOSED LOOP GAIN FOR DP2A AND DP4A AS THE CONTROL FLOWMETER.

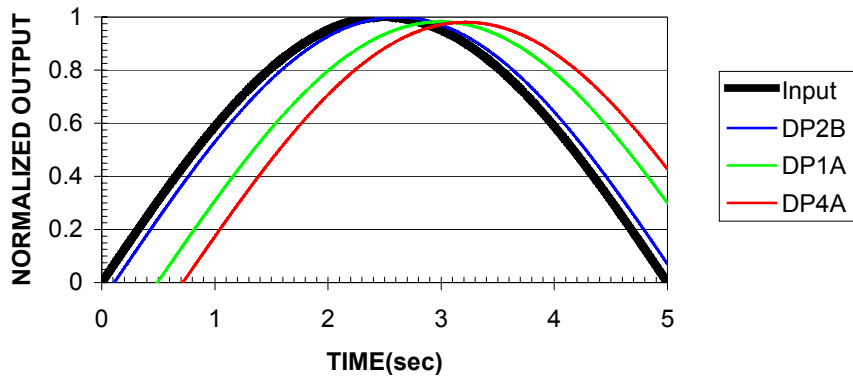


Figure 6. TIME RESPONSE OF DP2B, DP1A AND DP4A TO A 0.05 HZ SINUSOIDAL INPUT

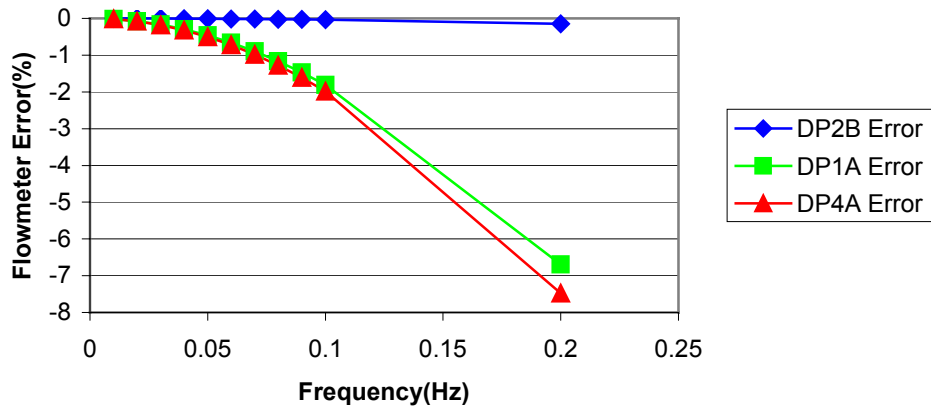


Figure 7. EFFECT OF DYNAMIC RESPONSE ON FLOWMETER ACCURACY

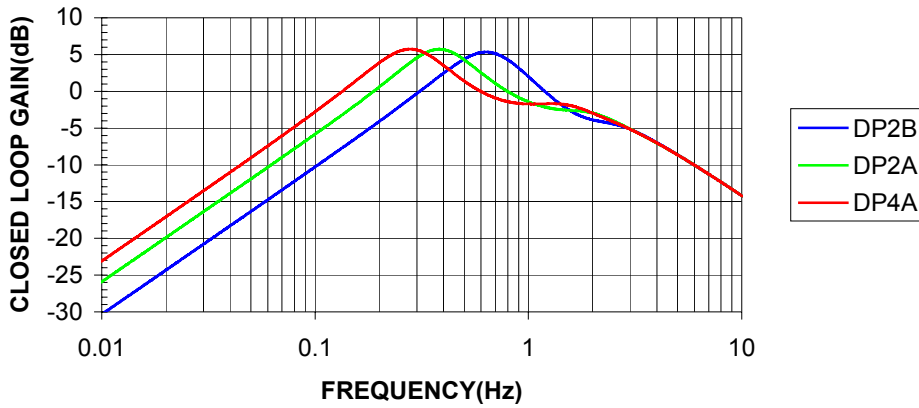


Figure 8. CLOSED LOOP GAIN, $G_m=7.11$ dB, $\phi_m=53.5^\circ$

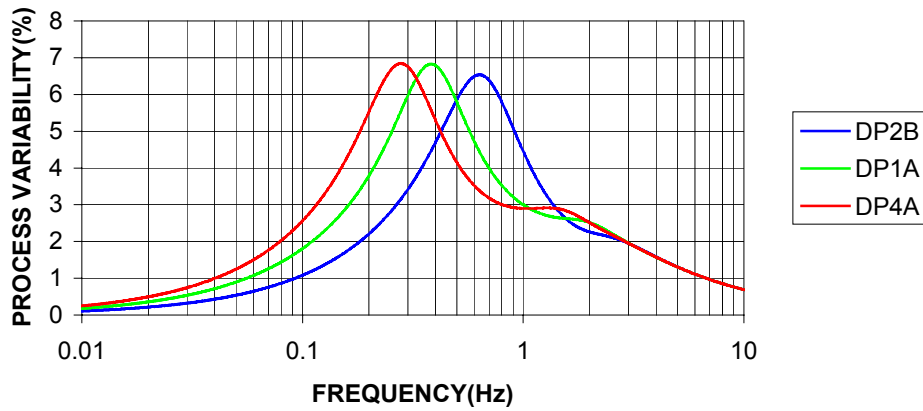


Figure 9. PROCESS VARIABILITY, $G_m=7.11$ dB, $\phi_m=53.5^\circ$, 5% DISTURBANCE AMPLITUDE, CONTROLLER SAMPLE RATE = 0.030 sec.

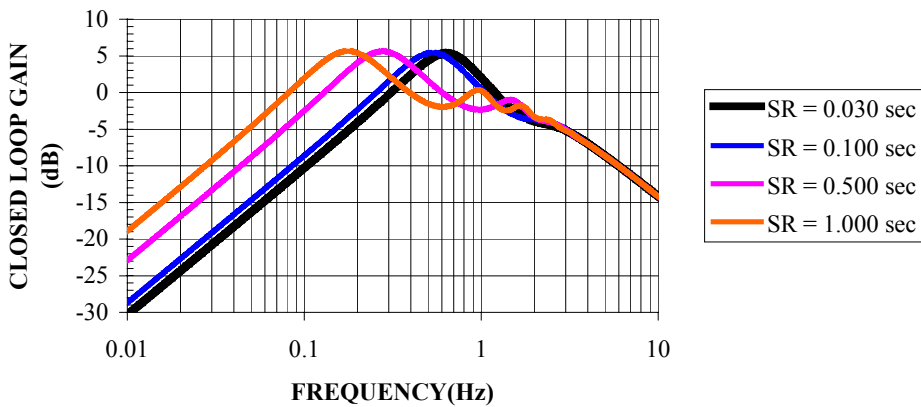


Figure 10. CLOSED LOOP GAIN AT VARIOUS CONTROLLER SAMPLE RATES (FLOWMETER DP2B, $G_m=7.11$ dB, $\phi_m=53.5^\circ$)

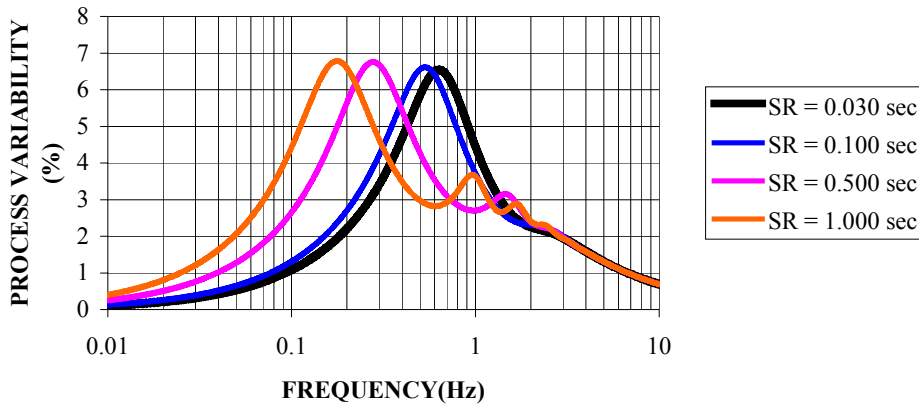


Figure 11. PROCESS VARIABILITY AT VARIOUS CONTROLLER SAMPLE RATES (FLOWMETER DP2B, $G_m=7.11$ dB, $\phi_m=53.5^\circ$, 5% DISTURBANCE AMPLITUDE)

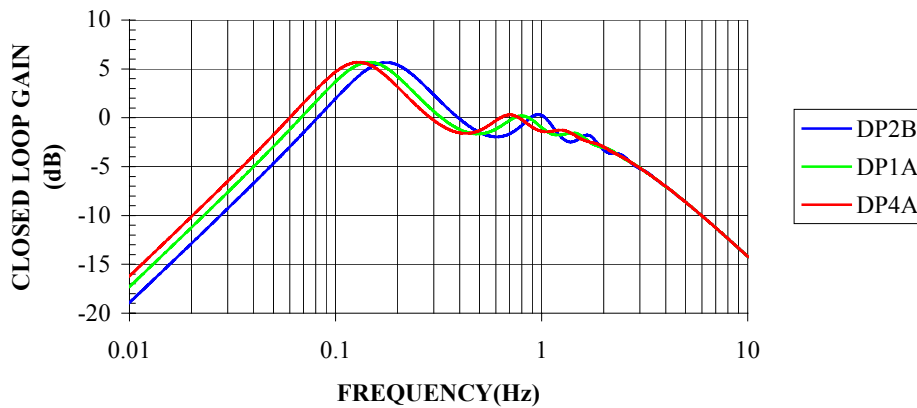


Figure 12. CLOSED LOOP GAIN AT CONTROLLER SAMPLE RATE = 1.000 SECONDS (FLOWMETER DP2B, $G_m=7.11$ dB, $\phi_m=53.5^\circ$)

Table 1. Transfer Function Parameters for Control Loop Comparative Tests

Flowmeter	τ_1 (sec)	τ_2 (sec)	τ_3 (sec)	τ_{dr} (sec)	$\tau_{dA/V}$ (sec)	τ_p (sec)	$K_{A/V}$	ω_n	ζ
DP2A(ref)	0.05	0.005	0.215	0.07	0.02	0.08	16.62	11.94	0.5
DP1A	0.306	0.02	0.215	0.17	0.02	0.08	16.62	11.94	0.5
DP4A	0.25	0.2	0.215	0.27	0.02	0.08	16.62	11.94	0.5

Table 2. Tuning Parameters for Control Loop Comparative Tests

Flowmeter	K	τ_i	Gain Margin (dB)	Phase Margin (degrees)
DP2A(ref)	0.88	1.0	7.25	103.4
DP1A	0.94	1.7	7.66	103.4
DP4A	0.82	2.05	7.35	103.1

Table 3. Tuning Parameters for Control Loop Simulation Tests

Controller sample rate = 0.030 sec				Controller sample rate = 0.100 sec			
Flowmeter	Damping	K	τ_i	Flowmeter	Damping	K	τ_i
DP2B(ref)	0.0	0.6135	0.245	DP2B(ref)	0.0	0.5236	0.2525
DP1A	0.0	0.6855	0.4555	DP1A	0.0	0.603	0.4524
DP4A	0.2	0.520	0.4779	DP4A	0.2	0.477	0.479
Controller sample rate = 0.200 sec				Controller sample rate = 0.300 sec			
Flowmeter	Damping	K	τ_i	Flowmeter	Damping	K	τ_i
DP2B(ref)	0.0	0.4365	0.2613	DP2B(ref)	0.0	0.3825	0.2729
DP1A	0.0	0.5793	0.4529	DP1A	0.0	0.4627	0.4521
DP4A	0.2	0.430	0.483	DP4A	0.2	0.3958	0.491
Controller sample rate = 0.500 sec				Controller sample rate = 1.000 sec			
Flowmeter	Damping	K	τ_i	Flowmeter	Damping	K	τ_i
DP2B(ref)	0.0	0.3198	0.300	DP2B(ref)	0.0	0.2583	0.3835
DP1A	0.0	0.3885	0.4753	DP1A	0.0	0.3018	0.5398
DP4A	0.2	0.351	0.5155	DP4A	0.2	0.2885	0.585

Table 4. Process Variability Data, 5% Disturbance at 0.08 Hz

Sample Rate (sec)	Process Variability (%)			Process Variability Reduction (%)	
	DP2B	DP1A	DP4A	DP2B-DP1A	DP2B-DP4A
0.03	0.865	1.441	2.026	0.576	1.162
0.10	1.047	1.638	2.231	0.591	1.184
0.20	1.307	1.922	2.523	0.615	1.216
0.30	1.567	2.203	2.816	0.636	1.249
0.50	2.091	2.778	3.400	0.687	1.309
1.00	3.455	4.260	4.887	0.805	1.432

Table 5. Example of Annual Savings Realized By Reducing Process Variability

Product Cost (\$/gallon)	Variability Reduction (%)	Annual Savings (DP2B vs DP1A)	Variability Reduction (%)	Annual Savings (DP2B vs DP4A)
1	0.805	\$42,311	1.432	\$75,266
5	0.805	\$211,554	1.432	\$376,330