# Optimizing Response Time to Improve Flow and Pressure Control

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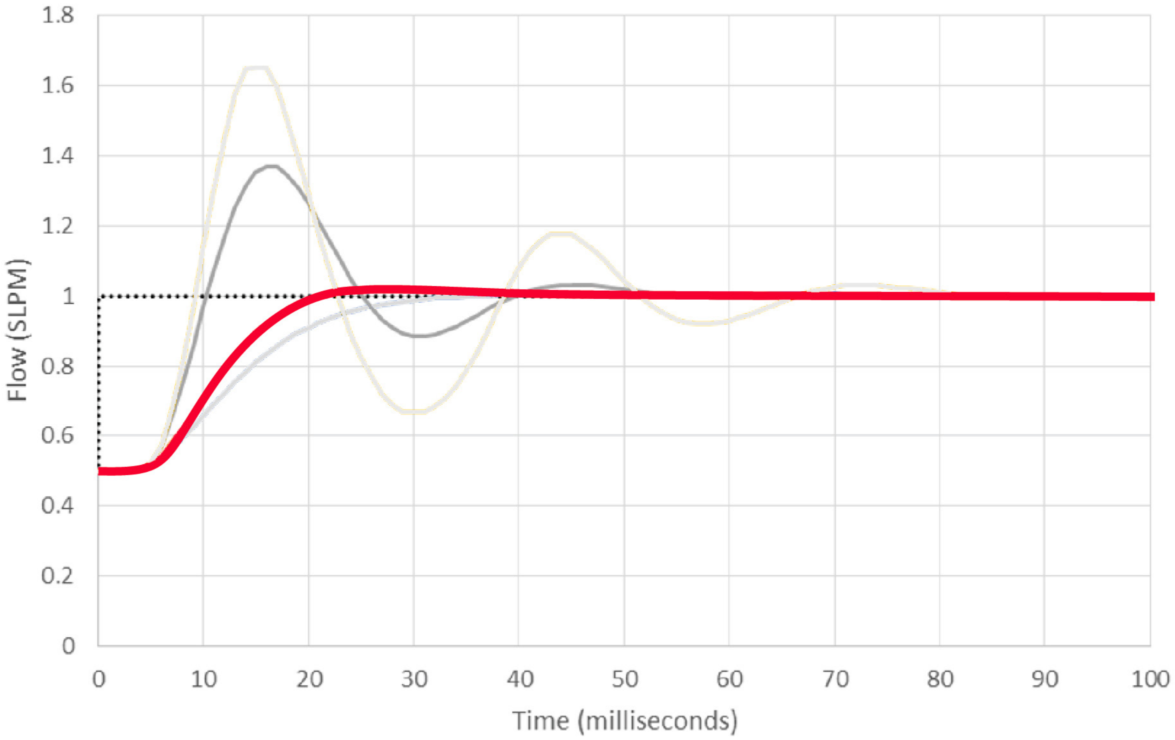

## Brian Clendenin

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Brian Clendenin is Senior Software Engineer at Alicat Scientific, leading instrument firmware development for mass flow and pressure controllers since 2014. He has over 30 years of experience in signal processing and control, beginning at Raytheon Missile Systems. Brian has a bachelor's degree in Engineering and Applied Science from the California Institute of Technology and a master's degree in Aerospace Engineering from the University of Michigan.

# Introduction

A control device must be able to sense changes within a system and respond quickly enough to mitigate them. Every control device will have a characteristic response; for some devices, that response time can be optimized based on the specific process and environment.

Manufacturers will set up new control devices to perform well over a range of standard conditions. If conditions change dramatically, or if a device needs to perform in a very specific way, then it may be beneficial to optimize the response to meet these new conditions.

This white paper discusses when and how optimization can help achieve the best system performance. Manual and automated methods for optimizing device response are presented and compared, providing a range of options for achieving excellent flow control in a specific environment.

# Flow Control Quality Depends on Response Time

Quality flow control is achieved through a combination of good system design and an excellent control system. Much has been written about good system design, so the focus here is on the control system.

For a simple process with little restriction, a good pressure regulator coupled with an orifice may provide a sufficient control system to maintain a desired flow rate. In such a simple system, the flow control response speed will have little impact on the overall system performance.

For more complex systems, however, a control loop may be required to mitigate the effects of changing pressures, temperatures, etc., all of which can impact the flow rate. Adding dynamic elements, such as valves that feed other devices in the process, will cause disturbances that can become the dominant factors in the performance of the system.

## Influences on Flow Control Response Time

A control system's ability to respond to setpoint changes and to mitigate system disturbances requires:

- a well designed system, with attention to restrictions, consistency of pressures, etc.
- an accurate, repeatable sensor
- a valve that can adjust the flow in small increments
- a control response time fast enough to overcome the particular system's range of fluctuating conditions.

This article will focus on response time.

# Definitions of Response Time

The definitions of response time vary from manufacturer to manufacturer. For this discussion, control response time is the sum of the dead time plus the time constant, as shown in **Figure 1**. The dead time, or time delay, is the period between when a command/setpoint change is received and when the valve begins to move in response. The time constant is the amount of time required to move 63.2% from the initial value to the new value.

In general, a faster device response will correct disturbances in a system more quickly, and it will track setpoint changes more closely. **Figure 2** illustrates this effect. In this figure, a pressure wave moves through a system. This type of disturbance may occur with the closing of a valve upstream of this device that feeds another device. The four measurements are taken from the same flow controller optimized for different response times. The initial effect of the disturbance is the same for all control devices—it is characteristic of the system. Devices with faster flow controller responses, however, will minimize the effects of the disturbance, keeping the flow closer to the desired setpoint and returning to the setpoint faster.

Manufacturers will typically list response times for their control devices. However, some list the fastest possible response times, while others list more conservative, and typically achievable, values. Because of this variability in how response times are reported, it can be difficult to compare devices. Directly measuring their response times is the most reliable indicator.

Ultimately, the most precise flow control will be achieved in a system that minimizes both the disturbances and the variety of conditions seen by the system and flow controller.

The example in **Figure 2** also shows that process disturbances have unique characteristics which the control device must accommodate. Some devices provide a single "speed factor" to optimize response time, which may be insufficient to match the characteristics of the process. A device which enables greater control over the specific response can allow more precise optimization for the process conditions.

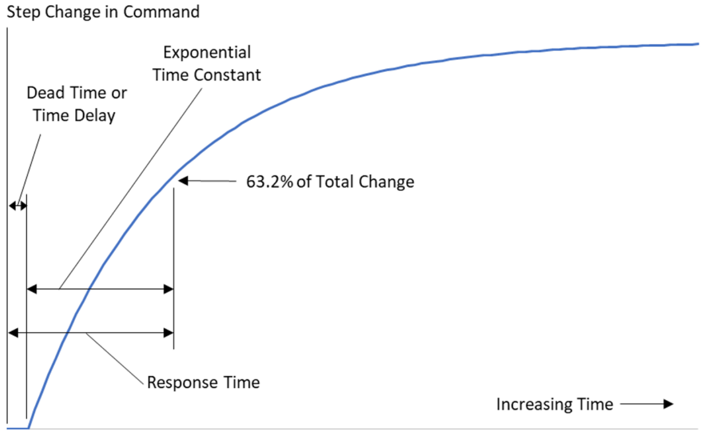


**Figure 1**. *A common definition of control response time.*

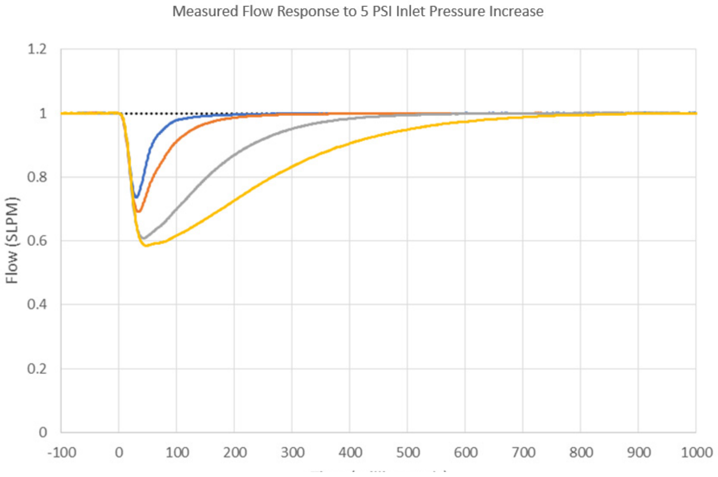


**Figure 2**. *When an upstream valve opens, a control device with faster response time (blue) can mitigate the disturbance more quickly and precisely.*

# Optimizing for Speed vs Varying Conditions

Optimizing the response time for a particular set of system conditions will ensure quality control, provided that the process conditions remain relatively consistent with that optimized state.

Conditions can vary, however, and that variability can significantly change the system characteristics. It is often preferable to optimize the response time under a broader range of potential conditions. In this case, the optimization prioritizes a reasonable response to most conditions over maximizing response for a particular set of conditions. This approach will typically provide more consistent performance, with the potential tradeoff of slower response speed than nominally possible for some conditions.

# When to Optimize Flow Control Response Speed

When a system changes significantly, the controlling device may no longer be able to provide the same level of performance. In **Figure 3**, a flow controller has been optimized while the inlet pressure was 30 PSIG. When the inlet pressure is changed significantly, the control response is degraded, as evidenced in **Figure 3** by the transients after a setpoint change. Optimizing the response time for the new process conditions can restore the level of performance.

Optimization can improve flow control performance in a variety of circumstances:

## At Installation

Though a device will be configured at the factory to handle a broad range of conditions, optimizing the response time in situ will improve the flow control performance for that particular system.

## Changes in the Process

Changing how a system is used may alter the system characteristics. For example, increasing or decreasing the system pressure may significantly change how the control system responds, as shown in **Figure 3**.

Changing the process gas can also create very different conditions. Even flow controllers that compensate for changes in gas properties can benefit from optimizing the system using the actual process gas.

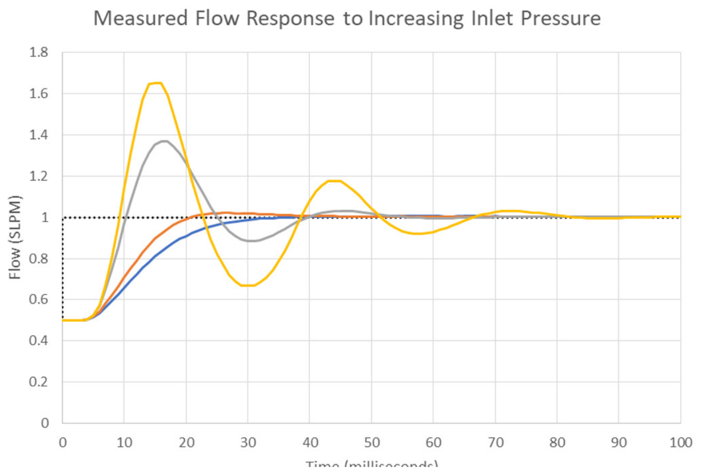


**Figure 3**. *Increasing the inlet pressure significantly after flow control has been optimized can impact flow control stability. Re-optimizing the control response time can restore performance.*

## Changes in the Physical System

Significant changes in system plumbing, such as the removal or addition of a volume or restriction, are likely to impact flow control performance.

In **Figure 4** and **Figure 5**, a device was optimized with a particular downstream process volume. **Figure 4** shows how increasing the process volume after the optimization has resulted in transients after the setpoint change. In **Figure 5**, the downstream volume was decreased, resulting in a slower response, which limits the controller's ability to track the setpoint and mitigate disturbances. In both cases, optimizing control can establish a similar response for the new physical systems.

## When Moving a Device Between Systems or Experiments

In some labs, a control device may be used across multiple experiments with very different configurations. Optimization will ensure performance whenever the device is moved to a new setup or when a setup is changed.

## When an Exact Response is Required

In some situations, an exact response speed may be required to protect a sensitive process, or when multiple devices may need to provide the same response within a connected system. Optimization can be used to reach a particular performance goal.

## When Improved Flow Control is Required

Over time the needs of the process may change, perhaps requiring faster or more precise control. Optimization can improve the response to achieve these goals.

*Credit: ZBT GmbH, Nadine van der Schoot*

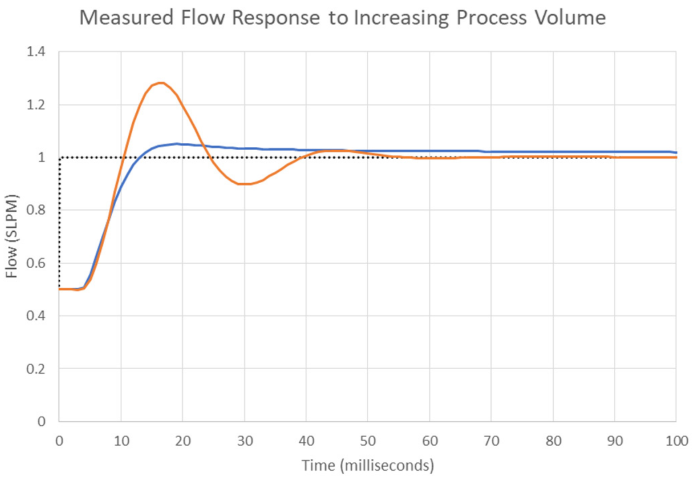


**Figure 4**. *The process volume downstream of the flow controller was increased after the device was optimized, resulting in decreased flow control stability, which appears here as transients after a setpoint change.*

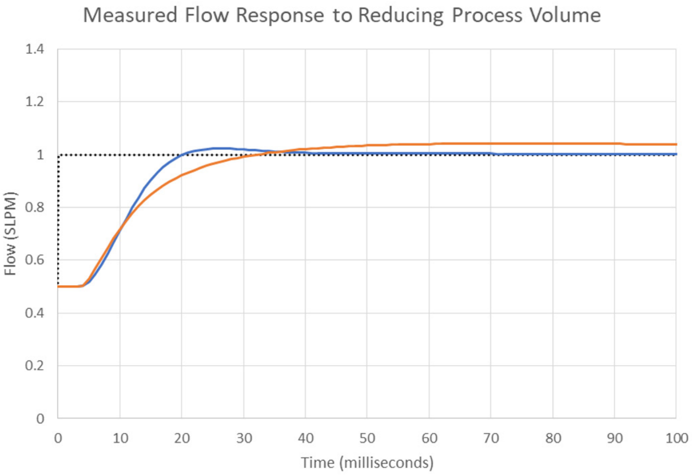


**Figure 5**. *The process volume downstream of the flow controller was decreased after the device was optimized, resulting in a slower flow control response.*

# Measuring the Flow Control Response

The flow control response can be measured to characterize system performance, to diagnose/improve system performance, or to indicate whether the system has changed enough that optimization may be warranted.

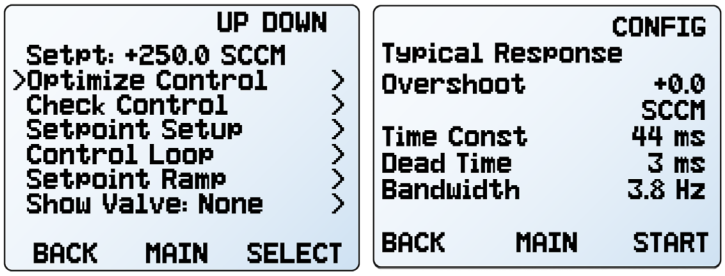
## Manual Measurement

Measuring the flow control response manually can be laborious and requires knowledge of control parameters and their calculations. Some flow controllers may require analog equipment or extensive digital integration in order to collect the necessary data. Thirdly, establishing a sufficiently fast channel to communicate with this equipment may require significant effort and may disrupt standard process communications.

## In-Device Measurement

Some controllers can capture and analyze their own control response without additional equipment or wiring.

The Check Control function in Alicat LC liquid flow controllers and MC model mass flow controllers is an example of an in-device method for measuring and reporting widely used control metrics. The Check Control function can be initiated from the device's display (**Figure 6**), via text serial commands, or using industrial protocols such as MODBUS RTU, EtherNet/IP, or PROFINET.



Setpt: +250.0 SCCM
>Optimize Control >
Check Control >
Setpoint Setup >
Control Loop >
Setpoint Ramp >
Show Valve: None >

Typical Response
Overshoot +0.0 SCCM
Time Const 44 ms
Dead Time 3 ms
Bandwidth 3.8 Hz

**Figure 6**. *In-device calculation of response variables with Check Control. Available on selected Alicat instruments with firmware 10v11 and later.*

During the Check Control process, the device completes a change to a user-provided setpoint, recording flow data for a user-specified time period. Following the change, several common control variables are reported:

**Overshoot**. The amount of process overshoot observed as a result of a setpoint change.

**Dead Time (time delay)**. The time between when the setpoint was changed and when the process began to change. This value can be directly used as the delay parameter in a first order model of the controller.

**Time Constant.** The amount of time required for the process to move 63.2% of the setpoint change after the process began to change. This value can be directly used as the time constant parameter in a first order model of the controller.

**Bandwidth**. The estimated frequency of the fastest sine wave setpoint that the device can reasonably follow. The device can be expected to reject most sinusoidal disturbances with a lower frequency.

# Autotuning Flow Control Response Speed

When optimization is warranted, the process can be completed manually or, in some cases, it can be completed automatically.

## Manual Optimization

There are many approaches to manually optimizing a control loop. However, most methods require additional equipment as well as knowledge of control system analysis and design. Most also require a significant amount of time to accomplish.

## Autotuning

In-device, automatic optimization, or "autotuning," can achieve excellent control for the specific process conditions and environment, without requiring the user to have extensive knowledge of control design or parameters.

The control response speed of Alicat LC liquid flow controllers and MC model mass flow controllers can be optimized automatically, from within the device. This function can be accessed from the device display (**Figure 7**), via serial commands, or industrial protocols such as MODBUS RTU, EtherNet/IP, or PROFINET.

During automated optimization, the device moves to a series of setpoints. For each setpoint change, the device determines system properties and optimizes control parameters. When the parameterization is complete, the device response is adjusted to the optimal settings, and the device reports the overshoot, dead time, time constant, and bandwidth of a typical response with the final settings (described in the Measuring Flow Control Response section above).

Autotuning is much faster than most manual techniques. For most alicat devices, for example, the process is completed in 30–90 seconds. Ultra-low flow devices (roughly 50 SCCM and below) may require longer; 0.5 SCCM devices may take up to 15 minutes.

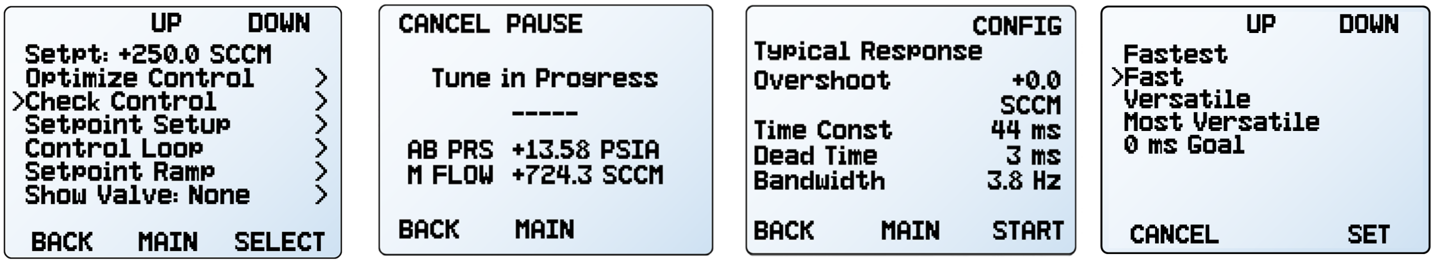
## Suggestions for Achieving the Best Optimization

Optimization is most effective when the process conditions maximize the pressure delta across the valve(s) involved. Unstable control may result when a device operates at a higher pressure delta or higher common mode pressure than it was optimized for. If operating conditions are expected to include higher pressures than are available for optimization, a speed level that emphasizes versatility is preferable.

Optimization is more sensitive to fluctuations in the environment than normal closed loop control. Most fluctuations will result in control loop gains that are smaller than they might otherwise be, as it is difficult to separate the effects of the disturbance from the response of the system. Ultra-low flow and other slowly responding devices will be much more sensitive to disturbances or other fluctuations in the system.

## Advanced Configuration Options

For most situations, automated optimization will determine the best response time without any user input. The function can, however, be further configured to support atypical process requirements or specific control goals.



```
Setpt: +250.0 SCCM
Show Valve: None
```

```
Tune in Progress
-----
AB PRS  +13.58 PSIA
M FLOW  +724.3 SCCM
```

```
Typical Response
Overshoot          +0.0
                   SCCM
Time Const        44 ms
Dead Time          3 ms
Bandwidth        3.8 Hz
```

**Figure 7**. *In-device response optimization (autotuning). Available on selected Alicat instruments with firmwave version 10v11 or later.*

### Speed

The Speed setting determines how the function will address the tradeoff between speed and the ability to handle process variability:

**FAST** is the default option which balances speed and versatility for most situations.

**FASTEST** maximizes response speed (i.e., minimizes the control loop response time constant), allowing a small amount of overshoot.

**VERSATILE** or **MOST VERSATILE** will provide a response speed that accommodates a wider range of conditions, but with the tradeoff of slower response. The control system may not be able to respond to quickly changing conditions.

**Figure 8** shows the response of a mass flow controller that has been optimized using these Speed options.

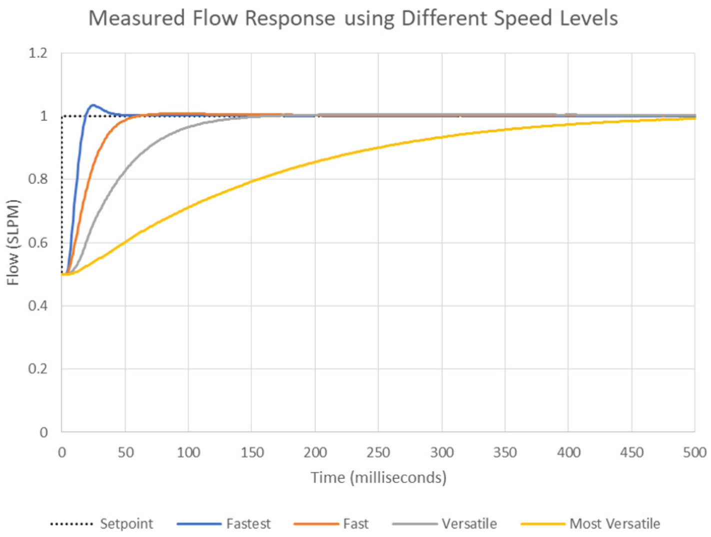


**Figure 8**. *The impact of Speed settings on the speed of response.*

**GOAL** is an additional Speed option for advanced users who need to achieve a particular response profile or who need to tune multiple devices to provide the same response. The function will attempt to achieve the time constant goal. When the goal is impossible to meet (e.g., if the goal is set to 0), the nearest possible time constant will be used (which is equivalent to the FASTEST option).

### Max Flow

During optimization, the device will move to a series of setpoints, some of which may be above the device's current setpoint. The Max Flow setting limits the maximum flow during optimization for situations in which the process needs to be protected from excessive flows. In unusual circumstances the maximum flow may still be exceeded; however, the device will attempt to minimize the duration.

### Loop Type

The optimization function will automatically use the best control loop based on the process. The AUTOMATIC option is, therefore, the default and recommended setting.

In some instances, advanced users may have specific requirements and may choose to specify either the $PD^2I$ or PDF closed loop algorithm during optimization.

# Conclusion

Control device optimization can provide the best response for a particular process and environment. New, automated tools make it possible to measure current performance and improve it. Automated Control Optimization tool is an example of Alicat's usability tools that provide excellent device performance without requiring extensive knowledge of control systems and parameters.

## Advantages of Autotuning

- **Fastest control system response time**
- **Tune control to the characteristics of the particular system**
- **Smoother flow over the range of process conditions**
- **Optimize system without additional equipment or control design expertise**

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