

Consistency Control Loop Dynamic Specification

(Version 1.0, 3/02)

Competitive Marketplace

The global market's continuing demand for quality and uniformity in manufactured products means there is even greater focus being given to process control equipment and its performance. EnTech Control has specialized in optimizing the performance of pulp and paper manufacturing where product uniformity specifications can now be as tight as 1%. Mill process variability audits frequently find that product variability can be increased by control loops that cycle on automatic. The consistency control loop is one of the most important loops in the pulp and paper mill as it determines the mass flow of fiber on which everything else depends. Applications range from the pulp mill through to the final point of dilution ahead of the paper machine, where variability of 1% of mean can be considered high, 0.5% is good, below 0.3% is excellent. ***This specification defines consistency control loop design and tuning criteria needed to minimize process variability. It is based on over a decade of experience.***

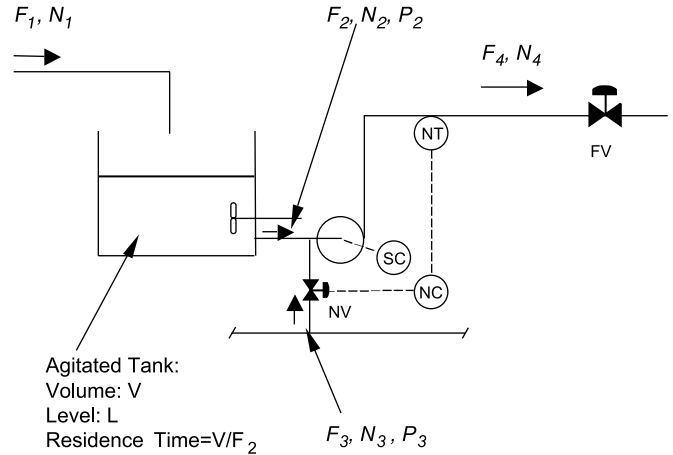


Figure 1 – Typical Consistency Control Loop

Purpose: to define the design criteria for high performance consistency control with a speed of response as fast as 10 seconds (closed loop time constant, Lambda [1]) and resonance at or below 125%, for the loop design shown in Figure 1. The specification sets limits for critical design and tuning parameters to achieve this performance, as well as best design practice needed to minimize consistency variability.

Content: The document has four sections, a) specification, b) technical discussion, c) definitions and d) references.

SPECIFICATION - High Performance Consistency Control Loop Dynamic Requirements

- 1) Min. closed Loop Time Constant (Lambda λ): 10 sec.
- 2) Lambda λ adapted as demand flow changes: $\lambda \geq 3T_d$
- 3) Total deadtime (T_d): max. 3 sec. for max. demand flow. Transmitter deadtime; < 1 sec.
- 4) Time constant (τ): \leq minimum total deadtime of 3 sec.
- 5) Process gain (Kp): from 0.5 to 2.0
- 6) Dilution Header Pressure (P_3): maintained to +/- 2%
- 7) Stock Tank Mixing Time Constant (τ_{tank}): > 5 minutes
- 8) Dilution Control Valve: as per EnTech Specification, Opening 20% to 80% over operating range. Valve characteristic: equal percent

Lambda & Deadtime Needed to Achieve High Performance with Resonance at or Below 125%

λ seconds	T_d seconds				
10	3				
12	3	4			
15	3	4	5		
20	3	4	5	6	
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30	3	--	--	9	10

For demand flow turndown ratio greater than 3:1 the $\lambda \geq 3T_d$ relationship must be maintained

TECHNICAL DISCUSSION

Consistency Control Loop System: The Specification considers the consistency control loop shown in Figure 1 as a dynamic system. This is the simplest control loop design and potentially has a speed of response as fast as 10 seconds (closed loop time constant, Lambda [1]). Other design configurations are discussed below. In Figure 1 the process design starts with an agitated stock tank. Stock enters the tank at flow F_1 and consistency N_1 . The level of the tank is controlled by adjusting stock flow F_1 . This tank is intended to smooth out fast consistency variability. Stock flows out of the tank at flow rate F_2 and consistency N_2 (typically in 4% to 5% range), and is diluted at the pump suction via a consistency control valve (NV) with dilution water supplied from a dilution header at pressure P_3 , flow F_3 and consistency N_3 (normally less than 0.3%). The dilution head-

er is a common source of fast process variability if the header pressure is uncontrolled and there are many users (most common case), or if the consistency N_3 is unstable. The stock pump is usually driven by a fixed speed pump, although variable speed pump drives are becoming more popular for flow control or pressure control. The consistency transmitter (NT) is normally located some distance down the pipe and this distance is the major contributor to the deadtime present in the control loop (NC). The demand flow F_4 at consistency N_4 (typically 3.5% to 4.5%, typical consistency cut ~0.5%) is supplied to the downstream process under flow control usually employing the flow control valve (FV) or alternatively using the variable speed drive on the stock pump (SC).

Other Consistency Loop Designs: there are many other designs, all of which degrade the potential dynamic response of the consistency control loop, hence are outside of this specification. Some involve adding a recirculation line after the consistency transmitter to recirculate stock to either the pump suction, or back to the stock chest. The motivation for this may involve refiner pressure control, prevention of pump deadheading, or an attempt to place the consistency transmitter in a constant flow environment. The presence of any substantial recirculation (more than 10%) causes the consistency loop dynamic response to have multiple responses recurring as the stock recirculates, with slower and more unpredictable dynamics, making high performance control virtually impossible. A control strategy design variation involves a flow control loop on the dilution water flow and the consistency controller adjusts the ratio between dilution water F_3 setpoint and demand flow F_4 . This is an excellent design to ensure that the dilution flow ratio is maintained constant (see mass balance section), but may suffer from a slower dynamic response (for $\lambda < 15$ seconds) due to the need to have an inner cascade loop (about 5 x slower). HD storage chest consistency control deserves special attention due to the slow dynamics of the HD mixing zone and is beyond the scope of this specification.

Consistency Transmitter (NT): selection of consistency transmitter is one of the most important decisions in the design of a consistency control loop. Pulp consistency has two potential definitions: mass percentage of fiber, or mass percentage of total pulp solids. [2]. The consistency measurement is exceedingly difficult to make accurately as consistency cannot be measured directly and existing measurement principles are all inferential by nature. The common methods include shear force, light absorption, and microwave. Some of the difficulties include the fact that shear force transmitters are more sensitive to long fiber than to small particles, and may also be flow sensitive. Light absorption is sensitive to fiber type and particle size. Air is almost always entrained in thick stock and can wreak havoc with microwave measurements, which otherwise promise to be very sensitive to fiber, but less sensitive to heavier additives. Whatever the final choice of transmitter the loop will attempt to keep the measurement constant, whatever its failings and this may not be a true measure of pulp consistency. Selection of the best consistency transmitter for the given application is beyond the scope of this specification.

Agitated Tank: Agitated stock chest design is covered in [3] and the key is to inject adequate agitation horsepower into the fluid. The tank is intended to smooth out consistency variability faster than the cut-off frequency of the tank ($f_{c-tank} = 1/(2\pi\tau_{tank})$) defined by the mixing time constant (τ_{tank}) and to prevent fiber separation. The recommended residence time for many stock chests is typically 12 minutes [3]. Mill variability audits frequently show that the stock chest mixing time (τ_{tank}) is often only about 50% of the residence time of the tank and in some cases shorter still. For fairly effective mixing efficiency the mixing time constant should be at least 5 minutes, at which point variability faster than 3 minutes per cycle should be reduced by about 90% in amplitude. The tank level controller should be Lambda tuned to prevent cycling, with Lambda greater than τ_{tank} .

Dilution Header: Design of the dilution header is a key process design consideration as the dilution header adds high frequency variability back in at the pump suction. For effective consistency control the header pressure should be maintained constant to +/-2% if possible.

Control Valve Selection: The performance of the dilution control valve is critical and it should track the controller output reliably in a timely fashion as defined by ISA S75.25 [4], EnTech Control Valve Dynamic Specification Versions 2.1 [5], or 3.0 [6] (Class: Nominal, 10 seconds). An equal percentage characteristic will help keep K_p constant. The valve should be sized for 20% to 80% opening over the operating range.

Dynamic Response: Consistency control is characterized by an open loop dynamic response given in Equation 1. Figure 2 shows a typical bump test response of the consistency transmitter after the dilution valve has been stepped in manual control. Multiple bump tests such as this should be carried out over a range of step response

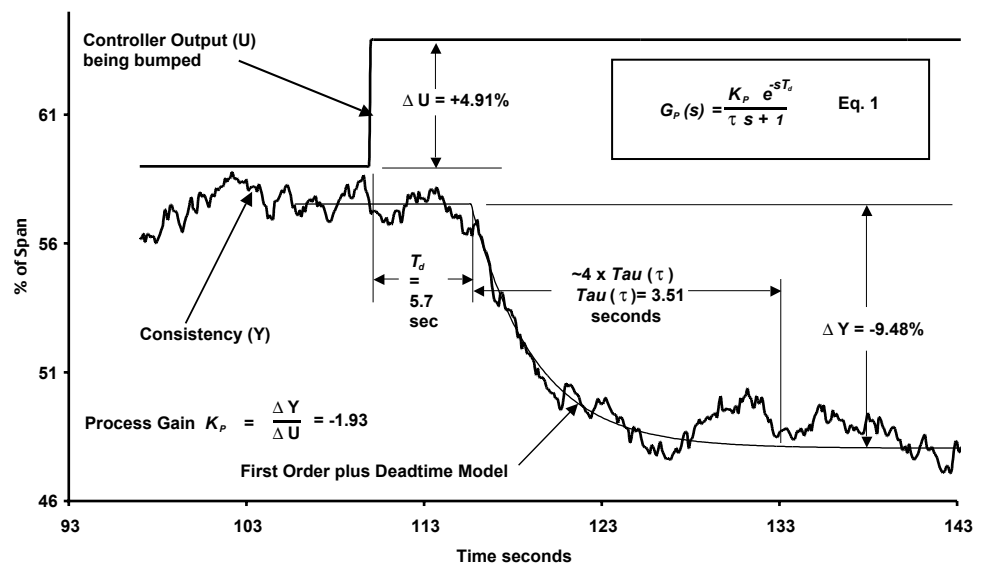


Figure 2 – Typical Bump Test

sizes to test the open loop dynamics before tuning is attempted. Values for K_p , τ and T_d should be averaged from these bump tests. In Figure 2, the controller output was stepped up by 4.91% (ΔU) from 59% at second 110. The lower curve shows the consistency transmitter signal running at about 57.5 % of Span, with a noise band of about 2.5%. The lower curve has an ideal model (first order plus deadtime) response superimposed on the data. Analysis of this model provides the resulting data in Figure 2. After a deadtime of 5.7 seconds (T_d) the consistency signal is seen to decrease due to the additional dilution water. The response follows a first order exponential response with a time constant (τ) of 3.51 seconds. The total decrease in consistency is -9.48% of Span (ΔY). The process gain (K_p) is the ratio of the consistency response change to the controller output step and is -1.93.

Deadtime (T_d): Deadtime is the most destabilizing dynamic parameter in a control loop. Ideally the deadtime in a consistency loop should be as short as possible, and no longer than 3 seconds at the maximum demand flow. There are two sources of deadtime. The most common source is due to the transport delay from the point of dilution water injection at the pump suction piping through to the location of the consistency transmitter. Some transmitters are affected by fluid turbulence and require a certain length of straight piping ahead of the transmitter hence resulting in a certain deadtime. Other transmitters can be located close to the pump discharge. Whatever the location, the transport delay is not constant and is a function of F_4 the demand flow ($T_d = V_{pipe} / F_4$). Since control loop tuning is a function of the deadtime, it stands to reason that high performance tuning requires automatic adjustment of the tuning parameters as the stock flow changes. If this cannot be done, then the loop should be tuned for the longest deadtime at the lowest demand flow. The second source of deadtime is due to transmitter design. Some transmitters have as much as 1 to 4 seconds of inherent internal deadtime caused by various compensation algorithms. For control loop performance reasons this deadtime should be kept as short as possible (< 1 sec.).

Process Gain (K_p): The process gain is the ratio of the transmitter response to the controller output change in steady state, and is determined by control valve (or final control element) sizing, process equipment sizing, and transmitter calibration. Ideally the process gain of the control loop should be 1.0. Large values of K_p compound poor control valve response due to inherent control valve nonlinearities [see 4, 5, and 6, including EnTech Control Valve Specifications]. Ideally K_p should also be as constant as possible over the operating range. However the process gain varies according to Equation 2 (directly with incoming consistency N_2 , inversely with demand flow F_4 and directly with the dilution valve C_v). Since the dilution valve opens as demand flow increases to maintain a constant ratio of dilution flow to stock flow, selecting an equal percentage control valve characteristic will help offset decreases in K_p that result from increased stock flow.

$$K_p = -\frac{100}{NT_{span}} \frac{N_2}{F_4} \frac{C_{V_{NV}}}{C_{V_{MAX}}} \sqrt{\Delta P} \dots \text{Eq. 2}$$

Time Constant (τ): Even though some pipe mixing contributes to the exponential response, the greatest impact on time constant is due to the consistency transmitter internal damping features. In older transmitters damping was arranged via an analog RC filter. This gives an ideal first order exponential response that is perfectly matched to the needs of the feedback controller. Most newer transmitters feature a first order filter as a default means of smoothing the signal. However, many have also adopted various optional schemes involving moving averages and spike suppression algorithms. These features are potentially very nonlinear and can destabilize control thus should not be used. The transmitter time constant setting should equal the deadtime at maximum demand flow (3 sec.), and should be constant over the operating range.

Control Loop Tuning: The consistency open loop dynamic response transfer function is given in Equation 1. The recommended control algorithm is a Proportional-Integral (PI) controller, and the recommended tuning method is the Lambda Tuning method [1].

The first step is to select the closed loop speed of response Lambda (λ) which should always be based on the deadtime (T_d). The faster the tuning the more the loop will reduce variability slower than the cut-off frequency (cut-off period $T_c = 2\pi(\lambda + T_d)$). Unfortunately, due to the deadtime, the faster the selected tuning the more the loop will resonate and amplify fast variability as shown in Figure 3. For this reason the selection of Lambda should be based on the table insert in Figure 3 and should be at least three times the deadtime in order to keep the resonance below 125%. The shorter the deadtime, the more it is possible to select longer values of Lambda in order to achieve lower resonance. Once Lambda has been selected, the controller (standard, classical or series PI form) is tuned by setting the reset time equal to the process time constant ($T_R = \tau$ should be constant over operating range) while the controller gain is calculated based on the

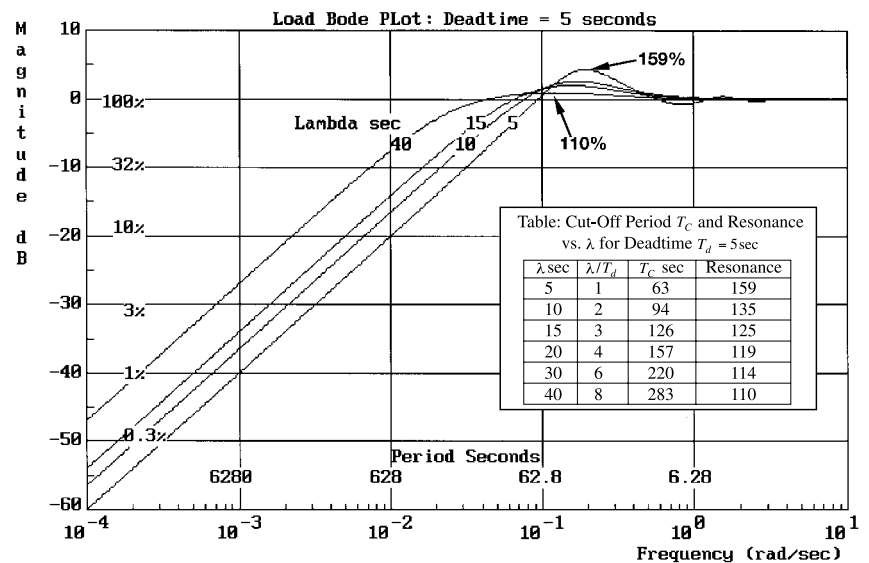


Figure 3 – Load Bode Plot

equation $K_C = T_R / (K_p(\lambda + T_d))$ Demand flow turndown changes will require Lambda to be adapted on-line as deadtime changes. If this is not possible it is best to tune for the smallest demand flow and Lambda equal to three times the longest deadtime.

Mass Balance: The consistency of the demand flow is governed by Eq. 3. It is clear from this balance that to maintain the demand consistency constant, it is important to maintain a constant ratio between dilution flow F_3 and demand flow F_4 .

$$N_4 = N_2 \left(1 - \left(1 + \frac{N_3}{N_2}\right) \frac{F_3}{F_4}\right) \dots \text{Eq. 3}$$

Control Strategy: The consistency control loop will experience changes in demand flow F_4 (turndown), and the control strategy needs three additional features. A) Feedforward control to move the dilution valve (by an appropriate amount based on Equations 2 & 3) when the demand flow changes (this requires a measurement of F_4 or knowledge of the Cv characteristics of the FV and potentially also a measurement of P_3 as well). B) Lambda should be adapted as deadtime changes ($\lambda \geq 3T_d$). C) The controller gain K_C should be adapted via a gain-scheduling algorithm to compensate for the changes in deadtime T_d , λ and process gain K_p resulting from the flow change. If the adaptation cannot be achieved then the loop should be tuned for a Lambda of three times the longest deadtime.

DEFINITIONS

F_1	=stock flow entering agitated tank (Figure 1)	N_3	=consistency of dilution water (Figure 1)
F_2	=stock flow leaving agitated tank (Figure 1)	N_4	=demand consistency (Figure 1)
F_3	=dilution water flow (Figure 1)	P_3	=dilution header pressure (Figure 1)
F_4	=demand flow (Figure 1)	PI	= Proportional-Integral algorithm,
K_C	= controller gain	τ	= process time constant
K_p	= process gain	τ_{tank}	=mixing time constant - stock tank ahead of the consistency loop
λ	=closed loop time constant	T_d	= deadtime
N_1	=stock consistency entering agitated tank (Figure 1)	T_R	= reset or integral time (standard and classical PID)
N_2	=stock consistency leaving agitated tank (Figure 1)		

Closed Loop Time Constant (Lambda (λ)): time constant of a control loop. The user can select λ value to achieve process objectives. The values of λ can be limited by the speed of response of the process, the transmitter and the control valve.

Dead time (T_d): the time period after an input signal step change and prior to the start of a response.

Nonlinear Dynamics: dynamic parameters (gain, time constants) which change over the operating range.

Process Gain (Kp): for a step change, the ratio of the change in process variable to the change in input signal.

Process Variable (PV): the process measurement used for feedback control by a loop.

Process Dynamic: the way a process variable responds, over time, to a change in controller output. This is best characterized by the step response, modeled by a transfer function and expressed in terms of process gain, time constants and deadtime.

Speed of Response: of a dynamic non-integrating system can be gauged by measuring the time constant of a first order model which approximates the dynamic response of the actual system.

Time constant (τ): the time required for a first order linear system to reach 63.2% of the full change after an input step change.

Time to Steady State (Tss): time at which PV is within 2% of its steady state value.

REFERENCES

- 1) William S. Levine, W.S (Editor), *The Control Handbook*, CRC Press and IEEE Press, 1996. ISBN 0-8493-85709. Chapter 72 – Bialkowski W. L., "Control of the Pulp and Paper Making Process".
- 2) Gerald F. Ostroot, *The Consistency Control Book*, TAPPI Press, 1993
- 3) D. Carl Yackel, *Pulp and Paper Agitation: The History, Mechanics, and Process*. TAPPI Press, (1990).
- 4) ANSI/ISA S75.25.01-2000 Test Procedure for Control Valve Measurement form Step Inputs, and ISA TR75.25.02-2000 Control Valve Measurement form Step Inputs
- 5) EnTech - Control Valve Dynamic Specification (Version 2.1, 3/94),
- 6) EnTech - Control Valve Dynamic Specification (Version 3.0, 11/98)

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