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Comparison of Cascade and Parallel Cascade Control

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ABSTRACT: Cascade control systems are widely used in industry for improving the dynamic response of systems. Cascade systems are particularly useful in reducing the effects of load disturbances that are introduced into the secondary or slave loop. The majority of these systems are of the series type i.e., the output of the secondary loop process transfer function is the input to the primary loop process transfer function. Typical example (Figure 1**)** is tray temperature control in a distillation column cascaded to reboiler steam flow control. Steam flow rate is the output of the secondary loop process transfer function, and steam flow is the input to the primary loop process transfer function (temperature/steam flow). These series cascade systems were quantitatively studied by Franks and Worley (1956).

KEYWORDS: dynamic response, Cascade systems

I.INTRODUCTION

Cascade control is sometimes used in process systems where the primary and secondary process transfer functions are not in series but are in parallel. Jauffret (1973) cited one example, the temperature control of subcooled reflux by cascade control of exit cooling water temperature in a condenser. The manipulative variable, cooling water flow, affects both exit cooling water temperature and reflux temperature through parallel transfer functions. Another example (Figure 6.1) is the overhead composition control of a distillation column by cascade control of a tray temperature. The manipulative variable, reflux flow, affects overhead composition and tray temperature through two parallel process transfer function

The purpose of this section is to explore quantitatively the differences between the series and parallel configurations.

II.STABILITY ANALYSIS

Figure 1 shows two cascade control loops on a distillation column. The lower temperature control loop maintains a temperature on some tray in the stripping section of the column by changing the setpoint of a steam flow controller. The secondary or slave process transfer function G_S in this system is the valve transfer function, the relationship between the flow controller output and the steam flow rate. The primary or master process transfer function G_M is the relationship between steam flow and tray temperature. These two process transfer functions are in series, as illustrated in Figure 2

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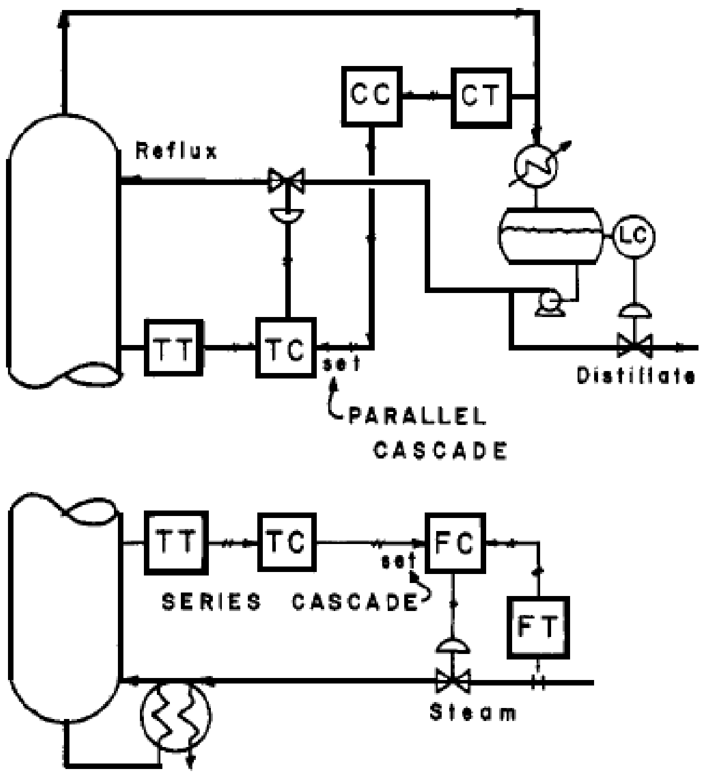

Figure 1 Distillation coloumn example of series and parallel cascade

The stability of the slave loop depends on the roots of the closed loop characteristic equation

$$1 + B_S G_S \tag{1}$$

The stability of the master loop in this conventional series cascade system, with the slave loop on automatic, depends on the roots of the closed loop characteristic equation

$$1 + B_M G_M \left[\frac{B_S G_S}{1 + B_S G_S} \right] \tag{2}$$

Without cascade control, the closed loop characteristic equation for the system is

$$1 + B_M G_M G_S = 0 \tag{3}$$

The upper temperature control loop in Figure 6.1 illustrates a parallel cascade process. Overhead vapor composition is controlled by changing the setpoint of a tray temperature controller. The manipulative variable in this system is reflux flow rate. It affects both overhead composition and tray temperature through two distinct transfer functions. Thus the process transfer functions are not connected in series. Reflux has parallel effects on temperature and overhead composition. These effects are, of course, interdependent and interacting. Reflux does not affect temperature first, which then affects overhead composition.

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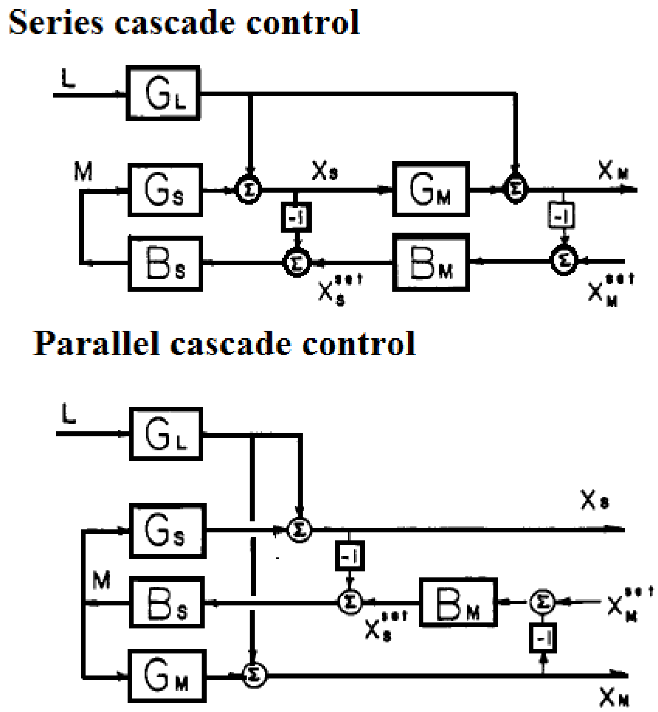

Figure .2 Blockdiagram of series and parallel cascade

Figure 2 gives a block diagram representation of the system. The two parallel process transfer functions are *Gs* and Ghl for temperature and composition, respectively. The slave closedloop characteristic equation is the same as in the series case, eq 1, but the closed loop characteristic equation of the master loop in this parallel cascade system, with the slave loop on automatic, is

$$1+B_M G_M\left[\frac{B_S}{1+B_S G_S}\right] \qquad (6.4)$$

This differs from equ (2) by the deletion of the G_S term in the numerator. Without cascade control, the closed loop characteristic equation is

$$1+B_M G_M=0$$

Without cascade control, the slave process transfer function G_S is not involved at all in controller design in this parallel system. This was not true in the series system (Based on equ 6.3).Thus these two processes are distinctly different, and the equations used to design the master controller B_M are different.

Two systems were studied. I n the first, both G_M and G_S were second-order lags.

$$G_M=\frac{1}{(\tau_M s+1)^2}$$

$$G_S=\frac{1}{(\tau_S s+1)^2} \qquad (6.6)$$

Proportional feedback controllers were used.

$$B_S=K_S$$

$$B_M=K_M \qquad (6.7)$$

The slave controller gain K_S was set equal to one to give a closed loop damping coefficient in the slave loop of 0.707. (See Figure 3.**)**

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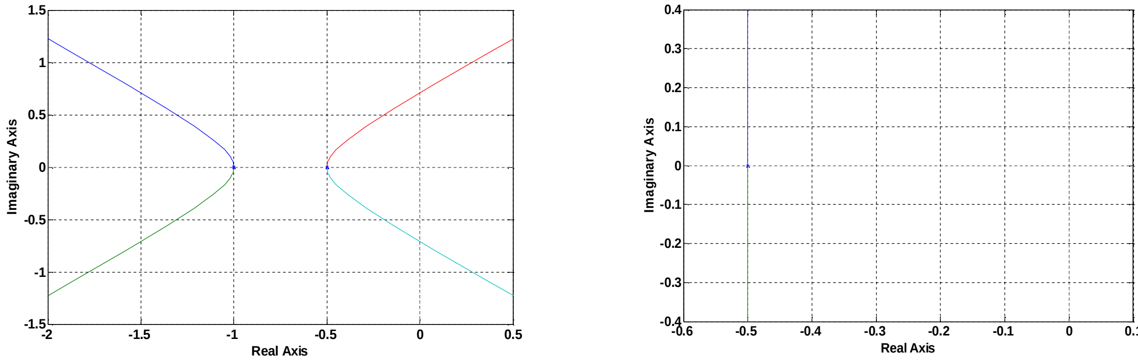

Series cascade control Parallel cascade control

Figure.3 Root locus plots without cascade

Root locus plots are given in Figure 4 for the series cascade system for values of τ_M between 0.5 and 4 with $\tau_S = 1$. The paths start ($K_M = 0$) a t the poles of the overall system open loop transfer function ($s = -1/\tau_M$ from the master process transfer function and $s = -1 \pm i$ from the closed loop slave loop). The series system is fourth order, so there are four paths. A design criterion of a 0.5 closed loop damping coefficient gives the values of master controller gain K_M shown in Table6.1. These gains increase as τ_M increases.

Table. Master controller gain settings Second order Process				
	$K_S = 0.5$ without cascade		$K_S = 0.5$ with cascade	
τ_M	Series	Parallel	Series	Parallel
0.5	0.7	3	0.6	2.5
1	0.7	3	1	2
2	0.7	3	2	4
4	0.7	3	3	13
Dead time Process K_M for gain margin = 2.0				
D	Parallel cascade		Without cascade	
0.5	2.5		2.5	
1	1.58		1.39	
2	1.134		0.896	

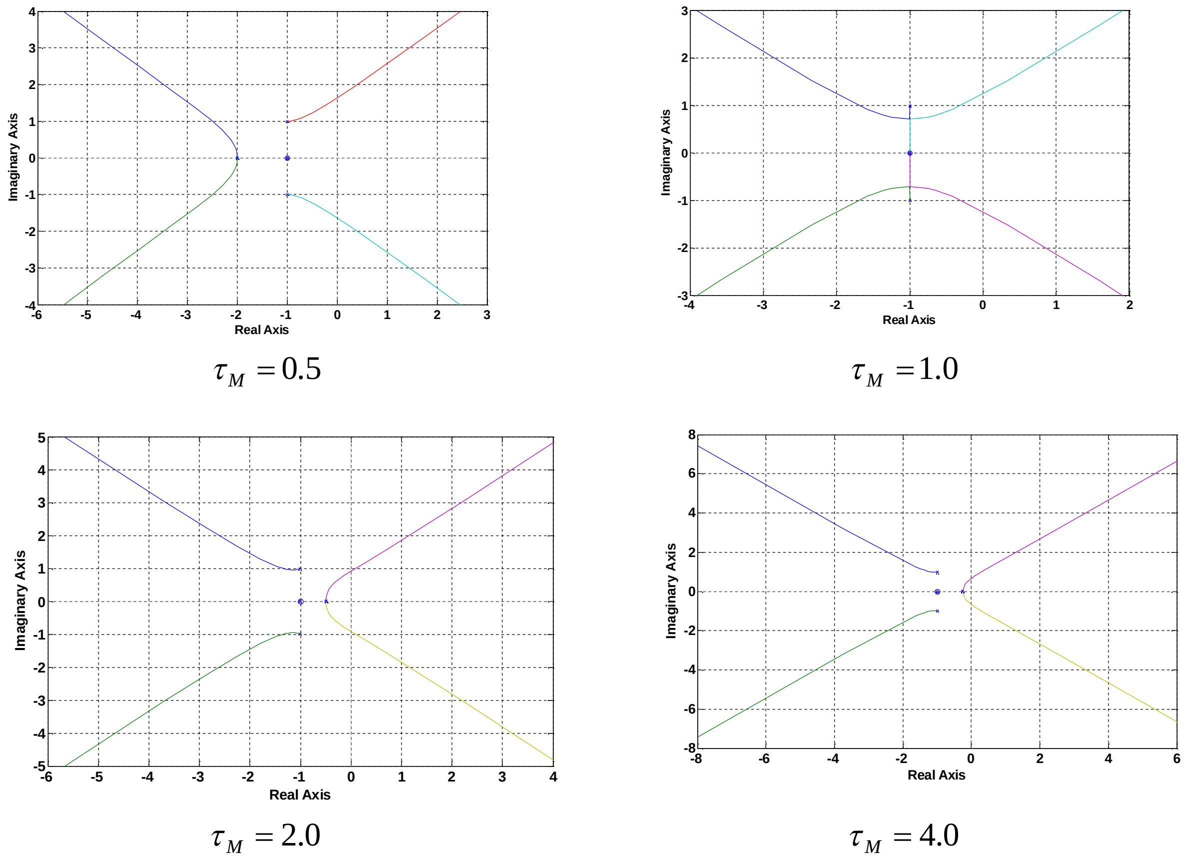

Figure.5 Root locus plots for series cascade control with $K_S = 1.0$ and $\tau_S = 1.0$

Root locus plots for the parallel cascade system are given in Figure *5.* The numerator of the overall system open loop transfer function is a fourth-order polynomial in s, so there are four paths. The net order of the system is only 2, so the asymptotes do not intersect the imaginary axis (there is no ultimate gain). Gains for a 0.5 closed loop damping coefficient are shown in Table I. They are, of course, different from those in the series system. The gain at $\tau_M = 0.5$ is higher than the gain at $\tau_M = 1$. For τ_Ms greater than 1 , the gain increases rapidly with increasing τ_M.

It should be remembered that these two systems are two different processes. They are not the same process with two different control systems. Therefore they cannot be directly compared as to which is the more effective. Each cascade system should be compared only with its noncascade equivalent.

Figure 3 shows root locus plots for the two processes with-out cascade control. The series system is fourth-order because the G_S and G_M transfer functions are both second order and are in series. The parallel system is second order since only
G_M is involved.

The second example considered was the same overhead composition-tray temperature distillation column system but with a dead time inserted in the overhead composition loop. Physically this could correspond to an analysis dead time. Figure 6.6 presents block diagrams of the second-order system studies with $\tau_M = \tau_S = 1$. A gain margin criterion of *2* was used to determine the value of *K M* with and without parallel cascade control for values of dead time D from 0.5 to *2.* Table 6.1 summarizes the results. Gains decrease as dead times increase. The gains with parallel cascade are larger than without cascade for dead times greater than 0.5.

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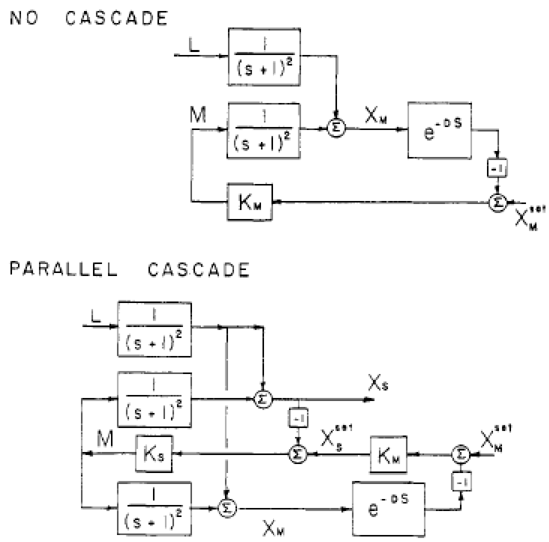
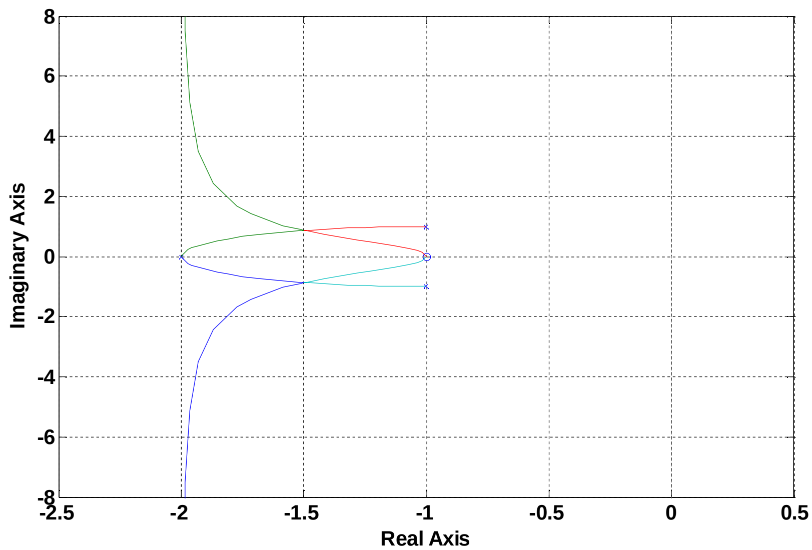
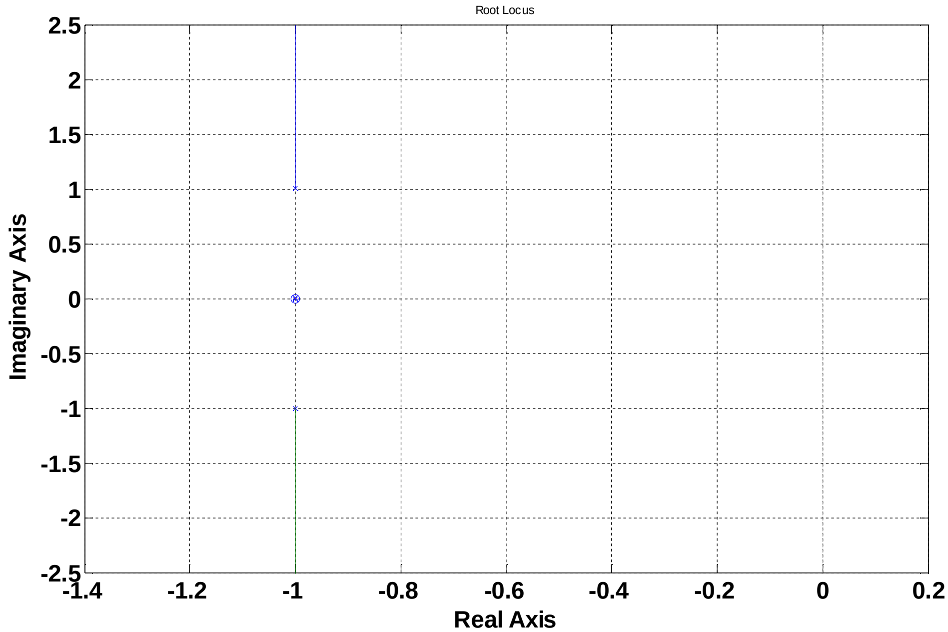


Fig. Block diagram of dead time system with and without parallel cascade

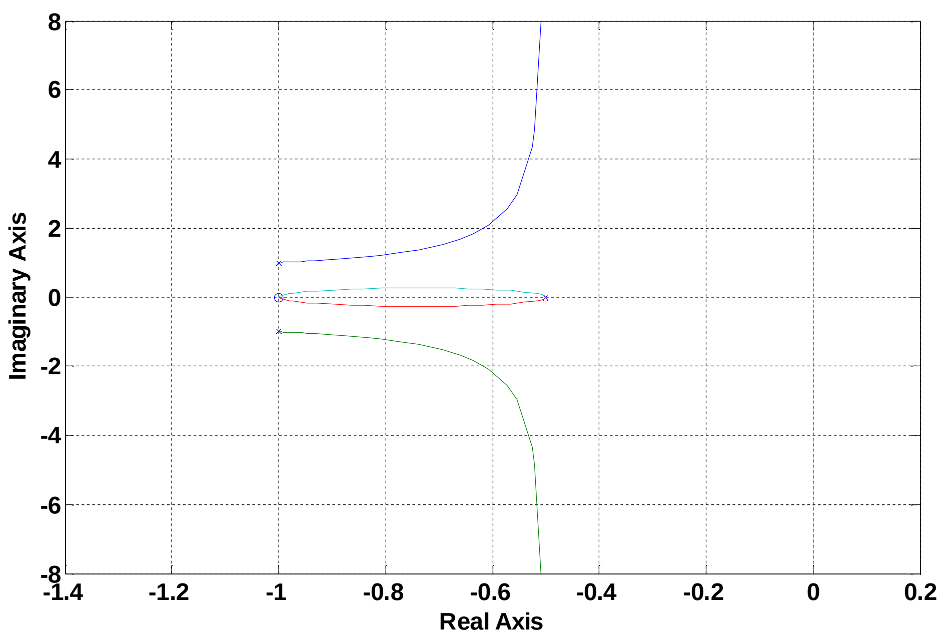


$$\tau_M = 0.5$$



$\tau_M = 1.0$

Figure 6.6. Root locus plots for parallel cascade control with $K_S = 1.0$ **and** $\tau_S = 1.0$



$\tau_M = 2.0$

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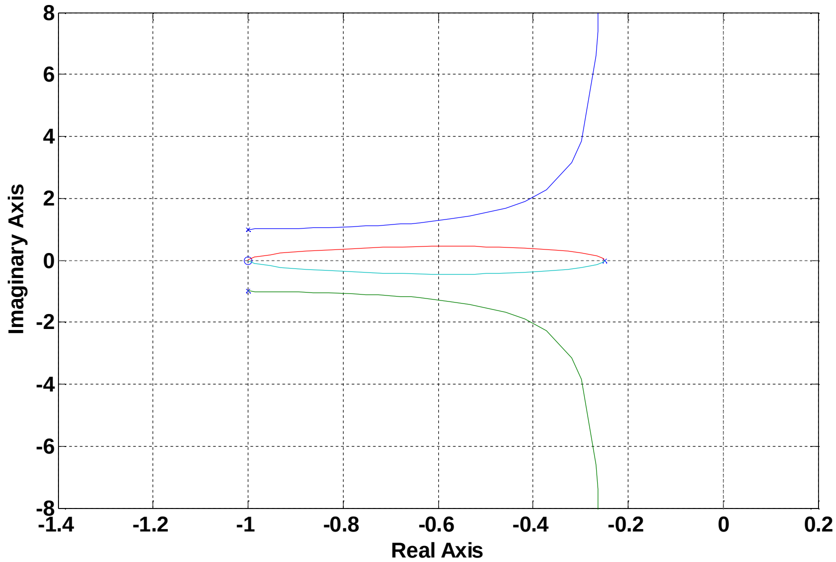

$\tau_M = 4.0$

Figure (Continued)

III.LOAD RESPONSES

The closed loop response of a process depends on where the load disturbance enters the process, as well as the control system used and the dynamics of the process itself. Load disturbances can enter in the master or the slave loop. In this section, the load disturbance L was assumed to affect both the slave variable x_S and the master variable x_M through the same load transfer function G_L (as given in Figure 2).

The closed loop transfer functions between the load L and the master variable x_M for series and parallel systems (x_M / L) are shown in Table 6.2.

Table 2.Closed loop transfer function for series and parallel systems

	No cascade	With cascade
Series	$\frac{G_L(1+G_M)}{1+B_M G_M G_S}$	$\frac{G_L(1+G_M+B_S G_S)}{1+B_S G_S(1+B_M G_M)}$
Parallel	$\frac{G_L}{1+B_M G_M}$	$\frac{G_L(1+B_S G_S - B_S G_M)}{1+B_S G_S + B_M B_S G_M}$

Frequency domain plots of these closed loop transfer functions provide a convenient way to compare load responses. Figures 6.7 and 6.8 show series and parallel systems, with and without cascade control, using the controller settings given in Table I. Since a perfect closed loop load transfer function is zero, the smaller the magnitude, the better the load response. The zero frequency intercept reflects the differences in controller gains. The improvements attainable by the use of cascade control can be seen for values of τ_M greater than 1 and for dead times greater than 0.5.

The parallel system with $\tau_M = 1$ produced an interesting result (given in Figure 6.8). The closed loop load transfer functions are identical with and without cascade control.

IV.CONCLUSION

Thus the differences between conventional "series" cascade control systems and configurations that are of a "parallel" type are investigated. Quantitative analysis and controller design for each type of system shows the improvements in load responses. Second-order processes, with and without deadtime, are studied over a range of time constants.

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