Using a parallel time constant Laplace transform to predict a possible unsafe condition will occur in a chemical process

Michael J. Needham
Process Control Chemist
Consultant
15506 Fawn Villa
Houston, Texas, 77068, USA

Abstract: - This paper experiment calculates a changing time constant Laplace transform in a Chemical Process using normal process control measurements. The object will be to see if the time constant transform will indicate a pending unsafe condition prior to a shutdown measurement being detected. The time constant transform will be placed parallel to the shutdown measurement as shown in Fig. 1 below.

The time constant transform will have some speed variations due to tuning parameters set in the Proportional, Integral, and Derivative controllers. Therefore these parameters will not be used in the time constant calculation.

Key-Words: - Time Constants, Laplace, Gain, Loop Performance, Bode, Frequency Response, Loop Capacitance, and Dynamic Capacitance. IMACS/IEEE CSCC'99 Proceedings, Pages:2361-2366

1 Introduction

A common applied practice in detecting, or measuring, an unsafe condition in Chemical Processes is to monitor discrete, shutdown measurements. These discrete shutdown measurements are installed at strategic locations through out the Chemical Process facility and judge the correct shutdown procedure based upon the measurement signal detected. The measurement shutdown values are generally 90% or 10% of the normal control measurement value. The normal control measurements used for a Chemical Process are separate form the shutdown measurements. As a Chemical Process's kinetics migrate from a safe, normally operating condition to an unsatisfactory, or unsafe condition, the time constants of that process change.

Chemical Process facilities are designed within limited, known time constants that are relative to a safely operated, or normally operating, facility based upon throughput. If a process starts to approach an unsafe operating condition, the time constants of that process change. These time constants are generally not calculated, as they are not required if the facility is operating normally, and also plainly speaking, shutdown microprocessors are excellent with regards to speed and accuracy.

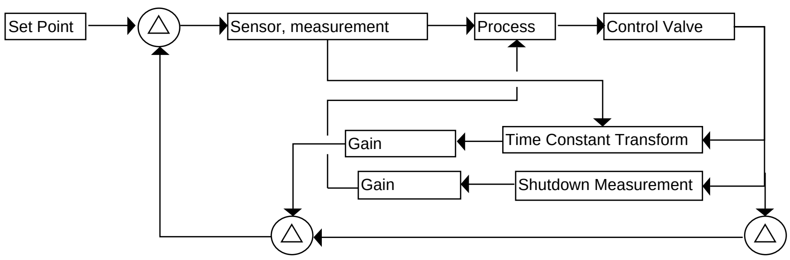


Fig. 1

2 Objective Function [1]

Regarding a simple statement for the object of this paper, increase a temperature control loop's performance by using an experimental variable based upon a changing flow rate.

3 Real-Time Measurement [6]

A graph depicting the response of a real-time temperature-measuring sensor is shown in Fig. 2 below [2]. The time for the sensor to reach 63.2% of the final response value is 100 seconds, which is technically called the "time constant". The time for the sensor to measure 90% of the final value is 235 seconds, which technically is called the "rise time" or time before plant shutdown. This means our experimental transform must detect a possible unsafe condition in less than 235 seconds or there would not be any perceived advantage in using a time constant calculation as compared with the temperature element.

4 Objective Statement

How will this paper relate the preceding real-time sensor response curve to our paper experiment?

First a "REFERENCE EXAMPLE" statement will be given for a process from which a static time constant can be calculated based upon a static, non-changing flow rate. Next a flow loop transform frequency response will be calculated and established as the goal for the performance for our temperature loop gain after it is modified. Then calculate a temperature loop transform frequency response and compare its gains with the preceding flow loop. Finally, a static variable in the temperature loop will be modified to a dynamic variable based up a changing flow rate.

REFERENCE EXAMPLE: A reactor vessel with material that has a specific heat of 0.8 Btu/(LB)('F), an Overall heat-transfer coefficient of 334 Btu/(min)("F), and 40,000 LB/min flowing ingress/egress would have a time constant of 96.06 minutes, with a generous flow measurement time of 10 seconds. If we reduced the flow to 34,000

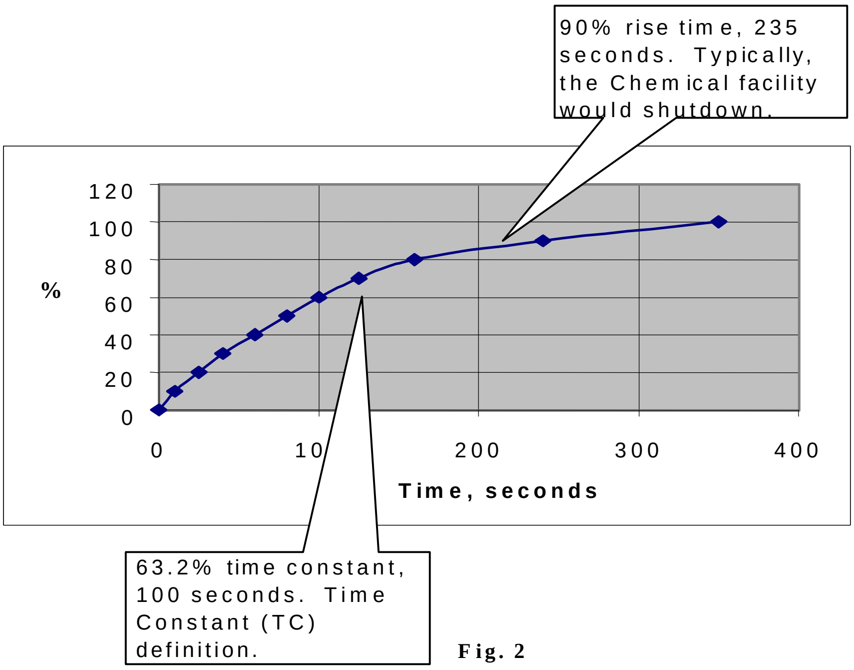


Fig. 2

LB/min, the time constant would decline to 81.4 minutes or 15 %. The process temperature will be controlled and shutdown by a temperature measurement element. At ninety (90%) of the temperature measurement span, the process will shutdown. The flow rate of material will be measured and cascaded with the temperature control loop.

Flow control loops typically control thermal or heat balances in Chemical Processes. Flow measurement and sensing is much faster when compared to temperature measurement and sensing [6]. This paper will attempt to integrate the speed of the flow measurement into the temperature loop to change its gain, thus performance and give a better estimate of time before shutdown.

5 Limits For The Experiments

Bode, frequency response curves will be calculated using Laplace transforms for typical temperature and flow loop parameters.

For the flow loop transform we will use the following models:

Flow sensor**:**

First-order lag plus dead time
Time constant = 3.5 seconds
Dead time delay = 0.24seconds
Gain = 1 (%output/input)

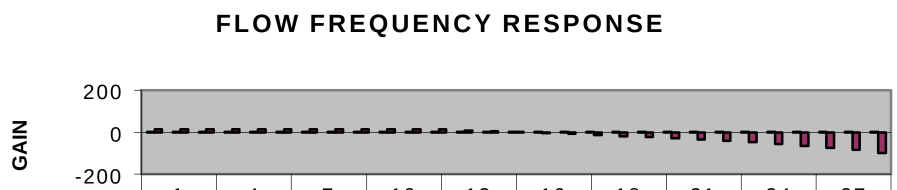
Flow process:

First Order Lag
Gain = 1 (%output/%inut)

Flow control valve:

Underdamped second-order lag
Time constants = 10.2 radians/second
Damping = 0.75
Gain = 5 (%output/%input)

The following graph shows the frequency response in radians per second (Y-axes) compared with gain (X-axes) for the flow loop previously described, see Fig. 3.



	1	4	7	10	13	16	18	21	24	27
Series1	1E-06	3E-05	0.003	0.095	0.001	0.006	0.309	0.1	0.179	1
Series2	14	14	14	13.7	9	-4.5	-14.4	-29.6	-47.9	-75.7

Fig. 3

The result shown in Fig. 3 above will represent the performance goals for our temperature loop.

For the temperature loop transform the following models:

A temperature-measuring element installed in a thermowell could have the following characteristics:

Overdamped second-order lag
Time Constant number 1: 50 seconds
Time Constant number 2: 240 seconds

A temperature control valve could have the following characteristics:

Underdamped second-order lag
= 21.6 radians/second
Damping ratio = 0.8
Gain = 8 (% output/ % input)

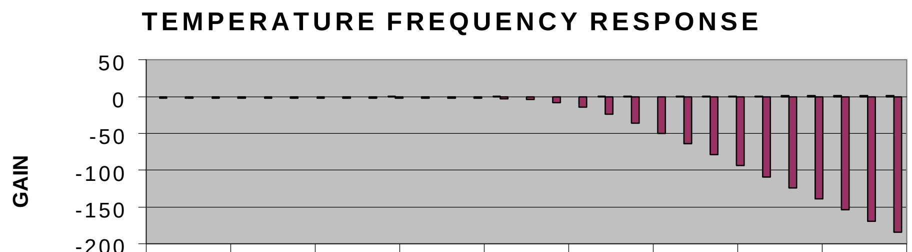
A possible process transform could have the following characteristics:

First-order lags plus dead time
Gain = 1 (% output/ % input)

The following graph shows the frequency response in radians per second (Y-axes) compared with gain

(X-axes) for the temperature loop previously described, see Fig. 4.

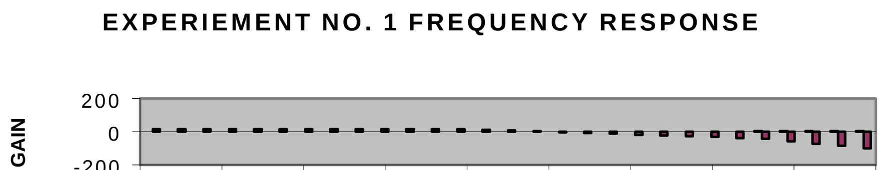
Comparing gains in Fig. 3 and Fig. 4, the flow loop gains at low frequencies, which are most likely to be the actual Chemical facilities responses, shows a very large difference. The intent is to increase the gains in the temperature loop at these low frequencies by using the flow loop measurement.



	1	4	7	11	14	17	20	24	27
Series1	1E-06	3E-05	0.003	0.01	0.171	0.01	0.032	0.179	1
Series2	-1.9	-1.9	-1.9	-2	-2.9	-14.5	-49.8	-109.1	-154.2

RADIANS/SECOND

Fig. 4



	1	4	7	11	14	17	20	24	27
Series1	1E-06	3E-05	0.003	0.0095	0.1715	0.01	0.0319	0.1786	1
Series2	18.1	18.1	18.1	17.6	11.4	-2.6	-17.5	-36.5	-71.9

RADIANS / SECOND

Fig. 5

6 Paper Experiments

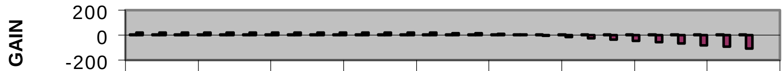
Examining the temperature's loop transfer function for the transmitter, two (2) time constants were estimated at fifty- (50) seconds and two hundred forty (240) seconds. These time constants represent the rise time of a temperature sensor in a protective thermowell. We first examine the frequency response of the temperature loop transform changing the time constants from fifty- (50) and two hundred forty (240) to one (1) second and one (1) second, see Fig. 5. This paper experiment will give an order of magnitude for changes to the thermal capacitance of this sensor.

Regarding Fig. 5, the gains at lower frequencies are higher than even the flow loop examined in Fig. 3 above. Of course this is not surprising with essentially no time delays resulting from thermal capacitances of the sensor. Referring back to the REFERENCE EXAMPLE above, a 15% decline in flow rate to the reactor vessel created a 16.6-minute reduction in the flow loop time constant. This would also reduce the rise time or time necessary to cause the facility to be shutdown at 90% as measured by the temperature loop.

Regarding the temperature loop transform which is the multiplication of the transmitter transform time process transform times control valve transform, we can very the change in the time constant several ways. One way to view this would be a virtual reduction in perhaps the thermal capacitance of the reactor vessel. Virtually thinking, if the time constant is reduced, the vessel thermal capacitance is a likely possibility. Continuing with this line of thought. The next experiment recalculates the temperature loop frequency response with the thermal capacitance of the reactor vessel reduced from 1070 to one (1) in order to get a change magnitude of the gain, see Fig. 6 below.

The gains at lower frequencies are very similar to the gains of Experiment No. 1, which is not interesting for this paper, but are also higher than the flow loops gain at similar frequencies which is of interest to this paper. Subsequently, for the purposes of this paper, a temperature loop's performance can be increased by modification of

EXPERIEMENT NO. 2 FREQUENCY RESPONSE



	1	4	7	11	14	17	20	24	27
Series1	1E-06	3E-05	0.003	0.01	0.171	0.01	0.032	0.179	1
Series2	18.1	18.1	18.1	18	17.3	8.8	-14.1	-54.7	-93.8

RADIANS / SECOND

Fig. 6

its individual transform components.

7 Final Objective Function

Simple statement: To force a relation between a changing flow rate and a temperature control loop by modifying the temperature transform reactor vessel's thermal capacitance with a dynamic variable based upon flow, see Fig.7 below.

Referring to our REFERENCE EXAMPLE above, the decreased flow rate to the reactor decreased the time constant from 96.06

$$\frac{e^{-s}}{1 + 1070s}$$

Static Capacitance

$$\frac{e^{-s}}{1 + 1070/(\text{Flow Rate})s}$$

Dynamic Capacitance

Fig. 7

minutes to 81.4 minutes. This was the result, of course, from the decrease in amount of material to be heated. The definition of time constant is Resistance times Capacitance. Thus, by reducing the virtual thermal capacitance, the time constant would be effectively reduced, see Fig. 7 below.

The results of this transform modification would mean that at low flow rates, the rise time or time before shutdown would be more reduced. Also, an increased flow rate would mean a rise time or time before shutdown would be increased, see Fig. 8 below.

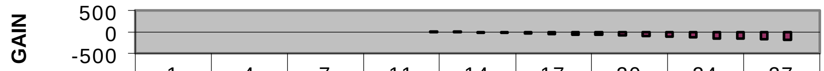
The Dynamic Capacitance function used was 1070/40,000. Thus, a reduction in flow rate from 40,000 to 34,000 would result in a capacitance value of 909.5.

The increase in gain resulting from the experimental variable, shown in Fig. 8 is insufficient for our purposes. Low gain increase perhaps because a first-order component was selected to be replaced by the experimental variable rather than a second-order component.

8 Conclusion

A normally static transform parameter was exchanged for an experimental dynamic variable in a temperature control loop. The results graphed in Fig. 8 show some loop performance increases at medium to high frequencies. Reactor vessel thermal capacitance was selected as the static variable to be modified with a dynamic variable in the temperature loop transform. This experimental parameter did not increase the gain sufficiently to out perform a typical temperature sensor installed in a thermowell.

FINAL OBJECTIVE FREQUENCY RESPONSE



	1	4	7	11	14	17	20	24	27
Series1	1E-06	3E-05	0.003	0.01	0.171	0.01	0.032	0.179	1
Series2	-1.9	-1.9	-1.9	-2.3	-8.3	-30.4	-68.2	-127.7	-172.7

RADIANS / SECOND

Fig. 8

References

[1] IEEE Press, VLSI Signal Processing IV, Miodrag Potkonjak & Jan Rabaey, “Retiming for Scheduling”, pp. 23 to 42, 1991.

[2] Robert N. Bateson, “Introduction Control System Technology”, Prentice Hall, Sixth Edition, pp. 162, 621 to 626, 1999.

[3] Karl J. Astrom & Bjorn Wittenmark, “Computer-Controlled Systems”, Prentice Hall, 1997.

[4] Katsushiko Ogata, “Modern Control Engineering”, Prentice Hall, Third Edition,1997.

[5] Norman S. Nise, Control Systems Engineering”, The Benjamin/Cummings Publishing Co. Inc., 1992.

[6] F. G. Shinskey, “Process Control Systems”, McGraw Hill, Third Edition, 1988.

[7] Gregory K. McMillan, “Tuning and Control Loop Performance”, Instrument Society of America, Second Edition, 1990.