The Journal of National Chiao Tung University
Vol. I, April 1976
pp.123-132

低靈敏度電子式 比例一積分一微分 控制器之新設計

A New Design of Noninteracting PID Electronic Controller with Low Sensitivity

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(Received January 15, 1976)

ABSTRACT — A new simple active RC circuit is given for synthesizing an ideal PID electronic controller. In the new design, the controller is of low sensitivity and noninteracting. An experimental example is given to illustrate the simple design procedure.

I. Introduction

Even though pneumatic controllers are still widely used, there has been a shift from pneumatic to electronic controllers recently. Now, more than half of the process instrumentation being bought is electronic [1]. The main reasons for this shift are fashion, convenience, good salesmanship, ease of installation, accuracy, computer and controller compativility, and of course, cost. In general, electronic instrumentation suits applications having fast control loops, long transmission distances and digital supervisory or reporting capabilities. Pneumatic instruments may have the edge in corrosive or hazardous atmospheres or where power supply disturbances are frequent [1].

Since 1960 several new types of electronic controllers have been developed to compete with pneumatic instruments for process application [2,6]. The heart of all electronic controllers is a high-gain operational amplifier connected between two electrical networks, input and feedback. The networks are formed by using only resistors and capacitors. The standard input and output signals have direct currents in the range 4 to 20 ma or have direct voltage in the range 1 to 5 volts.

The transfer function of an ideal PID electronic controller is

$$\frac{\Theta_o(S)}{\Theta_i(S)} = K_p \left(1 + T_d S + \frac{1}{T_i S}\right)$$

where K_p is the proportional gain, T_d is the derivative time, and T_i is the reset time. PID controller is used on process with sudden, large load changes when one or two mode control is not capable of keeping the error within acceptable limits. The integral mode provides a reset action which eliminates the proportional offset. The derivative mode produces an anticipatory action which reduces the maximum error produced by sudden load changes.

In practice, true derivative action is not easily achieved, i.e. unrealizable; in addition, true derivative action may not be desired since it amplifies noise and saturates the operational amplifier. So, generally, in commercial design of PID electronic controllers, the derivative action $T_d S$ is always modified to $\frac{T_d S+1}{\alpha T_d S+1}$ where $\alpha \ll 1$ and $\frac{1}{\alpha T_d S+1}$ is the limiter on the derivative action [2, 3]. Therefore, many industrial controllers, for example, Taylor Instrument Model 70RF 3-mode electronic controller [10], are more realistically described by the transfer function

$$G_c(S)=K_p\left(1+\frac{1}{T_i S}\right)\left(\frac{T_d S+1}{\alpha T_d S+1}\right)$$

Multiplying the integral and derivative terms in the above transfer function, we have

$$G_c(S)=K_p\left(\frac{T_i+T_d}{T_i}\right)\left[1+\frac{1}{(T_i+T_d)S}+\left(\frac{T_i T_d}{T_i+T_d}\right)S\right]\left(\frac{1}{\alpha T_d S+1}\right)$$

Notice that there is an interaction between the control actions in the above equation, resulted in a difficulty in controller tuning. Several important observations can be made from the above transfer function:

1. Where $T_d > T_i$, derivative time is affected more by the reset setting, and vice versa.
2. It is impossible to make the effective derivative time equal to or greater than the effective reset time.
3. As T_d approaches T_i, further adjustment will produce very little change in effective derivative time, so there is little purpose in trying to fine tune an interacting controller.

The interaction can be eliminated by generating proportional, derivative, and integral signals separately and then combining the signals.

In this paper, we present a new design of PID electronic controller which is of low sensitivity and noninteracting. An interesting fact is that the ideal transfer function of PID controller can be realized by using RC and OPAMP with a satisfactory result as illustrated in the example.

II. Design Philosophy

Almost all the pneumatic controllers are based on the basic structure of control system as shown in Fig. 1.

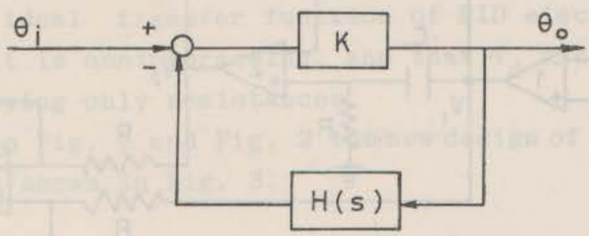

Fig. 1

The closed-loop transfer function of Fig. 1 is

$$\frac{\Theta_o(S)}{\Theta_i(S)}=\frac{K}{1+KH(S)}$$

If $|KH(S)| >> 1$, then $\frac{\Theta_o(S)}{\Theta_i(S)}$ can be modified to $\frac{\Theta_o(S)}{\Theta_i(S)}=\frac{1}{H(S)}$, which means that the basic philosophy for generating a desired control action is to insert the inverse of the desired transfer function in the feedback path. Thus, if PID control action is desired, we may just insert a bandpass filter having the transfer function $\frac{S/T_d}{S^2+S/T_d+1/(T_dT_i)}$ in the feedback path.

III. New Design of Noninteracting PID Controller

There are many bandpass filters [4,7] and any second order bandpass filter will be sufficient for H(S) according to the design philosophy in the above section. In this paper, we use a low sensitivity active bandpass filter by S. C. Dutta Roy [5] as shown in Fig. 2. Some of the important circuit features of Fig. 2 are:

1. low gain of the active elements, ensuring wide frequency range of application.
2. high input and low output impedances, facilitating cascading to other blocks, and independent post-design adjustments.
3. canonic in capacitors (note that a minimum of two capacitors is

needed)

4. low sensitivity of Q and W_n to active as well as passive components.
5. minimum spread in components.
6. simple design procedure.

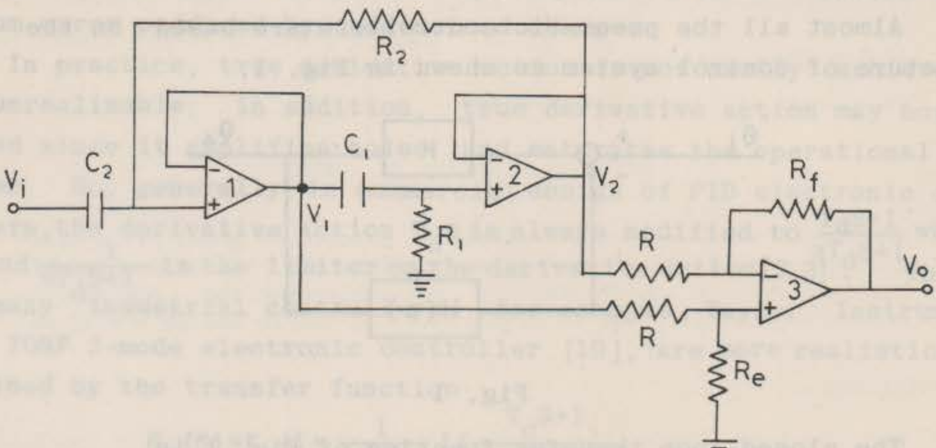

Fig. 2

It is not difficult to analysis the circuit of Fig. 2. Actually

$$V_1 = V_i \frac{S^2 + S/T_d}{S^2 + S/T_d + 1/(T_d T_i)}$$

$$V_2 = V_1 \frac{ST_d}{ST_d + 1} = V_i \frac{S^2}{S^2 + S/T_d + 1/(T_d T_i)}$$

where $T_d = R_1 C_1$, $T_i = R_2 C_2$

and $$\frac{V_1 - V_2}{V_i} = \frac{S/T_d}{S^2 + S/T_d + 1/(T_d T_i)}$$

which is the second order bandpass filter we desired. The proportional gain K_p is obtained from

$$\frac{V_1 - V_2}{V_o} = \frac{R_f}{R} \quad \text{if } R_e = R_f$$

Thus, the final transfer function of the second order bandpass filter we desired for PID synthesis is

$$\frac{V_o}{V_i} = \frac{R_f}{R} \frac{S/T_d}{S^2+S/T_d+1/(T_d T_i)}$$

and the inverse transfer function is

$$\frac{V_i}{V_o} = K_p(1+T_d S+\frac{1}{ST_i}) \quad \text{where } K_p = \frac{R}{R_f}$$

which is the ideal transfer function of PID electronic controller. Notice that it is noninteracting, and that T_d and T_i are easily adjusted by varying only resistances.

Refer to Fig. 1 and Fig. 2 the new design of noninteracting PID controller is shown in Fig. 3.

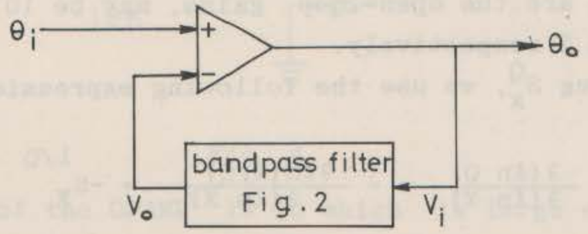

Fig. 3

IV. Sensitivity Analysis

By definition [4,7], the sensitivity of a quantity G to any parameter x is defined as the ratio of percentage change in G to the percentage change in x to which it is due, i.e., mathematically,

$$S_X^G = \frac{\partial G/G}{\partial X/X} = \frac{X}{G}\frac{\partial G}{\partial X}$$

Recall that, from Fig. 2, the undamped natural frequency W_n and the quality factor Q of the bandpass filter we used are given by

$$W_n = 1/\sqrt{T_d T_i} = 1/\sqrt{C_1 C_2 R_1 R_2}$$

and

$$Q = \sqrt{T_d/T_i} = \sqrt{R_1 C_1/(R_2 C_2)}$$

and that OPAMP 1 and OPAMP 2 are nominally unit gain follower. It is not difficult to see that if K_1 and K_2, gain of OPAMP 1 and 2 respectively, are not assumed to be unity, then

$$\frac{V_1-V_2}{V_i} = \frac{S/T_d}{S^2+S[1/T_d+(1-K_1K_2)/T_i]+1/(T_dT_i)}$$

Therefore, we get the same W_n but Q now becomes

$$Q = \frac{1}{\sqrt{T_i/T_d} + (1-K_1K_2)\sqrt{T_d/T_i}}$$

So, we have

$$S_{\mu_1}^{W_n} = S_{\mu_2}^{W_n} = 0 \quad \text{and} \quad S_{C_1}^{W_n} = S_{C_2}^{W_n} = S_{R_1}^{W_n} = S_{R_2}^{W_n} = -\frac{1}{2}$$

where μ_1 and μ_2 are the open-loop gains, may be 10^5 or greater, of the OPAMP 1 and 2 respectively.

For finding S_x^Q, we use the following expression [5].

$$S_X^Q = \frac{\partial(\ln Q)}{\partial(\ln X)} = -\frac{\partial \ln(1/Q)}{\partial(\ln X)} = -S_X^{1/Q}$$

Again if $x=x_1x_2$, then $S_{x_1}^Q = \frac{x_1}{Q}\frac{\partial Q}{\partial x_1} = \frac{x_1}{Q}\frac{\partial Q}{\partial x}\frac{\partial x}{\partial x_1} = S_x^Q = S_{x_2}^Q$

So, we have

$$S_{R_1}^Q = S_{C_1}^Q = S_{T_d}^Q = \frac{1}{2}, \quad S_{K_1}^Q = S_{K_2}^Q = Q^2, \quad S_{\mu_i}^Q = \frac{Q^2}{\mu_i+1}$$

and $S_{R_2}^Q = S_{C_2}^Q = S_{T_i}^Q = -\frac{1}{2}$

Thus, we conclude that the bandpass filter has low Q and W_n sensitivities to components. Notice that the sensitivities are all constant, i.e., independent of components.

V. Experimental Examples

Let us use the circuit configuration of Fig. 3 to synthesize the PID electronic controller:

$$\frac{\theta_o(S)}{\theta_i(S)} = K_p(1+T_dS+\frac{1}{ST_i})$$

where $K_p = \frac{R}{R_f}$, $T_d = R_1 C_1$ and $T_i = R_2 C_2$

If the numerical values are given as $K_p=1$, $T_d=0.5$, $T_i=2$, then, the value of components are designed to be $R=R_e=R_f=20K\Omega$, $C_1=1\mu f$, $R_1=500K\Omega$, $C_2=1\mu f$, and $R_2=2M\Omega$.

The OPAMP is of the Philbrick Researches P85 AU type. Here, we use Ziegler-Nichols one-quarter recommendation [8,9]. The ratio T_d/T_i is chosen to be 0.25.

For experimental requirement, the OPAMP of Fig. 3 is replaced by

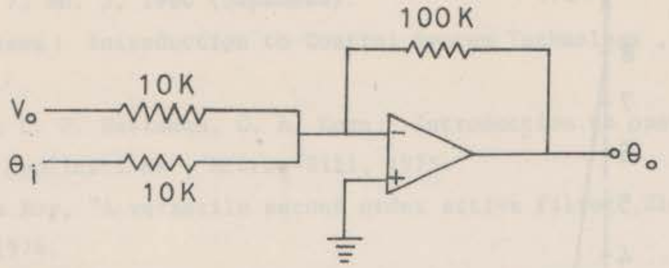

Fig. 4

The gain of the OPAMP is 10 which is large enough for the assumption $\frac{\Theta_o(S)}{\Theta_i(S)} = \frac{1}{H(S)}$ in section II. If a unit step of 0.8 volts is the input to Θ_i, then the step response Θ_o is shown experimentally as in Fig. 5.

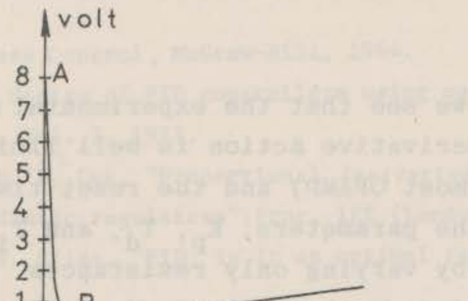

Fig. 5

If the numerical values are given as $K_p=1$, $T_d=4$, $T_i=2$, then the designed value of components are $C_1=3\mu f$, $R_1=1.33M\Omega$, $C_2=1\mu f$, $R_2=2M\Omega$, and $R=R_f=R_e=20K\Omega$.

The unit step response for 0.8 volts input is shown in Fig. 6. In this case, the ratio $T_d/T_i=2$, i.e. $T_d>T_i$. From Fig. 5 and Fig. 6, we see that it is possible to make derivative time greater than reset time, and that reset time is not affected by varying derivative time. These show the advantages of this new design of noninteracting PID electronic controller.

Further, we can see that the points A and B in Fig. 5 will be lower and higher respectively, as R_f becomes smaller. Also, point A is changed with input Θ_i.

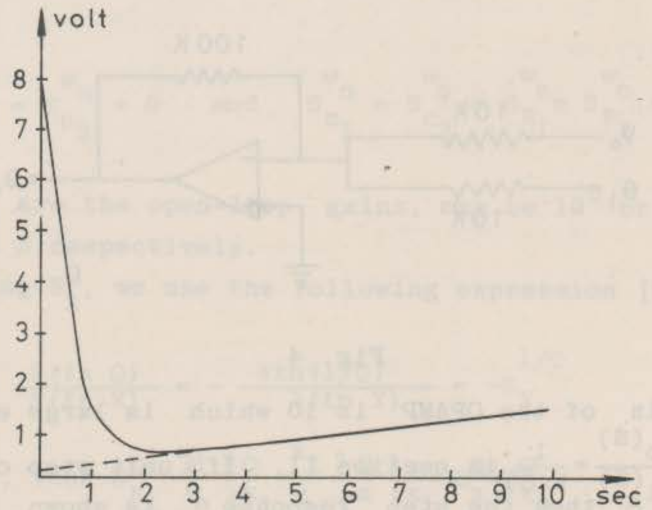

Fig. 6

VI. Conclusion

From Fig. 5, we see that the experimental result is very satisfactory, i.e. the derivative action is well limited within 10 volts (output voltage of most OPAMP) and the reset time is exactly equal to 2 seconds. All the parameters, K_p, T_d, and T_i are easily adjustable independently by varying only resistances.

A remarkable fact is that all standard PID controllers are interacting, but the new design is noninteracting and has low sensitivity. Mathematical structure of a noninteracting controllers is simpler, and its implementation is simple also in this new design.

The noble structure of Fig. 3 can be extended to synthesize other "unrealizable" transfer function, for example, if we want to synthesize $S^2+S/T_i+1/(T_1T_2)$, we can just insert a lowpass filter in the feedback path in Fig. 3.

The PID controller has been used in the realization of optimal linear regulator design [11-13], we believe that the noninteracting PID controller will be the best candidate for the hardware realization of optimal linear regulator design, because it is simpler, easier, and more effective.

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