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Journal of Process Control 11 (2001) 311–319
JOURNAL OF PROCESS CONTROL
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A two degree of freedom level control

Kwo-Liang Wu, Cheng-Ching Yu *, Yu-Chang Cheng

Department of Chemical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan 106, ROC

Abstract

A two degree of freedom control is proposed for liquid level control. The load estimation is achieved in an indirect manner. Only one design parameter is required for the load estimation. As for the feedback loop, a P-only feedback action is employed. It is equivalent to a P control at disturbance free condition and becomes a PI controller under load disturbance. Steady-state characteristics, dynamic properties and robustness issues are explored. Design procedures are also proposed. A surge tank example is used to illustrate the performance of the proposed control. The results show that the two-degree of freedom control gives good nominal performance and is robust with respect to modeling errors. Improved performance are also observed for systems with time delay or right-half-plane zero. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Level control; Load estimation; Two degree of freedom control

1. Introduction

Control of liquid level involves two conflicting considerations. First, changes in outlet flow rates should be as smooth as possible. Second, level should not be permitted to deviate too far from nominal liquid level. This is the problem of averaging level control. In a pioneering work, Luyben and Buckley [1] propose a feedforward/feedback configuration for level control: proportional-lag (PL) control. In PL control, the proportional control based feedback loop provides flow smoothing while the feedforward compensation eliminates steady-state offset in the liquid level [1,2]. The PL control utilizes the unique characteristic of level systems, integrator process, such that level control can be designed in a transparent manner. Similar to PL control, a simple method, Proportional plus set point ramp (PSPR) control [3] is proposed for liquid level control. These proportional control based level control strategies provide better flow smoothing. This is important for chemical processes with many interconnected units. In addition to flow smoothing (load rejection), sometimes, the liquid level is changed at different operating regimes, e.g., reactor level. Therefore, in some cases, both the regulatory and servo problems exist in level control problems. The two degree of freedom control offer a useful structure to solve the control problem [4–6].

Since the introduction of the "integrator plus dead-time" form to represent slow chemical processes [7], works have been done to study tuning [8], autotuning and dead-time compensation [9,10] aspects of integrator plus dead-time processes. Hang and Wong [11] and later Åström et al. [9] propose a new form of Smith predictor where load disturbance is estimated and, subsequently, compensated. Matausek and Micic [10] give a good description of the modified Smith predictor. Again, the modified Smith predictor utilizes the characteristic of integrator process to provide offset-free load estimation. This kind of controller structure was also proposed by Huang et al. [12] to compute Robust Stability Index (RSI) for controller gain adjustment in order to achieve robustness.

In this work, an extension is made to the PL level control. Instead of measuring the inlet flow rate, a load estimation scheme is proposed and design procedure for liquid level control is devised accordingly.

2. Level control with load estimation

In this section, a two degree of freedom level control is proposed, the load estimation is accomplished using a single constant. Before getting into the control and estimation aspects of level control, the process characteristic is presented.

Consider a surge tank with inlet flow rate q_i, outlet flow rate q, tank level h and tank cross section area A.

* Corresponding author. Fax: +886-2-2737-6644.
E-mail address: ccyu@ch.ntust.edu.tw (C.C. Yu).

PII: S0959-1524(00)00005-6

Nomenclature

A	tank cross section area
e_m	multiplicative modeling error
F	feedforward compensator
G	process transfer function
H	Laplace transformed tank level
h	tank level
$\bar{h}$	tank height
K	controller transfer function
K_c	feedback gain
K_F	feedforward gain
K_p	process gain
MPH	maximum peak height in level
$MRCO$	maximum rate of change in outflow
P	proportional control
Q	Laplace transformed outlet flow rate
Q_i	Laplace transformed inlet flow rate
q	outlet flow rate
q_i	inlet flow rate
$\Delta\bar{q}_i$	anticipated maximum inlet flow rate change
r	ratio of feedforward and feedback time constants
t_{peak}	time giving peak level

Greek Letters

τ_c	feedback time constant
τ_F	load estimation time constant
ζ	damping coefficient

Superscripts

set	set point
^	estimated value

Assuming constant density, the system can be described by:

$$A\frac{\mathrm{d}h}{\mathrm{d}t} = q_{i(t)} - q_{(t)} \tag{1}$$

Taking Laplace transform, the transfer functions describing the surge tank system become:

$$H_{(s)} = \frac{-1/A}{s}Q_{(s)} + \frac{1/A}{s}Q_{i(s)} \tag{2}$$

It is clear that this is an integrator system in the process side as well as the load part. Let

$$G_{(s)} = \frac{-1/A}{s} = \frac{K_p}{s} \tag{3}$$

We have:

$$H_{(s)} = G_{(s)}Q_{(s)} - G_{(s)}Q_{i(s)} \tag{4}$$

where $H_{(s)}$, $Q_{(s)}$ and $Q_{i(s)}$ represent the Laplace transformed tank level h, outflow q and inlet flow q_i, respectively, and $G_{(s)}$ denotes process transfer function.

Since the process and the load have the same transfer function $G_{(s)}$, the load estimation and compensation can be carried out in a simple configuration (Fig. 1). If a constant gain (K_F) is employed for load estimation, the estimated inflow changes, $\hat{Q}_i$, can be expressed as:

$$\frac{\hat{Q}_i}{Q_i} = \frac{1}{\frac{1}{K_pK_F}s+1} = \frac{1}{\tau_F s+1} \tag{5}$$

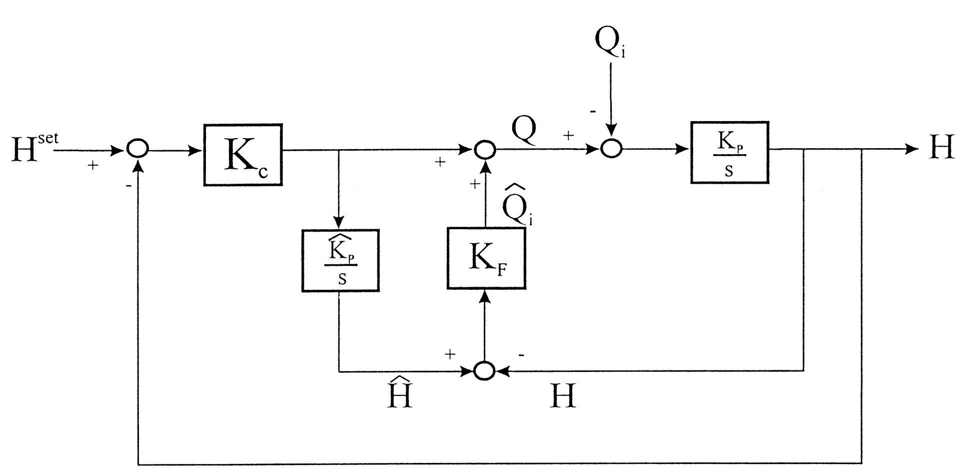

Fig. 1. Block diagram for the proposed level control configuration.

Furthermore, the dynamics of the disturbance is characterized by a first order response with a time constant τ_F. The reason for that is: similar to using P-only control in a feedback loop, a constant gain feedback can eliminate steady-state error (for complementary type of transfer function) for integrator systems under asymptotic constant changes.

As for the set point response, a proportional-only controller (K_c) is placed in the outer feedback loop. From Eq. (2), we have:

$$\frac{H}{H^{\text{set}}} = \frac{1}{\frac{1}{K_p K_c}s + 1} = \frac{1}{\tau_c s + 1} \tag{6}$$

It is clear that this configuration decouples the load estimation from the set point response and, moreover, the dynamics of these two effects are described by a feedforward gain (K_F) and a feedback gain (K_c) separately. Since we are interested in the overall effects on liquid level under load disturbance, the load response of level can be derived:

$$\frac{H}{Q_i} = \frac{\frac{1}{K_c}\tau_F s}{(\tau_c s + 1)(\tau_F s + 1)} \tag{7}$$

It is well understood that the smoothness of the outflow is an important factor in level control, the response of the outflow is:

$$\frac{Q}{Q_i} = \frac{(\tau_c + \tau_F)s + 1}{(\tau_c s + 1)(\tau_F s + 1)} \tag{8}$$

Fig. 2 shows the equivalent block diagram for the two-degree of freedom controller. Notice that the assumption of perfect modeling is assumed. It is interesting to notice that the controller is exactly the opposite of the reset windup ([13] p. 126). In other words, it remains a P-only controller in the disturbance free case (i.e., $d = 0$) and becomes a PI type of controller when load disturbance comes in (i.e., $d \neq 0$). Consider the disturbance-free case (i.e., $u = u_c$). From Fig. 2, we have:

$$u_c = u_p = K_c e \tag{9}$$

where u_c is the intermediate controller output, u_p is the output of the proportional control, K_c is the proportional gain and e is the error signal. For the case of inlet flow disturbance (i.e., $u \neq u_c$), the relationship between the controller output (u_c) and the error (e) becomes:

$$u_c = \left(1 - \frac{K_p K_c}{s}\right) u_p = K_c\left(1 - \frac{K_p K_c}{s}\right) e \tag{10}$$

This is exactly the form of a PI controller. Therefore, the two-degree of freedom control becomes a PI controller when the disturbance comes in. In the reset feedback, the integer action is turn-off when the controller output saturates (that implies $u \neq u_c$). Here, the integer action is invoked when $u \neq u_c$.

Next, the case of plant/model mismatch is studied. The modeling error in the steady-state gain is considered. The estimation error in the load change becomes:

$$\frac{\hat{Q}_i}{Q_i} = \frac{\tau_c s + 1 + e_m}{\tau_c \tau_F s^2 + (\tau_c + \tau_F)s + 1 + e_m} \tag{11}$$

where e_m is the multiplicative error in the steady-state gain:

$$e_m = \frac{\left(\hat{K}_p - K_p\right)}{K_p} \tag{12}$$

Eq. (12) shows that we have a zero offset in the load estimation, but the load tracking dynamics becomes a

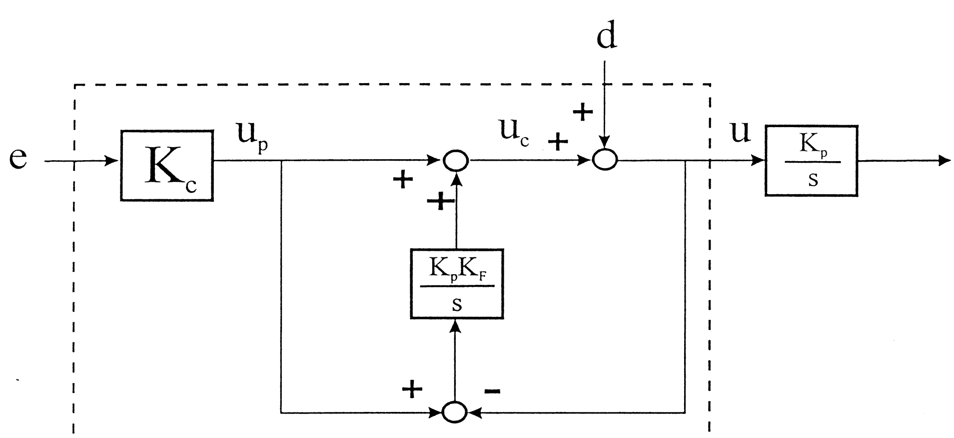

Fig. 2. Block diagram for level controller.

second order response. Similarly, for set point response, we have:

$$\frac{H}{H^{\text{set}}} = \frac{\tau_F s + 1 + e_m}{\tau_c \tau_F s^2 + (\tau_c + \tau_F)s + 1 + e_m} \tag{13}$$

The important property of zero steady-state offset is retained under plant/model mismatches.

3. Controller design

Following Cheung and Luyben [2], the feedforward gain, K_F, and the feedback gain, K_c, are tuned according to two rather operational specifications: maximum rate of change in outflow (*MRCO*) and maximum peak height (*MPH*). For a given inlet flow variation, $\Delta\bar{q}_i$, we have the following time domain responses:

$$h(t) = \frac{\Delta\bar{q}_i}{A}\left(\frac{\tau_F\tau_c}{\tau_F - \tau_c}\right)\left(e^{-\frac{t}{\tau_F}} - e^{-\frac{t}{\tau_c}}\right) \tag{14}$$

$$q(t) = \Delta\bar{q}_i\left[1 + \left(\frac{\tau_c}{\tau_F - \tau_c}\right)e^{-\frac{t}{\tau_F}} - \left(\frac{\tau_F}{\tau_F - \tau_c}\right)e^{-\frac{t}{\tau_c}}\right] \tag{15}$$

Setting the derivative of Eq. (14) equal to zero gives the time (t_{peak}) when the peak level occurs. One obtains:

$$t_{\text{peak}} = \frac{\tau_c}{1 - \left(\frac{\tau_c}{\tau_F}\right)} \ln\left(\frac{\tau_F}{\tau_c}\right) = \frac{\tau_c}{1 - \left(\frac{1}{r}\right)}.\ln r \tag{16}$$

where r is the ratio of two time constants. That is:

$$r = \frac{\tau_F}{\tau_c} \tag{17}$$

Substituting Eq. (16) into Eq.(14), *MPH* becomes:

$$MPH = H(t_{\text{peak}}) = \left(\frac{\Delta\bar{q}_i}{A}\cdot\tau_c\right)\cdot\left(\frac{1}{r^{\frac{1}{r-1}}}\right) \tag{18}$$

Similarly, *MRCO* can be obtained by finding the initial slope of $q(t)$ for a given $\Delta\bar{q}_i$. From Eq. (15), we have:

$$MRCO = \lim_{t\to 0}\frac{dq}{dt} = \frac{\Delta\bar{q}_i}{\tau_c}\cdot\left(1 + \frac{1}{r}\right) \tag{19}$$

In theory, we would like to keep these two specifications, *MPH* and *MRCO*, as small as possible. However, the equation structures indicate that as we decrease the *MRCO*, the *MPH* gets larger and vice versa. The question then becomes: given one specification, e.g., *MRCO*, how to keep the other specification, e.g., *MPH*, as small as possible. That is equivalent to minimizing the product of *MPH* and *MRCO*. From Eqs. (18) and (19), we have:

$$MPH\cdot MRCO = \left(\frac{\Delta\bar{q}_i^2}{A}\right)\cdot\left(\frac{1}{r^{\frac{1}{r-1}}}\right)\cdot\left(\frac{1+r}{r}\right) \tag{20}$$

Notice that this is a function of r only. Taking the derivative with respect to r and set it equal to zero, one obtains:

$$r = 1 \tag{21}$$

That implies by letting $K_c = K_F$ (or $\tau_c = \tau_F$), the other specification is minimized automatically. This provides useful guidance for the design of level controller.

Furthermore, under this circumstance ($\tau_c = \tau_F$), relevant parameters become:

$$t_{\text{peak}} = \tau_c \tag{22}$$

$$MPH = \left(\frac{\Delta\bar{q}_i}{A}\cdot\tau_c\right)\cdot e^{-1} \tag{23}$$

$$MRCO = \frac{\Delta\bar{q}_i}{\tau_c}\cdot 2 \tag{24}$$

Notice that the exponential term in Eq. (23) is obtained from: $e = \lim_{n\to\infty}(1 + 1/n)^n$. Design procedures can be devised from these equations. Procedures are classified according to the nature of applications.

3.1. Load responses

Generally, this is the major concern in level control. For the proposed controller structure, the design can be carried out in two steps. First, a single specification is given on either *MPH* or *MRCO*, then the feedback gain can be obtained. Next, from the result of optimization, set the feedforward gain equal to the feedback given. In summary, the tuning procedure becomes:

- S0. Define the maximum step change in inflow ($\Delta\bar{q}_i$) and a specification on maximum rate of change in outflow (*MRCO*) or maximum peak height (*MPH*).
- S1. Find the feedback gain K_c (or τ_c) from Eq. (23), for specification on *MPH*, or from Eq. (24), for specification on *MRCO*.
- S2. Set the feedforward gain K_F equal to K_c [Eq. (21)].

3.2. Servo and load responses

This is a less frequent situation, e.g., reactor level in a recycle plant, but the proposed control configuration is expected to do well under this circumstance. Since the set point response is decoupled from the load response, controller design can be carried out sequentially.

The procedure can be summarized as follows.

S1. Determine the feedback gain K_c (or τ_c) from Eq. (6) for specification on set point response.

S2. Define the maximum step change in inflow ($\Delta\bar{q}_i$) and, for specification on *MPH* or *MRCO*, find the feedforward gain K_F from Eq. (16) or (17).

Notice that the estimation and control is carried out using two tuning constants, K_F and K_c. Also it can be shown that the two degree of freedom control is equivalent to a PI control provided with a set point weighting [5].

4. Results and discussions

An example of Cheung and Luyben [14] is used to illustrate the design and performance of the proposed level control scheme. This is a tank with a cross-section area of 1m^2 ($A = 1$ m^2) and a working volume ($A \cdot \bar{h}$ where $\bar{h}$ is the height of the tank) of 2 m^3. Initially, the tank level is at 50% and the nominal flow rates are 1 m^3/min ($q_i = q = 1$ m^3/min). The maximum expected change in the inflow ($\Delta\bar{q}_i$) is 1 m^3/min.

4.1. Base case

If a specification on the *MPH* is given, i.e., 18.4% of the tank level, τ_c can, then, be computed from Eq. (23). Thus, one obtains: $\tau_c = 1$ (min) or $K_c = 1$. Following step S2, the feedforward gain is also equal to one ($K_F = 1$). This set of tuning constants corresponds to t_{peak} of 1 min and *MRCO* of 2 m^3/min/min. Fig. 3 shows that the system performs according to the specifications. Moreover, Fig. 3 shows that as we decrease K_F, smaller *MRCO* can be obtained at the cost of higher *MPH*. If the feedforward gain is further decreased to zero, it becomes a P-only control (Fig. 2). The opposite behavior can be observed for an increase in K_F. It is important to notice that all these load responses give exactly the same set point response as shown in Fig. 2. This is a unique characteristic of the proposed control.

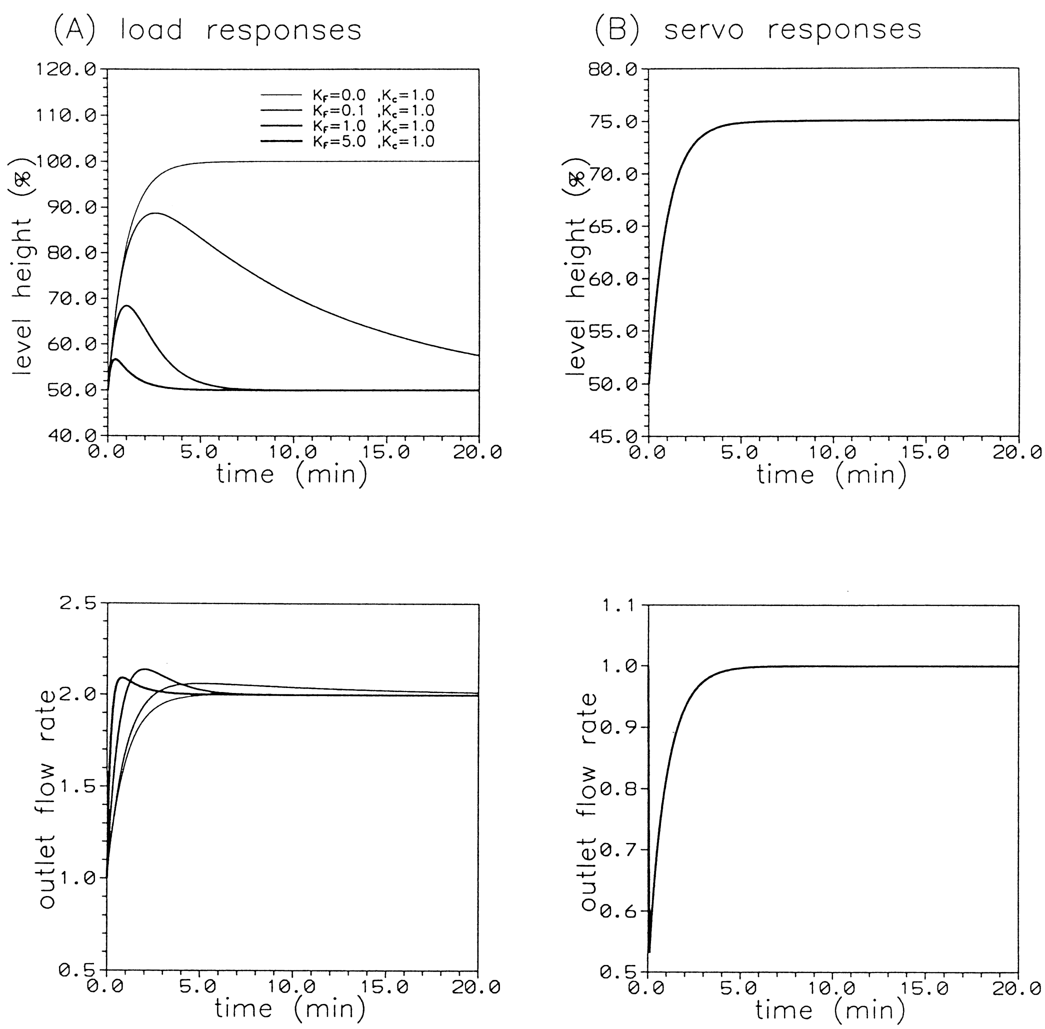

Fig. 3. Effects of K_F on surge tank level control: (A) load responses and (B) set point responses.

4.2. Robustness

The robustness issue is also studied. Consider the cases of ±20% errors in K_p (i.e., $e_m = \pm 0.2$). Again, for the surge tank studied, the *MPH* and *MRCO* at the nominal condition are 18.4% and 2, respectively. Fig. 4 shows the load responses under modeling errors. The results show that ±20% errors lead to +3.8 and −3.3% changes in *MPH* and −1.0 and +1.5% changes in *MRCO*. The results indicate that, little performance degradation is observed under plant/model mismatches.

4.3. PL Control

As pointed earlier, the performance of the two-degree of freedom control is exactly the same with the PL control at the nominal condition. For example, the proposed control with $K_c = 1$ and $K_F = 1$ is equivalent to the PL control with $K_c = 1$ and a feedforward element of $FF = 1/(s+1)$ (e.g., the response of the middle curve in Fig. 4). However, the behavior of the PL control under modeling error is very different from the proposed one. Consider a flash drum level control system in Fig. 5. The flash drum has the same dimensionality as the surge tank, but the inflow Q_i is 2 M^3/min where half of the inflow leaves the unit as vapor (V) and the other half leaves as liquid (L). That is: $V/Q_i = 0.5$ at the nominal condition. In this case we set the feedforward element to $FF = 0.5/(s+1)$. However, if the light component decreases and the fraction of the vapor decrease to 0.4, the PL control gives significant steady-state offset in the liquid level and the MPH is higher than expected (Fig. 6). Similar behavior can be observed for the opposite case (e.g., $V/F = 0.6$) as shown in Fig. 6. Therefore, the errors in the feedforward gain leads to steady-state errors in the liquid level which is quite different from the two-degree of freedom control (Fig. 4).

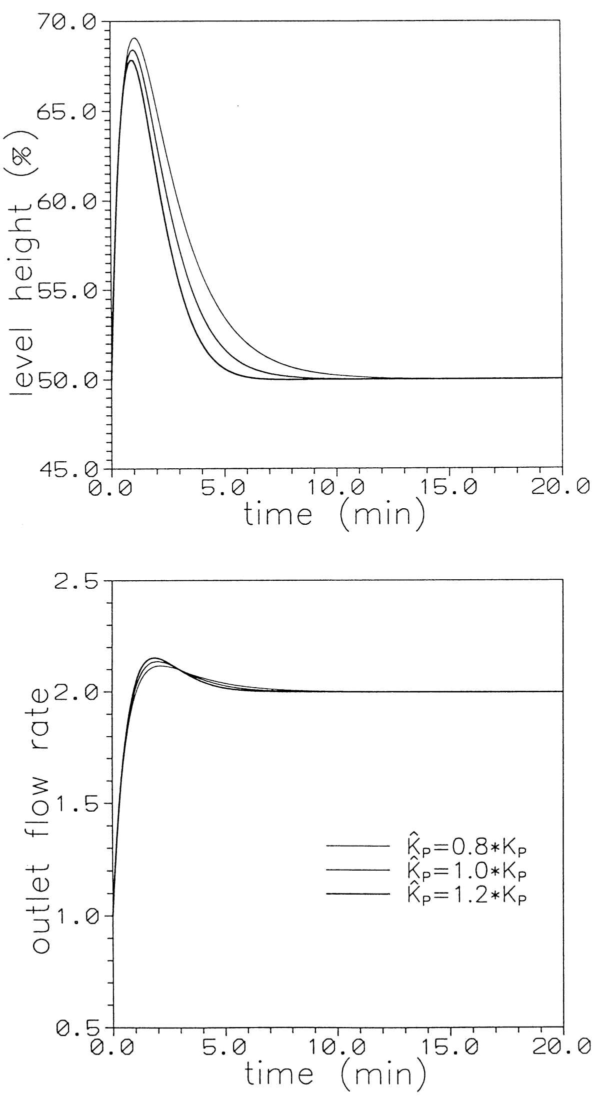

Fig. 4. Effects of modeling error on the proposed level control for a surge tank.

4.4. Dead time for level process

The level processes generally do not have the dead time except for some rare occasions. One possible situation is that one try to control the distillation column base level with the feed flow rate. For surge tank, the only possibility is the slow movement of the control valve. Therefore, the dead time in the level processes cannot be too large. Let us take our surge tank example to analyze the dead time behavior. If we have some dead time in the system (for example the control valve is located very far down the tank), the process transfer function becomes:

$$G_{(s)} = \frac{K_p e^{-Ds}}{s} \tag{25}$$

where D is the dead time. The ultimate gain (K_u) can be expressed as:

$$K_u = \frac{\pi}{2K_p D} \tag{26}$$

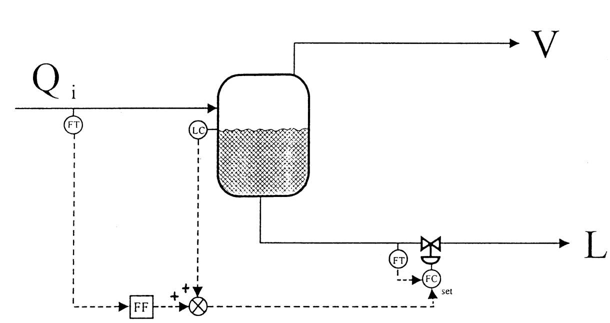

Fig. 5. PL level control of a flash tank.

For our case of $K_c = 1$ with the residence time (τ_{res}) of 1 min, the dead time has to be as large as almost twice of the residence time ($D = (\pi/2)\cdot\tau_{\text{res}}$) to reach the stability limit. That implies that it is not likely that the small dead time in the level loop will give rise to the stability problem in the level loop. Moreover, only little performance degradation is observed for the proposed control. It should be noticed that, in the simulation study, the dead time is included in the process transfer function only (since the delay comes from the placement of the manipulated variable). Fig. 7 shows the results for the level process with dead times range from 0 up to 10% of the residence time (we consider the 10% to be the upper limit). The peak height varies by 2%. The responses indicate that realistic size of the dead time has little effect on the control performance.

4.5. Level with inverse response

Inverse responses in liquid level are observed in distillation column base level when a thermalsyphon reboiler [15] is employed and in steam generator water level of nuclear power plants [16]. The non-minimum phase characteristics are caused by the "swell and shrink" effects. The "swell" can be explained as when an increase in the steam is made, the two-phase fluid in the tube bundles expands, leading to an initial increase in liquid level. Consider a general level process with inverse response.

$$G_{(s)} = \frac{K_p(-a\tau s + 1)}{s(\tau s + 1)} \tag{27}$$

where τ is the time constant and $1/(a\tau)$ is the right-half-plane (RHP) zero. In this case, the equations in Section

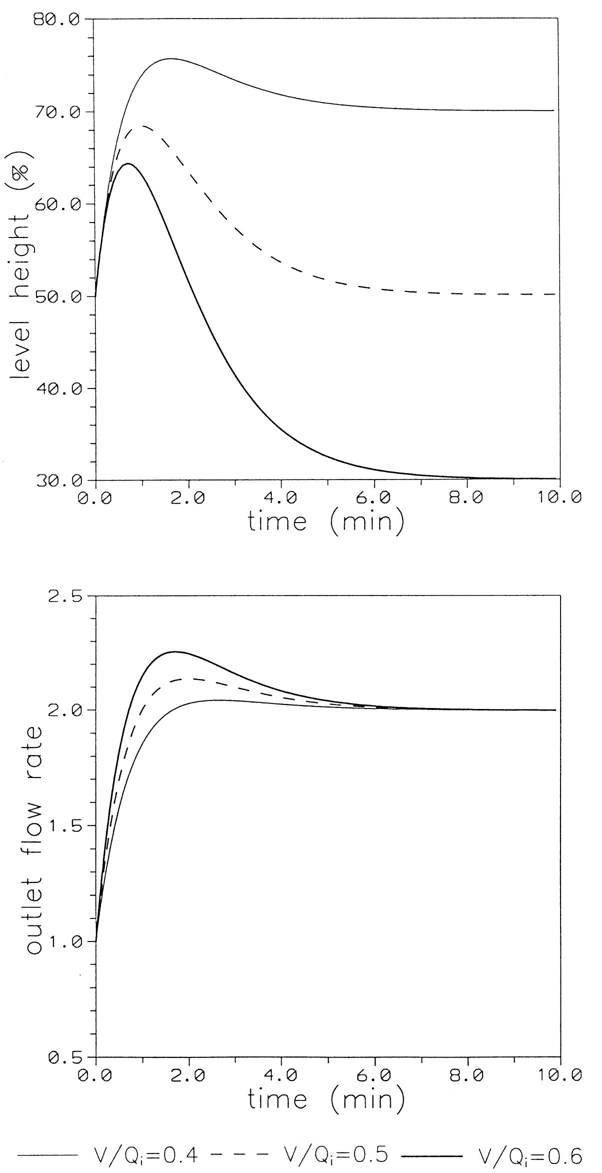

Fig. 6. Effects of modeling error (different V/Q_i ratios) on the PL control.

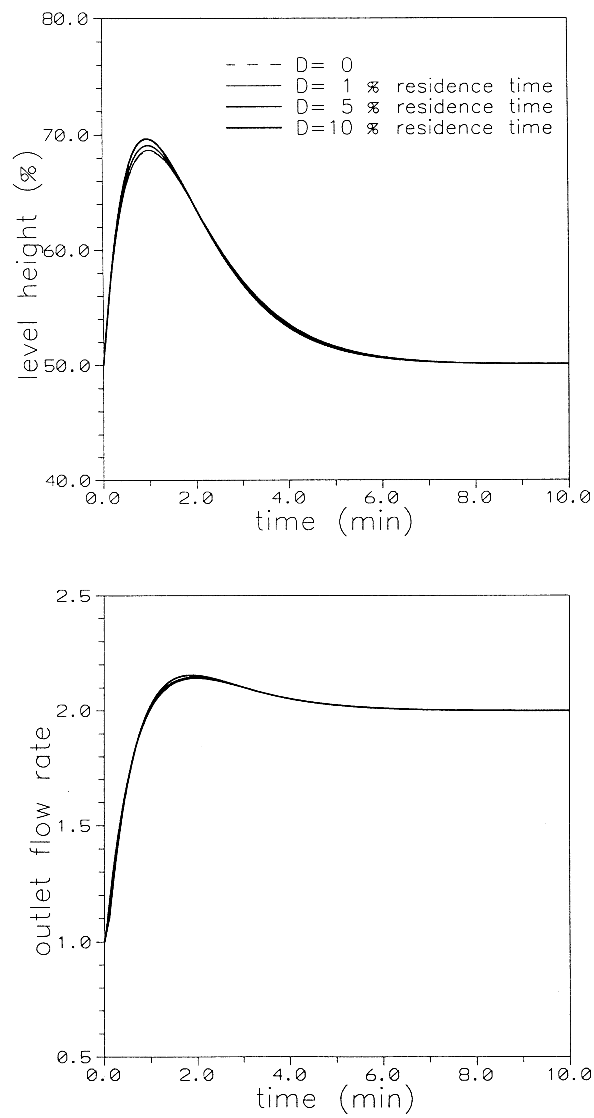

Fig. 7. Effects of dead time (as percentages of the residence time) on the proposed control.

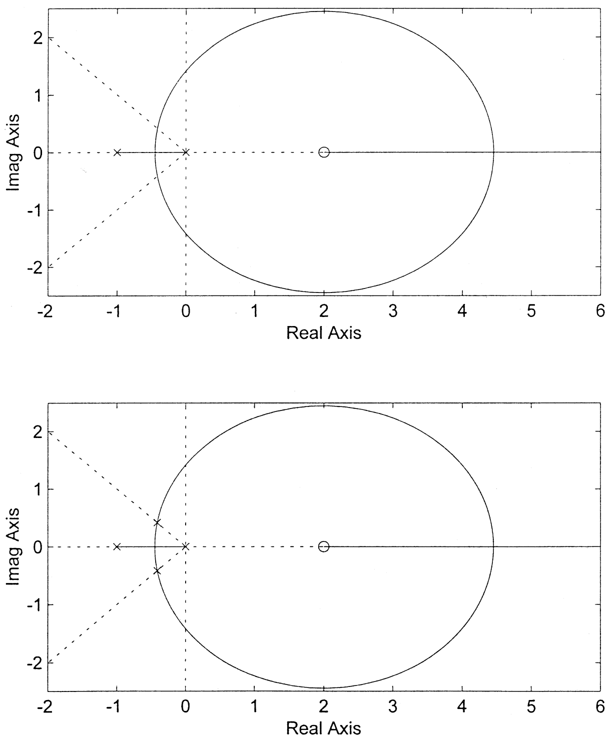

Fig. 8. Root locus plots for the non-minimum phase level processes with (bottom) and without (top) load estimation.

3 cannot be applied and the design procedure should be revised for the non-minimum phase level process. Since the system can become underdamped and then unstable as we increase the controller gain (K_c), the damping coefficient (ζ) can be used to design both controllers. Let us assume our level process has a RHP zero with $\tau = 1$ and $a = -0.5$ and the dimensionality of the holdup is the same as the surge tank example. The design procedure then becomes: (1) find K_c such that the closed-loop damping ratio is $\sqrt{2/2}$ for the load estimation free case $(1 + GK_c = 0)$ and (2) calculate K_F such that the closed-loop damping ratio is $\sqrt{2/2}$ for the case of load estimation $[(1 + GK_c)(1 + GK_F) = 0]$. The root locus plot of $(1 + GK_c)$ in Fig. 8 (top graph) shows and ultimate gain is $K_c = 2$ and $\zeta = 0.707$ corresponds to $K_c = 0.34$. Once the feedback gain is determined, the root locus plot is again utilized to find K_F. Fig. 8 (bottom graph) shows that $\zeta = 0.707$ again corresponds to $K_F = 0.34$ and $K_F = 2$ indicating the limit of stability. This design procedure places the two pairs of closed-loop poles on the same positions, with a damping coefficient of 0.707. For a disturbance half of the maximum expected change in the inflow ($\Delta q_i = 0.5$ m^3/min), Fig. 9 shows the load responses for different K_Fs. First, the system overflows for system without load estimation (since the feedback gain is about 1/3 of the original value). Second, the system

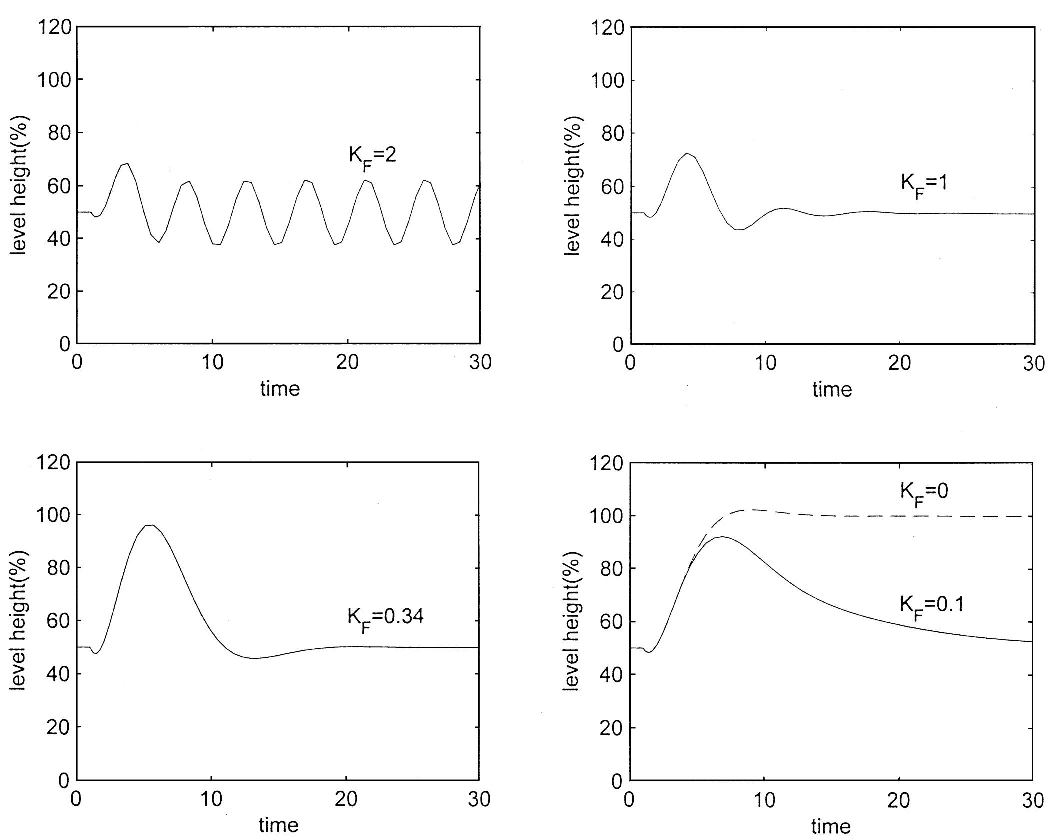

Fig. 9. Effects of K_F on the control of non-minimum phase level process.

reaches the limit of stability if the feedforward gain is set to 2. The proposed two-degree of freedom control ($K_c = K_F = 0.34$) gives reasonable load responses. It should be noticed that the characteristics of the non-minimum phase level processes are very different from the typical level process and it is much difficult to control. A design procedure, based on damping ratio, is proposed and results show that the two-degree of freedom control is demonstrated favorably via simulations.

5. Conclusion

Similar to PL control, a two-degree of freedom control is proposed for liquid level control. The proposed control uses a feedforward gain (K_F) for load estimation and a P-only controller (K_c) for the feedback control. The two-degree of freedom control remains as a P-only control in the disturbance free case and becomes a PI controller under load change. Moreover, it possesses a better robustness property than the PL control. Steady-state and dynamic characteristics of the proposed control are explored and, subsequently, the design procedures for both load and servo responses. A surge tank example is used to illustrate the effectiveness of the proposed control. Results show that the simple control gives satisfactory responses at nominal condition, under modeling error and systems showing dead time or inverse response.

Acknowledgements

We are grateful for the comments and suggestions made by the reviewers. This work was supported by the National Science Council of Taiwan under grant NSC-85-2214-E-011-002.

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