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Feedforward 보상에 근거한 3개의 탱크 액체 레벨 시스템의 통제 분리

(Decoupling Control of Three-tank Liquid Level Systems Based on Feedforward Compensation)

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요 약

실제 프로세스 제어 중의 3개의 탱크 액체가 이 결합 시스템을 통제하는 작업 원리에 근거하여 두개의 입력과 두개의 출력 시스템의 수학적 모델을 제시하였다. 귀로 사이의 결합 작용을 한 종류의 형식의 요소로 간주하고 Feedforward 보상에 근거하여 정형화한 형태의 통제 분리 방법을 제시하였다. 그리고 두 개의 입출력 결합 시스템에 대해 통제 분리를 진행하고 마지막으로 프로그래밍을 통해 이 통제 분리 프로세스의 실험을 수행하였다. 또한 시뮬레이션 결과는 그 방법이 양호한 통제 분리 효과를 얻을 수 있다는 것을 나타내었다.

Abstract

By considering decoupling between loops as a kind of measurable disturbance, a steady-state decoupling method based on feedforward compensation is proposed for a three-tank liquid level system often encountered in practical process control. In addition, the three-tank liquid level system's dynamic model with structure of two-input and two-output is presented according to its working principle. Finally simulation experiments given in C++Builder language demonstrate the effectiveness of the proposed method.

Keywords : Three-tank System, Decoupling Control, Feedforward Compensation

I. Introducation

The three-tank liquid level control system is a typical multi-input and multi-output (abbr. MIMO) system with couplings often encountered in practical processes. In order to achieve effective control, many MIMO systems are decoupled into several two-input and two-output (abbr. TITO) subsystems. However, in view of the couplings among loops, it is difficult for the coupled subsystems to make full use of the conventional controllers widely used in single loop systems, so the decoupling control is paid great attention to both control theorists and engineers in process control fields. Narendra[1] used multiple adaptive models to identify the unknown system with disturbance, but got poor performance. LIU[2] gave a analytical design of decoupling control for TITO processes in theory, not in practice. WANG[3] adopted auto-turning algorithm to decoupling also only in theory. In Refs.[4~6] multiple models adaptive decoupling controllers were designed for the minimum phase, non-minimum phase system and nonlinear system respectively, but their structures are

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not suitable for the three-tank liquid level control system. In this paper, the couplings between loops viewed as a measurable disturbance, a steady-state decoupling method based on feedforward compensation is proposed for three-tank liquid level control systems. The decoupled system is divided into two single loop subsystems with no couplings, and each of the subsystems is controlled by a PI controller. Compared with other methods mentioned above, though the proposed method is based on a known model, it is suitable to solve the coupled TITO systems with known models in practical processes, and has the advantage of easy implementation. Simulation experiments given in C++Builder language illustrate the effectiveness of the proposed method.

II. Description of the System

1. Presentation of Experiment Device

The experiment device of three-tank liquid level control system is a MIMO object with characters of strong coupling and nonlinear, it is composed of three columnar tanks (T1,T2,T3), two electromagnetic valves (V7,V8), two water pumps (P1,P2) and a trough as shown in Fig.1. By adjusting electromagnetic valves (V7,V8) to control the flux feeding into tanks (T1,T2) simultaneously, and to achieve the liquid level control of tanks T1 and T2 . Water in tank T3 only get from T1 or T2 and it's liquid level is not controlled, obviously, the three-tank liquid level control system is a TITO system with interactions.

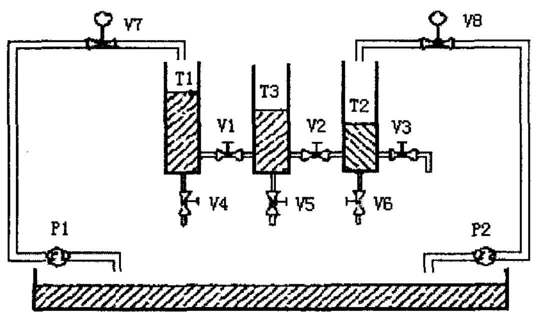

그림 1. 3개의 탱크 시스템의 구조도
Fig. 1. Schematic diagram of the three-tank system.

2. Foundation of System Model

According to the dynamic material-balance law, equations for tank T1, T2 and T3 are established as follows

$$\frac{dh_1}{dt} = \frac{1}{S}(q_1 - q_{13}) \quad (1)$$

$$\frac{dh_3}{dt} = \frac{1}{S}(q_{13} - q_{32}) \quad (2)$$

$$\frac{dh_2}{dt} = \frac{1}{S}(q_2 + q_{32} - q_{20}) \quad (3)$$

Where S is the cross section of tank T1,T2 and T3, h_i is the liquid level of tank i, $i \quad \{1,2,3\}$,q_1 denotes the flux via V7 to T1, q_2 denotes the flux via V8 to T2, q_{13} denotes the flux from T1 to T3 via V1,q_{32} denotes the flux from T3 to T2 via V2, q_{20} denotes the flux from T2 to trough via V3. Subject to the Torricelli law which is defined as

$$q = a_z S_n sgn(\Delta h)(2g\sqrt{|\Delta h|})$$

q_{13},q_{32} and q_{20} satisfy the following form

$$q_{13} = a_{z_1} S_n sgn(h_1 - h_3)(2g\sqrt{|h_1 - h_3|})$$
$$q_{32} = a_{z_3} S_n sgn(h_3 - h_2)(2g\sqrt{|h_3 - h_2|})$$
$$q_{20} = a_{z_2} S_n \sqrt{2gh_2}$$

define vectors $H = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix}, Q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$, Eqs.(1)~(3) can be conveniently rewritten as

$$\frac{dH}{dt} = CQ + D(h) \quad (4)$$

where $D(h) = \frac{1}{S}\begin{bmatrix} -q_{13} \\ q_{32} - q_{20} \end{bmatrix}, C = \frac{1}{S}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, Eqs.(4) is the state equation of this three-tank liquid level control system. According to Eqs.(4), the system's output variables h_1 and h_2 are coupled with input variables q_1 and q_2. It is obvious that this three-tank liquid level control system is a TITO system with couplings.

III. Analysis and Design of Decoupling

1. Analysis of Decoupling Method Based on Feedforward Compensation

Considering the couplings between loops, this three-tank liquid level control system can be described as Fig.2.

where $W_{c1}(s), W_{c2}(s)$ are PI controllers, $U_1(s)$, $U_2(s)$ are control variables, respectively. Matrix $W_p(s)$ with form of $\begin{bmatrix} W_{p11(s)} & W_{p12(s)} \\ W_{p21(s)} & W_{p22(s)} \end{bmatrix}$, denotes transfer function of the controlled object, where $W_{p11}(s)$, $W_{p22}(s)$ denote the transfer functions of tank T1 and T2, $W_{p12}(s)$, $W_{p21}(s)$ denote the transfer functions of interactions.

Generally speaking, $W_{p11}(s)$ and $W_{p22}(s)$ have the following form[7]

$$W_{p11}(s) = \frac{k_{11}}{T_{11}s+1}e^{-\tau_{11}s}, \quad W_{p22}(s) = \frac{k_{22}}{T_{22}s+1}e^{-\tau_{22}s}$$

For each single loop, the couplings between loops can be viewed as a measurable disturbance, namely the control variable $U_2(s)$ may be viewed as a disturbance to first loop while $U_1(s)$ may be viewed as a disturbance to second loop too. Because feedforward control[8] can eliminate system's measurable but uncontrolled disturbance, for each single loop, we adopt a feedforward-feedback compound control structure as shown in Fig.3, where $W_{ff2}(s)$ denotes the transfer function of the constructed feedforward compensator.

According to Fig.3, the first loop's output can be derived as follows

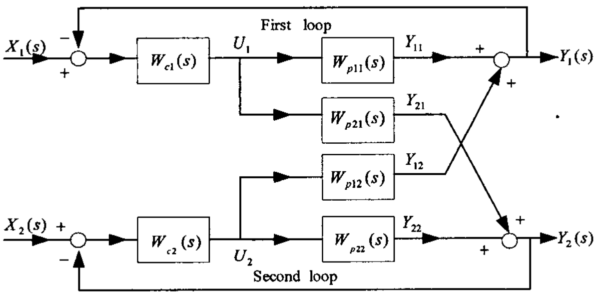

그림 2. 분리되기 전의 시스템 구조도
Fig. 2. Structure of system without decoupling.

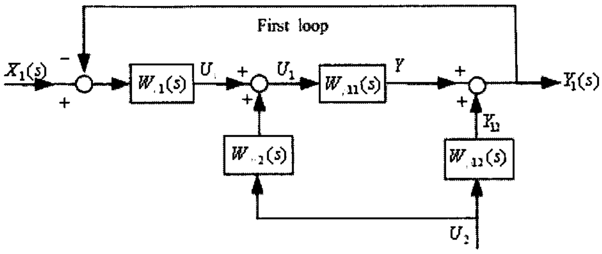

그림 3. Feedforward-feedback 복합 통제 체계
Fig. 3. Structure of feedforward-feedback compound control.

$$Y_1(s) = U_2(s)W_{p12}(s) + U_2(s)W_{ff2}(s)W_{p11}(s) - W_{c1}(s)W_{p11}(s)Y_1(s)$$

Namely

$$\frac{Y_1(s)}{U_2(s)} = \frac{W_{p12}(s) + W_{ff2}(s)W_{p11}(s)}{1 + W_{c1}(s)W_{p11}(s)} \tag{5}$$

According to Eqs.(5), the condition of realizing full compensation is $\frac{Y_1(s)}{U_2(s)} = 0$,

namely

$$W_{p12}(s) + W_{ff2}(s)W_{p11}(s) = 0$$

so the constructed feedforward compensator's transfer function in first loop is derived as following

$$W_{ff2}(s) = -\frac{W_{p12}(s)}{W_{p11}(s)} \tag{6}$$

Similar to above discussions, the second loop's feedforward compensator transfer function is

$$W_{ff1}(s) = -\frac{W_{p21}(s)}{W_{p22}(s)} \tag{7}$$

2. Design of Decoupling Method Based on Feedforward Compensation

According to Fig.2, the system's outputs are of the form

$$Y_1(s) = U_1(s)W_{p11}(s) + U_2(s)W_{p12}(s)$$

$$Y_2(s) = U_2(s)W_{p22}(s) + U_1(s)W_{p21}(s)$$

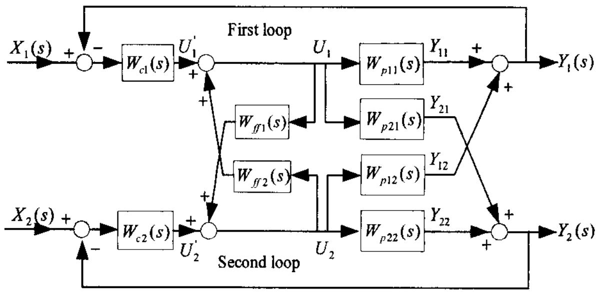

그림 4. 통제 분리된 시스템의 구조도
Fig. 4. Structure of the decoupled system.

For the first loop, we will construct a compensator $W_{ff2}(s)$ which can eliminate the coupling caused by the second loop. According to Eqs.(6), if the first loop achieves full compensation, the constructed feedforward compensator's transfer function have a form of $W_{ff2}(s)=-\frac{W_{p12}(s)}{W_{p11}(s)}$. Similarly, the second loop's feedforward compensator model is $W_{ff1}(s)=-\frac{W_{p21}(s)}{W_{p22}(s)}$, which also can eliminate the coupling caused by the first loop, hence, the decoupled three-tank liquid level control system is illustrated as Fig.4.

According to Fig. 4, the system's outputs are of the form

$$Y_1(s)=U_1(s)W_{p11}(s)+U_2(s)W_{p12}(s) + U_2(s)W_{ff2}(s)W_{p11}(s) \tag{8}$$

$$Y_2(s)=U_2(s)W_{p22}(s)+U_1(s)W_{p21}(s) + U_1(s)W_{ff1}(s)W_{p22}(s) \tag{9}$$

Since $W_{ff1}(s)=-\frac{W_{p21}(s)}{W_{p22}(s)}$, $W_{ff2}(s)=-\frac{W_{p12}(s)}{W_{p11}(s)}$, now by substituting $W_{ff1}(s), W_{ff2}(s)$ into Eqs.(8) and (9) respectively, finally, we obtain

$$Y_1(s)=U_1(s)W_{p11}(s) \tag{10}$$

$$Y_2(s)=U_2(s)W_{p22}(s) \tag{11}$$

According to Eqs.(10) and (11), it is obvious that the decoupled system is divided into two single-loop subsystems without couplings.

Ⅳ. Implementation of the Decoupled System

Steady-state decoupling and dynamic decoupling are two means of implementing decoupling, but steady-state decoupling method is suitable for those systems whose variables are paid great attention in steady-state. In practical processes, in order to simplify the processes, it is advisable to substitute the transfer function's ratio with the transfer functions' gain coefficient ratio, namely, the constructed feedforward compensators may be written as $W_{ff1}(s)=-\frac{k_{21}}{k_{22}}$, $W_{ff2}(s)=-\frac{k_{12}}{k_{11}}$. In this system, because we much concern the liquid level of tanks in steady-state conditions, so we adopt steady-state decoupling means to this system. Not only couplings but also time delays often exist in practical processes, however, because all the pipelines in this system are very short, so the time delays are very small and may be out of consideration. Because the single tank's model has a form of first order inertia, after experiments, the single tank's transfer function without couplings is chosen as

$$W_{p11}(s)=W_{p22}(s)=\frac{2}{5s+1}$$

The system's control indexes are $h_1=30cm$, $h_2=15cm$, since $h_1>h_2$, the coupling in second loop caused by input variable q1 must be taken into account while the coupling in first loop caused by input variable q2 may be overlooked. Considering the above cases, we let the coupled part transfer function as

$$W_{p21}(s)=\frac{8}{125s^3+75s^2+15s+1}, W_{12}(s)\approx 0$$

In the following simulation experiments, we let the decoupling coefficients $W_{ff1}=1$, $W_{ff2}=0$. Each of the decoupled subsystems is controlled by PI control algorithm. Hereto, the decoupled three-tank liquid level control system is described clearly.

V. Simulation Experiments

To demonstrate the decoupling ability of the proposed method, simulation experiments are done in C++Builder language, the realization steps are as following

1. Parameters definition

Variables used in program are defined as followling.

y11, y22 and y12 are subsystems' discrete liquid level, Y1, Y2 and Y3 are liquid level of tanks T1, T2 and T3, respectively. U11,U22 denote the outputs of each PI controllers, U1,U2 denote the outputs of the decoupled system.

2. Decoupling Programming

The following is a segment of source code to get the decoupled system's output values U1 and U2.

RIN=1; // step length
y11=0.3625*U1_1+0.8187*y11_1;
// discrete equation of transfer function $W_{p11}(s)$
y12=2.456*y12_1-2.011*y12_2+0.5488*y12_3
+0.0092*U1_1+0.03166*U1_2+0.0068*U1_3;
y22=0.3625*U2_1+0.8187*y22_1;
// discrete equation of transfer function $W_{p22}(s)$
Y1=y11;
Y2=y22+y12;
Y3=1.637*Y3_1-0.6703*Y3_2+0.071*U1_1
+0.0613*U1_2;
EK1=RIN-Y1;
EI1=EI1+EK1;
EK2=RIN-Y2;
EI2=EI2+EK2;
U11=KP1*EK1+KI1*EI1;
U22=KP2*EK2+KI2*EI2;
U1=U11+U22*0; //Wff2=0
U2=U22+U1*Wff1; //U1 and U2 are the decoupled system's output variables

3. Simulation Experiments

During simulation experiments, the most ideal control effect is gotten under the conditions of KP1=3, KI1=0.3, KP2=0.5andKI2=1. The simulations are shown in Fig.5~ Fig.6.

그림 5. T1의 액체 레벨 시뮬레이션 결과
Fig. 5. Liquid level control simulation results of T1.

그림 6. T2 의 액체 레벨 시뮬레이션 결과
Fig. 6. Liquid level control simulation results of T2.

It is obvious that the proposed steady-state decoupling method based on feedforward compensation has a effective control effect.

VI. Conclusions

e couplings between loops considered as a rable disturbance, a steady-state decoupling l method based on feedforward compensation is presented for three-tank liquid level systems in this paper, simulation experimental results derived from a practical engineering illustrate effectiveness of the proposed method. Compared with others' this method has advantages of relatively simple structure and easy implementation, but it neglects the system's time delays. In the future, fuzzy logic technologies will be considered to develop this method, thus, it can be extended to the processes with time delays[9].

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