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DECOUPLER DESIGN FOR AN INTERACTING TANKS SYSTEM

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ABSTRACT

The mathematical model for the two interacting tanks system was derived and the dynamic behavior of this system was studied by introducing a step change in inlet flow rate. In this paper, the analysis of the interaction loops between the controlled variable (liquid level) and manipulated variable (inlet flow rate) was carried out using the relative gain array. Also decoupling technique is applied to eliminate the effect this interaction by design suitable decouplers for the system. The results show that the gain of each loop is cut in half when the opposite loop is closed and the gain of other loop changes sign when the opposite loop is closed. The decoupling method show that the liquid level of tank one is constant when the second inlet flow changes and to keep the liquid level of tank two constant the first inlet flow must be changed.

KEYWORDS: Level Control, Relative Gain Array, Decoupler, Interacting Tank.

NOTATIONS

A: Cross section area of tank. (m^2)

H: Height of liquid level. (m)

K: Experimental steady state gain. (sec/m^2)

KP: Theoretical steady state gain. (sec/m2)

K': Closed loop steady state gain. (sec/m^2)

Q: Volumetric flow rate. (m^3/hr)

R: Flow resistance in the valve. (sec/m^2)

μ: Relative gain array. (-)

τ: Time constant of the tank. (sec)

INTRODUCTION

The control of flow and liquid level in tanks are a basic problem in the process industries. The process industries require liquids to be pumped, stored in tanks, and then pumped to another tank. Many times the liquids will be processed by chemical or mixing treatment in the tanks, but always the level of liquid in tanks must be controlled, and the flow between tanks must be regulated.

Two Interacting Tanks system is a multi-input/multi-output (MIMO) process which is more difficult to design and operate than single-input/single-output (SISO) process due to the interaction that occurs between the input and output variables. Interaction is defined as; in a multivariable system one input in general is influenced by more than one output, or conversely one reference input will influence more than one output. Often the tanks are so coupled together that the levels interact and this must also be controlled.

The relative gain array (RGA) method indicated how the input should be coupled with the output to form loops with minimal interaction. To design noninteracting system, decoupling control is required. Feedforward control is a form of decoupling such that changes in the disturbance variable do not affect the controlled variable. However, if the disturbance variable is another manipulated variable, decoupler is a more suitable terminology than feedforward, to indicate that control loops are decoupled and performed independently from one another [1]. Some studies have been made (Henary [2], Edgar [3], Esche [4], Johansson[5], Passino [6] and Douglas [7]) on the interacting tanks system.

With the progress in the modeling technique for the interacting system, many different model-based control methods have been proposed under different problem settings. Cooper and Dougherty [8] use Smith predictor model controller for interacting tanks system. The development of a model based control of a four tanks system have been made by Gatzke et al. [9]. They concluded that the controller provides perfect set point compensation and excellent disturbance rejection.

Edgar and Rueda [3] implemented PID control and developed a program which has a graphical interface that allows the engineer to follow the variations in the manipulated and controlled variables during the experiment.

The level control of interacting tank system requires the application of advanced control such as Fuzzy (Johannes and Marinits[10], Graham and Newell[11], and Gregorg et al [12]), adaptive control (Zumberge and Passino[6], Heiming and Lunze[13], and Ibrahim[14]). The previous experimental and simulation studies of interacting system clarify that the advanced control techniques were generally studied in the laboratory but in real plants the common control methods PI and PID were mostly applied.

Trierweiler [15] use RGA in the quadruple-tank process. He concluded that for minimum-phase operating point the interaction disappear at high frequencies. This means that if the controller can be fast tuned, the control loops behave as a completely non-interacting system. The relative gain array method indicated how the input should be coupled with the output to form loops with minimal interaction.

The design of the interacting system, decoupling is required. Design the decoupling of distillation and other chemical engineering equipments proposed by Oreilly[16] and McAvoy[17] and they have been successfully applied in industrial applications.

In this paper, the dynamic behavior of an interacting two tanks system was studied by two methods theoretically and experimentally. Relative gain array (RGA) is used as an interaction measurement and decoupling to design the control loop.

THEORY

1-Mathematical Model

The theoretical model of interacting tanks system shown in Fig.(1) is derived by using the material balance under the following assumptions:

- The flow resistance is linear with the liquid level in the tanks.
- The tanks have uniform cross-sectional area.

The density of water is constant.

A material balance can be written as:

Mass flow in – mass flow out = mass accumulation in the tank

For first tank

$$A_1 R_1 \frac{dH_1}{dt} + H_1 = R_1 Q_1 + H_2 \quad (1)$$

Taking Lapalce transform of the Eq. (1):

$$H_1(s) = \frac{1}{(\tau_1 s + 1)}\left[K_{P1} Q_1(s) + K_{P2} H_2(s)\right] \quad (2)$$

$$where\, \tau_1 = A_1 R_1 ,\ K_{P1} = R_1\ and\ K_{P2} = 1$$

At A_1 = 95 X 10^{-4} m^2 , R_1 = 10800 sec/m^2, and τ_1= 102.6 sec.

Eq. (2) can be written as:

$$H_1(s) = \frac{1}{(102.6\, s + 1)}\left[10800\, Q_1(s) + H_2(s)\right] \quad (3)$$

Similarly for second tank:

$$\left(A_2 \frac{R_1 R_2}{R_1+R_2}\right)\frac{dH_2}{dt} + H_2 = \left(\frac{R_1 R_2}{R_1+R_2}\right)Q_2 + \left(\frac{R_2}{R_1+R_2}\right)H_1 \quad .... \quad (4)$$

$$H_2(s) = \frac{1}{(\tau_2 s+1)}\left[K_{P3}Q_2(s) + K_{P4}H_1(s)\right] \quad (5)$$

$$where \ \tau_2 = A_2 \frac{R_1 R_2}{R_1+R_2}, \ K_{P3} = \frac{R_1 R_2}{R_1+R_2} \ and$$

$$K_{P4} = \frac{R_2}{R_1+R_2}$$

At A_2 = 95 X 10^{-4} m^2 , R_2 = 10800 sec/m^2, and τ_2= 51.3 sec.

Eq. (5) can be written as:

$$H_2(s) = \frac{1}{(51.3s+1)}\left[5400 Q_2(s) + 0.5 H_1(s)\right] \quad (6)$$

$$H_1(s) = \frac{10800(51.3s+1)}{5263s^2 + 1545s + 0.5} Q_1(s) + \frac{5400}{5263s^2 + 1545s + 0.5} Q_2(s) \quad (7)$$

$$H_2(s) = \frac{10800}{5263s^2 + 1545s} Q_1(s) + \frac{5400(102.6s+1)}{5263s^2 + 1545s} Q_2(s) \quad (8)$$

2-Loops Interaction

The response and stability of the multivariable system can be quite different from those of its constituent loops taken separately. The control of which can be quite complex and challenging to the process engineer. The interaction is affecting on the response of the feedback loops and the interaction between loops can be reduced or eliminated through the design of an appropriate controlled system by selecting the best way to pair the controlled and manipulated variables to reduce the effect of interaction.

Consider the interacting tanks system of Fig.(2) with two controlled variables, H_1 and H_2, and two manipulated variables, Q_1 and Q_2. It makes sense to pair each controlled variable with the manipulated variable that has greatest gain on it and we must find the gain of each manipulated variable on each controlled variable to make a decision.

The four open-loop steady-state gains for the system are:

$$K_{11} = \left[\frac{\Delta H_1}{\Delta Q_1}\right]_{Q2}, \quad K_{12} = \left[\frac{\Delta H_1}{\Delta Q_2}\right]_{Q1},$$
$$K_{21} = \left[\frac{\Delta H_2}{\Delta Q_1}\right]_{Q2}, \quad K_{22} = \left[\frac{\Delta H_2}{\Delta Q_2}\right]_{Q1} \quad (9)$$

Where K_{ij} is the gain relating the ith controlled variable to the jth manipulated variable.

The interaction measure or relative gain array provides exactly such a methodology and select pairs of input and output variables in order to minimize the amount of interaction among the resulting loops. The major advantage of the relative gain analysis presented here is that it requires only steady state process parameters specifically, the steady state gains.

For the system of Fig. (2), the steady state changes in the controlled variables caused by simultaneous changes in both manipulated variables are:

$$\Delta H_1 = K_{11}\,\Delta Q_1 + K_{12}\,\Delta Q_2$$
$$\Delta H_2 = K_{21}\,\Delta Q_1 + K_{22}\,\Delta Q_2 \quad (10)$$

To determine the closed loop gain for the pairing Q_1-H_1, we must introduce a feedback controller connecting Q_2 with H_2, as in Fig.(3). For the system of Fig.(2), the four steady state closed loop gains can be calculated from the four open loop gains. The relative gains for each of the other three pairs of variables are obtained by appropriately rearranging the connections of the feedback controller of Fig.(3). The resulting formulas are:

$$K'_{11} = \frac{K_{11}K_{22} - K_{12}K_{21}}{K_{22}}\,,\; K'_{12} = \frac{K_{11}K_{22} - K_{12}K_{21}}{-K_{21}}$$
$$K'_{21} = \frac{K_{11}K_{22} - K_{12}K_{21}}{-K_{12}}\,,\; K'_{22} = \frac{K_{11}K_{22} - K_{12}K_{21}}{K_{11}} \quad (11)$$

The relative gains can be now obtained their definition, Eq. (12)

$$\mu_{ij} = \frac{K_{ij}}{K'_{ij}} \quad \text{.............................} \; (12)$$

$$\mu_{11} = \frac{K_{11}K_{22}}{K_{11}K_{22} - K_{12}K_{21}}\,,\; \mu_{12} = \frac{-K_{12}K_{21}}{K_{11}K_{22} - K_{12}K_{21}}$$
$$\mu_{21} = \frac{-K_{12}K_{21}}{K_{11}K_{22} - K_{12}K_{21}}\,,\; \mu_{22} = \frac{K_{11}K_{22}}{K_{11}K_{22} - K_{12}K_{21}} \quad (13)$$

3-Decoupling of Interacting Loops The interaction between loops can be reduced or eliminated through the design of an appropriate control system and the simplest way to do it is by decoupling. The characteristic of decoupling is that in interacting systems, decoupling does to each loop what the other loops were going to do anyway. Fig.(4) represents the block diagram for the control of interacting tanks system. This block diagram shows graphically that the interaction between the two loops is caused by the process cross blocks with transfer functions $G_{12}(s)$ and $G_{21}(s)$. To circumvent this interaction, two decoupler blocks with transfer functions $D_{12}(s)$ and $D_{21}(s)$ are installed. The purpose of the decoupler is to cancel the effects of the process cross blocks so that each controlled variable is not affected by changes in the manipulated variable of the other loop. Decoupler $D_{12}(s)$ cancels the effect of manipulated variable $Q_2(s)$ on controlled variable $H_1(s)$ and $D_{21}(s)$ cancels the effect of manipulated variable $Q_1(s)$ on controlled variable $H_2(s)$. To obtain the design formulas for the decouplers:

$$D_{12}(s) = -\frac{G_{V2}(s)G_{12}(s)}{G_{V1}(s)G_{11}(s)} \qquad (14)$$

$$D_{21}(s) = -\frac{G_{V1}(s)G_{21}(s)}{G_{V2}(s)G_{22}(s)} \qquad (15)$$

The relationship between each controlled variable and its manipulated variable in the decoupled diagram is obtained by block diagram algebra.

EXPERIMENTAL WORK

1-Description of The Experimental Equipment

Laboratory interacting two tanks system is consisting of two vessels arranged in cascade. The system is show in Fig.(1). These vessels are of PVC and dimensions of the tanks are 0.11 m inside diameter and 0.5 m height. A small narrow pipe with valve is separated the two tanks.

Water supplied to the system at pressure 1.5 barg and with a maximum flow rate of 50 lit./hr. The two rotameter have stainless steel float with range of flow (1–20 lit./hr) of water at about 20^{o}C each were employed for measuring the flow rate of the inlet streams.

The control system consists of the PID controller, control valve, pressure transmitter, indicator bubble pipe I/P converter and air filter with regulator.

2-Experimental Arrangement

The two inlet streams were pumped to the vessels and adjust the valve in the inlet streams to give a nominal reading on the rotameter. Waiting until the levels in two vessels are steady, and the system should be left to stabilize. Reading of the levels on the vessels and flow reading has been steady for several minutes. The disturbances were made throughout the practical work:

1-The inlet flow rate of the tank one (Q_1) stepped up from 14 to 18 lit./hr by using the valve, and then the liquid levels of the two tanks were recorded with respect to time.

2-The inlet flow rate of the tank two (Q_2) stepped up from 10 to 14 lit./hr by using the valve, and then the liquid levels of the two tanks were recorded with respect to time.

3-The inlet flow rate of the tank one (Q_1) stepped down from 14 to 10 lit./hr by using the valve, and then the liquid levels of the two tanks were recorded with respect to time.

4-The inlet flow rate of the tank two (Q_2) stepped down from 10 to 7 lit./hr by using the valve, and then the liquid levels of the two tanks were recorded with respect to time.

RESULTS AND DISCUSSION

The dynamic responses of the interacting two tanks system was determined by direct step change in inlet flow rate are shown in Fig.(5) to Fig.(8). These graphs show the response of the system affected by inlet flow rate of the tank two is faster than the response of the system affected by inlet flow rate of the tank one at positive step change while it has the same response at negative step change.

The relative gains array (μ_{ij}) is calculated by using Eq. (13) from the experimental and theoretical final steady state conditions to a step change in inlet flow rate of the two tanks. The relative gains arrays (RGA) are:

$$\mu_{Theoretical} = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$

$$\mu_{Experimetal} = \begin{bmatrix} 1.55 & -0.5 \\ -0.55 & 1.55 \end{bmatrix}$$

This (RGA) indicates how the inlet flow rate of the tanks one and two should be coupled with the liquid levels to form loops with the smaller amount of interaction. From the values of (RGA) the best loops are obtained by pairing the liquid level of the tank one (H_1) with the inlet flow rate of the tank one (Q_1) and the liquid level of the tank two (H_2) with the inlet flow rate of the tank two (Q_2) because the μ_{11} and μ_{22} are positive and greater than one.

The relative gain $\mu_{11}= \mu_{22}= 2 =1/0.5$ indicates that the gain of each loop is cut in half when the other loop is closed, whereas the relative gain $\mu_{12}= \mu_{21}= -1 =1/-1$ indicates that the gain of each loop changes sign when the other loop is closed. Certainly, this last case is undesirable, because it means that the action of the controller depends on whether the other loop is closed or open.

Decoupler is designed by using the Eq. (14) and (15). The decoupler $D_{12}(s)$ is design to eliminate the effect that loop (2) might have on loop (1) using the following equation:

$$D_{12}(s)=\frac{Q_1(s)}{Q_2(s)}=-\frac{G_{V2}(s)G_{12}(s)}{G_{V1}(s)G_{11}(s)} \quad (18)$$

Substitute the value of $G_{12}(s)$ and $G_{11}(s)$ from Eq.(7) and solving this equation where $G_{v1}(s)= G_{v2}(s)$:

$$D_{12}(s)=-\frac{0.5}{51.3S+1} \quad (19)$$

To cancel the effect of loop (1) on loop (2), the decoupler $D_{21}(s)$ is designed using the following equation:

$$D_{21}(s)=\frac{Q_2(s)}{Q_1(s)}=-\frac{G_{V1}(s)G_{21}(s)}{G_{V2}(s)G_{22}(s)} \quad (20)$$

Substitute the value of $G_{22}(s)$ and $G_{21}(s)$ from Eq. (8) and solving this equation where $G_{v1}(s)= G_{v2}(s)$:

$$D_{12}(s)=-\frac{2}{102.6S+1} \quad (21)$$

Both decouplers are simple gains. This makes sense, because both inlet flows have exactly the same dynamic effects on the liquid levels of the two tanks. Decoupler $D_{12}(s)$ has a negative gain, because its purpose to keep the liquid level of tank one (H_1) when the second inlet stream (Q_2) changes. This requires that the first flow (Q_1) change in the opposite direction by exactly the same amount.

Decoupler $D_{21}(s)$ is positive, because its purpose to keep the liquid level of tank two (H_2) when the first inlet stream (Q_1) changes. To keep the liquid level of tank two (H_2) constant, first flow (Q_1) must be changed in the same direction and the ratio of the two streams must remain constant.

CONCLUSIONS

The following conclusions have been drawn from this study:

- The dynamic system has the faster response at positive step change in the inlet flow rate of the tank two.
- The decoupling has the same effect on each loop as the interacting loops had before decoupling.
- The action of the controller depends on whether the other loop is closed or open because of the relative gain $\mu_{12}= \mu_{21}= -1$.
- When the loop (1) is closed the gain of the loop (2) is cut in half because of $\mu_{11}= \mu_{22}= 2 =1/0.5$

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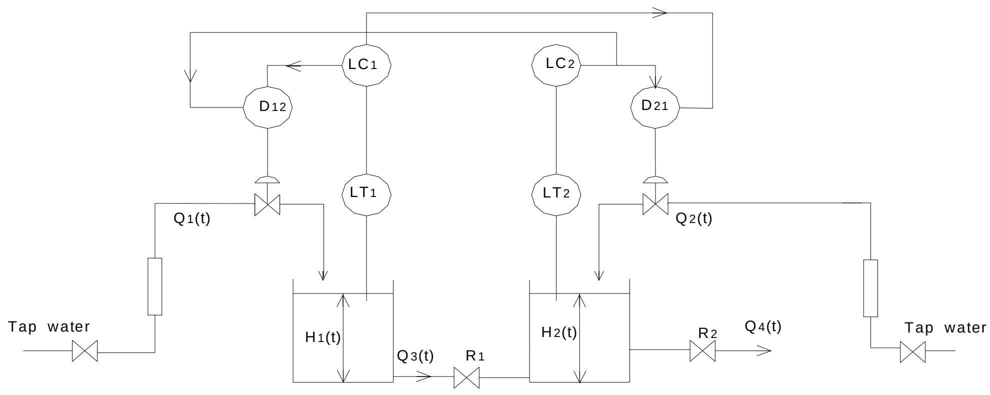
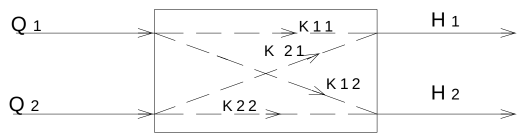


Figure (1) Schematic diagram of the interacting tanks system.



Figure(2)Schematic of interaction for controlled and manipulated variable

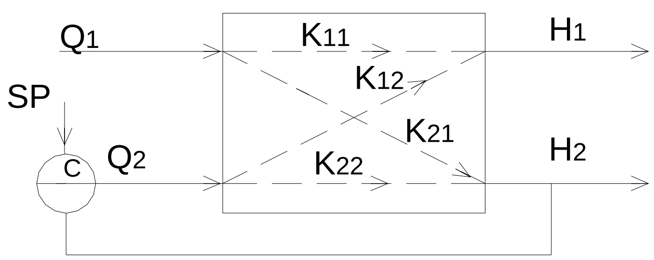


Figure (3) Schematic of interacting tanks system with one loop closed.

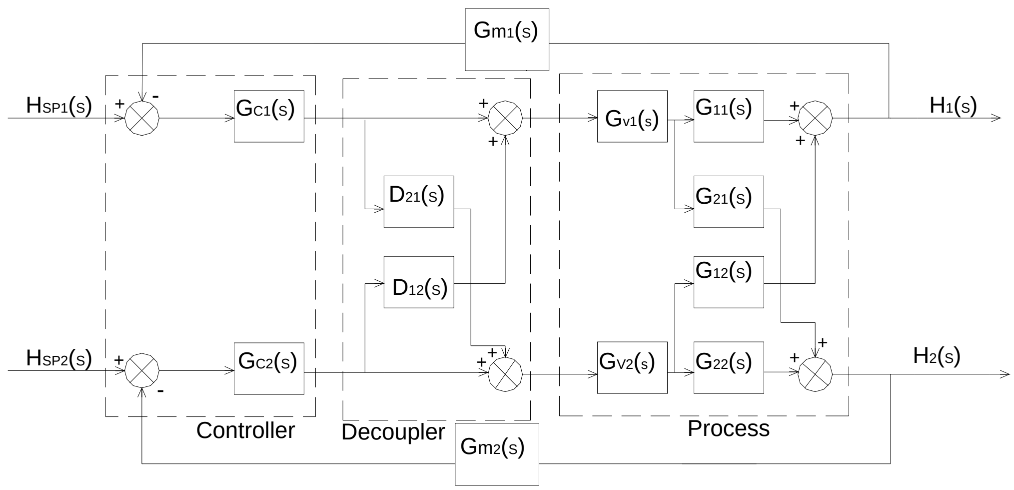


Figure (4) Block diagram of interacting tanks control system with decouplers.

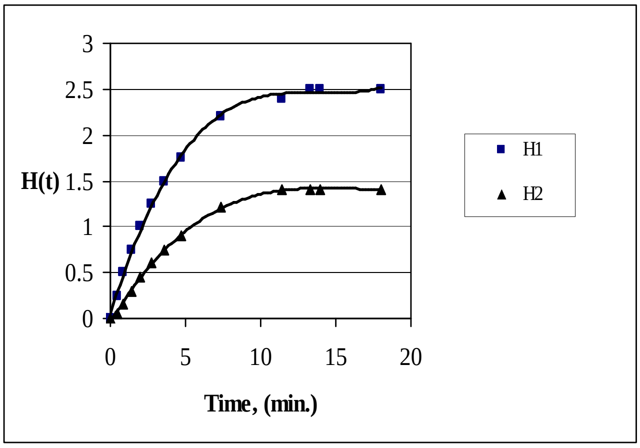


Figure (5) Experimental response of liquid level to step change in inlet flow rate of the tank one (Q_1) from 14 to 18 lit./hr.

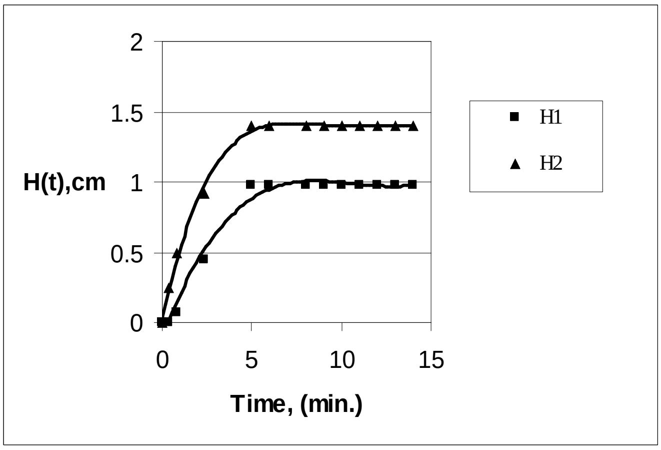


Figure (6) Experimental response of liquid level to step change in inlet flow rate of the tank two (Q_2) from 10 to 14 lit./hr.

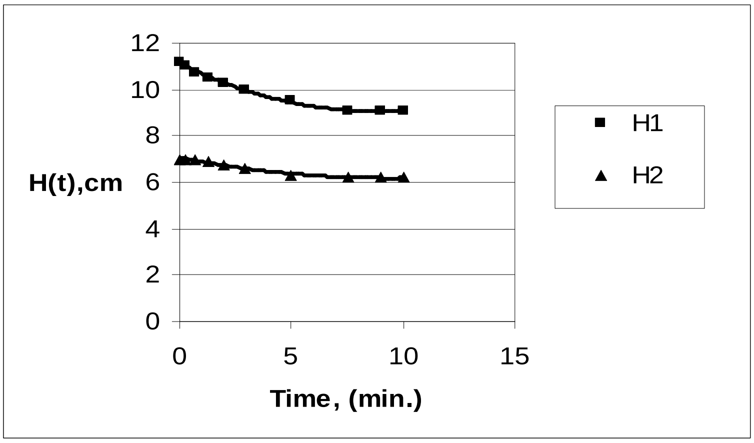


Figure (7) Experimental response of liquid level to step change in inlet flow rate of the tank one (Q_1) from 14 to 10 lit./hr.

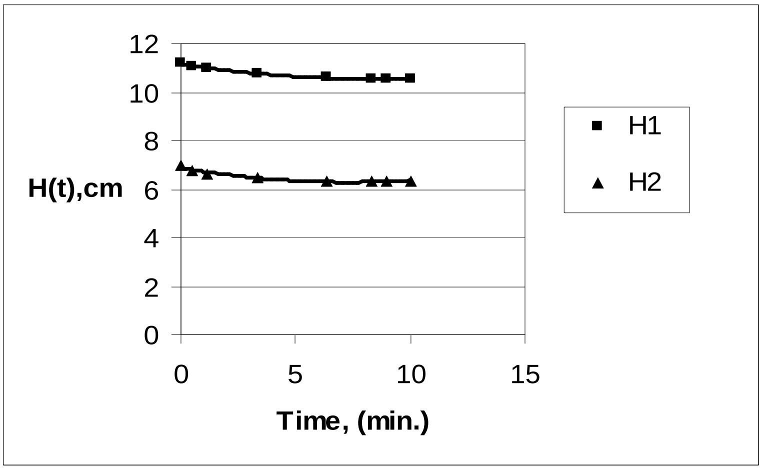


Figure (8) Experimental response of liquid level to step change in inlet flow rate of the tank two (Q_2) from 10 to 7 lit./hr.

تصميم فصل التداخل لنظام الخزانات المتداخلة

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مدرس

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الخلاصة

تم دراسة السلوك الديناميكي لنظام مكون من خزانين متداخلين من خلال تعريضه لتغيير درجي بمعدل الجريان الداخل الى النظام. تناول البحث تحليل درجة التداخل بين المتغيرات المسيطر عليها والمتحكم بها باستخدام طريقة مصفوفة الكسب النسبي. كذلك تناول البحث استخدام طريقة فصل التداخل بين هذه المتغيرات لازالة هذا التأثير وتصميم منظومة ملائمة. اظهرت النتائج بان كسب اي حلقة يقل الى النصف في حالة غلق الحلقة المقابلة لها وكذلك بالنسبة الى الحلقتين الأخرتين المقابلتين في حالة غلق الحلقة تتغير اشارة كسب الحلقة المقابلة لها. وكذلك اظهر البحث عند استخدام منظومة فصل التداخل بان ارتفاع مستوى السائل في الخزان الأول يبقى ثابتا عندما يتغير معدل الجريان الداخل الى الخزان الثاني وكذلك بالنسبة الى ارتفاع مستوى السائل في الخزان الثاني يبقى ثابتا عندما يتغير معدل الجريان الداخل الى الخزان الأول.

الكلمات الدالة: سيطرة مستوى السائل مصفوفة الكسب النسبي فصل التداخل الخزانات المتداخلة.