THE INDIVIDUAL CHANNEL ANALYSIS AND DESIGN METHOD APPLIED TO CONTROL OF A COUPLED-TANKS SYSTEM: SIMULATION AND EXPERIMENTAL RESULTS

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Abstract

The method of individual channel analysis and design (ICAD) is a neo-classical frequency-domain approach to analysis and design of multi-input multi-output control systems. In this paper the technique is applied to a two-input two-output nonlinear system involving two coupled tanks of liquid. The complete nonlinear model of the plant is presented and it is shown how the individual channel approach can provide useful insight for multivariable control system design based on linearised representations of the plant. Simulation investigations involving the nonlinear model have demonstrated that the overall performance of an ICAD-based control system design with proportional plus integral controllers satisfies a given set of performance specifications involving steady-state and transient requirements. Simulation results also show that this design provides good disturbance rejection and satisfactory robustness properties. The resulting control system has been implemented on the two-tank system and the paper includes experimental results.

Keywords: multivariable control, coupled tanks, frequency domain, nonlinear.

Author’s biography

David Murray-Smith is currently an Emeritus Professor and Honorary Senior Research Fellow at the University of Glasgow where he was Professor of Engineering Systems and Control in the Department of Electronics and Electrical Engineering until 2005. His current research interests lie mainly in the areas of inverse simulation methods and their practical applications and also in model testing and validation, mostly for control systems applications. He has been involved in research in a number of different application areas including the validation of helicopter flight mechanics models, helicopter flight control, ship and underwater vehicle modeling and control, as well as applications of modelling and simulation techniques to several biomedical problems.

1 Introduction

Problems of liquid level control are found extensively in many industries and common examples include control of levels in blending and reaction vessels for chemical processes. This paper relates to the development, implementation and testing of a control system for liquid levels in a pair of coupled tanks [1] through the application of individual channel analysis and design methods. Simulation methods are of central importance for the work reported in this paper.

The plant has two inputs, which are the liquid flow-rates into each of the tanks, and two outputs, which are the resulting levels of liquid in the tanks. There is one outflow from one of the tanks.

Simple analysis or simulation studies can show that there is significant nonlinear coupling between the two tanks and the development and validation of both nonlinear and linearised models of this coupled system has been the subject of previous publications (e.g. [1], [2], [3] and [4]). Optimisation of a simple proportional plus integral type of controller for two-input two-output control of this system has also been the subject of an earlier investigation [5].

Individual Channel Analysis and Design (ICAD) is a frequency-domain approach to problems of multi-variable control (e.g. [6]-[10]). Using this methodology an *m*-input *m*-output feedback control problem can be split into *m* individual single-input single-output problems, without loss of structural information. Each of the controlled outputs is paired, in a natural fashion, with a specific reference input to form what is termed a “Channel”. This approach has attractions in that it provides a framework within which many concepts from classical single-input single-output control engineering analysis and design can be applied in a rigorous fashion to multi-input multi-output systems that exhibit significant cross-coupling. It thus offers designers the possibility of applying traditional methods of analysis and design, which are well-proven in applications involving single-input single-output (SISO) systems, to multi-input multi-output (MIMO) problems. Examples of such methods include Nyquist and Bode plots and widely-used measures of robustness, such as gain and phase margins.

Not only does the ICAD approach offer benefits in that it is based on traditional methods familiar to all control system designers but it also provides useful insight concerning the dynamics of the plant and of the complete controlled system. Each channel has its own performance specification expressed in terms of SISO requirements.

2 Outline of the Individual Channel Analysis and Design approach

Any $m \times m$ linear time-invariant MIMO plant can be modelled using a transfer function matrix G. A diagonal control matrix K, positioned in the forward path in cascade with the plant G and immediately before it, allows a feedback loop to be created around the combined system described by the product KG. In designing controllers for multivariable systems of this kind difficulties arise because of the loop interactions between the different channels. The essence of the ICAD approach is to consider one loop at a time by opening one loop while all other loops remain closed.

For details of the methodology and applications that have been considered previously the reader should consult papers by Leithead and O’Reilly (e.g. [6], [7], [8] and [9]) who were responsible for the development of the approach. A useful bibliography relating to ICAD methods and their application has been provided by Kocijan [10].

The ICAD approach emphasises the significance of the ‘structure’ of the plant in the decomposition of the given MIMO system into the equivalent set of channels. In this specific context the word ‘structure’ is taken as relating to the number of right half-plane poles and the number of right half-plane zeros of the channels [6].

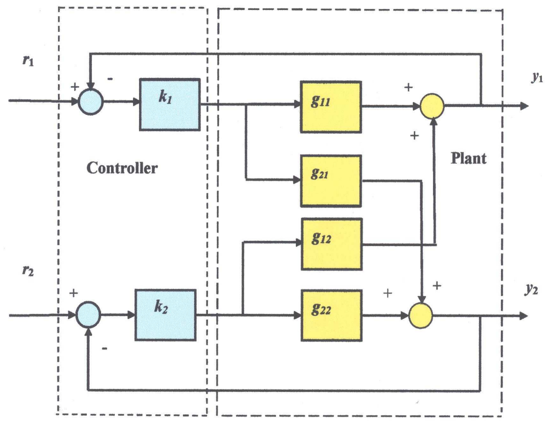

Fig. 1 Block diagram of a two-input two-output system with diagonal feedback (adapted from a diagram in [6])

The type of multivariable system structure being considered in this paper is a two-input two-output system with diagonal feedback involving two channels and Fig. 1 is a block diagram illustrating the structure of the type of multivariable control system being considered. In this case, if we consider the forward signal transmission from the reference signal r_1 to the associated output $y_{1,}$ it is clear that the signal follows two parallel pathways. One path is directly through the block g_{11} and the other is through the blocks g_{21}, g_{12} and a block involving k_2 and its associated feedback loop through g_{22}. This block diagram may therefore be simplified to give the structure shown in Fig. 2 for the Channel C_1 and, by symmetry, the Channel C_2 may be analysed in the same way to give the simplified block diagram of Fig. 3.

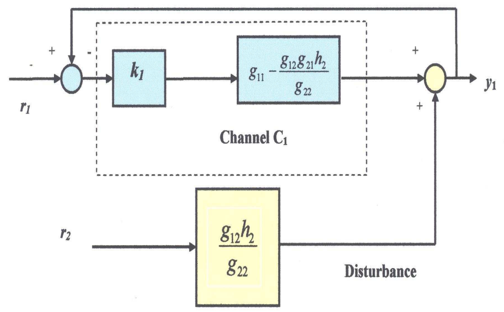

Fig. 2 Individual Channel C_1 with cross-reference disturbance signal and unity negative feedback (adapted from a diagram in [6])

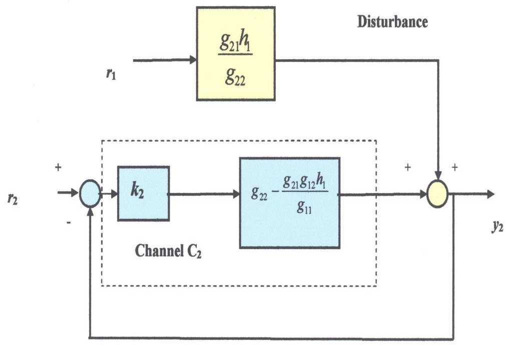

Fig. 3 Individual Channel C_2 with cross-reference disturbance signal and unity negative feedback (adapted from a diagram in [6])

It can be seen from these block diagrams that, ignoring the disturbance signal, each channel can be described using a single-input single-output transfer function to give:

$$C_1 = k_1 g_{11}(1 - \gamma h_2) \tag{1}$$

and

$$C_2 = k_2 g_{22}(1 - \gamma h_1) \tag{2}$$

where

$$\gamma = \frac{g_{12}g_{21}}{g_{11}g_{22}} \tag{3}$$

$$h_2 = \frac{k_2 g_{22}}{1 + k_2 g_{22}} \tag{4}$$

and

$$h_1 = \frac{k_1 g_{11}}{1 + k_1 g_{11}} \tag{5}$$

Without loss of information, the effects of coupling are represented as additive disturbance terms at the outputs of each Channel. It should be noted that ICAD is not a single-loop design method since loop interactions are preserved.

The quantity γ is the *approximate multivariable structure function*. It provides an indication of the strength of any given coupling and whether or not this is benign. In this particular case, involving a two input two-output system, there is only one multivariable structure function but this is not the case for systems with additional channels. In general, when a multivariable structure function is small in magnitude the interaction effects are small and, in the case of a two-channel system, the two channels behave very like two independent loops. On the other hand, when a multivariable structure function has a large magnitude, the loop interaction is significant. Iit can be shown [6], that if the Nyquist plot of the multivariable structure function does not approach the point (1,0), the ICAD methodology may be appropriate. However, if this condition is not satisfied the gain margins of C_1 and C_2 do not provide robust measures of stability and the ICAD approach may not be suitable.

The frequency response of each Channel can thus be used in the analysis of the nominal system in exactly the same way as for the analysis of a conventional feedback loop in a SISO control system application. However, the ICAD approach emphasises the fact that the properties of the multivariable structure functions, $\gamma(j\omega)$, may provide useful information about the robustness of the closed-loop system.

It is also necessary to ensure, for the successful application of ICAD approach to a two-Channel system, that the closed-loop bandwidth specification for one channel must not be too similar to the corresponding specification for the other channel [6].

3 The coupled-tanks system

Fig. 4 is a schematic diagram of the two-input coupled-tanks laboratory system being considered. It consists of a container of volume 6 litres having a central partition that divides the container into two separate tanks. Coupling between the tanks is provided by a number of holes of various diameters near the base of the partition and the amount of coupling may be adjusted through the insertion of plugs into one or more of these holes. The system is equipped with a drain tap, under manual control. The output flow rate from one of the tanks can be adjusted by means of this tap. Both tanks have inflows from electrically driven variable-speed pumps and are equipped with sensors that can detect the level of liquid and provide a proportional electrical output voltage.

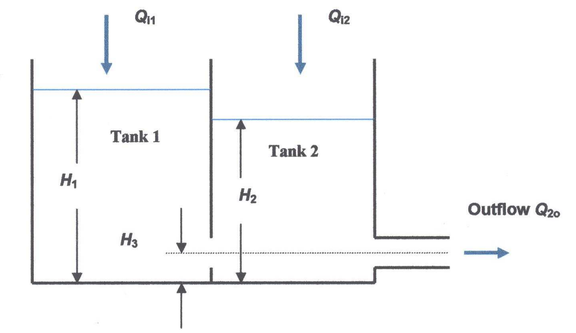

Fig. 4 Schematic diagram of the coupled-tanks system showing inputs (flow rates Q_{i1} and Q_{i2}) and outputs (levels H_1 and H_2)

The basic hardware, involving a single-input version of this equipment, was a commercial product intended for teaching applications (TecQuipment Ltd) [1] but has been modified at the University of Glasgow through the addition of the second pump to provide the second inflow and replacement of resistive level sensors by more accurate differential-pressure based depth sensors.

The derivation of a detailed nonlinear model may be found in a paper by Gong and Murray-Smith [2]. That model is based on the application of the conservation principle to the mass of liquid within each tank. Bernoulli's equations provide the basis for determining the flow from one tank to the other and from the second tank to the external environment. This leads to the following pair of equations :

$$A_1 \frac{dH_1}{dt} = Q_{i1} - C_{d1} a_1 \sqrt{2g(H_1 - H_2)} \qquad (6)$$

$$A_2 \frac{dH_2}{dt} = Q_{i2} + C_{d1} a_1 \sqrt{2g(H_1 - H_2)} - C_{d2} a_2 \sqrt{2g(H_2 - H_3)} \qquad (7)$$

These equations describe the dynamics of the coupled tanks system in nonlinear form for all cases for which the level in tank 2 is below that in tank 1. An equivalent set of nonlinear equations may be derived for situations in which the level in tank 2 is greater than that in tank 1.

Parameter values for the laboratory-scale system are as follows:

Cross-sectional area of tanks $A_1 = A_2 = 9.7 \times 10^{-3}$ m^2.

Cross-sectional area of orifice 1 $a_1 = 3.956 \times 10^{-5}$ m^2.

Cross-sectional area of orifice 2 $a_2 = 3.85 \times 10^{-5}$ m^2.

Height of outlet above base of tank $H_3 = 0.03$ m.

Gravitational constant $g = 9.81$ ms^{-2}.

Maximum flow rates

$Q_{i1\max} = Q_{i2\max} = 5 \times 10^{-5}$ m^{3}s^{-1}.

Maximum liquid levels $H_{1\max} = H_{2\max} = 0.3$ m.

In addition to the above parameters, electrical signals in the system are related to the variables of the model (as described by the equations above) through the following two parameters:

Pump calibration constant $G_p = 7.2 \times 10^{-6}$ m^{3}s^{-1}V^{-1}.

Depth sensor calibration constant G_d= 33.33 Vm^{-1}.

For control system design studies it is appropriate to consider a linearised model in which the model variables represent small variations of system variables about steady state values.

$$\tilde{h}_1(t) = \overline{H}_1 - H_1(t) \qquad (8)$$

$$\tilde{h}_2(t) = \overline{H}_2 - H_2(t) \qquad (9)$$

$$q_{i1}(t) = \overline{Q}_{i1} - Q_{i1}(t) \qquad (10)$$

$$q_{i2}(t) = \overline{Q}_{i2} - Q_{i2}(t) \qquad (11)$$

$$q_{23}(t) = \overline{Q}_{23} - Q_{23}(t) \qquad (12)$$

In Eqs. (8)-(12) variables with a horizontal bar refer to the values at the chosen operating point, which is normally defined by a steady-state condition.

Rearranging Eqs. (1) and (2) to the standard nonlinear state-space form:

$$\frac{dH_1}{dt} = f_1(H_1, H_2, Q_{i1}) \qquad (13)$$

$$\frac{dH_2}{dt} = f_2(H_1, H_2, H_3, Q_{i2}) \qquad (14)$$

Then, since the level H_3 may be assumed constant, linearization produces the standard linear state space model:

$$\begin{bmatrix} \frac{d\tilde{h}_1}{dt} \\ \frac{d\tilde{h}_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial H_1} & \frac{\partial f_1}{\partial H_2} \\ \frac{\partial f_2}{\partial H_1} & \frac{\partial f_2}{\partial H_2} \end{bmatrix} \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{bmatrix} + \begin{bmatrix} \frac{\partial f_1}{\partial Q_1} & \frac{\partial f_1}{\partial Q_2} \\ \frac{\partial f_2}{\partial Q_1} & \frac{\partial f_2}{\partial Q_2} \end{bmatrix} \begin{bmatrix} q_{i1} \\ q_{i2} \end{bmatrix} \tag{15}$$

In Eq. (15) all the partial derivatives must be evaluated at the operating point ($\overline{H}_1, \overline{H}_2, \overline{Q}_{i1}, \overline{Q}_{i2}$).

The resulting linearised equation, after evaluation of the partial derivatives, has the form:

$$\begin{bmatrix} \dot{\tilde{h}}_1 \\ \dot{\tilde{h}}_2 \end{bmatrix} = \begin{bmatrix} \frac{-\alpha_1}{A_1} & \frac{\alpha_1}{A_1} \\ \frac{\alpha_1}{A_2} & \frac{-(\alpha_1+\alpha_2)}{A_2} \end{bmatrix} \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{A_1} & 0 \\ 0 & \frac{1}{A_2} \end{bmatrix} \begin{bmatrix} q_{i1} \\ q_{i2} \end{bmatrix} \tag{16}$$

where $\alpha_1 = \frac{C_{d1}a_1}{2}\sqrt{\frac{2g}{\overline{H}_1 - \overline{H}_2}}$ (17)

and $\alpha_2 = \frac{C_{d2}a_2}{2}\sqrt{\frac{2g}{\overline{H}_2 - H_3}}$ (18)

The individual block transfer functions that describe the plant in Fig. 1 are therefore as follows:

$$g_{11}(s) = \frac{\frac{(\alpha_1+\alpha_2)}{\alpha_1\alpha_2}[1 + s\frac{A_2}{(\alpha_1+\alpha_2)}]}{1 + \frac{(A_1\alpha_1 + A_1\alpha_2 + A_2\alpha_1)}{\alpha_1\alpha_2}s + \frac{A_1A_2}{\alpha_1\alpha_2}s^2} \tag{19}$$

$$g_{21}(s) = \frac{\frac{1}{\alpha_1}}{1 + \frac{(A_1\alpha_1 + A_1\alpha_2 + A_2\alpha_1)}{\alpha_1\alpha_2}s + \frac{A_1A_2}{\alpha_1\alpha_2}s^2} \tag{20}$$

$$g_{12}(s) = \frac{\frac{1}{\alpha_2}}{1 + \frac{(A_1\alpha_1 + A_1\alpha_2 + A_2\alpha_1)}{\alpha_1\alpha_2}s + \frac{A_1A_2}{\alpha_1\alpha_2}s^2} \tag{21}$$

$$g_{22}(s) = \frac{\frac{1}{\alpha_2}(1 + s\frac{A_1}{\alpha_1})}{1 + \frac{(A_1\alpha_1 + A_1\alpha_2 + A_2\alpha_1)}{\alpha_1\alpha_2}s + \frac{A_1A_2}{\alpha_1\alpha_2}s^2} \tag{22}$$

The corresponding multivariable structure function is given by:

$$\gamma(s) = \frac{g_{12}g_{21}}{g_{11}g_{22}} = \frac{\frac{\alpha_2}{\alpha_1+\alpha_2}}{(1 + s\frac{A_1}{\alpha_1})(1 + s\frac{A_2}{\alpha_1+\alpha_2})} \tag{23}$$

and the expressions for $h_1(s)$ and $h_2(s)$ may be derived from Eqs. (4) and (5).

3.1 Control system design procedures

Design requirements

The specifications for the two-input two-output closed-loop system were based on equivalent requirements for a single-input single-output version of the coupled-tanks system for which there was extensive previous design experience. The design requirements for the two-input two-output case were thus as follows:

a.) Zero steady-state errors in liquid levels in both tanks.

b.) A maximum overshoot of 30% in liquid levels.

c.) A damping factor of approximately 0.7 corresponding to a phase margin of approximately 70 degrees for both channels.

d.) The gain cross-over frequency, on the basis of experience with the design of PID controllers for the single-input single-output case for control of the liquid level in tank 2 (using a single input flow to tank 1), should be at least 0.05 rad/s for both channels.

e.) It is essential, in the ICAD approach, to ensure that the polar plot of the magnitude and phase of the multivariable structure function does not approach the point (1,0).

An outline of the design process

The requirements outlined in Section 4.1 provide a basis for design using the ICAD methodology with the linearised versions of the plant model given in Eqs. (16) to (23), for selected operating conditions. Design has been based on the use of Matlab® software and has led to continuous and digital controllers involving proportional plus integral structures for each channel.

The first step in the design process involves establishing that the gain cross-over frequency of the open-loop transmittance of one channel will be significantly different from the gain cross-over frequency of the other. In this case it was decided, on the basis of physical reasoning, that the gain cross-over frequency of Channel C_1 should be higher than that for Channel C_2. This latter value would be chosen to be at least 0.05 rad/s.

The next step involves evaluation of the magnitude and phase of the multivariable structure function over the range of frequencies that are of importance for the intended application. Fig. 5 is a typical plot of the multivariable structure function in the form of a polar diagram showing the magnitude and phase of $\gamma(j\omega)$ for the complete range of relevant frequencies and it is clear that the resulting plot involves small values of magnitude and of does not come close to the (1,0) point. This is satisfactory for the operating point considered but similar plots for a range of operating conditions must be considered.

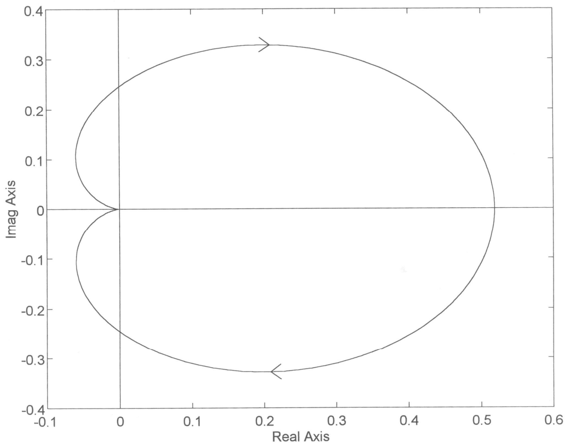

Fig. 5 Plot of the multivariable structure function for the coupled-tanks system for one specific operating point.

Next, it is necessary to design the controller $k_2(s)$ since the requirements in terms of gain cross-over frequency for Channel C_2 are less demanding than for Channel C_1. Eqn. (2) shows that the equation for Channel C_2 involves the transfer function $h_1(s)$ and the known multivariable structure function $\gamma(s)$. The first step is to assume $h_1(s) = 0$ and design the controller $k_2(s)$ initially on that basis. After obtaining that first approximation to $k_2(s)$ an initial single-input single-output design can be carried out for the controller $k_1(s)$ on the basis of the known $h_2(s)$. Having found an initial $k_1(s)$ this can then be used to determine $h_1(s)$ by substitution into Eqn. (5). The resulting gain and phase margins must then be checked and adjustments made to $k_1(s)$ if necessary. The process may have to be repeated once or twice. Then using the revised controller transfer function for Channel 1 the design can be completed for Channel 2 using a similar iterative procedure. Final checks must then be done on both channels to compare the gain cross-over frequencies with the design specifications and check that the gain and phase margins are all satisfactory.

Designs found for the two controllers both involved proportional plus integral controllers:

$$k_1(s) = 31\left[1 + \frac{0.16}{s}\right] \qquad (24)$$

$$k_2(s) = 5.61\left[1 + \frac{0.1}{s}\right] \qquad (25)$$

Discrete equivalents of these continuous controllers have also been found to allow digital control to be implemented. Experimental results presented in this paper are for the continuous control case where the controllers have been implemented using operational amplifiers.

5 Results

Extensive simulation studies have been performed using Matlab® and Simulink® to investigate the extent to which the performance requirements are met using the ICAD approach as outlined above, especially in terms of interactions between the two channels and the overall robustness of the control system. The full nonlinear model has been used in these investigations.

The performance of the controllers, as implemented in hardware for the continuous control case and software for digital control, has also been investigated experimentally in the laboratory using the coupled-tanks system hardware.

Fig. 6 shows typical results for a test involving simultaneous step changes in the required levels in the two tanks for the case with continuous control. The liquid levels in tanks 1 and 2 are shown by the upper and lower traces respectively. In the case of Channel 1 the step change of reference imposed is from 199 mm to 226mm, while for Channel 2 the change is from 165mm to 198mm.

It can be seen that the requirements have been *satisfied* and that the response of tank 2 is slower than that of tank 1, as expected. Although not included here, the simulation results are identical in terms of steady state performance and very similar in terms of the settling time of the transients. The main difference observed between the experimental and simulation results is that the transients found through simulation tend to be slightly less oscillatory than those found experimentally.

System interactions have also been investigated experimentally and through simulation. Fig. 7 shows typical results for the experimental case. The test involves introducing a step change of the desired level in one channel while maintaining the original set level in the other. The upper plot shows the level of liquid in tank 1 following the application of a step change of reference for Channel 1 at time t = 40 s. followed by a step change of reference for Channel 2 at time t = 106 s. The lower plot shows the corresponding measured level in tank 2. The results show a transient disturbance in the level of tank 2 when the set level of Channel 1 is changed but a negligible transient in the level in tank 1 when the set level of Channel 2 is altered by a similar amount. This difference is due to the different bandwidths in the two closed loop systems.

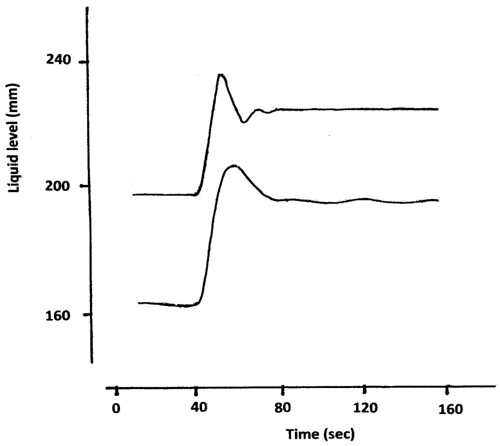

Fig. 6 Experimental results following simultaneous instantaneous step changes of the required levels for the case involving continuous control. The upper plot is for tank1and the lower for tank 2.

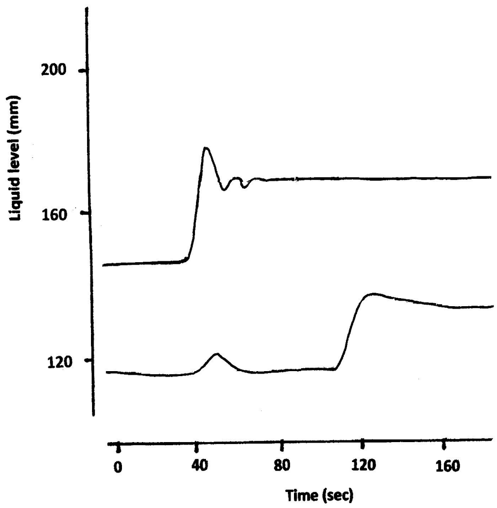

Fig. 7 Experimental results for tests to investigate interactions between reference changes for the two channels (for the case involving continuous control). The upper plot is for tank 1and the lower for tank 2.

Although the results shown in Figs. 6 and 7 are for specific operating points, comparison of experimental and simulation results for a range of different conditions has shown good overall agreement.

The behavior of the system when subjected to external disturbances is also of importance. Fig. 8 shows some typical experimental results where external disturbances have been introduced by adding a predetermined volume of water to each of the tanks in turn, with feedback control applied. The upper plot shows the level in tank 1 for a reference input of 227mm while the lower plot shows the level in tank 2 for a reference input of 198mm. Disturbance inputs are applied by introducing a measured volume of water to tank 2 at about time t = 18 s and a similar volume to tank 1 at about time t = 120 s. The effects of each of these disturbances on each channel are clearly visible in these records.

Simulation results are similar in character and show the distinctive actions of the two channels in countering the effects of the disturbance inputs. As with the tests involving changes of reference, it is clear (as would be expected) that the speed of response to disturbance inputs is influenced by the choice of bandwidths for the two channels

Extensive tests of robustness have also been carried out, mainly through simulation. Some experimental investigations to assess robustness have also been carried out, although in that case the changes in some quantities, such as the cross-sectional area of the orifice linking the tanks or the effective diameter of the outlet from tank 2, cannot be applied in an instantaneous fashion. Changes imposed in the simulation therefore differ slightly from the corresponding changes applied experimentally but results are broadly similar and the experimental findings confirm that the robustness properties of the two-input two-output control system are satisfactory.

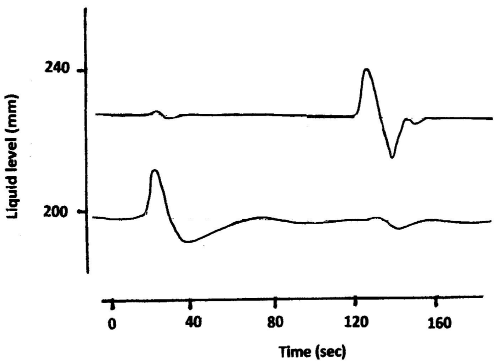

Fig.8 Typical experimental results where external disturbances have been introduced by rapidly adding a predetermined volume of water to each of the tanks in turn, with feedback control applied. The upper plot is for tank 1and the lower for tank 2

Differences between simulation results and experimental results are believed to relate mainly to limitations in the representation of the output flow from the second tank in the nonlinear model of the ystem. This aspect of the coupled-tanks system model has been considered in more detail in previous model validation studies for this system (e.g. [2], [4]).

One interesting practical finding, fully supported by simulation results, is that control of the level in tank 1 can only be achieved for operating conditions in which the demanded level in tank 1 is greater than that in tank 2. This is understandable in terms of the physics of the system since tank 1 has only one outlet (to the second tank) while tank 2 has two outlets (to the first tank and also through the drain pipe). If the demanded value of H_2 is greater than the demanded level of H_1 liquid will flow into tank 1 from tank 2 as well as from input 1 but no liquid will flow out. Since the input flows cannot be negative, satisfactory control of the level in tank1 is impossible in these conditions. Simulation investigations have confirmed that the addition of a drain pipe to the first tank would allow control for any combination of demanded levels.

4 Discussion and Conclusions

The work reported in this paper extends understanding of the use of the ICAD analysis and design approach for an application of this kind. Previous work [5] reporting the application of this method of design to this system was concerned more with tuning of parameters of the resulting controller structure and did not address issues of robustness and the effects of known model limitations. The availability of a detailed nonlinear simulation model has facilitated investigation of robustness issues and interactions between control loops. The opportunity to implement the controllers on the real system and make comparisons between simulation and experimental results has also provided important insight concerning the ICAD approach.

One interesting point of detail relates to the fact that control of the level in tank 1 was found to be possible only if the demanded level in tank 1 was greater than that in tank 2

In conclusion, it can be stated that the coupled tanks system provides a useful test-bed for investigation of issues of multivariable control system design and implementation. The availability of a comprehensive nonlinear model of the system together with linearised representations appropriate for control system design makes this a used basis for the teaching of practical aspects of multi-input multi-output control system design through the use of ICAD or other approaches. It is believed that this work could provide the basis for a useful case–study (for use at postgraduate level) on the ICAD methodology and illustrating the benefits of integrating simulation investigations within the control system design process.

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