AN IMPROVED QUALITATIVE CONTROLLER

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Abstract

The basic concepts cocerning the use of qualitative reasoning in process control are discussed. The method is applied to the control of single-input single-output (SISO) systems, using the two coupled-tanks system as an application example. We show here that a controller using a pure qualitative model of the process is inefficient for practical applications. Significant improvement in the performance of the controller can be achieved by combining the qualitative model with process-related quantitative knowledge.

I. Introduction

Research in the fields of "Qualitative Reasoning" and "Naive Physics" produced several different approaches to the problem of describing the qualitative behaviour of physical systems [1], [2], [3]. These methods have produced consistent results which adequately reflect the dynamic behaviour of these systems. Recently these methods have been investigated in relation to process control with the object of overcoming some of the problems that stem from the inadequacies of numerical modelling. In particular, the need to provide exact numerical values for the parameters of the differential equations describing the dynamics of any physical system, and the failure of conventional techniques to produce a robust control system that covers the full operating range, are of great significance [4], [5].

The qualitative reasoning approach is different from the conventional shallow knowledge expert system methods used in process control. Expert systems have been used for the online modification of the settings of a conventional controller using the knowledge of an expert control engineer, this is known as "Expert Control" [6]. Another method is to formulate the knowledge of expert plant operators to design a rule-based controller [7]. Qualitative control on the other hand depends on the deep knowledge extracted from the understanding of the physical interaction between the different components of the plant. This knowledge is used to construct a qualitative model that is used in the control operation. A useful comparative study that shows the advantages and the disadvantages of both deep and shallow knowledge systems can be found in [8].

A qualitative controller has the potential to overcome the tuning problems and the effects of nonlinearities which can occur when a conventional PID controller is used and tuned according to conventional methods.

II. Basic Principles

The qualitative control methodology described here concerns SISO systems and is related to that presented in [4] and [5]. The problem is approached by considering the process as a series of sub-systems, each of which is represented by a state variable. A qualitative quantity space defines the possible values of these state variables. The quantity space used here is the set (+, 0, -). Therefore the sub-system i, for example, can be represented by the variable Xi, which can take a value of (+), (0), or (-), at any instant in time.

The nature of the dynamic interaction between any two adjacent sub-systems is then considered. By adjacent sub-systems we mean any two sub-systems where the change in the variable representing one of them causes a direct change in the other. In qualitative terminology this interaction can either be represented by a monotonically increasing or a monotonically decreasing function. A monotonically increasing relationship means that one variable increases as the adjacent variable increases and vice versa. This can be represented by;

X2=M-plus(X1).

Figure (1) shows two sub-systems with an increasing relationship. A decreasing relationship on the other hand refers to the case where one variable decreases as the result of an increase in the adjacent variable and can be represented by;

X2=M-minus(X1).

A process can thus be modelled by the effect of each of its sub-systems on the neighbouring one as shown in figure (2).

The concepts of the monotonic analytical functions and their use in qualitative reasoning has been well formulated by Kuipers [3].

Considering the interaction between any two adjacent sub-systems with an M-plus relationship, we can construct a set of control (or interaction) rules with the objective of controlling the value of X2 by using X1 as a control variable. These rules are derived by common sense reasoning and they state the value that X1 should acquire in order that a specific state transition of X2 from an old to a new qualitative value can be achieved. Table (1) shows these control rules.

X1	Old X2	New X2
* 0 +	+	+
-	+	0
-	+	-
+	0	+
0	0	0
-	0	-
+	-	+
+	-	0
* 0 -	-	-

Table (1)
Control Rules

The situations involving the transition of X2 to, or from a (0) state are straigtforward, so are the cases in the (+) to (-), and the (-) to (+) transitions. However, two possibilities arise when it is required to maintain X2 at a (+) or a (-) state as shown in the first and the last rows of table (1). We reason here that to keep the value of X2 at a (+) or a (-) value, it is better to stabilise the value of X1 at a (0) state. This is done in order to prevent uncontrolled increases or decreases that might lead to the quantitative limits imposed on the physical system being exceeded. This is typical in the problem of the two coupled-tanks where it is required to prevent water overflow. Thus we choose the options marked by a star in the first and last rows of table (1), to leave a final set of nine control rules that govern the interaction between the two sub-systems.

A similar set of rules has been defined by other researchers. However, in this work a 'physical' approach is used to explain why a certain action has been chosen in the cases of maintaining a (+) or (-) value for X2 as mentioned above. Clocksin and Morgan [4], used a logical "VOTE" function to derive the same set of rules without explaining the physical origin of that function. Francis [5], uses a routine that finds the correct action, again without clearly stating how a decision is reached in the case where more than one possibility exists.

III. The Basic Qualitative Controller

The Application

The method is applied to the two coupled-tanks system shown in figure (3) to control the level in tank-2. The process is considered as four sub-systems identified by four variables. These are the pump input to tank-1, the rate of change of level in tank-1, the rate of change of level in tank-2, and the error in the level in tank-2 with respect to a set point. The model is shown in figure (4).

The levels in the two tanks are sampled at a fixed sample-action interval (SA-interval). The qualitative error value is established by comparing the level in tank-2 with the set point. The qualitative values of the rate of change of the two levels are found by comparing the measured level at the current time instant, with the one measured directly at the previous sample. If the difference between these two measurements is greater than zero, within a pre-defined resolution, the level is evaluated as (+) or (increasing). If the difference is less than zero then the level will be (-) or (decreasing). Otherwise if the values are within the defined resolution then the level is (0) or (steady).

After sampling and evaluating the qualitative values of the variables, the procedure works backwards through the sub-systems applying the control rules of table (1), to determine the required state of the variables that would achieve a (0) error state. The final application of the rules eventually gives the required state change in the pump output which is achieved by applying a pre-determined incremental change to the pump control voltage.

The Results

Tests have been carried out to investigate the effect of varying the SA-interval, and the incremental pump voltage on the performance of the qualitative controller. Table (2) shows data obtained from tests carried out by introducing a 50% step change in the set point. The table shows the effect of using different SA-intervals and voltage increments on the speed of the transient response of the level in tank-2 (measured as a percentage of full scale (FS) per second), and on the steady-state response (represented by the average steady-state error as a percentage of the full scale). Figure (5) shows the response of the level in tank-2 for tests (5), and (6) which are typical of the cases listed in table (2). The steady-state response for the same tests is shown in figure (6).

Examining the results shown in table (2) for SA-intervals of 1 and 0.5 second we can deduce the following;

(i)- The speed of the transient response for a fixed SA-interval increases as the voltage step increases.

(ii)- For a fixed SA-interval, the steady-state is most satisfactory at a particular voltage increment, but it starts to deteriorate if the increment is increased or decreased away from that particular value. It can be seen from the table that the best steady-state was obtained with an increment of 0.5 volt for both the 1 second and 0.5 second SA-interval cases.

(iii)- The third point to notice is that reducing the SA-interval from 1 to 0.5 second at the same voltage increment results in a faster transient response but a deterioration in the steady-state.

The above observations suggest that a compromise between the SA-interval and the voltage increment is required to obtain the most satisfactory response.

Test No.	SA (sec.)	V (volt)	MR (%/sec.)	AS (% of FS)
1	1	.1	.053	.316
2	1	.5	.171	.189
3	1	1	.187	.535
4	.5	.05	.116	.315
5	.5	.1	.136	.480
6	.5	.5	.204	.280
7	.5	1	.250	.750
8	.1	.05	.670	5.760
9	.1	.1	.636	5.030

TABLE (2)
SA-SA-interval
V-Voltage Increment
MR-Measured Rate of Change of Level-2
AS-Average Steady-State Error

Interesting results are obtained by reducing the SA-interval to 0.1 second as shown in table (2). Both the speed of the transient response and the steady-state error seem to increase dramatically. It was found that these effects occur due to the erroneous evaluation of the qualitative states of the measured variables as a result of the small SA-interval. The problem is that the program depends on two consecutive samples to find the current qualitative state . As the interval between two measurements becomes smaller, the two measured values fall within the resolution used to compare the samples. Thus although the levels are actually increasing, the controller would evaluate them as being steady.

To explain the effect of this evaluation error on the speed of response, we take the case where the error in level-2 is negative, and both level-1 and level-2 are increasing or (+). As a result of the small SA-interval, level-1 and level-2 will appear to be steady or (0). Applying the rules of table (1) to the interaction between the error and level-2, the new value of level-2 should be increasing or (+). And applying the rules again to the interaction between level-2 and level-1, the new value of level-1 must be increasing, resulting in the demand on the pump voltage to increase. This process will continue, as the procedure will keep on evaluating the levels as steady, saturating the pump output at the maximum value until the error becomes (0) or (+). This gives the same kind of effect that results when a conventional controller saturates at the output giving a limit cycle oscillation.

Trying to overcome the problem by increasing the measurement resolution is not possible because of the practical limitations of the measuring equipment and the fact that measurement noise is significant when two samples, separated by a very small time interval, are compared.

IV. The Improved Qualitative Controller

Improving The Steady-State

The problem associated with small SA-intervals, can be solved by introducing the concept of the "Trend Interval" [9]. The trend interval is a period of time along which the trends of the state variables, (rates of change of levels in this case), are evaluated. Naturally the trend interval should be larger than the SA-interval inorder to cure the problem. Thus instead of comparing two samples separated by the SA-interval, the set of samples during one trend interval is used to evaluate whether the level of one tank is increasing, steady, or decreasing.

Tests were carried out to study the effect of introducing the trend interval on the performance of the qualitative controller, and a sample of the results is shown in table (3). In these tests a fixed SA-interval of 0.1 second was used together with three different values for the trend interval (0.5, 1, and 2 seconds). Each test was based on a 50% step change in the set point and was executed twice, each time with a different fixed voltage increment (0.05 and 0.01 volts). As a sample of the effect of the trend interval, figure (7) shows the steady-state response of tests (10), (12), and (14).

Test No.	SA (sec.)	TR (sec.)	V (volt)	MR (%/sec.)	AS (% of FS)
10	.1	.5	.01	.116	.307
11	.1	.5	.05	.126	.162
12	.1	1.0	.01	.056	.158
13	.1	1.0	.05	.069	.080
14	.1	2.0	.01	.027	.071
15	.1	2.0	.05	.068	.179

TABLE (3)
SA=SA-interval
TR=Trend Interval
V=Voltage Increment
MR=Measured Rate of Change of Level-2
AS=Average Steady-State Error

The following conclusions can be drawn from the results of these tests;

(i)- Increasing the trend interval produces a slower transient response.

(ii)- For the same settings of the SA-interval and the trend interval, increasing the voltage increment causes a faster transient response.

(iii)- There is no definite rule for choosing the best settings of the SA-interval, trend interval, and voltage increment, to give the best possible steady-state response. But the steady-state is generally improved by introducing the trend interval.

(iv)- The best possible steady-state response was obtained by using the values of 0.1 second, 2 seconds, and 0.01 volt for the SA-interval, trend interval, and the voltage increment respectively. With an average error of 0.071 % of full scale, the qualitative controller is comparable to the performance of the best conventional controllers under steady-state operating conditions.

(v)- Using the trend interval has improved the steady-state response of the qualitative controller, but the transient response is still too slow for practical applications.

Improving The Speed Of The Transient Response

Consider again table (2), we note that a fast transient response resulted in the case when a small SA-interval (0.1 second) was used. This is due to an evaluation error, as was discussed previously. Using a similar principle it is possible to use an artificial evaluation error to enhance the speed of response in a controlled manner. In the case of the 0.1 second SA-interval of table (2), the qualitative values of the levels in the two tanks were evaluated to be steady when they were actually increasing, which meant that the controller was asking the pump to increase its output.

In the discussion of the basic controller it was mentioned that the level of one of the tanks is increasing if the change in two consecutive measurements was greater than zero. After introducing the trend interval, the level is evaluated as increasing if the average change along the trend interval is greater than zero.

By shifting the comparison value for tank-2 from zero to a value which is greater than zero (call it A), the set of the possible qualitative values of level-2 will change from (+, 0, -) to (>A, A, <A). Thus level-2 will be evaluated as increasing if the average change along the trend interval is greater than (A). Figure (8) explains this process. Now if the controller was trying to achieve a new, higher set point for the level in tank-2, and the level was increasing at a rate less than (A) along the trend interval, the level will be evaluated as decreasing. This means that the controller will require that the level in tank-1, and the pump output increase in order to achieve the required rate of increase in the level of tank-2. At the same time the controller will ensure that the rate of increase does not exceed the value of (A), hence maintaining a fast, controlled transient response. The method can be used to control the rate of decrease of the level in a similar manner.

The comparison value of zero (i.e. the (+, 0, -) set) must be restored when the output is close to the required set point in order to achieve a steady value of the level. The question now is how far away from the set point must the comparison value be restored to zero?

Table (4) shows the results obtained by applying the above method to provide a fast transient response. The required rate of increase (or decrease) is shown as a percentage of full scale per second and referred to as (RR). The margin around the set point where the zero comparison value is restored (RM) is shown as a percentage of full scale.

Test No	SA sec	TR sec	V v	SP %	RM %	RR %/sec	MR %/sec	MOS %of FS	AS %ofFS
16	.1	1.0	.05	36.4	10	.54	.45	—	.126
17	.1	1.0	.05	36.4	10	1.63	.79	—	.135
18	.1	1.0	.02	40.0	5	1.08	.63	3.04	.166
19	.1	1.0	.05	40.0	5	1.08	.79	2.55	.171
20	.1	1.0	.1	40.0	5	1.08	.91	1.17	.397
21	.1	1.0	.05	60.0	5	1.08	.83	3.94	.123

TABLE (4)
SA-SA-interval
TR-Trend Interval
V-Voltage Increment
SP-Set Point
RM-Zero Comparison Margin Around SP
RR-Required Maximum Rate of Change
MR-Measured Rate of Change of Level-2
MOS-Maximum Overshoot
AS-Average Steady-State Error

The following conclusions can be drawn from the results shown in table (4);

(i)- The measured rate of change is always less than the required value. This is because we are applying the new comparison value (which we called A) only to tank-2, while the comparison value in tank-1 is maintained at zero. Hence level-1 will be evaluated as (+) if it is increasing at any rate , while level-2 must be increasing at a rate faster than (A) to be evaluated as (+). Now if level-2 is (-) or (0), the controller will try to push it to (+) by achieving a (+) value for level-1 according to the rules of table (1). As soon as this (+) value in level-1 is achieved, the controller will maintain it by holding the pump output constant. This action is taken and is independent of whether or not the rate of change in level-2 is equal to or less than (A). The rate of change of level-1 will be held at an increasing value without necessarily achieving the required rate of change in tank-2. This differs from the basic controller which, according to the control rules of table (1), trys to restore level-1 to a (0) value while level-2 is increasing. Figure (9) shows two responses of level-2 for two different transient speeds, corresponding to tests (16), and (17) of table (4).

(ii)- Examining tests 18, 19, and 20 of table (4), we can see that the measured rate of increase approaches that required as the voltage increment increases. This is because the controller achieves an increasing state of level-1 at a higher pump voltage in the case of a higher voltage increment. Figure (10) shows the results of these three tests.

(iii)- Again examining tests 18, 19, and 20 , shows that there is a smaller maximum overshoot , but a larger average steady-state error associated with a higher voltage increment. This is because a large voltage increment results in "faster acting" correction when the system overshoots. However the large voltage increment leads to more oscillation about the steady-state, hence a larger average error.

(iv)- The maximum overshoot increases as the margin around the set point, (in which the zero comparison value for two measurements is restored), is reduced. This can be seen from table (4) as there is no overshoot when a margin of 10% is used (tests 16 and 17), while some overshoot is present in all the cases where a 5% margin is used.

(v)- A larger overshoot occurs when the step change required in the set point is increased (tests 19 and 21). Figure (11) shows these two cases.

The above conclusions suggest another improvment in the controller. This can be achieved by applying two different voltage increments, a large one outside a defined margin around the set point, and a smaller increment inside that margin. The large increment will help in speeding up the transient response and reducing the overshoot peak, while the smaller increment will achieve a better steady-state response. Figure (12) shows the response resulting from the implementation of the above procedure, where a voltage increment of 0.1 volt is applied outside a 5% margin around the set point. A 0.02 volt increment is used inside that margin. Figure (13) shows the response of level-2 for a 50% step change in the set point using a PID controller for comparison.

V. Conclusions

Previous experimentation by other researchers has shown that a controller based on a pure qualitative model of the two coupled-tanks process can achieve the control objective of maintaining the level in the second tank steady at the required set point. In this work, we have applied the same model and control rules used in the these previous experiments, although minor differences exist especially in the cases where common-sense suggests more than one possible control action, as was described when we constructed the control rules of table (1).

It is obvious that although the qualitative controller works, it does not perform effectively in practice. The main drawbacks, as demonstrated by the results listed in table (2), are the slow transient response and the oscillatory behaviour at steady-state. These drawbacks are natural consequences of the generality and simplicity of the qualitative model, and the lack of process-related quantitative information.

The first quantitative parameter that we have introduced to the basic qualitative controller is the "Trend Interval". This can be considered as the time span across which the important changes in the value of a state variable (a tank level in this case), can be detected. In a way the trend interval is related to how slow (or fast) the variable changes in response to the input change. Thus instead of comparing two measurements separated by a single SA-interval to find the qualitative value of the level, the general trend along the trend interval is used for that purpose. This has allowed the use of a minimal SA-interval which resulted in a faster correcting action by the controller, hence improving the steady-state performance significantly.

Setting the value of the trend interval to 2 seconds, while using a 0.1 second SA-interval, produced a very satisfactory steady-state response for our two tanks system.

After improving the steady-state response of the controller, the second stage was to enhance the speed of its transient response. This was achieved by shifting the value that determines whether the level in tank-2 is increasing, steady, or decreasing, from zero to a new quantitative value. This new value is related to the desired rate of change in that level. It is positive for the case of level increase, and negative for the case of level decrease. This value was used outside a defined band around the set point, while the zero value was restored inside that band to achieve the steady-state.

After studying the effects of the set point band size, the resulting overshoot, and observing how close the resulting rate of change is to that required, we were able to add one more improvement. This was using a larger voltage increment outside the set point band, while keeping the previously determined small increment inside that band. This helped in maintaining the rate of level change closer to the required value, reduced the overshoot to a minimum, and at the same time maintained a good steady-state response.

A qualitative controller can be useful in practice only after adding quantitative information to enhance the performance. More research is required to establish whether this extra effort can justify the use of qualitative controllers where a quantitative controller is difficuilt to tune

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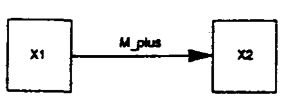

Fig. (1)

Subsystems with an M_plus relationship

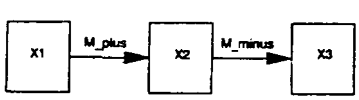

Fig. (2)

Process representation

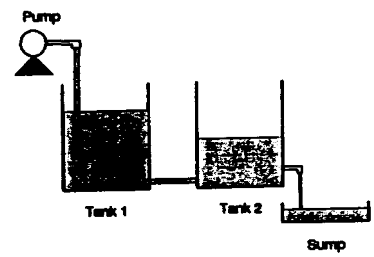

Fig. (3)

The Coupled Tanks System

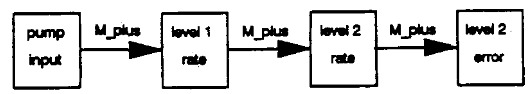

Fig. (4)

The two tanks model

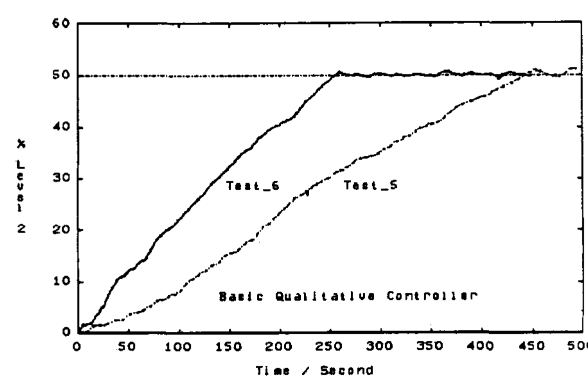

Fig. (5)

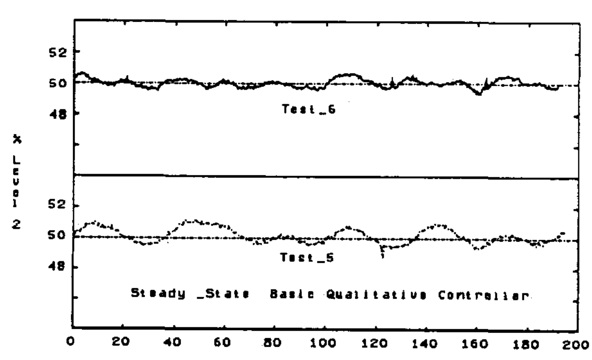

Fig. (6)

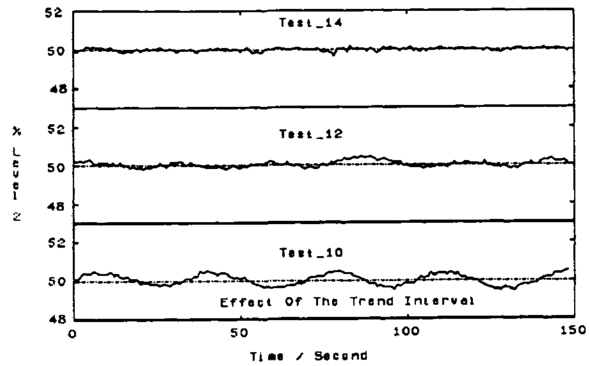

Fig. (7)

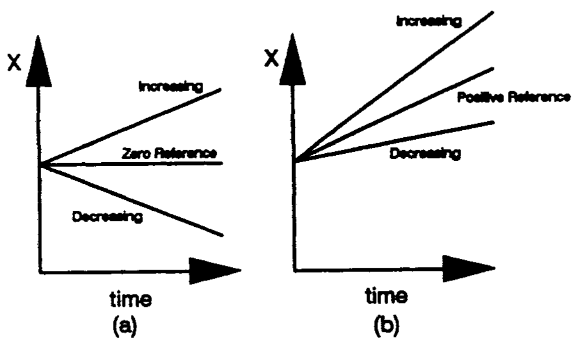

Fig. (8)

Controlling the rate of increase of X

a) Steady state b) Transient

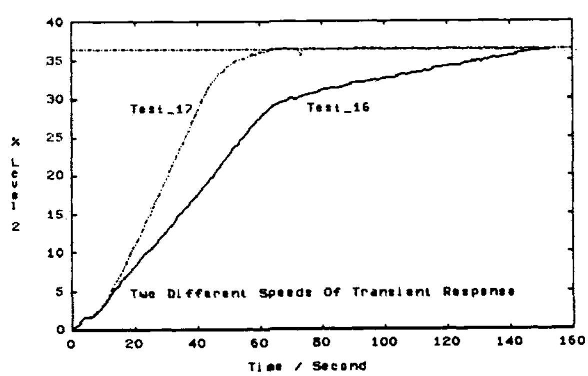

Fig. (9)

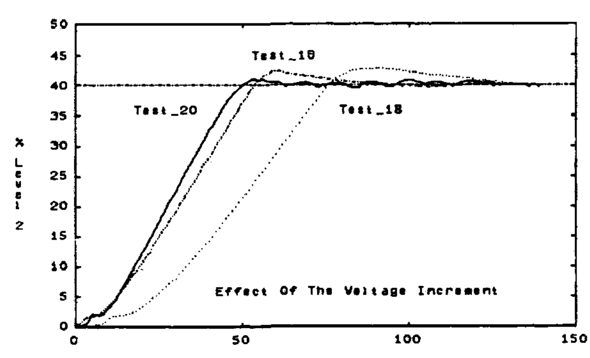

Fig. (10)

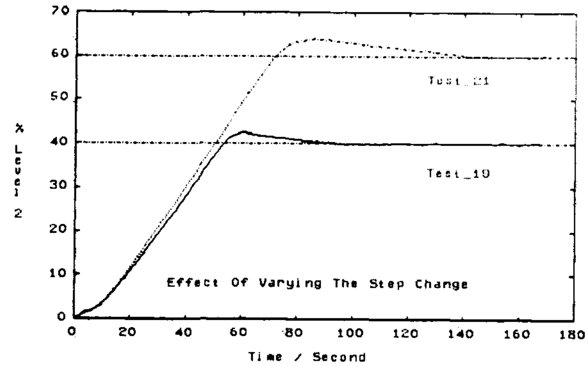

Fig. (11)

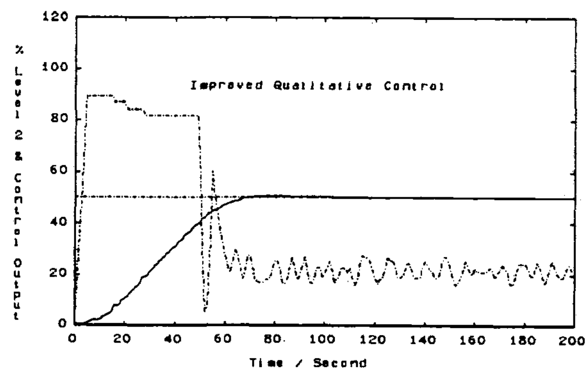

Fig. (12)

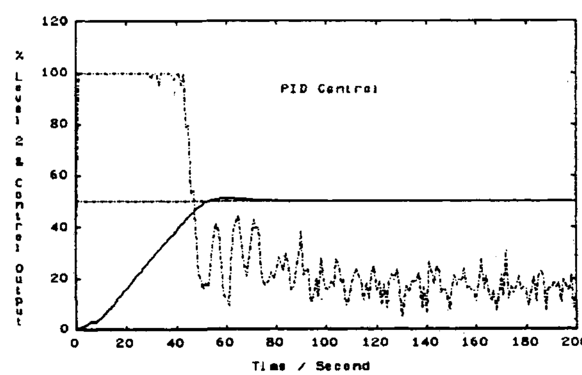

Fig. (13)