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# Model Based Evaluation of Controller Using Pole Placement Technique for nonlinear spherical tank process.

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## ABSTRACT

Developing a model for a conductivity based process has a recent importance. It has found extensive application in chemical industry more so in effluent treatment plant and power plants. A system with varying transportation lag has been chosen for model generation and hence to select control parameters. Two percent sodium chloride solution has been suddenly injected in to the system and the response is observed using online Honeywell conductivity analyzer. The data fitted a first order plus dead time model with an error of less than 3percent. From the model parameters, PID and state feedback Controllers were designed using MATLAB. The closed loop performance was studied for both servo and regulator problems. Based on overshoot, rise time, settling time, and ISE, it is found that the state feedback controller is better suited for this process
**Keywords:** Conductivity, FOPDT Model, Time constant, Transportation lag, Transfer function.

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## INTRODUCTION

Process control is of vital importance in the operation of chemical, pharmaceutical, biochemical, power plant, semiconductor, paper and bleach processes. Strict environmental regulations and growing concern for prevention of pollution have recently increased its importance. Hence there is an interest in many industries to improve the present practices of process control. In industrial processes, the drive to reduce operating costs and develop new markets has frequently emphasized improvements in product quality, better use of energy resources and reduced environmental emissions. These objectives, in turn, have placed stringent requirements on the available process control systems. Technological developments have made it possible for the successful production of chemical and bio-chemical products depending on the proper functioning of a large number of control systems used in this process. Design of modern process control systems are challenging especially for highly non linear and multivariable process with interactions. Due to constraints on manipulated and controlled variables, time delays, system uncertainties, system modeling errors, environmental disturbances, other problematic dynamic characteristics as well as uncertainties arise from imperfect knowledge of the system. The design of most of this control system is based on process model. A traditional modeling technique is to describe the process models such as hemispherical, spherical, and cylindrical vessels, which may contain dead time and bypass flows. In traditional design the process is usually assumed to be in a nominal operation point so that the flow rates and volumes are constant, but this assumption is not always valid. Because of disturbances and intentional changes in the production rate, the flow rate through a process entity is not always constant hence the online model identification techniques have been proposed for this study. Electrical conductivity is one of the transport properties frequently encountered by chemists and engineers, since it is widely used in water treatment plants, distilleries, pharmaceutical plants and in refineries for process control applications [2]. It has been applied to monitor the purity of solvents, to develop high-energy batteries and also in chromatographic separation techniques [3, 4]. Conductivity measurements are an important tool for quality control of aluminum alloys in aircraft manufacture [5]. The measurement of electrolytic conductivity is widely applied as a control parameter for different types of aqueous solutions [17].All systems cannot be represented with their full physical intricacies and therefore idealizing assumptions are always made for the purpose of analysis and synthesis. A physical system can be modeled in a number of ways depending upon the specific problem to be dealt with and the desired accuracy. A commonly adopted approach for handling a new problem is to first build a simplified, linear model by neglecting nonlinearities and arrives at an approximate model by open loop analysis of the process. A complex model is then constructed for detailed analysis .Rajendran and Neelamegam [10] have developed a setup for measuring conductivity of ionic solutions using micro controller. A modified AC Wheatstone bridge network is used, to measure conductivity, along with a microcontroller. G. Jones [8] designed a system for the trace measurement of the conductivity of water. The method is based on the measurement of the resistance of a column of water of accurately known dimensions. There is an electrode polarization effect and the conductivity is extrapolated as a function of inverse frequency to find the value at zero inverse frequency.Dharmalingam have developed model using process reaction curve.[11]sundram developed model for four process with transportation lag.[12] Sundaram et al [13-19] have developed a conductivity measurement setup for designing control system. For controlling the process Industries have been using the conventional PID controller in spite of the development of more advanced control technique. The importance of the PID controller comes from its convenient applicability and clear effects of each proportional, integral and derivative control. Linear PID controllers are the most popular method for controlling chemical processes due to their simplicity in implementation and understanding. In the past four decades, there are numerous papers dealing with the tuning of PID controllers. The PID settings can be obtained using step responses of the closed-loop systems and compare the overshoot, rise time and settling time. An alternative is to use the integral error as a performance index. However, these time domain performance measures do not address directly another important factor of closed-loop system robustness. Actually, the development of PID tuning rules has been one of the major areas of research about the PID controller. Ziegler and Nichols [20] and Cohen and Coon [21] designed a number of methods for PID controller tuning. Time delay problem may be characterized by large and small delays. A linear time invariant systems with finite delay can be modeled as $G(s)^{e-s}$. Where G(s) is a rational transfer function of s. Note that the delay corresponds to a phase shift of $w_j$ where $w_j$ denotes the frequency. Small phase shifts at frequencies of interest may be viewed as perturbations and incorporated in to a delay free design with sufficient phase margin. A large delay is classified as a delay that significantly affects the stability and phase margin to the point that the delay free design methods will not be sufficient. The conductivity system control using PID controller contains large transportation lag, a disturbance in set point or load does not reach the output of the process until delay units of the time elapsed. Till elapse of delay time no control action occurs, with a result that the overall closed loop response becomes sluggish and unsatisfactory. To overcome this sluggish and unsatisfactory control action a state feedback controller has been designed for a conductivity control system. State space models has attracted attention in the year (2003) Christopher has presented a new approach for a control performance monitoring technique based on the output covariance and suboptimal control performance using generalized eigen vector analysis[22]. Stabilization method for linear time delay systems using pole placement method is proposed. Marchant[23] has discussed about simulation of the performance of a state feedback controller for an active spray boom suspension. A method is proposed for finding the optimal model for a distillation column using state space analysis [24]. Grimble et al [25] have developed state equation based controller for rolling mill applications In this work, coiled pipes of varying length are used to establish the effect of time delay in designing controllers for flow control. The process model is experimentally determined from the step response analysis obtained by monitoring online electrical conductivity. From this experimental value the model parameters are estimated and controllers were designed.

## Methodology for measurement

Figure 1 Experimental setup for determining the process model and photographic view

The experimental setup for determining the process model and photographic view is shown in the Figure1 A concentrated tracer solution and fresh water are fed to a 40 liter spherical tank through two Gallen Kamp rotameters. The conductivity is monitored at the outlet using online Honeywell conductivity sensor. The spherical tank process is divided into three levels (L1, L2, L3) longitudinally and various transportation lag is realized in each region using valves v4, v5 and v6. The sensor output is interfaced to a PC using real time data acquisition card from M/S AD Instruments. The card can be connected directly to the USB port of the computer. It has in built anti aliasing filter. The card supports 16 ADC and DAC channels with voltage range of ±15 volt. The conversion speed of the card is 200000 samples per second with 16 bit resolution

## Experimental Procedure

For determining the flow model the feedback path was removed from the experimental setup shown in figure1 and open loop test was conducted. The flow rate of water at the inlet is fixed at 2 Lit/min (using valves v1 and v2) and one weight percent sodium chloride solutions is injected suddenly at the rate of 250cc/min using the following procedure. Water is allowed to flow into the process at a constant flow rate of 2 LPM. The cell indicates a constant conductivity value in micro mhos and this constant value is recorded. A two-weight percent sodium chloride solution is injected at a constant flow rate of 250 cc/min in the inlet along with the water. The conductivity of the outlet water increased slowly and reached a steady value depending on the pipe length. The recorder indicates the variation in conductivity measured by the conductivity sensor. Different coil diameters are considered to study the effect of conductivity on conduits of varying diameters. The open loop variation of conductivity with respect to time for different water flow rate ranging from 1lit/min to 5lit /min and concentration and flow rate of tracer injected into the system ranging from 1-5 weight percent and 100ml to 1lpm respectively were studied. The variation of conductivity with respect to time for the spherical tank processes is shown in Figure2.

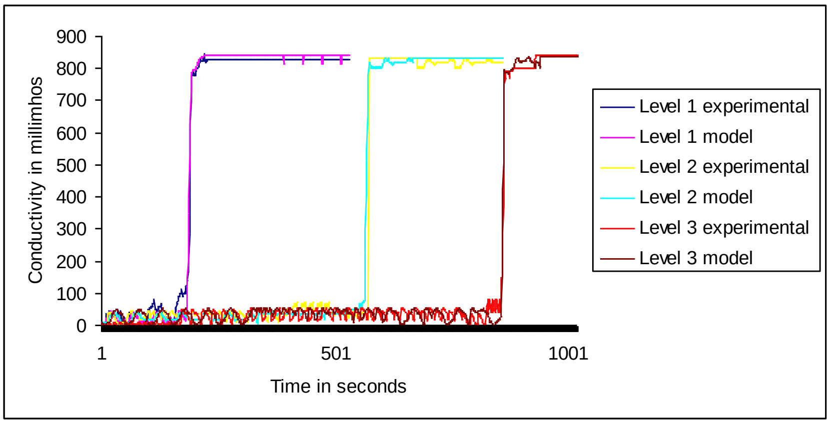

**Figure2 variation of conductivity with respect to time for the spherical tank processes.**

## Controller design

In the conventional approach to design a single input-single output (SISO) control system based on the performance of the uncompensated system the form of the controller is preselected, such that the dominant closed loop poles have a desired damping and un damped natural frequency. However in this approach the order of the system cannot be raised more than one or two pole zero cancellation takes place and the design results in large overshoot and settling time, particularly when the process has an integrating element, ON-OFF control or if the process has large transportation delay. To overcome this difficulty state feedback by pole placement technique has been used in this work, which gives greater freedom for the conductivity control system to achieve the desired performance. The objective of the pole-placement method is to design a feedback controller such that the dominant poles of the closed-loop system reflect the desired figures of merit. It is assumed that, the control signal is a scalar otherwise the mathematical aspects of the pole placement scheme become complicated and the state feedback gain matrix is not unique. Time delay problem may be characterized by large and small delays. A liner time invariant systems with finite delay can be modeled as $G(s)e^{-s}$ where G(s) is a rational transfer function of 's'. Note that the delay corresponds to a phase shift of $w_j$ where $w_j$ denotes the frequency. Small phase shifts at frequencies of interest may be viewed as perturbations and incorporated in to a delay free design with sufficient phase margin A large delay is classified as a delay that significantly affects the stability and phase margin to the point that the delay free design methods will not be sufficient. The conductivity system control using PID controller contains large transportation lag, a disturbance in set point or load does not reach the output of the process until delay units of the time elapsed. Until the delay time elapses no control action occurs and the overall closed loop response becomes sluggish and unsatisfactory. To overcome this sluggish and unsatisfactory control action a state feedback controller has been designed for a conductivity control system.

## State Space Model:

To derive the state space model of the process shown in Figure 1 consider the Transfer function of P1, given by equation (3.1) for unit step input .i.e.

$$G_{p1}(s)=\frac{0.138e^{-38s}}{(24s+1)(20s+1)} \tag{3.1}$$

By first order pade approximation equation (3.1) can be written as

$$\frac{(0.138(1-19s))}{(24s+1)(20s+1)(1+19s)} \tag{3.2}$$

i.e.

$$Gp1(s)=\frac{0.151-0.287s}{s^3+0.146s^2+0.002035s+0.000107}$$

The above transfer function can be split as $G_{p1}(s)=\frac{Y(s)}{U(s)}=\frac{X1(s)}{U(s)}.\frac{Y(s)}{X1(s)}$

where

$$\frac{X1(s)}{U(s)}=\frac{1}{s^3+0.146s^2+0.002035s+0.000107} \tag{3.3}$$

and $\frac{Y(s)}{X1(s)}=0.138-19s$ (3.4)

From equation (3.3)

$$U(S)=(s^3+0.1436\,s^2+0.00203\,s+0.00010\,)X_1(s) \tag{3.5}$$

Taking inverse Lap lace transform of equation (3.3) it becomes

$$U(t)=\dddot{X}_1(t)+0.1436\,\ddot{X}_1(t)+0.00203\,\dot{X}_1(t)+0.00010\,X_1(t) \tag{3.6}$$

Defining the state variable as

$$\dot{X}_1(t)=X_2(t);\ddot{X}_1(t)=\dot{X}_2(t)=X_3(t);and\dddot{X}_1(t)=\ddot{X}_2(t)=\dot{X}_3(t)$$

Substituting the state variables in equation (3.6) it becomes

$$U(t) = \dot{X}_3(t) + 0.1436\,X_3(t) + 0.00203\,X_1(t) + 0.00010\,X_1(t) \qquad (3.7)$$

Rearranging equation 3.7), it gives

$$\dot{X}_3(t) = U(t) - 0.1436\,X_3(t) - 0.00203\,X_1(t) - 0.00010\,X_1(t) \qquad (38)$$

and $\dot{X}_2(t) = X_3(t);$ (3.9)

$\dot{X}_1(t) = X_2(t);$ (3.10)

From equation (3.4) $Y(s) = (0.151 - 0.287\,s)X_1(s)$ (3.11)

Taking inverse Lap lace Transform, equation (3.11) becomes $Y(t) = 0.151X_1(t) - 0.287\,\dot{X}_1(t)$ This can be written as $Y(t) = 0.151X_1(t) - 0.287\,X_2(t)$ (3.12)

Arranging equation (3.8), (3.9) and 3.10) in matrix form the state equation of the process P₁ is

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -0.00010 & -0.00203 & -0.1436 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} U \qquad (3.13)$$

From equation (3.12), and initial condition the output equation is given by

$$y = \begin{bmatrix} 0.151 & -0.287 & 0 \end{bmatrix} \begin{vmatrix} X1 \\ X2 \\ X3 \end{vmatrix} + 260u \qquad (3.14)$$

Where 260 is the initial value of water conductivity in micromhos/cm before sodium chloride solution is injected

**Pole Placement Design**

Before the pole placement design, it is necessary to check the controllability of the system. The controllability matrix M can be found by

$$\mathrm{M} = \begin{vmatrix} 0 & 0 & 1 \\ 0 & 1 & -0.1436 \\ 1 & -0.1436 & 0.0186 \end{vmatrix}$$

Since the rank of the matrix M=3, the system is completely state controllable and arbitrary pole placement is possible. The characteristic equation for the system matrix ‘A’ is given by the determinant of (SI-A), i.e.

$$\text{Determinant of (SI-A)} = \begin{vmatrix} s & -1 & 0 \\ 0 & s & 0 \\ -0.00010 & -0.00203 & s+0.1430 \end{vmatrix}$$

and is given by $S^3+0.0237S^2+0.0187S+0.000493=0$

Let the closed loop poles be placed arbitrarily at $\mu_1 = \mu_2 = \mu_3 = -0.079$. Hence the desired characteristic equation becomes (S+0.079) (S+0.079) (S+0.079) =0, i.e.

$S^3+0.0237S^2+0.0187S+0.000493=0$.hence the coefficient of the desired characteristics equation are $Z_1 = 0.237$; $Z_2 = 0.01872$; $Z_3 = 0.000493$.

Now the feedback gain matrix K can be found by

$$K= \{[Z_3-a_3]\ [Z_2-a_2]\ [Z_1-a_1]\} \qquad (3.15)$$

Substituting the values in equation (3.15), the fed back gain matrix K is given by

K = [0.00053821 0.015547 0.1159]

The state feedback gain matrix ‘k’ and the system state equation are defined by equations (3.16) and (3.17)

$$K= \{K_1 \quad K_2 \quad k_3] \qquad (3.16)$$

$$\dot{X}(t) = AX(t) + BU(t) \qquad (3.17)$$

Let the input vector using feedback be

$$U(t) = -KX \qquad (3.18)$$

Substituting equation (7.18) in (7.17), the state equation becomes

$$\dot{X}(t) = (A\_BK)X \qquad (3.19)$$

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0.00010 & 0.0203 & 0.346\end{bmatrix}\begin{bmatrix}X_1\\ X_2\\ X_3\end{bmatrix}+\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}U \qquad (3.20)$$

Similar state feedback controller design was designed for the hemispherical and spherical and the designed controllers are simulated in MATLAB. The closed loop responses of the processes with state feedback are compared and given in Tables .1.The response of the output and the state variables for spherical tank process are shown in Figures 3. The output response for the PID controller for three processes is shown in Figure 4

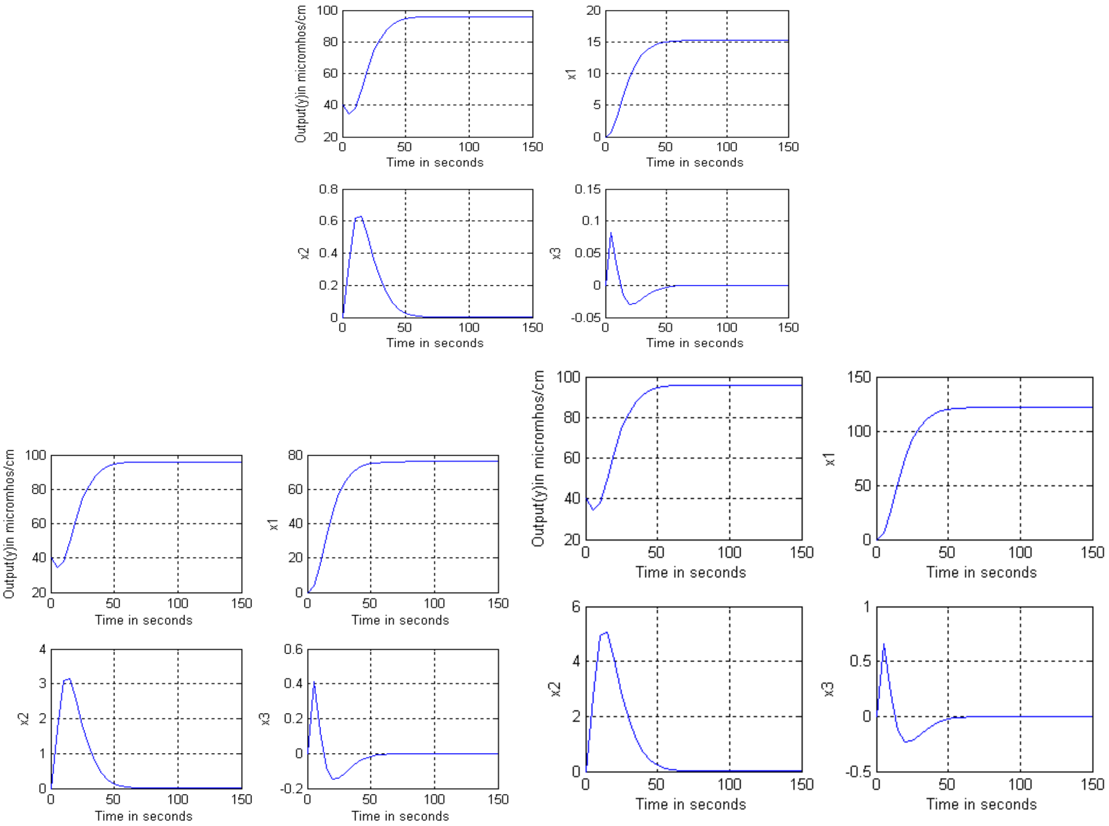

**Figure 3 (a) to (c) State space controller output response for different flow rate of tracer solutions for spherical tank process**

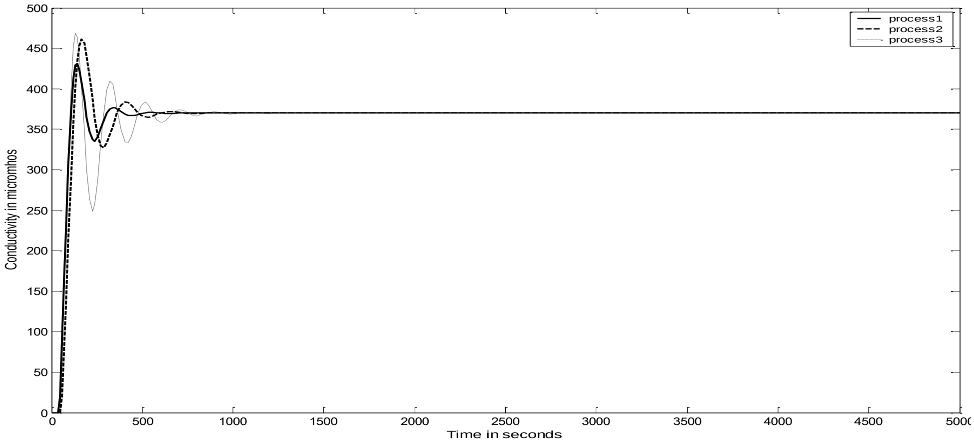

**Figure 4 Output responses of the process1, process2 and process3 for PID controller**

**Table.1 Comparison of PID & state feedback controller**

| Controller | Cylindrical Process | Rise Time (sec) | Peak Time (sec) | Overshoot (%) | Settling Time (sec) |
|---|---|---|---|---|---|
| PID | Level 1 | 85 | 100 | 16.21 | 400 |
| | Level 2 | 100 | 125 | 35.1 | 600 |
| | Level 3 | 120 | 160 | 29.72 | 480 |
| State Feedback | Level 1 | 45 | 75 | 0 | 120 |
| | Level 2 | 50 | 85 | 0 | 115 |
| | Level 3 | 60 | 95 | 0 | 110 |

## CONCLUSIONS

Model identification for a conductivity control system with different transportation lag was carried out with data generated experimentally. Different control strategies such as PID controller tuning techniques, state feedback by pole placement design methods were carried out for an online conductivity control system. The performance of the PID and state feedback controller compared in Table 1 .It is observed that the state feedback controller gives minimum rise time, settling time without any overshoot

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