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ABSTRACT

A required senior-level chemical engineering course at Colorado State University is described. The first nine weeks are devoted to the theory portion of the course, which includes the following topics: LaPlace transformations and time constants, block diagrams, inverse transformations, linearization, frequency response analysis, graphical stability criteria, dead time and distributed parameters, and analog computations. The next seven weeks are devoted to computer-oriented experiments designed to complement the theoretical material. Each experiment is outlined in detail. (MLH)

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PROCESS DYNAMICS AND CONTROL, A THEORY-EXPERIENTIAL APPROACH

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Historical

The first course offered at New Jersey Institute of Technology in the Department of Chemical Engineering and Chemistry which could be considered as dealing with the area of Process Dynamics and Control was on the graduate level. Introduced in 1953 on a strictly lecture approach the course was titled "Chemical Engineering Instrumentation" and concerned itself with the theory of instruments commonly associated with the process industries. However, as the field developed and new faculty were added with interests in the more modern approaches to Process Dynamics and Control, a more theoretical mathematical graduate course was developed and introduced in 1966. Simultaneously, a companion undergraduate course was added and both courses were of the lecture type. At this time the instrumentation course was discontinued. Although for all intents and purposes students had no experimental experiences associated with the newly developed courses two experiments were available in the undergraduate senior level Unit Operations laboratory. The first of these experiments was a Panellit Pneumatic Demonstrator (Circa 1960) which had been donated to the department by Worthington Corporation and could be used for controlled-uncontrolled process simulation. The other process dynamics and control experiment (Circa 1966) was a typical liquid level control system. Here students could experience an actual process, and study the characteristics of the component parts individually and/or as an integrated system. In 1967 the department received an undergraduate NSF equipment grant to improve its Process Dynamics and Control facilities. This grant was used to purchase two TR-20 EAI analog computers with associated electronic devices and a Procedyne pneumatic function generator. In addition, an Autodynamics 501 Process Control Trainer was purchased by the department from monies received from State funds. During this period of time two other experiments, a continuous stirred tank reactor for frequency response studies and an experiment utilizing a chemical reactor for determining optimum controller settings were in various stages of planning and construction. As these actions and events unfolded serious questions were raised on how and where these experiments were to be integrated into the curriculum. Integration of these experiments into the Unit Operations Laboratory imposed serious limitations on the purpose and integrity of this course. The most serious problem encountered by students in any proposal to incorporate the experiments into the Unit Operations laboratory was that students would be undertaking experiments prior to undertaking the in-class study of the principles associated with process dynamics and control. Since the individuals involved with the process dynamics and control course believed in and were committed to exposing the students to an experiential learning process the only question was how to accomplish this objective. Basically two options were considered, namely:

(1) A conventional theory course with an associated laboratory being undertaken by the student concurrently.

(2) A newer concept of an integrated one semester sequential theory-laboratory course.

Option (1) was rejected due to overall curriculum time-credits constraints as well as other educational time usage-return limitations often encountered with this type of course. The current course was expanded by one class hour, and restructured in content to provide for the laboratory sequence as per option (2).

To make the overall sequence of events even more interesting and challanging during this time period, 1967-1969, was the prospect of a move from the existing facilities the department was housed in to a new Chemical Engineering Building. In this time frame the State of New Jersey was proposing, and did initiate, the proper procedure for a bond issue to support construction of new facilities at various institutions of higher education. N.J.I.T., at that time Newark College of Engineering, was to receive a share of these funds for construction of a new chemical engineering building which is now our existing Tiernan Hall. This bond issue was subsequently passed and the facilities became a reality in 1972. However, returning to our tale of the original development of our laboratory which was to be in the then existing facility, it was decided to go ahead with the completion of our proposed hardware experiments, but to build the main components from salvaged materials. In our minds this was a temporary facility and we had great confidence in the citizens of the State of New Jersey passing the bond issue referendum.

Course Formating and Content

The course is a required course for ChE seniors which meets four hours a week in two hour blocks. The first nine weeks are devoted to the theory portion of the course during which the following topics are presented using "Introduction to Chemical Process Control" by D.D. Perlmutter and special lecture notes:

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1. LaPlace Transformation and Time Constants
2. Block Diagrams
3. Inverse Transformation
4. Linearization
5. Frequency Response Analysis
6. Graphical Stability Criteria
7. Dead Time and Distributed Parameters
8. Analog Computations

The next seven weeks are devoted to experiments which are designed to compliment the theoretical material presented. The experiments, five in number, are both hardware and electronic computer oriented. The topics covered are as follows:

1. Liquid Level Control. This hardware experiment is used to illustrate mathematical modeling, block diagram development, individual component transfer function determination, and controller action on the system.

2. Temperature Control of a Chemical Reactor. The simulation of a steam jacketed flow chemical reactor is undertaken on an Autodynamics 501 process control trainer. The effects of derivative, integral and proportional control on the system response are investigated when the reactor steam pressure is subjected to a step change.

3. Analog Computer. A TR 20 analog computer is utilized to simulate concentration control for a tubular reactor. This experiment is designed to illustrate the effect of proportional gain on stability.

4. Frequency Response Analysis. This hardware experiment is based

on the classic well stirred tank with sinusoidal, step, and impulse variations of the inlet flow concentration. The experiment illustrates the use of Bode diagrams to determine the system model and transfer functions.

5. Temperature Control of a Zero Order Reaction in a Continuous Stirred Tank Reactor. This hardware experiment illustrates the use of the Ziegler-Nichols method to determine the process transfer function and for the experimental determination of optimum controller settings.

In order to maximize student participation, class size is limited to twenty-one students or less, and each laboratory group size is limited to three students. In addition, complete group reports and/or individual memo type reports are required of each student for each experiment.

The Laboratory

Once the students have studied all the theory in the first 9 weeks of the semester, the remaining 7 weeks are spent full time in the laboratory.

Students are then exposed to pilot plant scale equipment in experiments covering liquid level control in a tank, Frequency response analysis in a mixed vessel and on-line temperature controller tuning for a backmix reactor. In addition, a reactor concentration control experiment is simulated on two fully equipped TR-20 analog computers and controller modes are studied on an Autodynamics Process Control Trainer.

I. Liquid Level Control

In this experiment, the process, transducer, valve and controller are calibrated to determine the response of each element of the feedback loop.

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Then, a step load distrubance is imposed on the closed loop system and the system response is measured. The measured response is compared with the predicted control response based upon the calibrated characteristics of each element in the closed loop. Slide 1 is a picture of the actual apparatus, and Slide 2 shows a sketch of the apparatus. A liquid stream enters the tank at a flow rate x(t). A controller and automatic valve maintain the level in the tank y(t) at a constant value set on the controller set point for any disturbances in the load variable x(t). The level signal is transmitted to the controller by a transducer which converts the pressure caused by the liquid height to an air pressure signal to the level controller recorder (LCR). This signal is compared to a set point and the controller calculates the error and transmits an air pressure signal to the valve. The valve increases or decreases the effluent rate u(t), and brings the level to its desired value.

Slide 3 is a block diagram of the process. Slide 4 shows the load response for the open loop system with a time constant of about 240 seconds. Slide 5 is the transducer calibration showing output signal as a function of level in the tank. Slide 6 is the calibrations for the non-linear valve showing flow rate as a function of diaphragm pressure. The linearization for the block diagram analysis is also shown at about 8.5 psi. Slide 7 shows the open loop response of the process to a step change in the pressure to the valve diaphragm at fixed load. Slide 8 shows the controller gain. The measured gain of 4.73 compares with an approximate proportional band setting of 25% (gain of 4) with no integral or derivative action present. Slide 9 is the measured response curve.

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Finally, Slide 10 shows the change in level in the tank for a closed loop step change in load and the corresponding calculated response from the calibrated elements in the block diagram.

II. Reactor Temperature Control on Process Control Trainer (Slide 11)

The purpose of this experiment is to illustrate to the student the effect of different modes of control on a process. A flow diagram of the system is shown in Slide 12.

The simulated process is a flow chemical reactor in which heat is provided to the reactants by a steam jacket surrounding the reactor. Excess heat is removed by an internal cooling system located inside the reactor. The only control on the reactor is by temperature sensing of the reactor contents and adjusting the steam control valve.

It is desired to study the effect of derivative, integral and proportional control on the system when the upstream steam pressure is subjected to a step input. In addition, the effect of a reduction in heat transfer coefficient on closed loop system dynamics is studied. Slide 13 shows the signal flow diagrams.

The block diagram including the process transfer function is a standard closed-loop feedback system with the load variable being the upstream system pressure. The manipulated variable is the flow rate of steam to the reactor jacket.

Slide 14 shows as an example the effect of P.B. - 50%, Reset Rate at 0.5 min^{-1} and demonstrates the proportional-integral mode of temperature control for a step change in steam pressure to the jacket. Students thus compare, proportional control at various settings, proportional-integral control at various settings and proportional-integral-derivative control at various settings for the same step disturbance in jacket steam pressure.

III. Use of Analog Computer in Process Dynamics and Control

The Use of Concentration Control of a Tubular Chemical Reactor

The purpose of this experiment is to demonstrate techniques used to formulate a quantitative dynamic model of a process system and to investigate the model's characteristics by computer simulation. The dynamic model, represented by differential equations, can be solved by a TR-20 analog computer, shown on Slide 15 which gives the variation of response variables with respect to time plotted on an X-Y plotter. The three-vessel cascade problem given in the text by Perlmutter is chosen to illustrate the procedure and the technique involved.

The students are required to develop the system equations, develop the analog computer diagram, amplitude scale, time scale, and patch the computer board.

After the system has been simulated, the effect of proportional controller gain is determined for a step change in the controller set point and system stability is studied.

Slide 16 is a diagram of the reactor system outlet concentration control. Slide 17 is a block diagram of the process with proportional control only. Slide 18 is a scaled analog computer diagram. Slides 19, 20, and 21 show the output concentration response to a change in controller set point. Marginal stability is shown in Slide 19 at gain, K_c of 8. Slide 20 also shows an unstable situation at K_c = 27. Other gain values

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give differing stable controlled responses.

IV. Dynamic Analysis of a Stirred Tank

In this experiment, shown on Slide 22, both frequency response analysis and transient response analysis are used to determine the dynamics of the stirred vessel. In the frequency response tests a sinusoidal input disturbance and measured output disturbance are analyzed with a Bode Diagram to determine the process transfer function.

In the transient tests, both a step input and an impulse are used. For the step input, the Zeigler-Nichols approximation is used to determine the systems parameters. A first order process with dead time is also used for the impulse test and the constants determined from the data. These results are then compared with the theoretical process transfer function for a perfectly mixed vessel on the Bode Plot.

The mixing process is shown in Slide 23 in which a stream of solution containing dissolved salt flows at a constant volumetric flow rate q into a tank of constant holdup volume V. The concentration of the salt in the entering stream, x(t) (mass of salt/volume), varies with time. The time lag in the measuring element is τ_o and the effluent concentration is y(t).

If the system is disturbed by a sinusoidal input as with a sine wave generator sending an air signal to the diaphragm of a linear valve, a sinusoidal output will result. Slide 24 shows such an input distrubance and output response. From the amplitude ratio and the phase lag, a Bode plot is shown in Slides 25 and 26 and compared with that of a first order process with time lag.

When a step input is imposed on a system, the output response is the

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characteristic process reaction curve. From this curve, using the Zeigler-Nichols Approximation, the constants for the approximate first order process transfer function can be determined. The results can also be presented on the Bode Plot.

Slide 27 and 28 show data for a Zeigler-Nichols response curve following a step change in the input salt concentrations. Slides 29 and 30 show the resulting Bode diagram for the first order approximation of the process.

Data obtained from an impulse test are also useful in obtaining process transfer functions. These are particularly useful because the processes are only disturbed for a short time. A Bode diagram can be prepared from a Fourier Transform analysis.

To aid the students, a prepared program is available on a Hewlett-Packard, 9180A, mini computer (Slide 31). Slide 32 shows the impulse disturbance and Slides 33 and 34 show the Bode Plot for the first order process with dead time. Students also compare measured dead time to actual calculated dead time by calculations from dead volume and flow rate.

V. <u>Temperature Control of A Stirred Tank</u>

<u>Determination of Optimum Control Settings</u>

Field tuning of controllers for existing plants and processes involves empirical methods in the determination of the best controller settings for proportional band, integral time and derivative time. In this experiment three of these methods are used and their results compared. The equipment is shown in Slide 35 and the system diagram in Slide 36.

Three methods that have been developed to determine optimum controller

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settings empirically are:

1. Reaction-curve Method
2. Continuous-Cycling Method
3. Damped Oscillation Method

1. The Reaction Curve Method

The reaction curve method or Zeigler-Nichols method involves the typical process reaction curve. The controller is placed on manual operation, thus opening the feed back control loop. Then, a step change is made in the valve position and the typical process reaction curve is obtained. The data obtained from this curve is used to calculate the optimum settings. Slide 37 shows the typical reaction curve for the process following a step change in steam rate. Optimum Controller Settings are calculated by the Zeigler-Nichols approximation.

2. Continuous Cycling Method

The system with closed loop control using proportional band only is perturbed by a step change in the set point, for various values of proportional band. The response of the system is observed until continuous cycling at constant amplitude is obtained. At this value of proportional band the system is marginally stable. The period of oscillation is the ultimate period and the recommended controller settings for a proportional-integral-derivative controller are calculated from published equations. Slide 38 shows the continuous cycling method at marginal stability and the ultimate period.

3. Damped-Oscillation Method (Harriot)

In many plants, the continuous cycling method is not suitable because the system is upset more than desired. In such cases, the damped oscillation method is used. With the system in proportional control only, the gain is adjusted until the response of the controlled system shows an amplitude decay ratio of 1/4. When the decay ratio is 1/4, the period is determined and these values for integral time and derivative are then set into the controller and the procedure is repeated until the proper gain is found for a decay ratio of 1/4.

The course approach described above has been utilized at NJIT for the past several years and based on student response has been highly successful.

Instrumentation

As one can gather from the previous presentation classic instrumentation concepts are not covered in the course excepting in informal discussions between the students and the instructor within the laboratory framework. Primary emphasis is placed upon the basic concepts of dynamics and control principles, and the experiential reinforcement process. However, basic instrumentation of the analytical and visual types are widely integrated throughout the undergraduate laboratory experiments. Students use such analytical devices as gas chromatographs, refractive index, infrared spectophotometers, etc., in our junior-senior chemistry courses. In addition, our chemical engineering laboratory experimental hardware are replete with such devices as recorder-controllers, temperature sensing devices, (thermocouples), pneumatic and manual type valves, pressure gages, rotometers, manometers, transducers, and simple electronic recorders. These devices are integrated into the experiments for control and data gathering purposes. To give an industrial type setting to the integrated systems the experiments each have their own simulated central control room in the form of a cohesive panel unit.

The Future

What we have discussed up to this point is what our students are exposed to in our existing Dynamics and Control course and other laboratory courses in our curriculum. The newly conceived Process and Dynamics course will be expanded from its current four class hours per week to a six hour course with a slight increase in the laboratory portion of the course. Experiments are currently under design with emphasis on component operating characteristics and revision of existing experiments. In addition, direct digital control of any one of several experiments, either in the Dynamics and Control or Unit Operations Laboratory, utilizing mini computers are in the planning stage.

Hopefully, these plans will become realities with the introduction of our newly revised curriculum scheduled to go into effect in September of 1977.

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Slides Presented

Slide Number	Description
Introduction	
1	New Tiernan Hall
2	Panellit Pneumatic Demonstrator
3	Temperature Control Reactor
Laboratory	
1	Overall view of liquid level control experiment.
2	Schematic drawing, liquid level control
3	Signal Flow Diagram, liquid level control
4	Open Loop Process Response to Step Change in Load
5	Transducer Calibrations, Liquid Level Control
6	Non-Linear Valve Calibration, Liquid Level Control
7	Open Loop Process Response to Step Change in Valve Pressure
8	Controller Gain Calibration, Liquid Level Control

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Slide Number	Description
9	Closed Loop Measured Level Response to Step Change in Load
10	Comparison of Calculated and Measured Response
11	Autodynamics 501, Process Control Trainer
12	Flow Diagram Simulated Chemical Reactor
13	Signal Flow Diagram, Simulated Chemical Reactor Temperature Control
14	Closed Loop Temperature Response with Proportional-Integral Control For Step Change in Steam Pressure
15	EAI TR-20 Analog Computers
16	Reactor Outlet Concentrations Control
17	Signal Flow Diagram, Reactor Concentrations Control
18	Scaled Analog Computer Diagram, Reactor Concentrations Control

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Slide Number	Description
19	Concentration Response to Step Change in Set Point
20	Concentration Response to Step Change in Set Point
21	Concentration Response to Step Change in Set Point
22	Overall view Frequency Response Experiment
23	Schematic Diagram of Frequency Response Experiment
24	Inlet Sinusoidal Distrubance at 2^7 sec/cycle and Outlet Response
25	Amplitude ratio versus frequency, Sinusoidal Test
26	Phase Angle versus frequency Sinusoidal Test
27	Output Response to Step Change in Input Salt Concentrations, Frequency Response Experiment.
28	Zeigler-Nichols Approximations Frequency Response Analysis

Slide Number	Description
29	Amplitude Ratio, First Order Zeigler-Nichols Approximations
30	Phase Angle, First Order Zeigler-Nichols Approximations
31	Hewlett-Packard, 9180A
32	Output Response to Impulse Change in Input Salt Concentration
33	Amplitude Ratio, Impulse Test
34	Phase Angle, Impulse Test
35	Overall view, Reactor Temperature Control
36	System Diagram, Reactor Temperature Control
37	Process Reactions Curve For Reactor Temperature For Step Change in Input Steam
38	Continuous Cycling Method to Determine Optimum Controller Settings

Slide Number	Description
Instrumentation	
1	Continuous Heat Transfer Panel
2	Bath Heat Transfer Panel
3	Gas Absorption Panel
4	Distillation Panel
5	Tubular Reactor Panel
Future	
1	H-P 9820