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"DESIGN OF A DIGITAL CONTROL SYSTEM: THE COUPLED TANK"

By

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DESIGN OF A DIGITAL CONTROL SYSTEM:

THE COUPLED TANK APPARATUS

The examining committee considers this
thesis satisfactory and acceptable for
the award of the degree of
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TO
MY FATHER , MY MOTHER
MY SISTER ,
MY BROTHERS ,
AND MY UNCLE DR. MARWAN KAMAL,
TO ALL OF YOU
FOR YOUR SUPPORT TO CARRY ON

THANK YOU.

الملخص

تهدف الرسالة الى تصميم وتشغيل نظام تحكم محوسب لاغراض تعليمية . يتضمن ذلك تصميم الجهاز نظريا وتجميعة عمليا ومن ثم اختباره بمحاكاة المدخلات باستخدام مولد اشارة عند ترددات مختلفة.

النظام عبارة عن جزئين أحدهما يتكون من الكترونيات والاخر عباره عن برنامج لتنسيق وتشغيل تلك الالكترونيات مع بعضها البعض. استخدم من اجل بناء الاول قطع الكترونية متوافقة مع نظام الحاسب (BASIC) اما بناء البرنامج فكان باستخدام لغة (APPLE)

بعد تصميم الجهاز تم تشغيله واختباره باستخدام مولد الاشارة . كانت النتائج مرضية فتم الانتقال للمرحلة التي تليها وهي استخدام ذلك النظام للتحكم في تطبيق عملي يستخدم كثيرا وهو التحكم بمستوى السائل في صهاريج التخزين.

يتم التحكم في مستوى السائل عن طريق تغيير سرعة المضخة التي تصب السائل داخل الخزان وتتم تغذية خلفية لمستوى السائل باستخدام مجس للارتفاع موجود في الخزان. تم توصيل جهاز تشبيهي موجود في مختبر التحكم الالي / قسم الهندسة الصناعية ونتج عن التجارب نجاح التحكم باستخدام اسلوب التناسب الطردي.

تم ايجاد صيغة رياضية تمثل النظام وحولت الصيغة الى برنامج استخدم لحساب تجاوب النظام ومنه تمت مقارنة النتائج العملية بمثيلتها النظرية باستخدام طرق احصائية رياضية لحساب مدى تقارب النتائج. كل ذلك اظهر نجاعة نظام التحكم.

من خلال البحث المقدم تم عرض ملخص لبعض الافكار المهمة ومن ثم كيفية تصميم النظام مع شرح موجز لمكوناته . في الجزء الثالث تم عرض المحاكاة ونتائجها. وبعد ذلك تطرق البحث الى النتائج العملية وايجاد الصيغة الرياضية المذكورة اعلاه. اما الجزء الاخير فقد احتوى على المقارنة بين النتائج العملية والنظرية وعرض الخلاصة.

ABSTRACT

This thesis aimed at developing a computer control system for educational purposes. Design and testing of the digital control system were elaborated on in detail.

After designing the system and implementing the required hardware and software, simulated input was introducedto the controller. The results were satisfactory. The coupled tank apparatus, an example of a real life control problem, was hooked up to the digital controller.

Results were recorded. The system was modeled mathematically. Experimental data were compared with theoretical results. Statistical analysis of experimental results employing Goodness-of-fit test was performed. The test showed that the control technique was successful.

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CHAPTER ONE

INTRODUCTION & IMPORTANT CONCEPTS

1.1. INTRODUCTION

1.1.1 HISTORICAL BACKGROUND

Applications of digital computers to industrial control began in the late 1950s. This was initiated by the manufacturers of digital and electronic equipment, who were looking for new markets for their products after it had failed had failed to be adopted by the *military*. The Louisiana Power and Light Company was the first to install a Daystron computer system forplant monitoring at their power station in Sterling. This was not a control system ; the honor of the first industrial computer control system went to Texaco who installed an RW-300 system at their Port Arthur refinery in Texas, which achieved closed - loop control on March 15, 1959 (1).

Problems then arose especially in the *software* development and programming. The solution appeared to lie in the development of general purpose operating systems and high level languages, and hence in the late 1960s process FORTRAN compilers appeared.

Problems involved in attempting to do everything on one computer led the users towards the new minicomputer which proved to be ideally suited. By 1970 it was possible to consider having two computers on the system, one simply acting as stand-by in case of failure.

1.1.2. CONTROL SYSTEMS

Any computer that works in an environment external to the computer and in real life is said to be working in

real-time. There are three types of real-time control systems. The first is *clock-based* systems where sampling is performed at a rate determined by the plant time-contants. Operations are performed every and on each sampling interval.

The second type is *sensor-based* systems. Using this type of control, actions have to be executed not at a periodic rate or following specific time intervals, but in response to some events. Such systems normally employ interrupt signals to inform the computer system that an action is required.

The third type is the one that employs *interactive programming*. The real time requirement is usually expressed in terms of the average time (2) .

1.1.3. ELEMENTS OF A COMPUTER CONTROL SYSTEM

The best way to explain these elements is with the aid of an example, in this case we will consider the coupled tank apparatus. In this experiment we have two coupled tanks with water flowing into the first and it isdesired to control the height of water in the second.

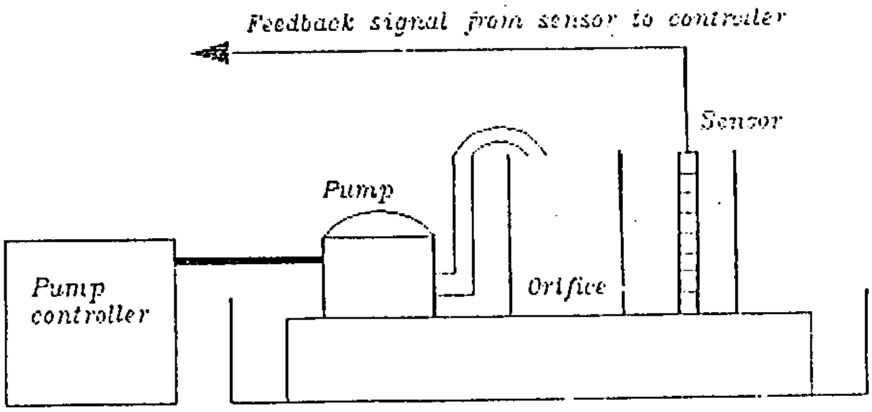


Fig.1.1.1 Coupled tank apparatus.

As seen from figure (1.1.1) , the feedback signal coming from the sensor would complete the closed - loop system. The error signal would be fed to the controller that will give the decision to the pump whether to increase or to decrease the water flow rate. The controller here is a *digital computer.*

The computer needs to be interfaced to the real world via

1) Data conversion techniques , and
2) Time interfacing techniques.

This is because the computer accepts only digital data and has a nonreal time clock. The first can be done by the aid of *analog - to - digital* converters and *digital - to - analog* converters discussed thoroughly in later sections.

The second can be accomplished by designing a clock that would communicate with the computer at discerte instances of time only that will be consistent with real time. A schematic diagram of the elements of the computer control system can be seen in Fig.(1.1.2)

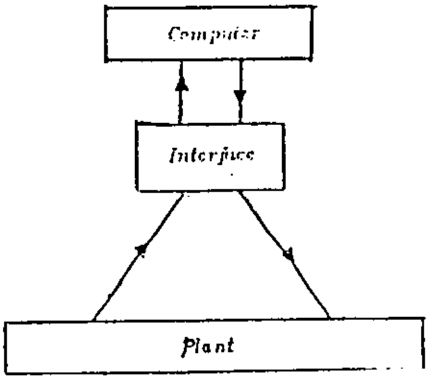


Fig.1.1.2. Elements of a computer control system.

1.1.4. PROGRAMMING TECHNIQUES

Any computer control system will need a program that when executed will give the desired control action. *Sequential programming* produces actions strictly ordered as a time sequence. The behavior of the program depends only on the effects of individual actions and their order.

If *multi-tasking programming* actions are to be performed in parallel; sequential relations between the actions may still be important.

A *real-time program* gives the ability to have the sequence of actions determined by the environment; not the designer (2).

1.2. DIGITIZATION AND SAMPLING

1.2.1. TYPES OF SIGNALS

Signals are either continuous or discrete in time. A continuous-time signal (a) is a signal defined on a continuous range of time . A quantized continuous signal (b) is a representation of the former one on a scale of finite distinct values (2), see figure (1.2.1.).

A discrete-time signal (c) is a signal defined only at discrete instances of time. If the amplitude of the signal is taken on a continuous range, then the signal is called sampled data signal, see Fig.(1.2.1). The difference between quantized signals and sampled-data signals lies in the fact that the first spans a finite range of values for the amplitude, whereas the second spans a continuous range of

values. The signal we employed through this project was a *digital signal* which is the same as a quantized - sampled signal.

A *digital signal* (d) is a discrete-time signal quantized in amplitude. This signal may be generated by quantizing an analog signal both in time and amplitude. This type of signals is the one that can be read by the computer (digital controller).

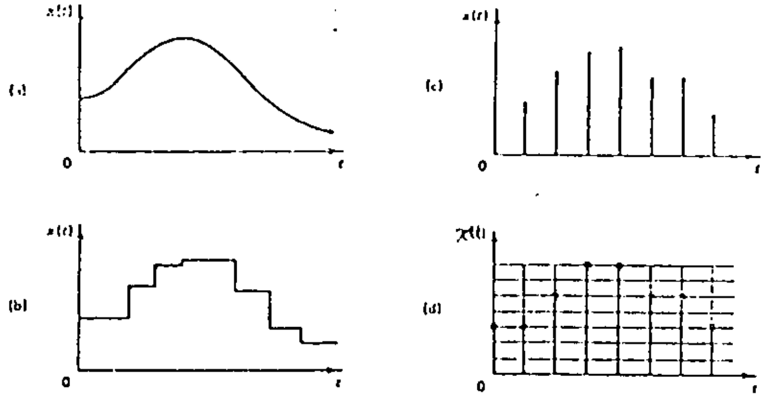


Fig.1.2.1. Types of signals.

1.2.2. A SIMPLIFIED DIGITAL CONTROL SYSTEM

In this section, we will discuss the transition of a signal throughout the various elements of digital control systems. The following figure shows a simple digital control system with the basic elements and types of signals coming in and out of the different constituent blocks. A brief description of these elements is given hereby.

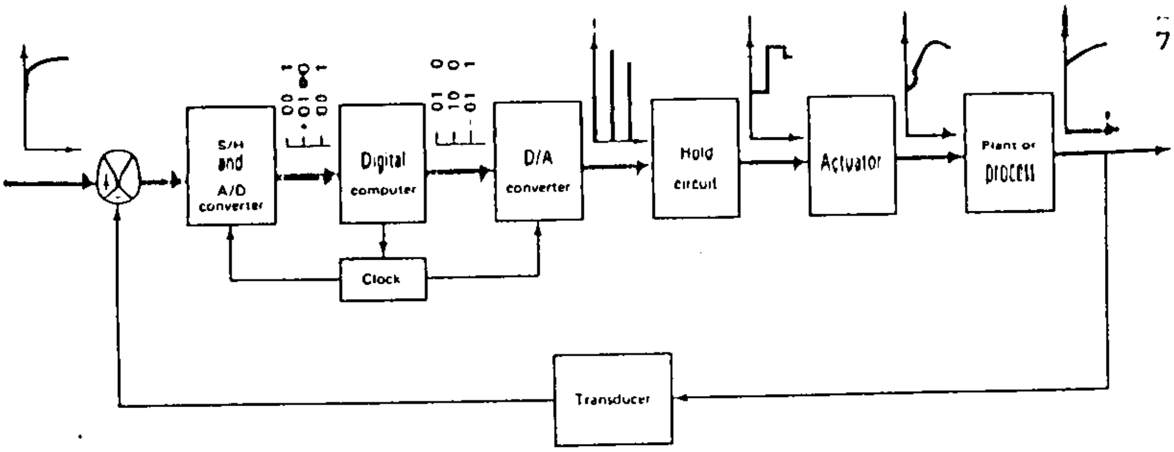


Fig.1.2.2 A simple digital control system

Sample-and-Hold (S/H) is a general term used for a sample-and-hold amplifier. It describes the circuit that samples an analog signal,holds it at a constant value for some time, and then sends it out as an output for another part of the digital circuitry.

An **Analog-to-Digital Converter (A/D)** is an encoder which converts an analog signal into digital form , usually a numerically valued signal. S/H circuit is an integral part of the commercial A/D converter. This part of the digital circuitry is a major component because it acts as an interface between an analog component and a digital one.

A **Digital-to-Analog Converter (D/A)** is a decoder that converts a digital signal (numerically coded data) into an analog continuous one. It is needed when the signal has to be taken from digital form to the analog world .

Plant or process is a physical variable or set of variables to be controlled . The output to be controlled is fed back to the controller through a transducer .

Transducer is a device that converts an input signal into an output signal of another form (e.g. temperature to voltage) (3).

Computer is a device that manipulates the numerically va

signal inside a program of required steps . The instructio of manipulation are fed to the computer by the system user. The manipulated signal is then sent out to the computer motherboard .

The theory implied behind operation of each of the elements described above is rather long and out of the scope of this thesis . However some concepts will be defined in the next section.

1.2.3. IMPORTANT CONCEPTS

The main operations done in conversion from analog to digital forms are sampling, amplitude quantizing and coding. In the Quantizing process, the amplitude is permitted to have distinct values (states) only, that means if a value is between two states, then it will be represented by the state nearest to the actual.The quantization level is the range between two adjacent points and is given by

Q= Full Scale Range / 2^n, (n = no. of bits in a computer word).

The Coding process is the one to follow quantizing where the quantized states are given codes in numerical binary form.

Sampling Theorem states that *the sampling frequency* ω_s *must at least equal twice the highest significant frequency in the signal.* This condition is imposed in order to enable the reconstruction of the original signal from the sampled signal [4].

If the *Laplace* transform of a sampled signal is given

by

$$F^{*}(s) = L\ [\ f^{*}(t)\ ] = \sum_{n=0} f(nT)\ e^{-nTs},$$

then, the Z- transform of a sampled signal can be defined as a further transformation :

$$z= e^{Ts} \qquad F(z) = F^{*}(s)\ \Big|_{z=e^{Ts}}$$

$$F(z) = Z[f(t)^{*}]= \sum_{n=0}^{\infty} f(nT)\,z^{-n}$$

Z **Transfer Function** of a system is the ratio of the Z transforms of its output and input sequences. These can be used to describe the action of a control algorithm as well as the relation between sampled inputs and outputs of continuous systems(4).

1.3. APPARATUS AND EQUIPMENT

1.3.1. APPLE 2e COMPUTER

This type of computers uses 6800 microprocessors as a central processing unit. This computer is used to manipulate the signal coming from the sensor and send it back to the plant to execute the requested action. Also,it controls the data transmission through the system. The computer with its operating DOS can handle BASIC or ASSEMBLY programming languages.

ASSEMBLY programming has a higher speed in communicating with the microprocessor compared to BASIC programming. On the other hand the BASIC language is easier to understand and debug by the user than the ASSEMBLY language.

This is because it is written in English as instructions while the ASSEMBLY language is written in machine code instructions(5).

1.3.2. APPLE 2e INTERFACE UNIT

The unit comprises two boards. The first is a printed circuit board (P.C.B.) which plugs into one of the eight peripheral connectors along the back edge of the APPLE motherboard. The second is a screen printed board that carries the 8255/A programmable I/O unit, a screw terminal block and an installation displacement header. The two boards are connected to each other via a 14-way ribbon cable (6).

There are three 8-bit ports on the screen board, designated as A,B,C. Ports A & B are both 8-bit ports and could be configured as input-output ports. Port C is divided into two 4-bit ports, C0 to C3 & C4 to C7. The benefit of the disection is that each port can be configured individually with its 4-bits as required by the application. Electrical specifications of the units are given in the unit manual (6).

Port configurations are done in a systematic way and should be considered in programming to distinguish between input & output ports. The configuration is set by introducing a write operation of the control word to the control register which will contain information needed.

Each port of the unit has an address that can be called by the program with the read or write operations. The addresses are changed by changing the slot used on the

computer motherboard. Each slot has a base address given for port A, table 1.3.1 shows these addresses.

SLOT NO.	BASE ADDRESS	
0	USUALLY USED FOR MEMORY EXPANSION	
1	C090H	49296D
2	C0A0H	49312D
3	C0B0H	49328D
4	C0C0H	49344D
5	C0D0H	49360D
6	C0E0H	49376D
7	C0F0H	49392D

PORT A = BASE ADDRESS. PORT B = BASE+1.
PORT C = BASE+2. CONTROL REGISTER =BASE+3.

Table 1.3.1 Addresses of the slots.

Having specified the base address for port A,we can get the addresses for ports B & C and the control register by simply adding one to the previous address, an example is given below (6).

Assume slot 4 is used :

A	49344
B	49345
C	49346
Control Register	49347

Configuring the ports needs sending a control word to the control register, the control word data can be obtained from the following table (6).

CONTROL WORD.		PORT A.	PORT C(UPPER)	PORTB	PORT C(lower).
128D	80H	0	0	0	0
129D	81H	0	0	0	I
130D	82H	0	0	I	0
131D	83H	0	0	I	I
136D	88H	0	I	0	0
137D	89H	0	I	0	I
138D	8AH	0	I	I	0
139D	8BH	0	I	I	I
144D	90H	I	0	0	0
145D	91H	I	0	0	I
146D	92H	I	0	I	0
147D	93H	I	0	I	I
152D	98H	I	I	0	0
153D	99H	I	I	0	I
154D	9AH	I	I	I	0
155D	9BH	I	I	I	I

Table 1.3.2. Control word.

One last thing worth mentioning is that if a port is configured as output then it will be latched, that is, it will keep holding the last value until a new one comes. Input ports are not latched.

1.3.3.DIGITAL TO ANALOG CONVERTOR

It is an 8-bit device with an output switch selectable to be either :

Unipolar	0 V to +5 V.
Bipolar	-5 V to +5 V.

All digital inputs are TTL compatible . The unit requires three regulated supplies

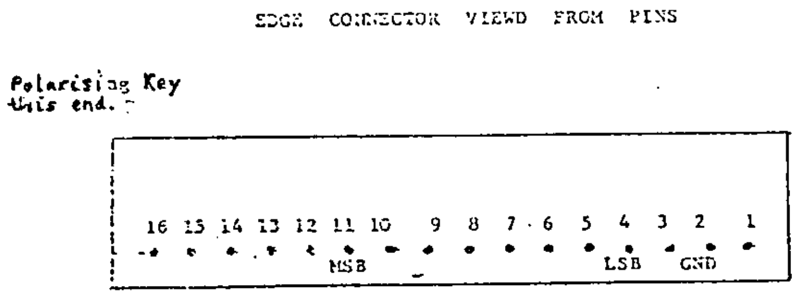
+ 5 V ∓ 0.25 V	current 5 mA.
+12 V ∓ 0.60 V	current 6 mA.
-12 V ∓ 0.60 V	current 6 mA.

The output voltage , operating in unipolar mode, is derived from the internal 5 volts reference voltage

$$V_o = \frac{B * 5}{256} ,$$

where B is the decimal output of the computer program. Then, the minimum signal obtained is *zero* , while the maximum signal corresponding to most significant bit MSB is (255 * 5 / 256 = 4.9805 V).

The figure shown hereby shows all the connections that are necessary to connect the kit to the computer (7).



Pins 1 & 2	to be left unconnected
Pins 12 – 16	to be left unconnected
Pin 3	connected to GND on microcomputer
Pins 4 – 11	connected to digital output lines on microcomputer with pin 4 connected to least significant bit (LSB) and pin 11 to most significant bit (MSB).

Fig.1.3.1. Connections to the computer.

1.3.4. ANALOG TO DIGITAL CONVERTER

The device required to carry out the quantizing and coding processes is the A/D converter. The chip used is an ADC 0804 LCN. A two position switch is there to choose between unipolar (0 to +5 V), and bipolar (-2.5 to +2.5 V) modes. The unit is supplied with a 5 V regulated voltage supply (8).

1.3.5. OTHER EQUIPMENT

Other equipment used were the following :

An oscilloscope to display input and output signals.

A power supply for regulated input DC voltages.

A function generator to simulate input signals to the analog to digital converter at varying frequencies and amplitudes.

A chart recorder .

A voltmeter used during calibration .

The coupled tank apparatus.

CHAPTER TWO

STARTING UP & SOFTWARE DEVELOPMENT

2.1. EXPERIMENTAL WORK

2.1.1. WORK PLAN

The work plan of this thesis took the following steps to accomplish its goals :

1) Analysis of the system.
2) Design of the interface card.
3) Developing the required software.
4) Testing the digital controller including software,using simulated signals (AC & DC).
5) Hooking up the coupled tank to the computer and testing the closed loop system.
6) Comparing experimental performance to theoretical analysis using Z transform techniques.
7) Checking validity of data and results through proper statistical analysis.

The project followed the above stated steps. This chapter will elaborate on the work done for steps 1 through 4 . The main objective was to accomplish the digitization process. The work consisted of two parts, hardware connections and software development.

2.1.2. HARDWARE CONNECTIONS

In any digitally controlled system, the analog feedback signal is converted into digital form, necessary manipulations are carried out at a digital manipulator, and then reconverted back to the analog form where it will be fed to the actuator preceeding the plant or process.

During the test phase , a digital control system

was simulated. The input analog signal came from a function generator and not from a real sensor, also the output signal was read by a chart recorder or an oscilloscope and not fed to a real actuator. The results of this stimulation were used to ensure that the forward digital controlled path is functioning properly.

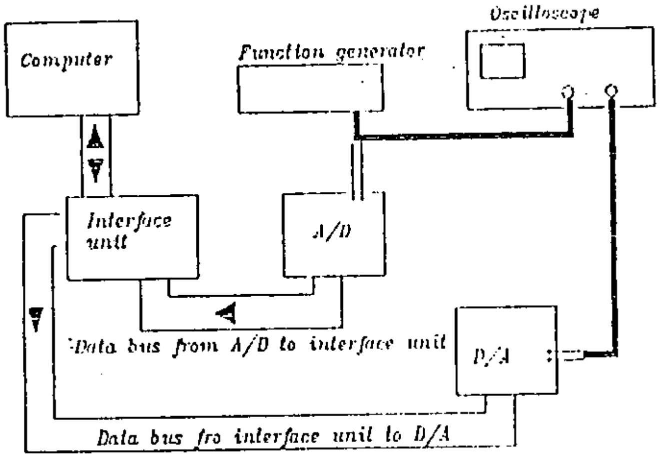


Fig.2.1.1. Simulated digital control system.

The basic parts and connections of the simulated digital control system are shown in figure (2.1.1). The following notes are to be cleared :

- The ±15 volts outputs of the A/D converter were used to supply equivalent voltage inputs to the D/A .
- The ground of the whole circuit was commoned with the ground of the computer.
- The ports were configured as follows

  Port A as output of the interface unit to the D/A converter.

  Port B as input to interface unit from the A/D converter.

  Port C upper as output and C lower as input.

The synthesis and operation of the system is presented in the following section.

2.1.3. SOFTWARE DEVELOPMENT

The hardware connections of the preceeding section will mean nothing to the computer, " Just like a car without a driver " (9)without a program thatwould control input, manipulation, and output processes. The main operation of the needed software is as follows :

An input analog signal is given to the A/D converter, then after configuring the ports by the control word, the program tells the A/D converter to start conversion which would take about 200μsec. After the conversion is completed, the A/D sends a signal to the computer informing it that the conversion process has been completed, which is the same as data is ready for transmission. Afterwards , the computer permits the data to pass through the computer by the data enable signal. Manipulations being carried out, the program sends the data to the output port, latched to the preceding value, and then to the D/A converter which will give the final output in an analog form (9).

The details of these steps are shown in the following program written in BASIC language. A description of each statement is there,too.

```
10    X = 49347
20    POKE X,131
25    POKE X,48
30    POKE X,8
40    POKE X,9
```

```
50    POKE X,10
60    Y = PEEK (49345)
70    Z = Y * 1
80    POKE 49344,Z
90    POKE X,11
100   FOR K=1 TO 300 : NEXT K
110   GOTO 30
120   End
```

This program is composed of several statements that all together will control the hardware configuration. Before we go on elaborating on those statements and their functions, we must give an explanation of the procedure in which the controlling signals are used.

The conversion process is controlled by the generation of 4 signals, namely, *Start Conversion (SC)*,*End Of Conversion (EOC)*, *Data Enable (DE)*, and *End Of Conversion Enable (EOCE)*. These signals are all active *low*; that is, they are initially set to *high* and should be set *low* if needed. The figure below shows a schematic diagram of the connections between the A/D converter and the interface unit preceeding software programming.

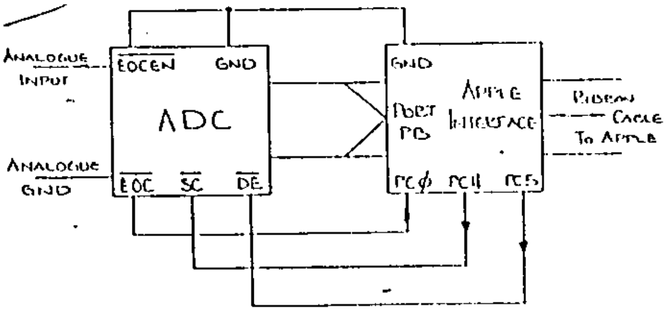


Fig. 2.1.2. A/D converter to interface unit connections.

At first the program sets the *SC* signal at low; to inform the A/D that the conversion process is to begin. The A/D takes the analog data and converts it, returns a signal, *EOC*, to the program, that informs the program of the completion of conversion process. Later, the program sets the *DE* low meaning that the data is ready to be transferred. The computer, then, reads the output port of the A/D and takes it into its memory . Necessary manipulations are then carried out and sent back to the D/A . The timing of the signals is shown in the following figure(6).

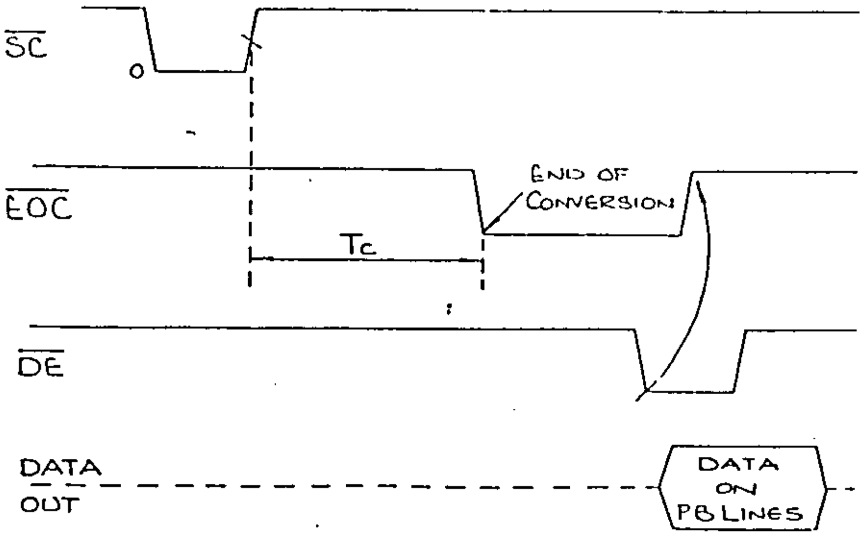


Fig.2.1.3. Timing of the control signals.

A description of the functions of the program is presented below

X = 49347 : This gives the variable X the value of the the control register address for future use in the program.

POKE X,131 : This write operation is done to configure

the ports as input and output (Table 1.3.2) . This word instructs the computer to define port A as output, B as input, C_{Lower} as input, C_{Upper} as output.

POKE 49346,48 : This write statement is sent to the 49346 address which is the C port. It sets all bits to high.

POKE X,8 : Sets *SC* low.

POKE X,9 : Sets *SC* high.

As we note that the *SC* is set high immediately, since we need it only to initiate the conversion process. It is obvious that we can't keep it low all the time because the A/D converter will keep on conversion based on its conversion time and not on the sampling time set by the program.

POKE X,10 : Sets *DE* low.

Y = PEEK (49345) : The data is read by the program from port B with 49345 address.

*Z = Y * 1* : Data manipulation is carried out here.

POKE 49344,Z : The data is sent through a write statement to the address 49344 which is port A that is connected to the D/A converter.

POKE X,11 : Sets *DE* high again.

FOR K=1 TO 300 : NEXT K : This is a delay that specifies the sampling time.

2.2. TESTING AND SIMULATION

2.2.1. INPUT SIGNALS APPLIED AND RESULTS

The simulated signal control system was used with DC and AC signals. Several DC voltages were applied taking

into consideration that the unipolar voltage did not exceed 5 volts, since it is the maximum allowed voltage (9).

Different AC waveforms were applied also, namely, sinusoidal, square and triangular. These signals were applied with a DC offset, since we are working with positive values only. The results of these experiments showing input signals applied and output waveforms are given in Appendices C , D.

2.2.2. SIMULATION OUTCOME

After the completion of this part of the project, we were able to proceed to interface the digital control system to a real life problem. The following points are to be highlighted :

* At first, we should say that the digitization process has been achieved on the APPLE computer with avery acceptable accuracy. This can be seen clearly from the charts in the appendix for which the synchronized ladder waveform of the output is a clear indication of good digitization process. This accuracy is good enough to make the system applicable to real life problems.

*An important feature of any digitization process is the sampling rate. In the theory part it was stated that the sampling rate should be at least twice the highest significant frequency of the signals received. For practical applications, it should be 10 times to yield good results.

This was experimentally proved when we applied a 0.2 Hz signal to the system with sampling rate of 2 Hz. The charts

in the appendix show that signals with frequencies higher than 0.2 Hz were tending to lose more information.

* During the experimentation phase, a PRINT statement was introduced to print decimal input and output values to keep a close eye on what was happening. This software command led to a great change in the sampling time , hence, the frequencies acceptable to the system. That PRINT statement was removed and only employed when no results were extracted.

In the following figure, the graph was obtained on a chart recorder. It is a clear indication to proceed to the next step.

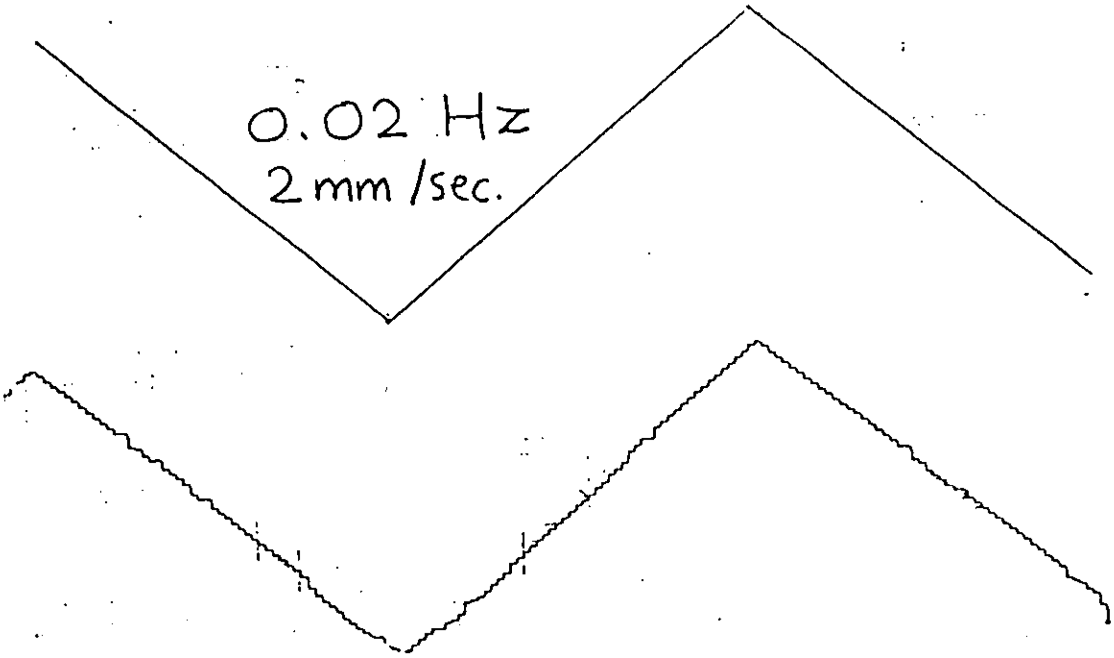


Fig.2.2.1. A simulated response of the system.

CHAPTER THREE

REAL LIFE APPLICATION OF A DIGITAL CONTROL SYSTEM

THE COUPLED TANK

3.1. THE COUPLED TANK APPARATUS

3.1.1. INTRODUCTION

A commonly occurring control problem in the chemical process industries is the control of *fluid level* in storage tanks, chemical blending and reaction vessels. A typical situation is one in which it is required to supply fluid to a chemical reactor at a constant rate q_o. This may be achieved by a *feedback* control loop which maintains a constant level H of fluid in the tank by controlling the input flow rate q_i (10).

Fluid level control is therefore a very basic and important problem in automatic control. The Industrial Engineering department of the University of Jordan has been offering laboratory experiments on a model set up to demonstrate concepts of *Automatic Control Theory.*

The basic experimental set up consists of two hold-up tanks which are coupled by a group of orifices. The input is supplied by a variable speed pump, which supplies water to the first tank. The basic control problem lies in how to control water level (H2) in tank 2 by varying the pump speed. The system is a simple one with a transfer function of the 'second' order.

$$T(s) = \frac{H_2(s)}{Q_i(s)} = \frac{K}{(1 + s * T_1)(1 + s * T_2)}.$$

The schematic diagram of the coupled tank apparatus is shown in the figure below (10).

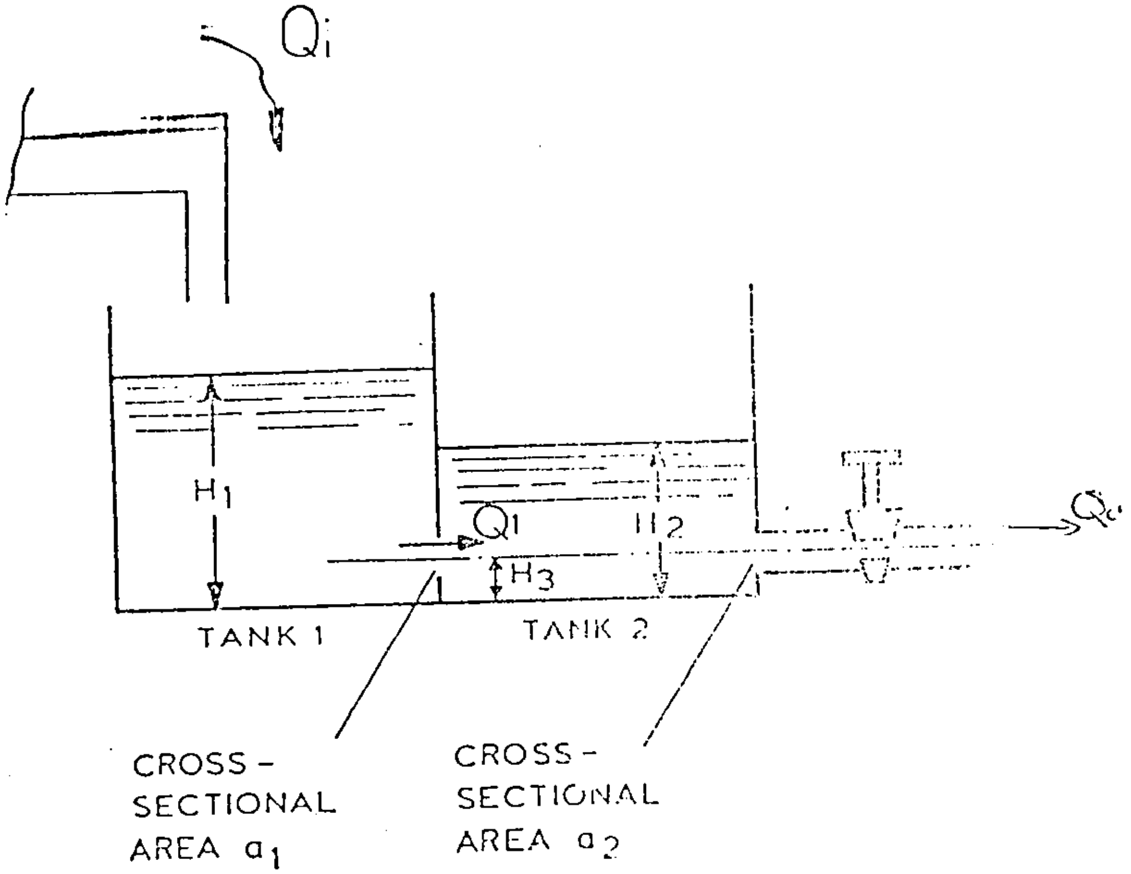


Fig.3.1.1 Schematic diagram of the Coupled Tank.

The aim of this apparatus is to demonstrate the following points :

a) Determining the dynamical characteristics of a *slow* process system.

b) Design of different control algorithms.

3.1.2. MODELING

The open loop control system is as shown in the following figure.

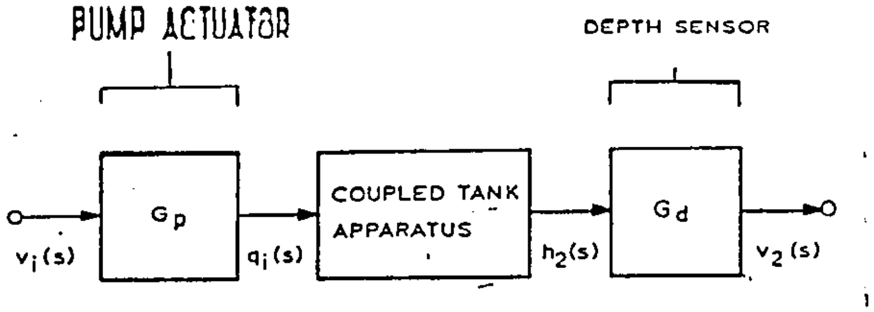


Fig.3.1.2. Forward path block diagram.

The open loop transfer function can then be written as

$$G(s) = \frac{V_2(s)}{V_1(s)} = \frac{K}{T_1 * T_2 * s^2 + (T_1 + T_2)s + 1}.$$

where K_p = control action , K_{plant} = plant constant

K_{sensor} = sensor calibration constant

$K = K_p * K_{sensor} * K_{plant}$.

The feedback control loop can be closed around the open loop system as shown in the following figure. Here, K(s) specifies a given controller form (10).

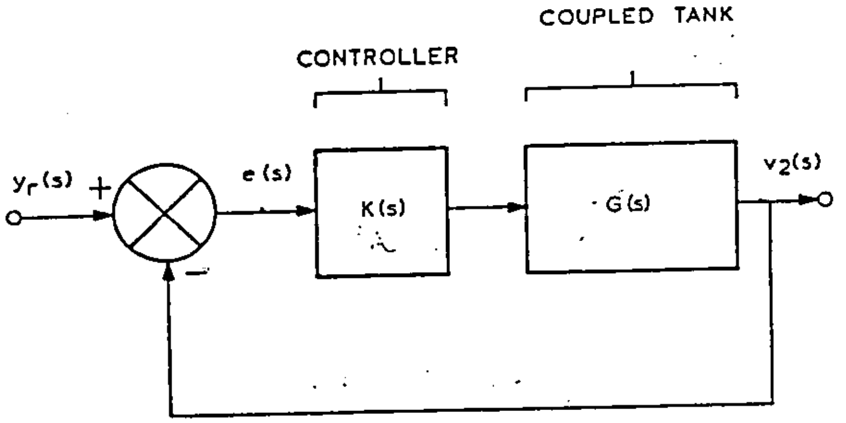


Fig.3.1.3. Closed loop control.

The closed loop transfer function is

$$\frac{V_2(s)}{Y_r(s)} = \frac{K(s) * G(s)}{1 + K(s) * G(s)} .$$

This transfer function guides the experimenter to the controller design process according to the desired response (10).

3.2. DIGITAL CONTROL OF THE COUPLED TANK

3.2.1. PROBLEM DEFINITION

The coupled tank apparatus discussed previously is to be used to demonstrate digital control applications. The apparatus is now being controlled via an analog computer. This means of control has some drawbacks. One is the difficulty to produce a fine range of gains due to resistance value limitations. Adapting the mode of control from analog to digital gives the flexibility to introduce a whole range of gains.

Moreover, it is rather easier to do manipulations when generating different control algorithms, by using digital computers. Analog controllers require additional circuitry when changing from one control algorithm to another (e.g. from proportional to proportional plus integral). The requirement may differ from operational amplifiers to capacitances and resistors used for feedbacks and gains . Making use of digital computers, performing the same functions requires only few more computer statements inside the software.

The digital control system developed takes a single input signal and returns back a single output signal. The incoming signal should range from *zero to five volts*. *Negative values* are discarded and not manipulated. The input signal coming from sensor # 2 on the coupled tank will be processed under the following operations:

1. *Sampling* at a periodic rate of sampling.
2. *Quantization* according to the specifications of the analog

to digital converter.

3. *Manipulation* inside a computer software.
4. *Digital to analog conversion* that returns the signal as a semi analog one.

The output signal produced after step 4 is fed to the pump where the control action is to be executed. The input signal coming out of sensor #2 is continuously varying leading to a continuously varying output.

3.2.2. CONFIGURATIONS

Previous practice recommends various configurations of digital control systems . These configurations are different in the way the different elements are placed in. Some place the sensor in the forward path , whereas others place it in the feedback path.Likewise, the location of the*sample and hold* circuit is another distinguishing factor. All of the above, affect the way signals are to be treated (11).

Two simple configurations used to build digital control systems are shown below

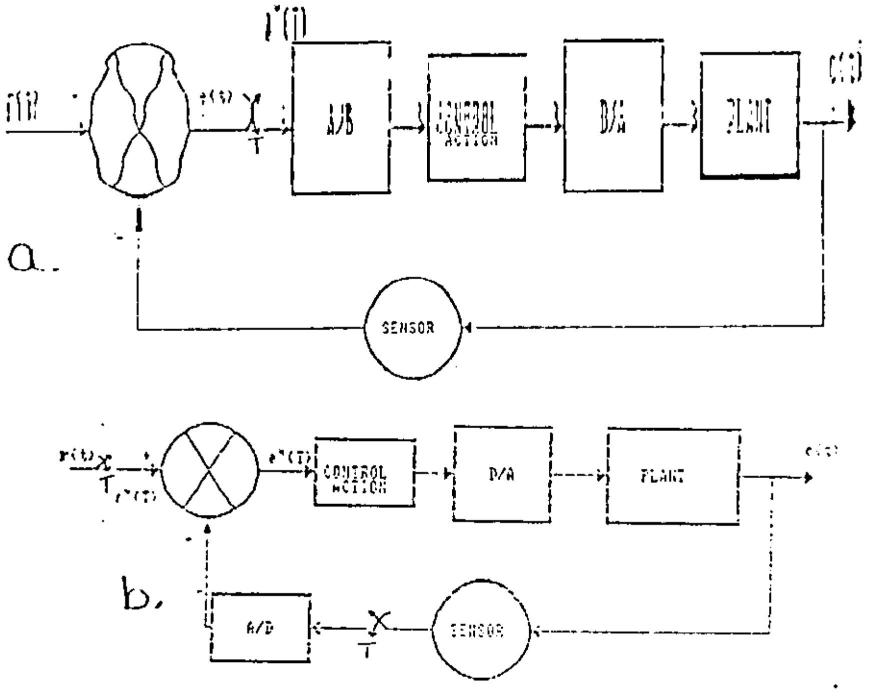


Fig.3.2.1. Configurations used to build digital control systems.

For the first one, the reference voltage signal is summed to the feedback signal in an analog form. The resulting error signal is now in analog form and is fed to the *sample and hold* circuit. The signal then is processed as explained earlier.

For the second configuration, the signal coming out of the plant sensor as a feedback is digitized, and summed to the input in digital form . The summing is performed inside the software while for the first case by an operational amplifier.

The choice between both configurations relies on the requirements of the user. The first case ,as mentioned above, requires an analog part to handle the summing. The second one requires a precise calibration procedure for both digital signals , reference and sensor,. to be of one to one correspondence.

For our experimental work, the second configuration was

adopted. The reason for that was mainly due to the need to reduce elements involved in building the system ; hence, reduce irregularities.

The model configuration used assumed that signals coming to the summing point are binary valued.

3.2.3. S & Z - PLANE PLANT TRANSFER FUNCTIONS

The block diagram of the plant being under *analog* control is reproduced below.(Fig.3.2.2.)

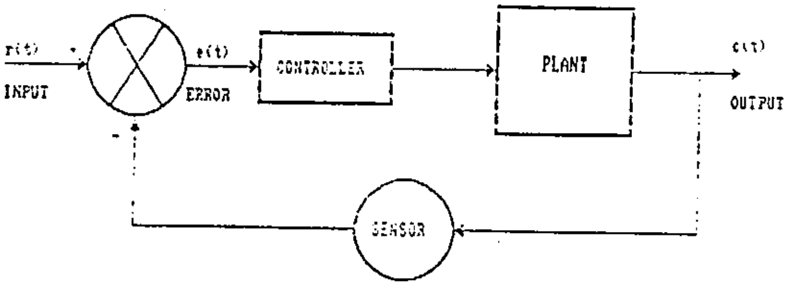


Fig.3.2.2. Block diagram of the plant under analog control.

The forward path transfer function for a proportional controller with gain of K_p is

$$G(s) = \frac{K_p * K_{pump} / K_2}{(s*T_1+1)(s*T_2+1)}$$

Introducing the sensor in the forward path to allow for the same units for in the numerator and the denominator (volt / volt instead of cm / volt) , the numerator constants will be multiplied by $K_{sensor} = 0.2$.

Let the constant $K = K_p * K_{pump} * 0.2 / K_2$ where

$K_{pump} = 11$, K_2 = Plant Constant = 2.28.

Then we are going to deal with one constant in the numerator. Experimental work carried out on the coupled

tank apparatus adopted the equations listed above .

Adapting the system to be digitally controlled led to the need to introduce a new transfer function to include the new elements added to the model.

The ZOH circuit has an s-plane equivalent equal to $\dfrac{1-e^{-sT}}{s}$.

The A/D and the D/A were calibrated to have a forward overall gain of one. Then, the *controller* that lies in between both elements has a transfer function characteristic of the control algorithm applied. The forward path is shown here.

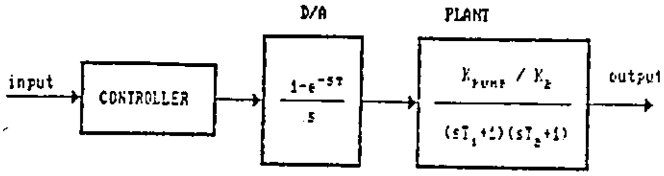


Fig.3.2.3. Forward path in the digital controlled plant.

Assuming that *proportional* control is applied, the closed loop model of the system is reduced to,

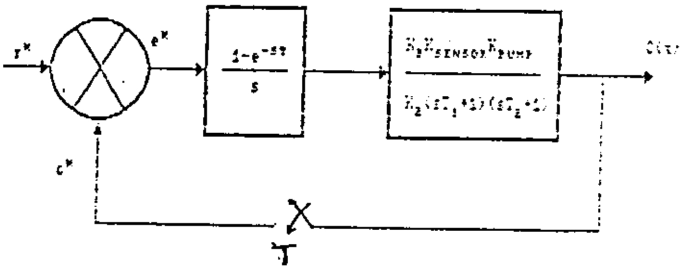


Fig.3.2.4.Closed loop digital control in s-plane.

The *Laplace* transform of the transfer function

is then

$$T(s)=\frac{K*(1-e^{-sT})}{s*(s*T_1+1)(sT_2+1)+(1-e^{-sT})*K}$$

The D/A acts as a *ZOH* circuit in the forward path. The Z-transform equivalent of the forward path is now

$$G(z) = (1-z^{-1}) * Z\left\{ \frac{K}{s(s*T_1+1)(s*T_2+1)} \right\}$$

$$T(z) = \frac{G(z)}{1 + G(z)} ,$$

Partial fraction expansion was used to find the z-transform ,

$$T(z) = \frac{K * H * z + K * P}{z^2-(A+B-K*H)*z+(A*B+K*P)}$$

where

$A= e^{-T/T1}$, $B= e^{-T/T2}$

$M = T_2 - T_1$, $F = T_1/M$, $J= T_2/M$

$H = 1+(A*T_1-B*T_2)/M$, $P = (A*B*M + T_1*B-T_2*A)/M$

Those variables are dummy variables, and were only employed to reduce large terms coming out of mathematical operations. Those variables were also used for computer programs coded to find the system response by following some steps that will be discussed at later sections.

3.3. PREPARATION WORK

3.3.1. SYSTEM INITIATION

As the computer software for AC & DC experiments was successfully tried out, and as for the hardware elements of the digital control system were working properly , it was time to hook up the coupled tank apparatus to digital elements. The initiation process involved some steps that are to be discussed hereby.

The *reservoir* of the coupled tank apparatus was filled with water up to a certain level to avoid air being pumped in,which causes pump burn out. The tanks were filled with some water to give initial conditions for the system.

A lead was connected from the input port on the *analog to digital* converter to the output of sensor #2.

A second lead was connected from the output port on the *digital to analog* converter to the input of the pump. The pump was activated by signals coming out of the computer through this second lead.

Both A/D and D/A converters were set at the unipolar mode due to the following reasons. Negative signals going out to the pumphasno meaning because the pump can't reverse its rotation direction. Another reason is that the whole decimal scale(0-255) will have to cover both negative and positive values which leads to smaller input sensitivity .

The pump was secured not to receive any voltages greater thanfive volts because of D/A converter

specifications that state " maximum output voltage = five volts " . By this , we have been ready to start the calibration procedure.

3.3.2. SYSTEM CALIBRATION

System elements were calibrated to ensure accuracy and consistency . Three locations in the model were precisely adjusted for this purpose.

First, a voltmeter was connected at the sensor output and a *Print* statement

```
PRINT E
```

was introduced after reading the input signal as discussed earlier. Water level at the tanks was varied to collect a set of points. At each point, the voltage was read on the voltmeter as well as on the computer screen in *decimal* values. Those readings were used to generate a scale of *reference* values to be entered at the summing point in the computer program. Moreover, thosereadingsin conjunction with similar ones obtained at the output port were used to to establish a one - to - one gain of both converters. Second, the same process was repeated at the output port. A screen output statement was used to display the processed value

```
PRINT Z
```

and compare it with voltmeter readings that was placed at the pump input. The unity gain was obtained by changing the potentiometer resistances placed at the top of both converters.

A statement in the program

Z = E

transmitted the same input to the output port. At a set of points, both voltmeter readings were ensured to be typically equal.

The calibration procedure produced the following scale

1 VOLT ≡ 52 DECIMAL READING ON THE COMPUTER SCREEN.

This means that when we require a reference voltage of, say , 3.2 volts , a value of 167 has to be entered at the summing junction. Calibration curves are given in Appendix E.

Calibration was carried out at a third point. *Sampling time* controlled via the delay statement inside the software was obtained at various points . The delay statement in the program is

```
FOR K = 1 TO D : NEXT K
```

and D was varied at the beginning of the program to obtain a set of sampling rates (sampling rate = 1 / sampling time). Statements in the software have relatively small execution time (0.2 µsec). However, they were kept the same all the time and the change in the sampling time was only due to changing the value of D.

Two points were obtained and used throughout the experimental process.

D	T (sec.)
300	0.45
150	0.25

Table 3.3.1. Sampling time at different delays.

Special attention is to be taken when measuring the sampling time if any long-execution time statements are included in the program. **PRINT** statements that send data to a monitor or to a printer affected noticeably the value of T measured. This is due to the fact that before processing to the next software statement , the *central processing unit* is to communicate with the screen or the printer , thus delaying execution.

Typical values of the sampling time were chosen for every group of data extracted from the experimental data . It was cited whenever the topic was under analysis.

Those three locations where calibration was carried out were adjusted every time data was obtained for analysis. A slight change in the settings produces tremendously deviated results.

CHAPTER FOUR

EXPERIMENTS AND RESULTS

4.1. EXPERIMENTAL WORK

Passing both the calibration and initiation procedures, the system was ready to experiment on. Before applying closed loop control, the system has been tested to produce feasible data. Two tests had to be conducted to accomplish the basis for closed loop digital control.

Forward path operation was tested by feeding in an error signal starting at zero for the A/D converter and observing the response at the other end. Feeding in this error signal was done through filling the tank with water to a certain limit , writing the *reference voltage* to the computer through the statement :

E = REF - Y (Y is the digitized signal coming from the sensor).

and then monitoring the response of the plant at the D/A converter on a chart recorder. This was done to check for excessive I.C. loading emerging from the system behavior. Moreover, as a precautionary measure, a 0-5 volts *zener diode* was connected across the input terminal stage to limit excessive overshooting . This was done after having damaged an *integrated circuit* during testing due to overloading the A/D converter.The diode was connected between the sensor output and the A/D input.

Backward path operation was tested by connecting the sensor, as when calibrating the model , to the A/D converter where the D/A converter was not connected to

the pump. The pump was driven by a d.c. voltage supply ranging between 0 and 5 volts. The response was then observed on the computer screen by printing the control signal for a certain reference voltage. The control signal used was

$$Z = E * K_p.$$

The value of K_p was then varied and response was watched to detect any overshoots at the output end. This provided protection for the pump.

Both tests gave the *clear* signal to start applying closed loop digital control. The model was initiated , calibrated ,tested for any irregularities. Then, the sensor output which is the same as C(t) was observed and results were recorded . A chart recorder was connected at that point to obtain hard copies of the data. The A/D converter was connected to the sensor whereas the D/A converter was connected to the pump. The software had to be altered to handle the new model . The statements added were

```
E = REF - Y
  IF E < 0.01 GOTO 117
  Z = E * Kp.
```

The input signal is read and assigned the parameter Y. The error is formed by subtracting the Y- value from a reference voltage coded in decimal form. This error is tested for negativity because the D/A converter was set to a *unipolar* mode. Negative values on the output port result

in execution errors. Then, using this statement led to discarding thosesamples producing negative error signals. When the control signal Z isready, it is sent to the output port. The loop is reinitiated to take a new value. This step was common for both negative and positive Z-values.

4.2 CONTROL ALGORITHMS AND RESULTS

4.2.1. INTRODUCTION

Throughout the rest of this chapter, results obtained from the lab will be plotted against results obtained from the theoretical model analysis.The following experiments were carried out and reported :

1. At the same sampling rate
    a. different values of proportional gain K_p in response to different step input values.(transient response under analysis)
    b. different K_p's with the same step input.(steady state error under analysis)
    c. PI control experiments to reach stability.
2. At two different sampling rates : same K_p with same step input.

4.2.2. COMPARISON BETWEEN THEORY AND EXPERIMENTAL RESULTS

In this section, response of the coupled tank C(t) due to a certain step input value is to be compared to the theoretical response obtained after modeling the system in the Z- plane.

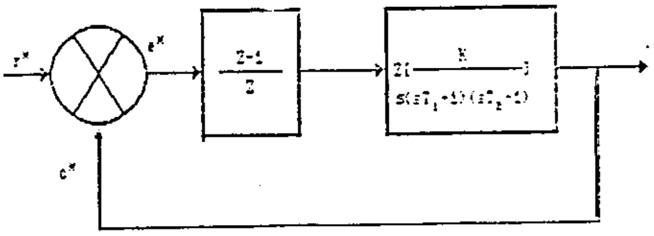


Fig.4.2.1. Z-transform of the model.

To take the *z-transform* of the function

$$\frac{K}{s(s*T_1+1)(s*T_2+1)} ,$$

partial fraction analysis was used. Then,

$$Z\left\{ \frac{1}{s(s*T_1+1)(s*T_2+1)} \right\} = \left[\frac{z}{z-1} + \frac{T_1*z}{M(z-B)} - \frac{T_2*z}{M(z-A)} \right]$$

where $M = T_2 - T_1$

$A = e^{-T/T2}$; $B = e^{-T/T1}$.

Adding the terms, multiplying by the zero - order hold equivalent z-plane transform , and simplifying the term leads to the following equation :

$$G_1(z) = \frac{K * H * z + K * P}{z^2 - (A+B)*z + A*B} .$$

Introducing the controller function which is

$D(z) = K_p$, resulted in a forward loop gain

$G(z) = K_p * G_1(z)$

The transfer function of the closed loop system is

$$T(z) = \frac{G(z)}{1+G(z)} .$$

Activating the system by the following step input

$R(s) = K_s/s$, $R(z) = K_s * \frac{z}{z-1}$,

and keeping in mind that $T(z) = C(z) / R(z)$, leads to the following

$$C(z) = \frac{R * z^2}{z^3 - Y * z^2 + Q * z - W}$$

where $R = K_s * K * H$, $D = K * P * K_s$

$V = A + B - K*H + 1$, $Q = A*B + K*P + A+B - K*H$

$W = A*B + K*P$.

Using time recurrsive technique to obtain the value of $C^{*}(t)$ at a set of sampling points, the following equation was used to find $C^{*}(t)$ $^{(4)}$.

$$C_n = V * C_{n-1} + Q * C_{n-2} - W * C_{n-3} + R * \delta_{n-1} + D * \delta_{n-2}.$$

This equation and other parameter definitions with the constant values were coded in a BASIC language software that enables its user to find enough theoretical results under different situations (different k_p & T values).

Transient response of the plant was recorded on a chart recorder. Data points were interpolated on the graph and compared to corresponding ones obtained theoretically. Curves of those data samples are shown next.

```
1 KP = 5
2 REF = 180
4 D = 300
10 X = 49347
20  POKE X,131
30  POKE 49346,48
50  POKE X,8
60  POKE X,9
80  POKE X,10
90 Y =  PEEK (49345)
92 E = REF - Y
94  IF E < 0.001 GOTO 115
97 Z = E * KP
110  POKE 49344,Z
115  POKE X,11
117  FOR K = 1 TO D: NEXT K
120  GOTO 50
130  END
```

Fig.4.2.2. Listing of the software used for K_p control.

Applying the proper statistical tests, which is to be discussed later, the digital control system proved that it was performing satisfactorily.

On the next pages , curves are listed for the following cases:

A. TRANSIENT RESPONSE ; PROPORTIONAL CONTROL

i. $C^*(t)$

1. $K_p = 5$; $T_s = 0.45$; $K_s = 0.59$
2. $K_p = 10$; $T_s = 0.45$; $K_s = 0.196$
3. $K_p = 5$; $K_s = 0.59$; $T_s = 0.45$ vs. $T_s = 0.25$
4. $K_p = 5$; $K_s = 0.59$; $T_s = 0.25$

ii. $E^*(t)$ *Experimental only*

1. $K_p = 5$; $K_s = 0.59$; $T_s = 0.45$ vs. $T_s = 0.25$.
2. $K_p = 10$; $K_s = 0.19$; $T_s = 0.45$ vs. $T_s = 0.25$

Note: K_s = Step input amplitude.

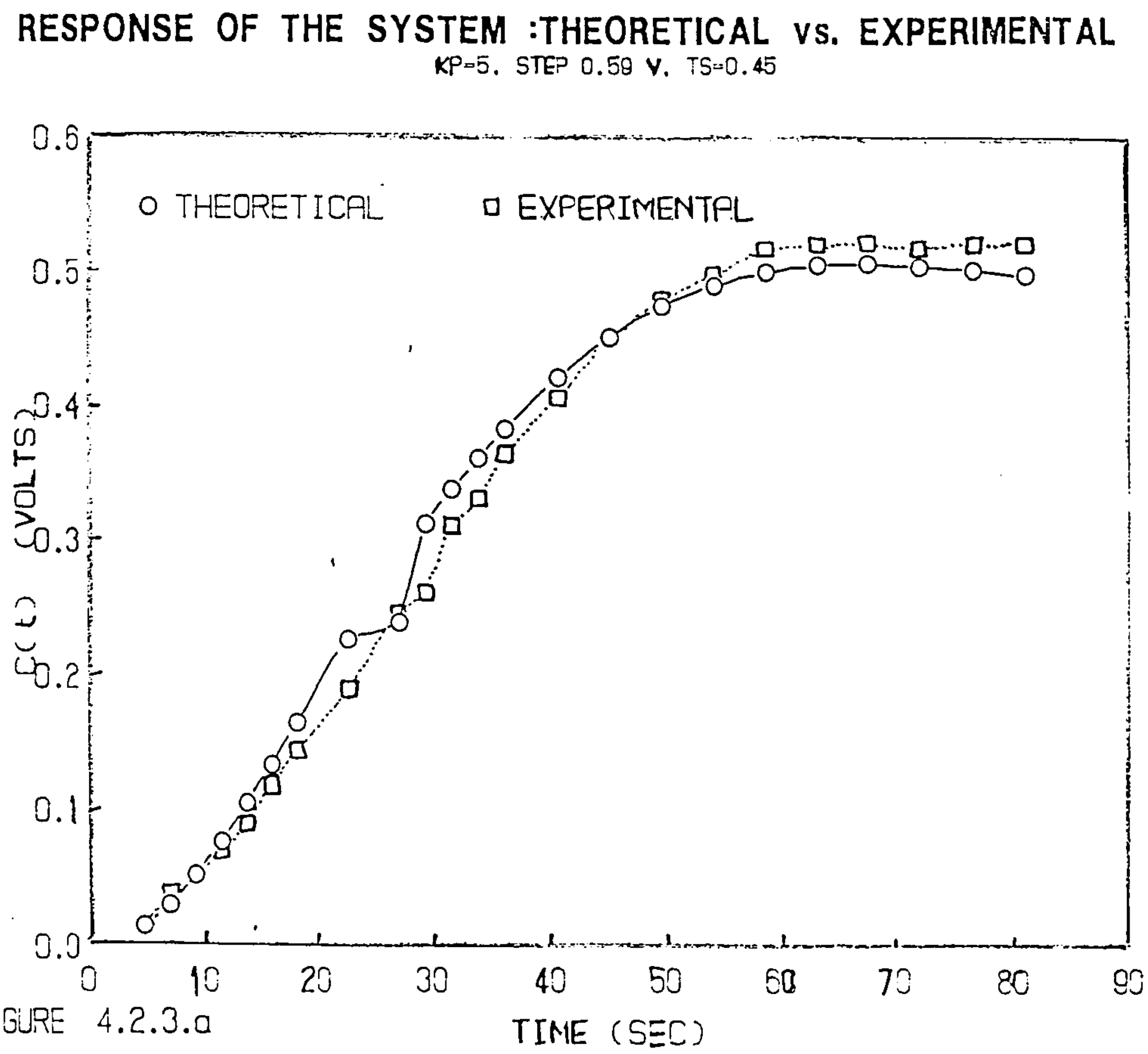

RESPONSE OF THE SYSTEM :THEORETICAL vs. EXPERIMENTAL
KP=5. STEP 0.59 V. TS=0.45
○ THEORETICAL
□ EXPERIMENTAL
C(t) (VOLTS)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
60
70
80
90
TIME (SEC)

FIGURE 4.2.3.a

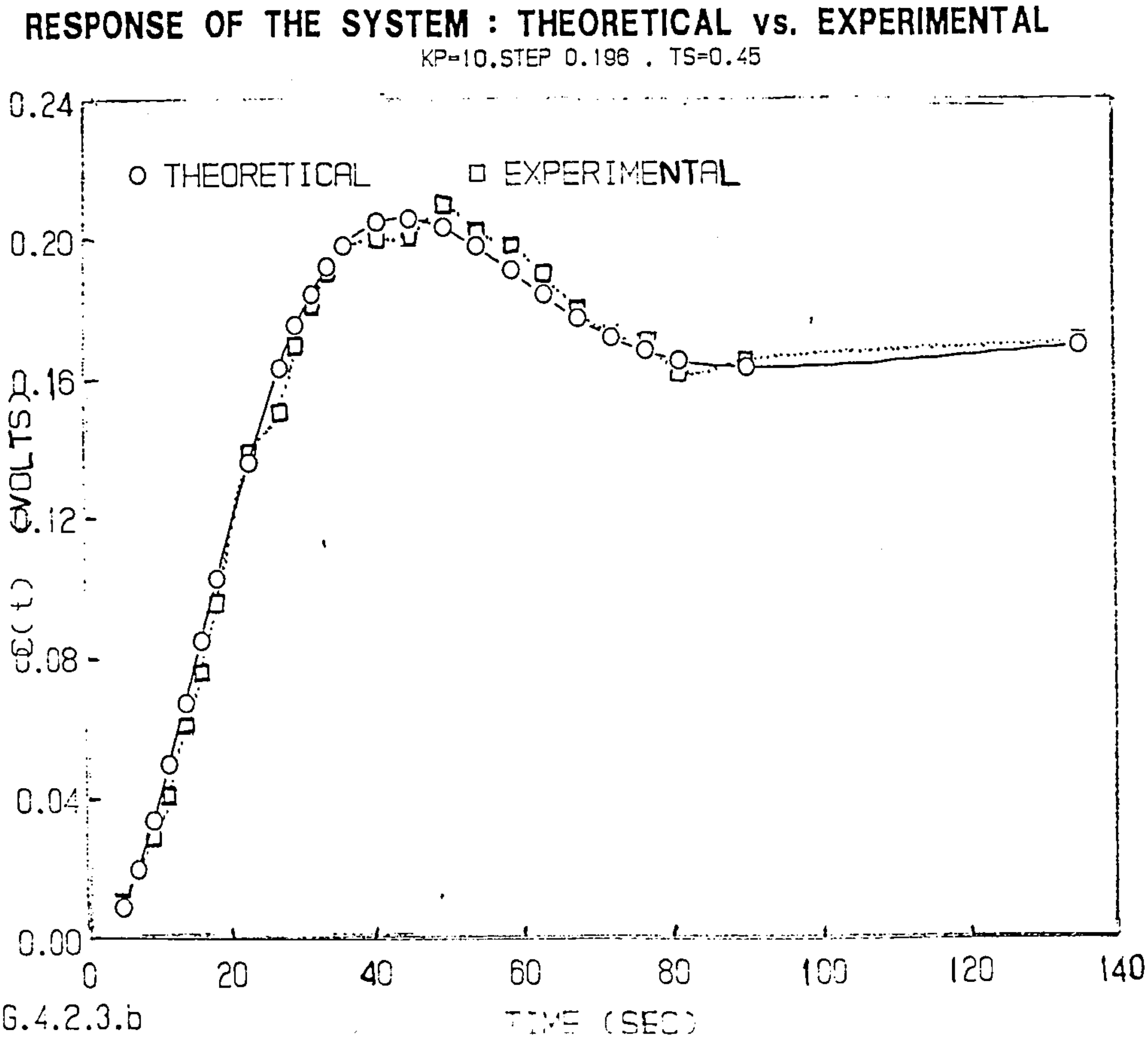

RESPONSE OF THE SYSTEM : THEORETICAL vs. EXPERIMENTAL
KP=10.STEP 0.196 . TS=0.45
○ THEORETICAL
□ EXPERIMENTAL
0.24
0.20
0.16
0.12
0.08
0.04
0.00
C(t) (VOLTS)
0
20
40
60
80
100
120
140
TIME (SEC)

FIG.4.2.3.b

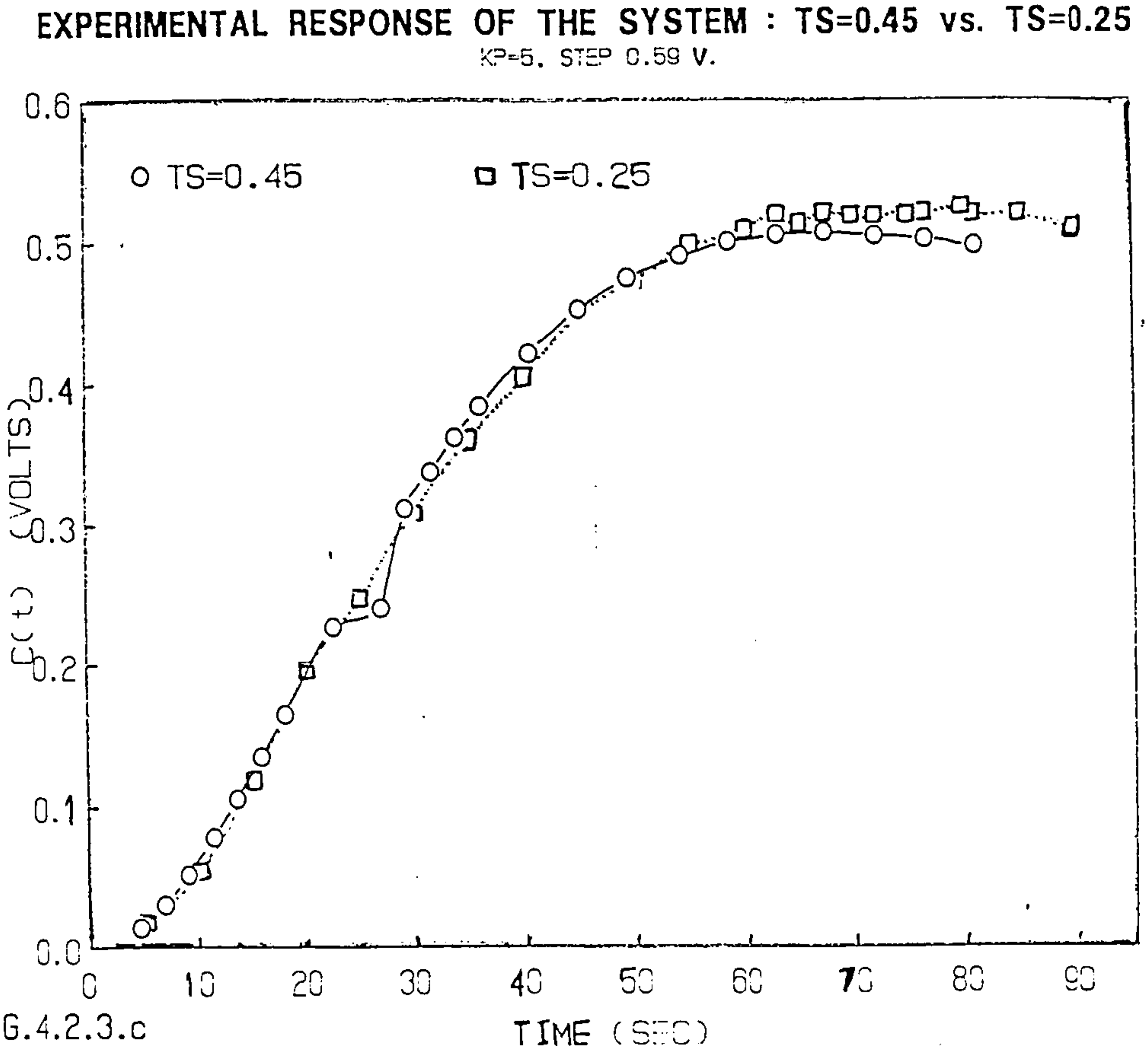

EXPERIMENTAL RESPONSE OF THE SYSTEM : TS=0.45 vs. TS=0.25
KP=5. STEP 0.59 V.
○ TS=0.45
□ TS=0.25
C(t) (VOLTS)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
60
70
80
90
TIME (SEC)

FIG.4.2.3.c

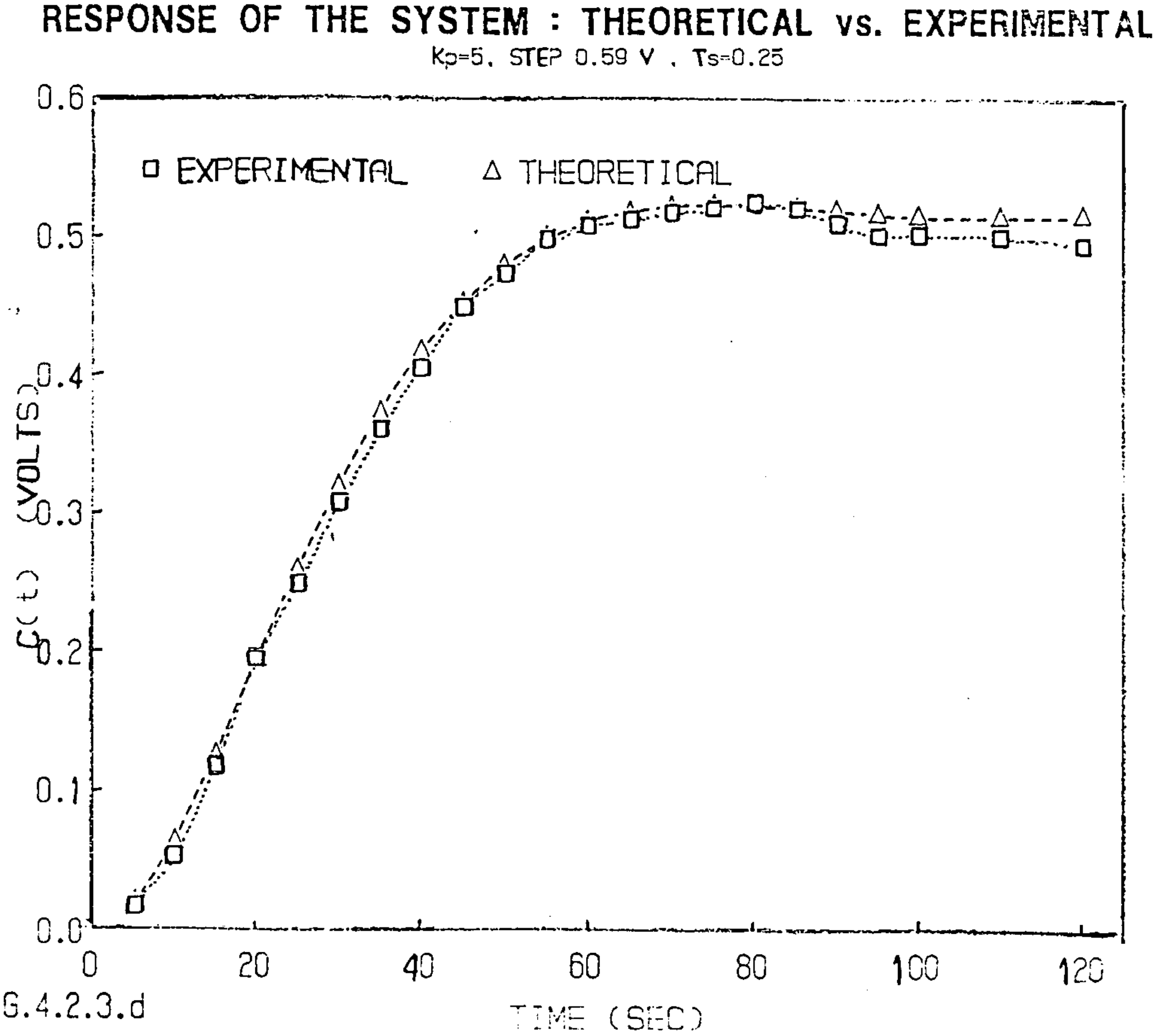

RESPONSE OF THE SYSTEM : THEORETICAL vs. EXPERIMENTAL
Kp=5, STEP 0.59 V , Ts=0.25
□ EXPERIMENTAL
△ THEORETICAL
C(t) (VOLTS)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
20
40
60
80
100
120
TIME (SEC)

FIG.4.2.3.d

ERROR OBTAINED AT THE SUMMING POINT

Ts = 0.5 vs. Ts = 0.25

KP= 10 , STEP = 0.196 V.

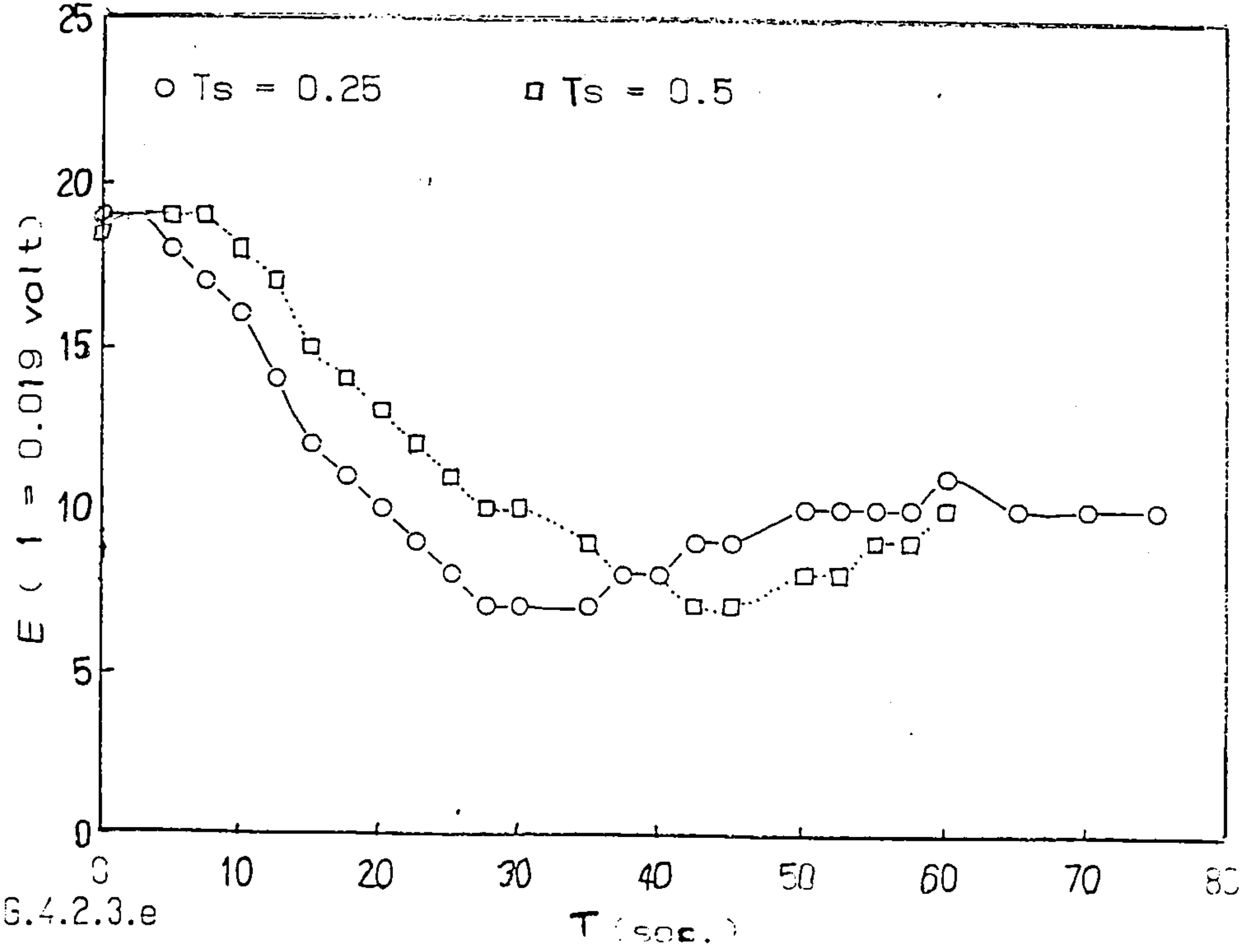


FIG.4.2.3.e

ERROR OBTAINED AT THE SUMMING POINT

Ts = 0.5 vs. Ts = 0.25

KP= 5 , STEP = 0.59 V.

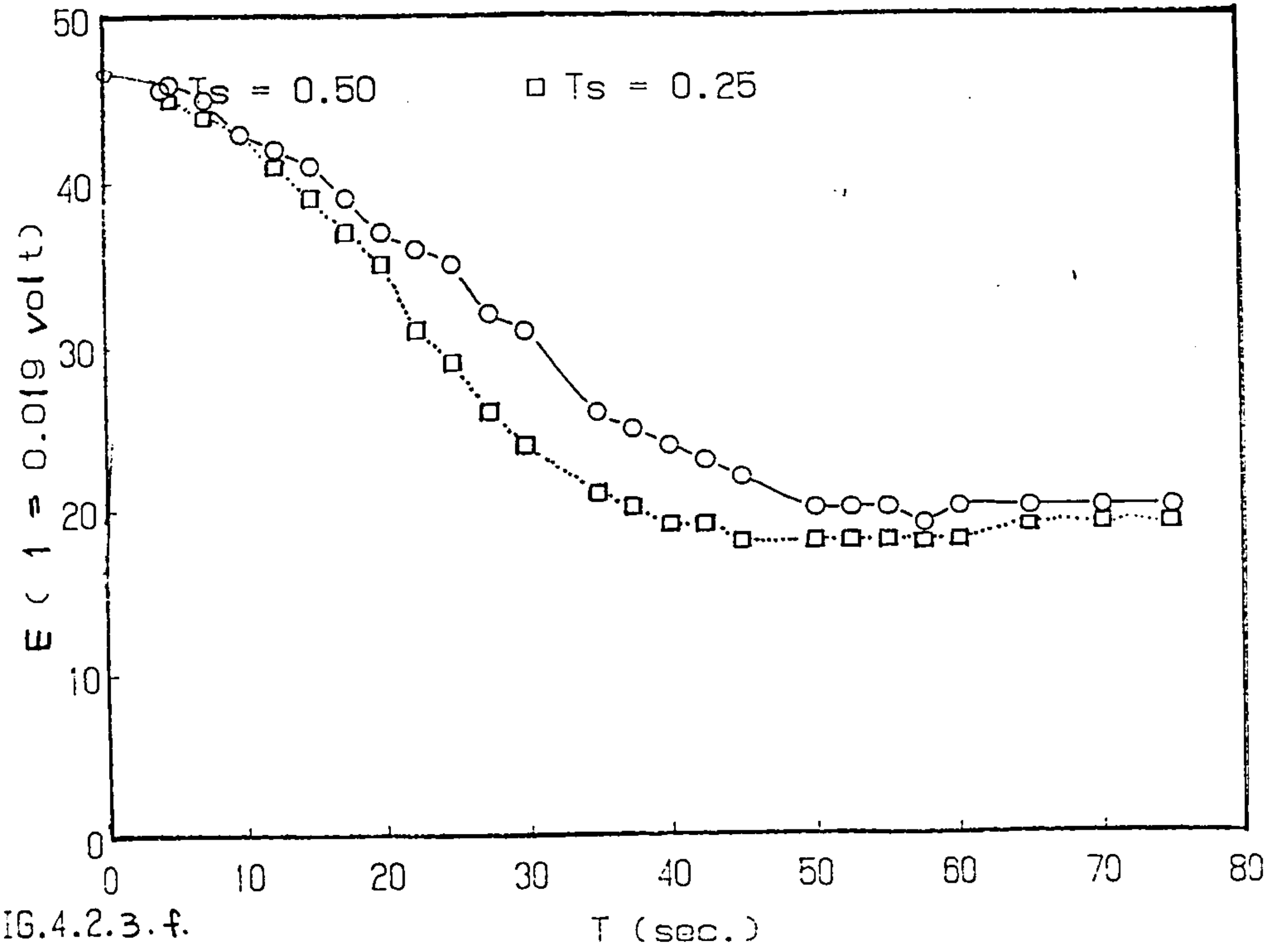


FIG.4.2.3.f.

Remarks following are for the curves shown on previous pages :

1. As a result of decreasing the sampling time , transient response judged by the percentage overshhot was better. At $T_s = 0.45$, P.O.= 12.8 % , whereas for $T_s = 0.25$, P.O.= 8.33 % .
2. The results show that the higher the K_p value , e_{ss} was smaller. This is clear from the next topic discussed hereby.

STEADY STATE ERROR

Steady state error is a criterion to judge the accuracy of the step response. Steady state error is experimentally defined as the difference between the steady state value the output reaches, and the applied input . Mathematically speaking

$$e = c - r$$

$$e_{ss} = \frac{\text{Perturbation in Output} - \text{Perturbation in Input}}{\text{Perturbation in Input}}$$

Theoretically, the mathematical formula used to find the error differs following the way steady state is reached. The static steady state error is determined by the response characteristics of the system elements. However, if steady state is reached by introducing a step input for a given K_p value and a type-0 system, then it is a *dynamic error*. This type of error is given by

$e_{ss} = 1/(1 + K_{pp})$; where $K_{pp} = \lim_{z \to 1} G_1(z) * D(z)$

$D(z) = K_p$ [4].

The value of K_{pp} for our model is

$K_{pp} = K_p * 0.2 * 11 / K_2$.

Using the equations above , a set of data were observed at the lab and compared to theoretical results at T = 0.45 . The step input introduced was 0.192 volts.

K_p	THEORETICAL %	EXPERIMENTAL %
2	34	37.5
4	20.6	21.875
6	14.73	11.46
8	11.47	6.25
10	9.39	6.25

Table 4.2.1. Steady state error .

The graph next is a representation of the effect of K_p.

THE RELATION BETWEEN KP AND STEADY STATE ERROR

THEORETICAL vs. EXPERIMENTAL

STEP 0.196 V.

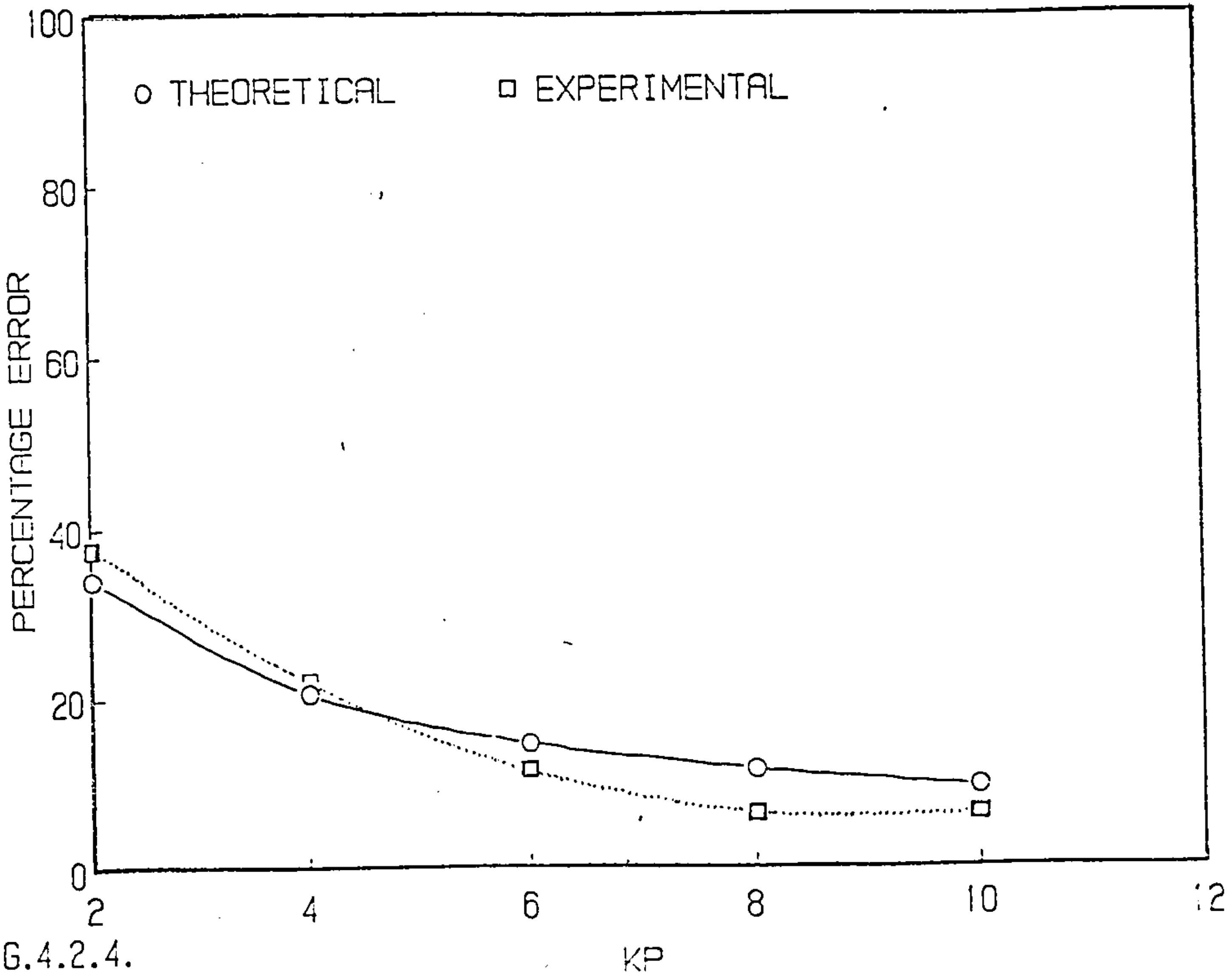


FIG.4.2.4.

B. PROPORTIONAL PLUS INTEGRAL CONTROL ALGORITHM

Another widely used control algorithm is the one called PI. This algorithm has some advantages over P-controllers. Steady state error gets closer to zero when PI control is used for a type-0 system and a step input. System overshoot and transient response are optimized by properly selecting values of K_p & K_I.

PI control algorithms make use of the history of plant behavior as a second parameter , the first is the mean time error, to get control over the system. It is *mathematically* defined as

$$K_p * E(t) + K_I * \int_0^t E(t)\, dt.$$

Experimental work was carried out during this project to apply PI control. The error was accumulated at a register, inside the software. The above mathematical equation had to be approximated because our software can't handle *integral* terms. The integration was approximated using the rectangular approximation. The statements added to the software are highlighted next. V is a register tohold the cumulative error

V = T * E

```
1 KP = 5
2 KI = 0.1
3 REF = 180
5 V = 0
10 X = 49347
20  POKE X,131
30  POKE 49346,48
50  POKE X,8
60  POKE X,9
80  POKE X,10
90 Y =  PEEK (49345)
91 E = REF - Y
92 V = V + E
94  IF E < 0.01 GOTO 115
97 Z = KP * E + KI * 0.5 * V
110  POKE 49344,Z
115  POKE X,11
117  FOR K = 1 TO 300: NEXT K
120  GOTO 50
130  END
```

Fig.4.2.5. Listing of the PI control software.

Running this software with the following parameter values

$K_p = 5$, $T = 0.5$

and changing the value of K_I produced an *unstable* response at the plant output, but in no way it is to mean that PI control is not applicable to our system. However, changing T experimentally as low as 0.25 sec ,the lowest acheivable sampling time, was no good. A plot of the response is shown in the appendix.

4.2.3. STABILITY ANALYSIS

It is important to prove theoretically that the closed loop system is unstable for given defined controller parameter values. The plant equation is

$$G_1(z) = \frac{K * H * z + K * P}{z^2 - (A+B)*z + A*B} .$$

The new controller is $N = K_p + K_I * T_s$.

The new transfer function for the whole system is

$$T(z) = \frac{D * z^2 + V * z - R}{z^3 - (A+B) * z + A * B} ;$$

where $D = K * N * H$, $R = K_p * K * P$

$V = N * K * P - K_p * K * H$, $X = A * B + R$

$Q = A + B + 1 - D$, $W = A * B + A + B - V$

and A , B , H , P , M are as defined earlier.

Applying the same input, as in P-control and following the same procedure to find the plant response at a series of T values , led to the following equation

$$C_n = (1 + Q) * C_{n-1} - (W + Q) * C_{n-2} + (X + W) * C_{n-3}$$

$$- X * C_{n-4} + K_s * D * \delta_{n-1}$$

$$+ K_s * V * \delta_{n-2} - R * K_s * \delta_{n-3}.$$

Those equations were coded into a BASIC language computer program , the resulting response was unstable at

$K_p = 5$, $T = 0.45$, $K_i = 0.1$.(look at the appendix for graphs, C.3)

Stability tests are useful means to find the range of values that cause instability. However, only one unknown parameter could be solved for. Such tests are Root locus, Nyquist, and the Routh-Hurwitz. The last one , the *Routh-Hurwitz* criterion, tests the characteristic equation of a plant with the following transfer function

$$T(s) = \frac{G(s)}{1 + G(s) * H(s)} .$$

The characteristic equation ,then, is $1 + G(s) * H(s) = 0$.

It is ,usually, of the form $B_1 * s^m + B_2 * s^{m-1} + \ldots + B_m = 0$.

The next step is to form the following table of coefficients

$$\begin{array}{l|llll}
s^m & B_1 & B_3 & B_5 & \ldots\ldots \\
s^{m-1} & B_2 & B_4 & B_6 & \ldots\ldots \\
 & U_1 & U_3 & U_5 & \ldots\ldots \\
 & U_2 & U_4 & U_6 & \ldots\ldots \\
s^0 & & & &
\end{array}$$

Where $U_1 = \dfrac{B_2 * B_3 - B_1 * B_4}{B_2}$, $U_3 = \dfrac{B_2 * B_5 - B_1 * B_6}{B_2}$

etc.

The criterion states that only those parameter values which do not cause a change in the sign of the first column set the stability margin.

For a digital control system, to use the Routh - Hurwitz criterion , the characteristic equation has to be modified. The criterion should be only applied in the W - PLane , where

$$z = \frac{1 + w * T/2}{1 - w * T/2} \quad , \quad w = \frac{2}{T} * \frac{z-1}{z+1} \quad .$$

To test the model, every z is substituted for in terms of w in the characteristic equation. The new equation is

$$X_4 * w^3 + X_5 * w^2 + X_6 * w + X_7 = 0,$$

where X_4 , X_5 , X_6 , X_7 are dummy variables used in the algebra to reduce the number of terms. K_p and T were held constant ($K_p = 5$, $T = 0.5$)where K_I was the parameter to solve for. The Routh - Hurwitz table became

$$\begin{array}{c|cc} W^3 & X_4 & X_6 \\ W^2 & X_5 & X_7 \\ W^1 & \frac{X_6 * X_5 - X_7 * X_4}{X_5} = U_1 & \\ W^0 & X_7 & \end{array}$$

Those variables were found ,in terms of K_I, to be

$$X_4 = 0.1226494 - 2.249062 * 10^{-8} * K_I$$

$$X_5 = 9.292612 * 10^{-3} - 4.525475 * 10^{-6} * K_I$$

$$X_6 = 4.375 * 10^{-4} + 3.5985 * 10^{-7} * K_I$$

$$X_7 = 6 * 10^{-7} + 7.24076 * 10^{-5} * K_I .$$

Solving the U_1 term for K_I, the result showed that for stability, the value of K_I should be *zero,* or a *negative*

number (less than $-2.5 * 10^{-3}$).

It is recommended to go for higher sampling rates to reach stability. For Ts = 0.25 , the results show K_I should be zero or negative (less than $-6.11 * 10^{-4}$). To reach positive K_I values, the sampling time is to be as low as 0.01 seconds.

The analogy used above is one of the many techniques used to find stability margins.

5.1. DISCUSSION

5.1.1. GOODNESS OF FIT TEST

Walpole and Myers (12) mentioned in their book "*Probability and Statistics for Engineers and Scientists*", that a meaningful technique to test if a population (a group of data points) has a specified theoretical distribution is the *Goodness of fit* test. The test is based on evaluating the quantity

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

where O_i = Obseved value (experimental readings).

E_i = Expected value (theoretically calculated).

χ^2 is the value of a random variable whose sampling distribution is approximated very closely by the *chi- square* distribution with $V = K - n$ (K = number of data points, n = no. of freely determined parameters ,V = no. of degrees of freedom).

The decision criterion is that for a certain level of significance equal to α , we find the critical χ^2 value from the tables (12, then , $\chi^2_{computed} > \chi_\alpha$ is a critical region value. The test rejects the hypothesis that the population follows a specified theoretical distribution if the computed value fell in the critical region (12).

The test was applied in this project wherever *theoretical* vs.*experimental* data were available .

The *chi-square* test requires that all data points entered in the tables to be *greater than* 5. All data was,

then, multiplied by 1000. These values were then fed to a computer program in BASIC that calculated the above stated sum for different cases. The results are listed in the following table.The value of α was chosen to be 0.025.

CASE	$\chi^2_{computed}$	V	χ^2_{table}
Transient $K_p=5$, $T_s=0.45$ $K_s=0.59$	35.01	22	36.781
Transient $K_p=10$, $T_s=0.45$ $K_s=0.196$	7.74	24	39.364
Transient $K_p=5$, $T_s=0.25$ $K_s = 0.59$	6.111	21	35.479
Steady state $K_p=10$, $T_s=0.45$ $K_s = 0.196$	4.5	4	11.143

Table 5.1.1. Chi square goodness of fit test.

Different values of α were entered in the formula. Starting with a value $\alpha = 0.01$ (to be 99 % sure) the first test point fell into the critical region that meant moving to a smaller level of significance. The test results listed in table (5.1.1) show that in all cases we are 97.5 % sure that experimental results have the same distribution that theoretical ones follow. So, the results fit the theoretical model. Also, it is apparent from the results that increasing the K_p value led to reducing the difference between ideal and experimental responses.

Moreover, the last row in the table treats *steady state error* rather than the transient response. The test shows that,

also, data fit the theoretical model.

However, it is essential to note that choosing a higher level of significance α results in the first set of experimental readings falling in the critical region . This only was the case for the first configuration.

5.1.2. SOURCES OF ERROR

The digitally controlled system had some sources of error. Some of these errors couldn't be avoided ; others were due to repeating the calibration procedure rather than having a consistent one from one run to another.

1. Integrated Circuit saturation was a continuously recurring problem. The saturation quantity differs each time the instruments were used. This variation, although relatively small, affected the readings. It was difficult to measure the saturation level to an accuracy of 0.01 volts on a digital voltmeter, and so to account for it when data were extracted. As an example, the saturation level affected the calibration procedure every time the *decimal* equivalent of 1 volt was measured (51.4 to 52.1). However , 52 was chosen to the equivelant of 1 volt. This choice is made because it is only easier to deal with whole numbers rather than fractional numbers.

2. The APPLE 2e computer BASIC language compiler distributes evenly the full scale range of 5 volts on the integer numbers from 0 to 255 . This limitation meant that the smallest signal manipulated was (quantization level) as low as 0.0192 volts. Transition of states below this amplitude

was not considered. This problem is a typical one when dealing with 8-bit processors. The quantization level of the A/D converter should be the same.

3. The time the digital controller took to evaluate,manipulate and output each sample, sampling time , was difficult to determine very precisely. This was due to the not precise time measuring procedures used (chart recorder with a function generator).

Moreover, any additional statements added inside the program accounted for significant decrease in sampling rate.

4. *Human errors* are listed among sources of errors every time experimental work is carried out. Though it was my aim to reduce the effect of this type of errors on this project,they were there. Values read on the graphs produced using the chart recorder involved some approximation due to the small scale used.(0.01 volt= 1mm)

5. Chart recorders and voltmeters have their own sources of errors wether mechanical or electrical.

From the above, we can find the reason for the small discrepancies between theoretical and experimental data. However, as said earlier, the results were acceptable.

5.2. CONCLUSION AND FURTHER RESEARCH

5.2.1. CONCLUSION

The experimentation carried out with the discussion of results preceeding indicated that the digital control system was working properly and satisfactorily. P control was tried and gave successful results.The input signal was treated as requested by the control algorithm installed .

Previously, students were using the same kits used for our project with ribbon cables already configured and with written supplied software to carry out experiments in the field of digital control. Now, students of the *Industrial Engineering* department may start carrying out new experiments on several control problems using the same technique followed for this project . The steps to be taken to do those experiments are:

1. Define the problem.
2. Define available input signal , requested manipulation , and anticipated output signal.
3. Design the digital part using ready made kits or available designs.
4. Develop the software required to input, manipulate , and output signals based on the problem requirements and design specifications.
5. Test the system using simulated input signal , prior to hooking the plant to the controller. Adjust if necessary.
6. Hook up . Produce a set of response data points due to a

certain input.

7. Derive a mathematical model for the digitally controlled system . Include the various elements with gains. Produce output equivalent data points.

8. Compare both results. Review the model and the system analysis if large discrepancies were there.

Those are the steps that were followed in this project and might be followed when designing a *digital controller* for a given process.

5.2.2. FURTHER RESEARCH

Suggested further research for this project includes the following points:

1. I suggest ,as a completion of this project, to carry out experiments using **PI** & **PID** control algorithms and a faster computer. Then using the same analogy, experimental data could be compared to theoretical data.

2. I suggest to apply the digital controller to other processes else than the coupled tank apparatus, like environment temperature control (single input single output).

3. The **IBM** compatibles are the most widely used computers rather than **APPLE** ones, now. So, I suggest to build an interface kit for those types of computers for the same purpose of our project rather than buying market available kits. The new kit may include the facility to handle multiple input, multiple output signals. Analysis of the results is the same whatever computers or kits are used.

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APPENDICES

A. Simulated Control System Results.

B. Computer Programs to Calculate Theoretical System Response.

C. Chart Recorder Plots of the Experimental System Response.

D. Computer Program to Evaluate the Chi-Square Sum.

E. Calibration Curves.

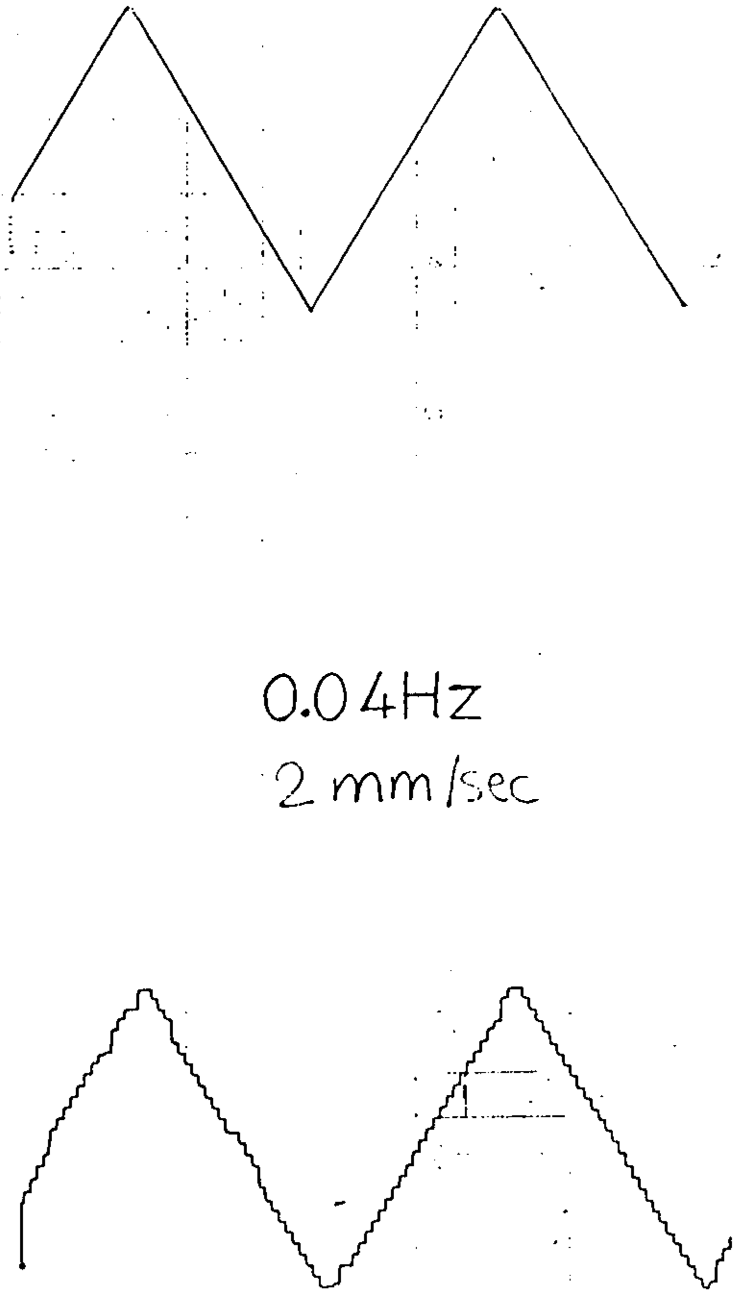

Fig.A.1. Simulated computer controlled system response.

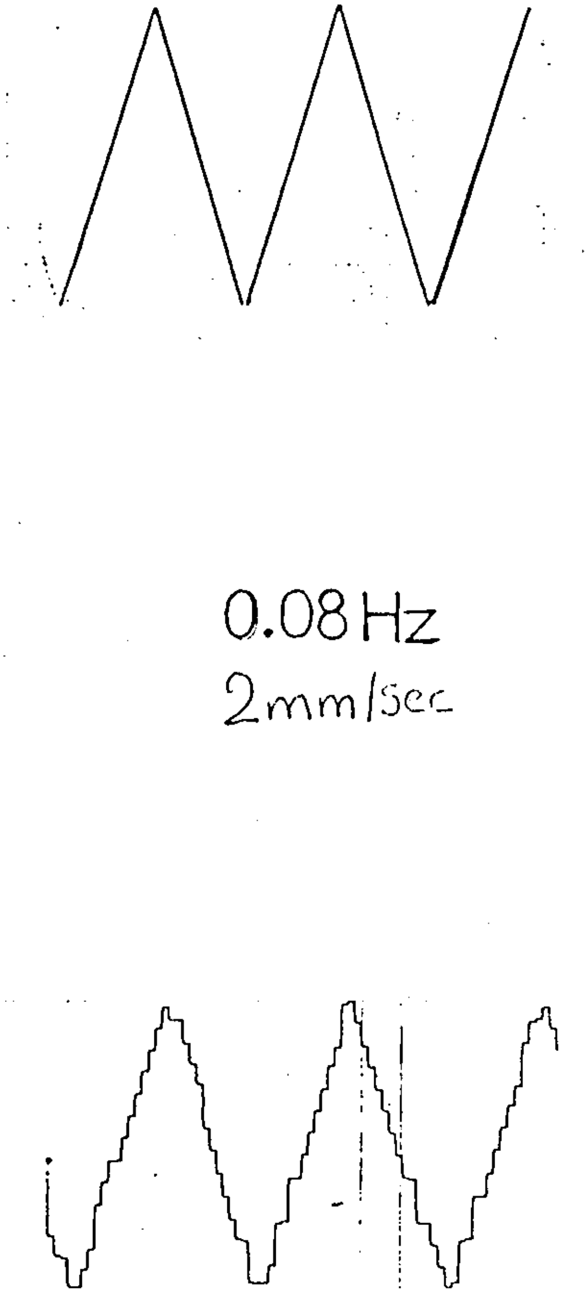

Fig.A.2. Simulated computer controlled system response.

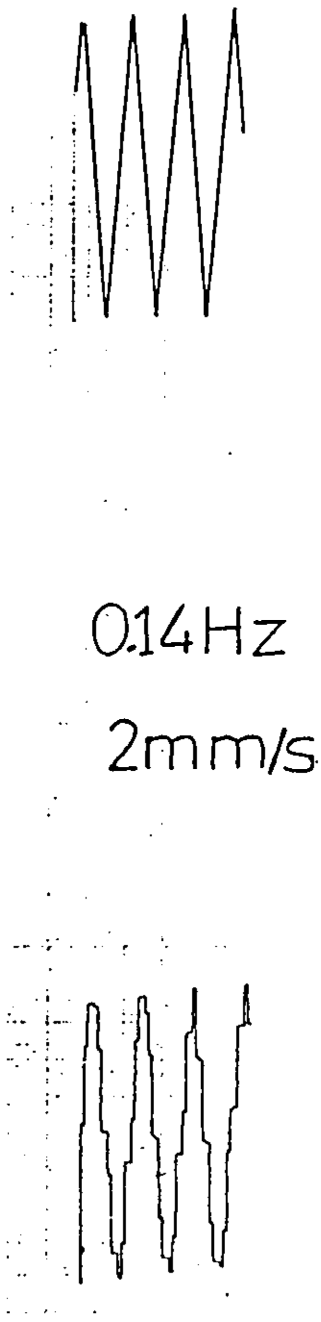

Fig.A.3. Simulated computer controlled system response.

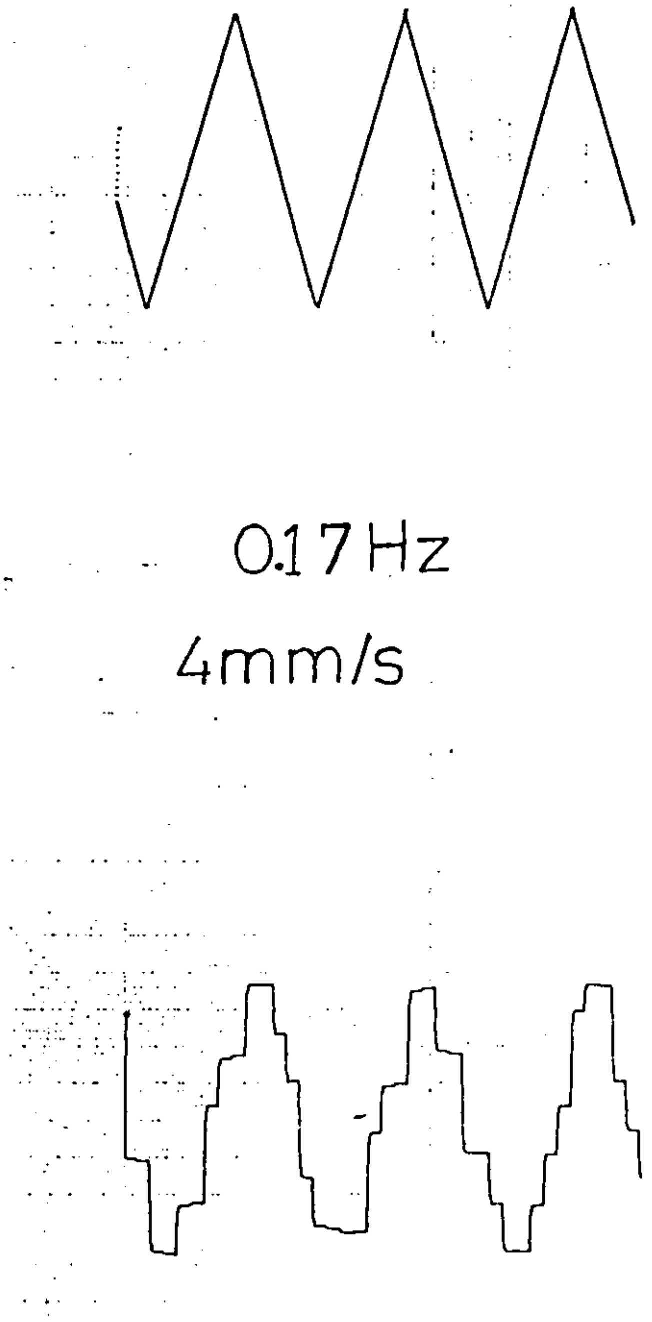

Fig.A.4. Simulated computer controlled system response.

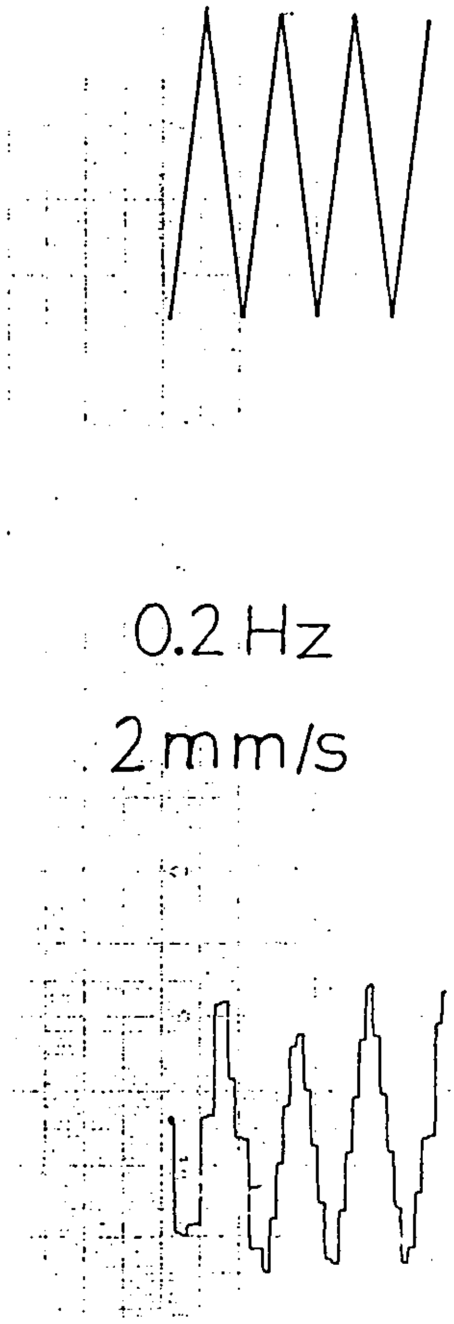

Fig.A.5. Simulated computer controlled system response.

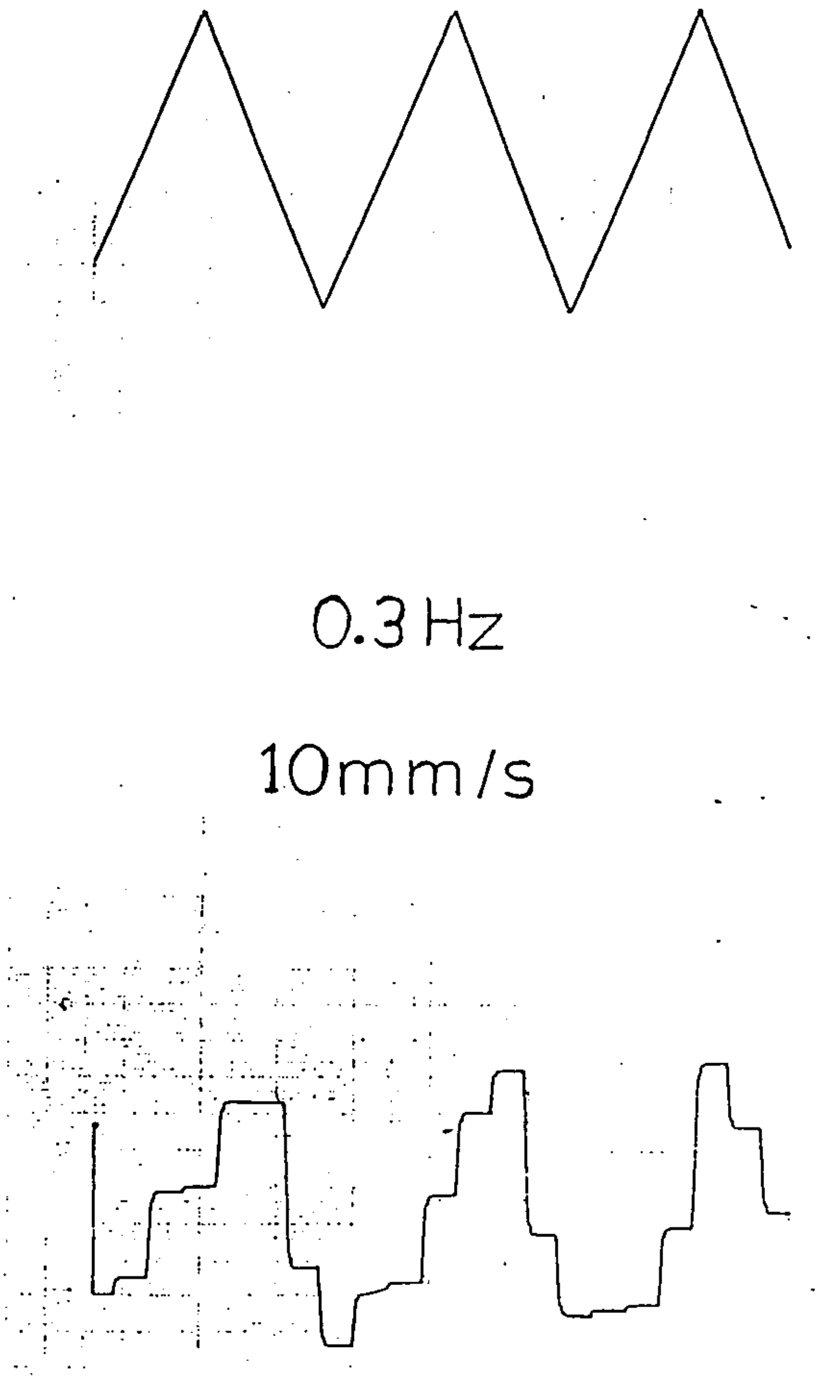

Fig.A.6. Simulated computer controlled system response.

[illegible]

Fig.B.1.Listing of the computer code used to calculate the theoretical response; P- control.

[illegible]

Fig.B.2.Listing of the computer code used to calculate the theoretical response ; PI-control.

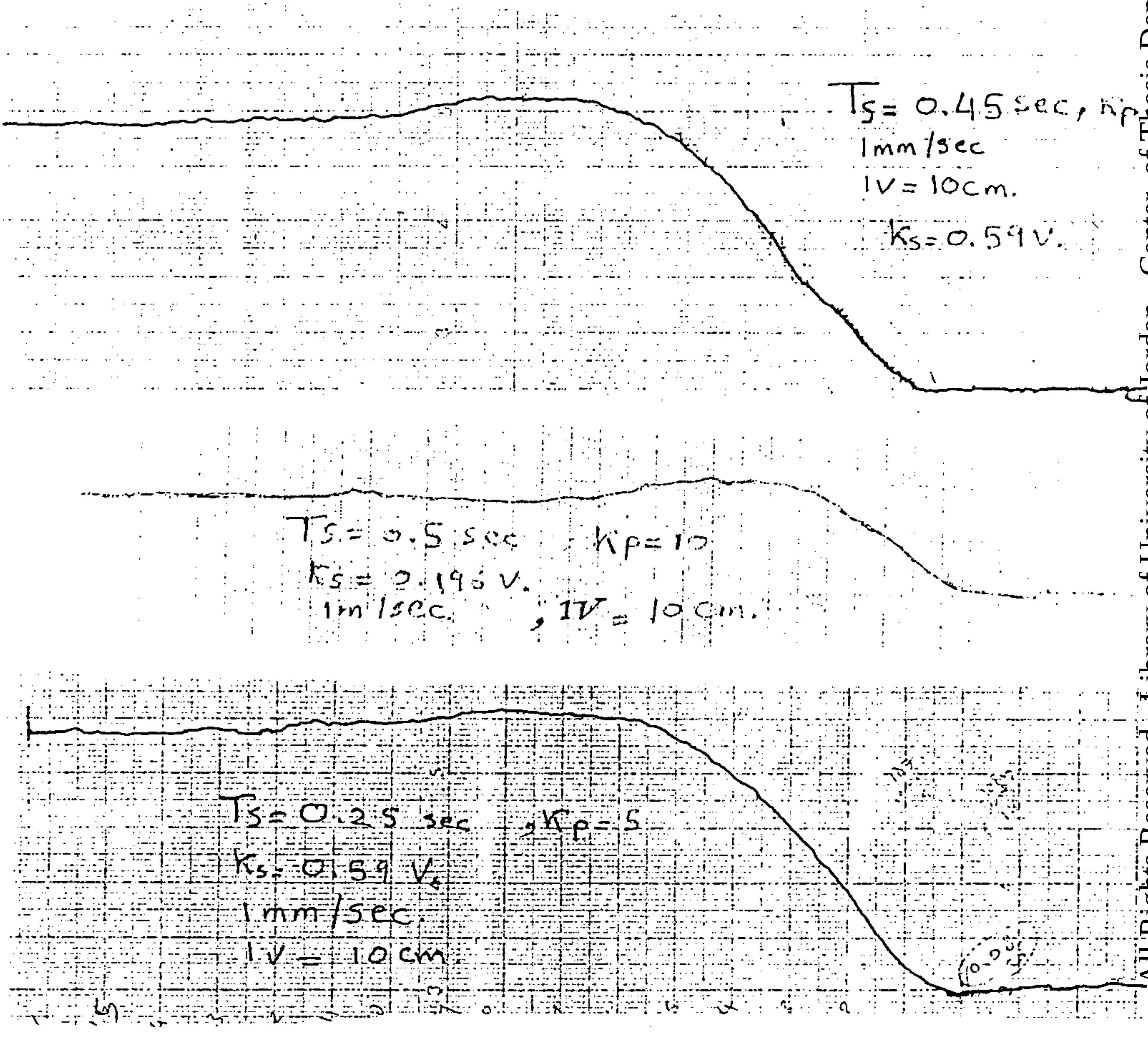

Fig.C.1. Chart recorder output of the computer control system ; P- control Algorithm.

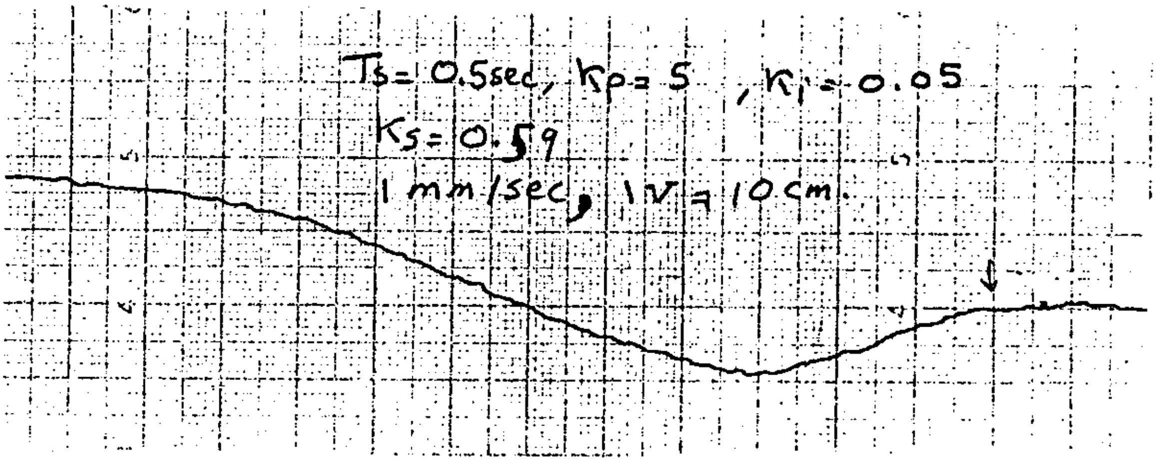

Fig.C.2. Chart recorder output of the computer control system ; PI- control Algorithm.

```
[illegible]
[illegible]
        [illegible]
        [illegible]
        [illegible]
        [illegible]
        [illegible]
        [illegible]
        INPUT T(I),E(I)
        NEXT I
        FOR J=1 TO N
        [illegible] ((T(J)-E(J)) [illegible]
        [illegible]
        [illegible]
        [illegible]
        [illegible]
```

Fig.D.1.Listing of the computer code used to calculate the Chi-square sum for the goodness of fit test.

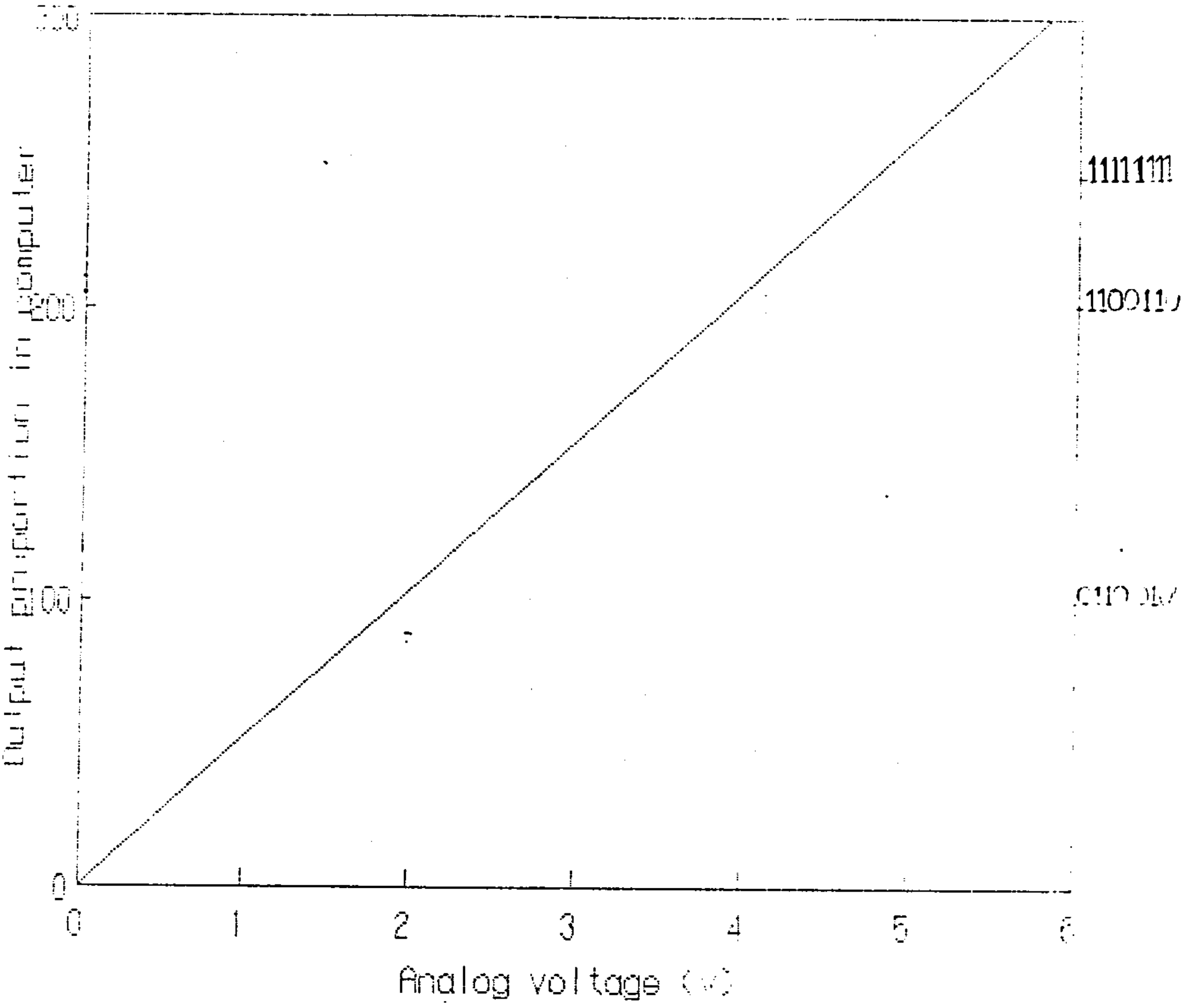

Fig.E.1. Calibration curve.