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LABORTORY WORKSTATIONS IN ELECTRICAL ENGINEERING

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ABSTRACT

Computers, configured for data acquisition and control, have been used in undergraduate laboratories at Cornell University's School of Electrical Engineering since the early 1970s. The introduction of personal computers in the introductory laboratory course sequence (Fall/Spring of Junior Year) has permitted a dramatic expansion of this practice. Previously, computers were used in group experiments with limited student interaction. Now each student has access to an IBM Personal Computer with analog and digital input/output capabilities as well as the usual electronic instruments.

Instructionally, data acquisition is emphasized during the fall semester. BASIC commands and programs are implemented to exercise analog-to-digital and digital-to-analog converters. A "canned" program collects samples (to 20,000 samples/sec) and performs spectral analysis (FFT) on periodic waveforms including the exciting current of a transformer.

Three experiments in the spring semester demonstrate the capabilities of the laboratory workstation. (1) The spectral analysis program is used to demonstrate aliasing and examine distortion in a class-B amplifier. (2) A computer controlled experiment determines the impurity profiles of p-n junctions by sampling the capacitance as a function of reverse bias. (3) Filter circuits are tested automatically for transient and frequency response using the computer. Numerical integration, FFT, and inverse FFT are used to simulate circuit responses.

INTRODUCTION

The School of Electrical Engineering at Cornell University has pioneered the concept of using computers attached to experiments in undergraduate laboratories. For the past 15 years, the introductory laboratory course sequence required of all electrical engineers included three experiments in laboratory applications of computers. Although the experiments demonstrated principles the students needed to explore, there was very little student interaction with the computers.

Recently a new approach was implemented concerning the instructional use of computers in the basic undergraduate electrical engineering laboratories. The computer, previously treated as a specialized tool, now is treated as a general purpose instrument, a so called laboratory workstation. It is introduced early in the junior laboratory sequence and available thereafter just like the oscilloscope.

BASIC UNDERGRADUATE ELECTRICAL ENGINEERING LABORATORY SEQUENCE

These courses, "affectionately" known as Super Lab, are required of all majors in electrical engineering. The course format includes one 3 hour laboratory and two 75 minute lecture periods per week. The fall semester covers various topics in electronic instrumentation, AC circuits (single and three phase), semiconductor devices, and general electronic circuit applications. The spring semester is broken into four areas; microwaves, AC/DC machines, semiconductor devices, and laboratory applications of computers.

Personal computers were introduced into the laboratory because it was felt that the students were familiar with them, that the PCs were versatile, and that it would be possible to have students interact with the machines on an individual basis, something we had not been able to accomplish in past years. Although there are many uses to which the workstations could be put, we limited ourselves to data acquisition, data analysis and reduction, automatic testing and simulation.

HARDWARE FOR LABORATORY WORKSTATIONS

Each IBM PC is configured with a dual disk drive, 128KB of RAM memory, asynchronous communication adapter, monochrome display and graphics printer with adapter, and TECMAR's Lab Tender board for data acquisition and control functions.

The Lab Tender, a single plug-in board, provides 32 singled ended (16 differential) analog inputs multiplexed to a single analog-to-digital converter, 16 analog outputs demultiplexed from a single digital-to-analog converter, 24 bits of digital input/output, and multiple timer-counter functions. Both converters are 8-bit devices with +/−5 volt ranges only. An external box with BNC connectors provides access to 4 analog inputs and 4 analog outputs of the Lab Tender.

IMPLEMENTATION OF LABORATORY WORKSTATIONS

FALL SEMESTER: The workstation is introduced in the fall semester as other electronic instruments are. One laboratory period is dedicated to data acquisition and data analysis, reduction and transformation (Fast Fourier Transforms—FFT) with the workstation (see Appendix A). Time varying signals both transient and periodic are collected, manipulated, and analyzed. Students write short programs (in BASIC) to implement these functions and discover the limitations of interpreted and compiled BASIC programs. Assembly language and Turbo Pascal programs are then provided to the students to allow them to perform experiments in realistic times.

The PCs are then available for other experiments during the semester. At present, the workstation is part of only one other experiment which deals with transformer characteristics. The exciting current of a transformer is collected with the workstation (figure 1) and then a FFT performed on the periodic waveform to demonstrate the harmonic content of the exciting current (figure 2). The workstation is being written into other experiments for the fall of 1985.

SPRING SEMESTER: The spring semester of the Junior Laboratory has always had three experiments devoted to laboratory applications of computers. These experiments have been modified and expanded such that the workstation can be used to implement them. The experiments involve more data acquisition, computer controlled experiments, and simulation.

Distortion in a class B amplifier is examined; odd harmonics are produced by crossover distortion and even harmonics are produced by gain distortion (see Appendix B). This harmonic distortion can be easily determined using the FFT programs available in the workstation. The impurity distribution in junction diodes can be determined from the a plot of capacitance as a function of reverse bias on the diode (see Appendix C). The workstation is used to produce the reverse bias and monitor the capacitance via a ac voltage that is proportional to capacitance. Time response of first and second order systems are examined by applying voltage steps from the workstation and monitoring the circuits' responses. Frequency response of these systems are examined by using a voltage-controlled-oscillator to sweep frequency and monitoring the output of the system with the workstation (see Appendix D). These systems are also simulated and provide the student with a theoretical solution to compare to the real response.

SOFTWARE

A combination of interpreted BASIC, compiled BASIC, assembly language, and compiled Turbo Pascal programs have been used with the workstation. Students typically begin with interpreted BASIC programs. Most of the programs available to the students have been written by C. Pottle in Turbo Pascal.

OTHER APPLICATIONS OF WORKSTATIONS

The VLSI (very large scale integration) semiconductor design course has made use of the workstations to test VLSI chips that are fabricated from students' designs. Input-output files, generated during the design process, are transferred from the Computer Assisted Design Facility to the IBM workstations through the building computer network and the asynchronous communication ports of the IBM PCs. The inputs are then passed to the integrated circuits via the Lab Tender's digital outputs. The circuit's performance is checked by monitoring its digital outputs and comparing them against the desired outputs.

The workstation has also been used in the Bio-instrumentation course for general data acquisition and some simulation. One application had students simulate physiological characteristics of a patient (heart rate and blood pressure) using the workstation and other students design a heart and blood pressure monitor using another workstation. The "patient" and instrument communicated through the A-to-D and D-to-A converters of the Lab Tenders.

The workstation has also been used with a color monitor for classroom demonstrations. One demonstration (figure 3) shows in real time how a periodic waveform can be recreated from a series of harmonic sine and cosine terms. Other demonstrations of aliasing and frequency transformation were also implemented and used in the classroom.

CONCLUSIONS

In less than two years more than 700 students have used the laboratory workstations in the School of Electrical Engineering and their response has been extremely favorable. Our only equipment failures have been with disk drives and some input buffers on the Lab Tenders; those failures have been minimal and none were critical.

IBM Personal Computers, used as laboratory workstations, has allowed us to implement our new approach to laboratory applications of computers. We were able to perform the type of experimentation we had done with a variety of minicomputers on the IBM PCs and increase significantly the level of student interaction. But more importantly, the workstation has and will continue to open new possibilities, particularly in the area of computer simulations, computer assisted design and real-time dynamic control of experiments. The potential of the workstation exceeds by far any device that has been taken into the laboratory. The workstation has had extensive impact on the content and quality of experimentations as well as the educational techniques employed to illustrate and emphasize the engineering concepts of the laboratory experimentations.

As educators and engineers we have never had a tool which allowed us to implement innovative laboratory experimentation while at the same time provided us with the pedagogical possibilities that the laboratory workstation does. This combination is unique and the development of this idea has to be one of the most exciting challenges in engineering education in a long time.

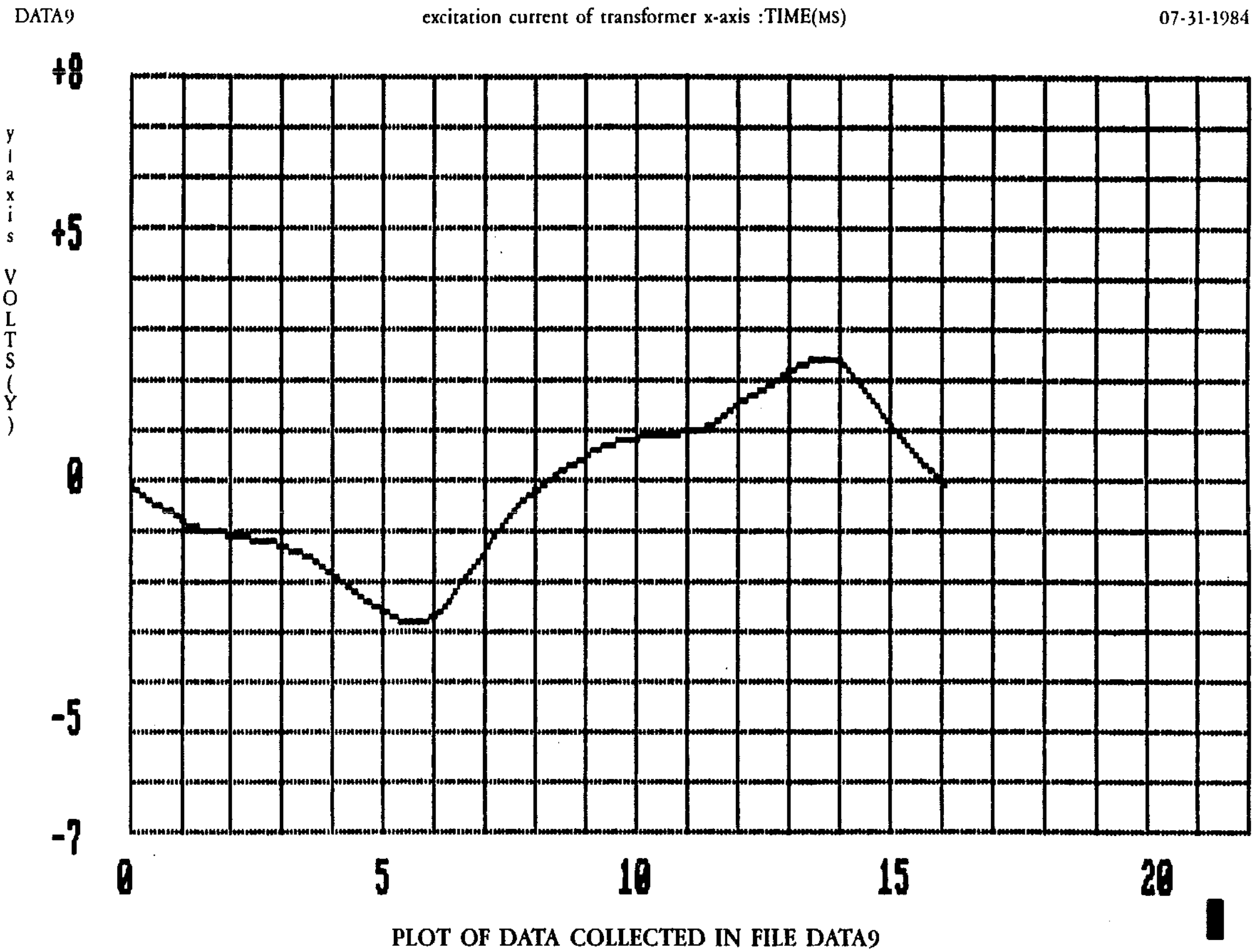


Figure 1: Excitation Current of Transformer

```
EE316 Run number 9 00:23:22 01-01-1980 ANESHANSLEY
EXCITING CURRENT OF TRANSFORMER
Numbr of samples = 64     Sampling rate = 1613
LISTING OF FILE PLOT9:
PLOT OF        AMPLITUDE (scaled)        AGAINST     FREQUENCY (cycles/units)
O                                                        (KHZ)
I----I----I----I----I----I----I----I----I----I----I
*                                                 :  0.00     0.02
*                                                 :  0.03     0.02
****************************************          :  0.06     1.01
*                                                 :  0.08     0.04
*                                                 :  0.11     0.02
*                                                 :  0.13     0.02
*************                                     :  0.16     0.33
*                                                 :  0.18     0.02
*                                                 :  0.21     0.02
*                                                 :  0.23     0.04
*******                                           :  0.26     0.19
*                                                 :  0.28     0.02
*                                                 :  0.31     0.04
*                                                 :  0.33     0.03
******                                            :  0.36     0.16
*                                                 :  0.38     0.04
*                                                 :  0.41     0.03
*                                                 :  0.43     0.01
****                                              :  0.46     0.11
*                                                 :  0.48     0.03
*                                                 :  0.51     0.01
*                                                 :  0.53     0.04
***                                               :  0.56     0.08
*                                                 :  0.58     0.01
*                                                 :  0.61     0.03
*                                                 :  0.64     0.03
****                                              :  0.66     0.09
*                                                 :  0.69     0.03
*                                                 :  0.71     0.03
*                                                 :  0.74     0.01
***                                               :  0.76     0.07
*                                                 :  0.79     0.03
*                                                 :  0.81     0.01
I----I----I----I----I----I----I----I----I----I----I
:       *     *                                   :
```

Figure 2: Plot of Amplitude Components from Fast Fourier Transform of Exciting Current of Transformer

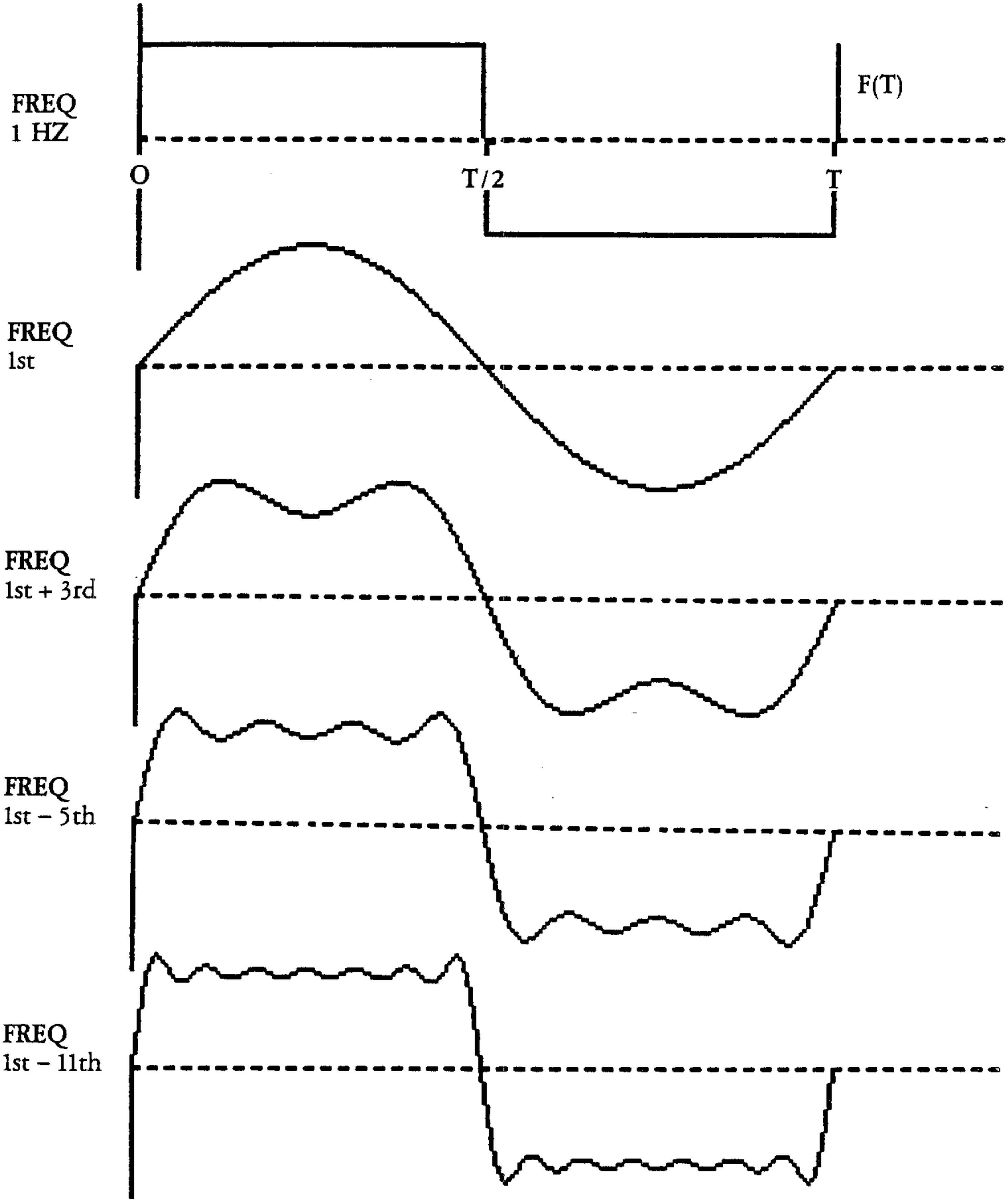


Figure 3: Composite of screens from Lecture Demonstrations which show recreation of square wave by addition of odd harmonics. Number and order of harmonics used to produce each waveform is indicated.

EXPERIMENT X3
PERSONAL COMPUTERS AS LAB WORKSTATIONS

PREPARATORY EXERCISE

For those of you who are not familiar with the IBM PC or have never used a personal computer, you are to go to the Computer Resource Room of Mann Library and perform the following exercise.

Introduction to IBM PC

a) Obtain disk called "Exploring the IBM PC, Monochrome, 1/84." Insert the disk in drive A and turn the machine on (power switch at back right side). If the machine is on, insert the disk and depress, the Ctrl and Alt keys and then depress Del while still holding Ctrl and Alt down. This is the system reset sequence.

b) The "Exploring the IBM PC" tutorial should execute automatically. Examine the 5 "Chapters" of this exercise as you deem necessary.
   i) Exercise instructions
   ii) Keyboard*
   iii) Disk Storage and DOS
   iv) Basic Programming
   v) Printer

*Skip "Funwriter," depress alt and PgDn keys to go to chapter iii.

PREPARATORY QUESTIONS

1. Write a BASIC program that will produce a 4.0 volt level on D-to-A channel 0 of the Lab Tender. Modify the program such that it will generate a continuous triangular waveform at D-to-A channel 0. The amplitude of the waveform should be approximately +/ – 2.5 volts and each cycle should be defined by 256 points. Indicate how you could control the frequency of the waveform by changing the program.

2. Write a BASIC program that will read the voltage at A-to-D channel 0 of the Lab Tender. If the voltage at the input to A-to-D channel 0 is +1.5 volt, what digital value do you expect to read. Modify your program to convert the digital value to its corresponding voltage and have the program print that voltage to the screen (PRINT ____) and line printer (LPRINT ____).

3. Write a BASIC program which samples A-to-D channel 0 of the Lab Tender 1000 times and stores the sampled values. Indicate how you would determine the rate at which channel 0 is sampled by using BASIC's TIME$ function (X$ = TIME$ sets X$ equal to current time in hours: minutes: seconds). Modify the program such that the waveform, once saved, is regenerated continuously at D-to-A channel 0. The program will turn the PC into a storage oscilloscope (of sorts). Scale time arbitrarily, as it is difficult to make the playback and sampling rate equal.

4. An unknown periodic waveform is connected to A-to-D channel 0 of the Lab Tender which is set-up to sample the signal every 1.25 ms and to store 64 samples.

   a) How should the parameters of the "CONTROL" program be specified in order to collect data as indicated.

   b) A FFT is performed on data collected as specified above. What frequency information is available, that is, what frequency components are shown in the FFT (number of components, maximum and minimum component, and interval between frequency components).

5. A square wave of amplitude 2.5 volts peak and 50.0 Hz is applied to A-to-D channel 0 of the Lab Tender.

a) What sampling rate would you use to collect 4 cycles of this waveform in 64 samples?

b) If a FFT were performed on the above data, what harmonics would be present and how much of each relative to the fundamental? (This question is answered by determining the Fourier Series for a square wave and relating that to the way in which waveform was sampled.) Assume aliasing is of no consequence for frequencies greater than 1600 Hz.

LABORATORY EXPERIMENTATION

1. Start-up.
   a) Insert the disk marked EE315 System Disk in drive A. This disk should be found in the back of DOS Manual.
   b) Turn the machine on (power switch on right side at rear). If machine is on, depress the Ctrl and Alt keys and then depress Del key which is still holding Ctrl and Alt keys down (this is the system reset sequence).
   c) Enter the date and time as requested or strike RETURN key twice.
   d) Start BASIC interpreter, type BASIC after >A prompt.
2. Introduction to Lab Tender's D-to-A System.
   a) Exercise the Lab Tender's D-to-A converter from basic.
      i) Produce a 4 volt level at D-to-A channel 0 (Prep. Ques. 1.) Make a program listing on printer (LLIST) and include it in your report. Measure voltage at D-to-A channel 0 with HP Digital Voltmeter. Change the digital value by + and − one digit and measure the voltage produced by these values at channel 0.
      ii) Record the time it takes this voltage to drop to zero volt after D-to-A channel 0 is disabled. You will need to use the second hand of a watch or the lab clock to record this time which is approximately a minute. This drop in voltage is called "sag."
   b) Enter and list BASIC program that generates a continuous triangular waveform at the D-to-A output of channel 0 (Prep. Question 1). Record the frequency of the waveform. Alter your program to increase the frequency of the waveform; use at least 32 points to define one cycle of the waveform in all cases. Record the maximum frequency you attain and indicate the change(s) made to your program.
3. Introduction to Lab Tender's A-to-D System.
   a) Exercise the Lab Tender's A-to-D converter from BASIC.

      NOTE: A-to-D inputs of the Lab Tender should be within + / − 5 volts. The input-circuits of Lab Tender may be damaged if these levels are exceeded.
      i) Enter and list program that will read and print voltage at A-to-D channel 0 (Prep. Quest. 2). Connect a 1.5 volt battery to channel 0 and measure the voltage 10 times (strike F2 key to run the program). Measure the battery voltage with the HP Digital Voltmeter and compare the two values.
      ii) Reverse the battery connections to the A-to-D converter and repeat the above measurements.
   b) Enter and list BASIC program that samples A-to-D channel 0 1000 times and "replays" the sampled waveform (Prep. Question 3). Use the HP Function Generator to produce a sine wave or other appropriate time varying signal. Be sure the amplitude of the wave is with the + / − 5 volt limit of the converter. Determine (and record) the sampling rate as set by the program. Can you increase the sampling rate?

      OPTIONAL PART: Do this if you have time at the end of the laboratory.

c) Another way of measuring the sampling rate.

A periodic wave with a frequency equal to the sampling rate or frequency should produce a d-c value when sampled at that sampling rate. The program ALIAS (available on the system disk) is similar to the program of part 3b except it only collects 100 samples and the playback reproduces the 100 samples followed by 100 samples at + 5 volts (this provides a way to trigger the scope during playback). Also striking any key causes another sample to be taken

- i) Load ALIAS and obtain a listing.
- ii) Sample and display sinewaves in the range of 2–10 Hz.
- iii) Now sample and display sinewave approximately equal to the sampling rate calculated in part 3b (125 Hz). Once satisfied that the frequency of the sine wave is as close to the sampling frequency as possible, measure the frequency on the HP Frequency Counter or the period on the oscilloscope.
- iv) Based on your knowledge of aliasing predict the next frequency that will give a dc value and check it.

4. Sampling Transient Events.
   - a) Load the BASIC program SAG.BAS. This program will
     - i) apply a 5 volt level to D-to-A channel 0,
     - ii) then disable the D-to-A channel 0,
     - iii) and record the voltage as it decreases, sags towards − 5 to − 6 volts.
   - b) Run the SAG program.
     - i) Follow the directions given after you execute (RUN) the program.
     - ii) Include a listing of the data collected by the program.
5. Sampling Periodic Waveforms and Analyzing them with FFTs.
   - a) Set-up
     - i) Return to the DOS (Disk Operating System), type SYSTEM
     - ii) After the prompt A> type CONTROL. This loads and begins execution of a program that allows you to sample waveforms at sampling rates of approximately 20,000 Hz. These waveforms can be saved, plotted, and analyzed with FFT. (Occasionally during an FFT the system will fail. If this occurs simply restart the program by typing CONTROL and try the FFT again.)
   - b) Set the signal generator to produce a + / − 2.5 V sine wave at 50 Hz. Set-up the CONTROL program such that it will collect two cycles of the 50 Hz signal in 64 samples. Collect the data using the Lab Tender and the GET program. Did you collect exactly two cycles, if not why not? Take a FFT of your collected waveform and PLOT the results. Describe what the FFT plot tells you about the sampled waveform. Is the FFT plot what you would have expected from a pure sinewave, if not indicate what is different?
   - c) Using the DISPLAY command adjust the frequency of the function generator such that you do collect just 2 cycles of the waveform in 64 samples. Collect a sample with GET function and analyze the collected data as in part (a).
   - d) Set the signal generator to produce a + / − 2.5 V square wave at 50 Hz. Set-up the CONTROL program such that it will collect two cycles of the 50 Hz signal in 64 samples. Collect the data using the Lab Tender and the GET program. Did you collect exactly two cycles, if not why not?

e) Make adjustments such that you do collect in 64 samples just two cycles. Take a FFT of your collected waveform, LIST the amplitude and phase results and PLOT the amplitude results.

OPTIONAL PART: Do this only if you have time at the end of the laboratory.

f) Repeat parts (d) and (e) for a 50 Hz triangular waveform an amplitude of 2.5 volts peak volts.

EE316

Spring 1985(4)

EXPERIMENT C-1
THE COMPUTER AS A LABORATORY INSTRUMENT
DISTORTION IN CLASS B AMPLIFIERS

PURPOSE

This experiment is intended to provide further familiarity with the use of the small computer as a waveform analyzer. One specific application is to the study of the harmonic distortion arising in Class B push-pull transistor amplifier pairs. Theory indicates that one form of nonlinear behavior leads to the generation of odd harmonic distortion, while another leads to even harmonic distortion.

PREPARATORY QUESTIONS

(1) If a sinusoidal waveform is sampled at 1600 Hz

a) What is its frequency if exactly 4 periods are contained in 128 samples?

b) Which spectral lines are nonzero?

c) What is the next higher frequency the waveform can have while keeping the same spectral appearance?

d) For the waveform in (c), what do 128 samples represent?

e) For a waveform of frequency intermediate to those of (a) and (c), how will the spectrum appear? Why?

f) What is the frequency of the waveform whose odd numbered samples are all zero, and whose even samples alternate signs, but have the same magnitude?

(2) Using a program (WaveformAnalysis) which will take a given number of samples of a waveform of adjustable frequency at a given sampling rate, and which will display the sampled waveform on an oscilloscope at the given rate,

a) Devise and present an experiment using this program which will demonstrate the phenomenon of *aliasing* of sampled data waveforms;

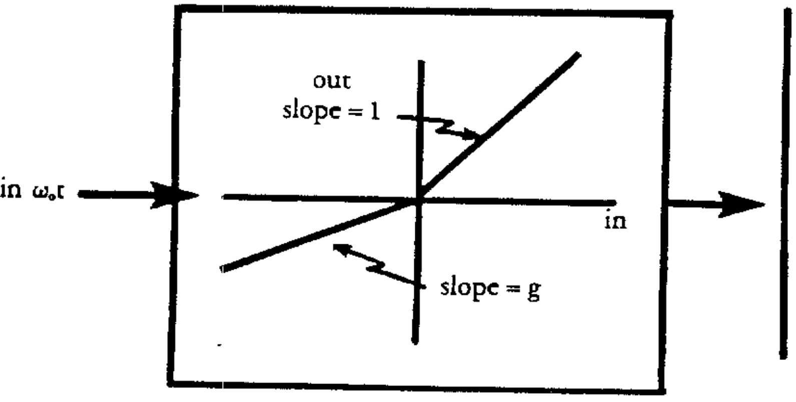
b) Devise and present an experiment, using the HP Frequency Counter to measure accurately the frequency output by the function generator, which will verify the sampling rate being used by the Lab Tender.

(3) The following program fragment is from SampleSeries, a Turbo PASCAL PROCEDURE used in WaveformAnalysis. Its purpose is to initiate the collection of sampled data from a waveform when the waveform has reached the trigger level desired with the slope direction desired. Give an English paraphrase of this algorithm in the style of what might have been written in a structured programming approach in the step immediately preceeding this PASCAL code. Note that

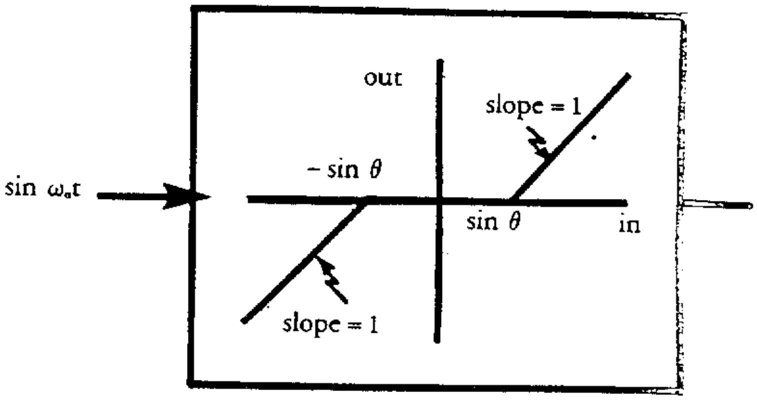
i SHL j yields $i*2^j$;
Port[i]: = j sends byte j to output port address i;
j: = Port [i] assigns the value of input port address i to j;
DIV means integer divisions; and
KeyPressed is a boolean function which is true if a key on the keyboard has been pressed.

```
    i: = Port[ADAdr + 1];
    Go: = (ChannelNo SHL 1) + 1;
    Port[ADAdr]: = Go;
    WHILE Port[ADAdr] < 128 DO BEGIN END;
    new: = Port[ADAdr + 1];
    newdiff: = new — level:
    IF slope < > 0 THEN
        REPEAT
            olddiff: = newdiff:
            old: = new;
            Port[ADAdr]: = Go:
            IF Keypressed THEN
            WHILE Port[ADAdr] < 128
            new: = Port[ADAdr - 1];
            newdiff: = new - level
       UNTIL ((newdiff*olddiff< = 0)
            AND ((new-old) DIV slope > 1)
            OR (flag > 0));
   {Start the counter and do the sampling}
```

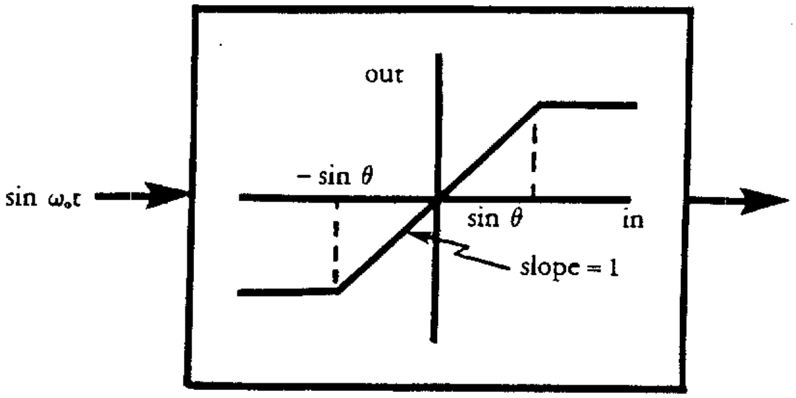
(4) Find the Fourier Series coefficients a_n or b_n (arrange for one or the other to be mostly zero) of the output waveform of *one* of the nonlinear amplifiers whose transfer characteristic appears below.



(a) Beta-difference Distortion



(b) Crossover Distortion



(c) Clipping (saturation)

Handy Formulas

$$\int \sin\phi \sin n\phi \, d\phi = \frac{\sin (n-1)\,\phi}{2(n-1)} - \frac{\sin (n+1)}{2(n+1)}$$

$$\frac{\sin\phi}{\phi} \to 1, \phi \to 0$$

EE316

Spring 1985(4)

EXPERIMENT C-1
THE COMPUTER AS A LABORATORY INSTRUMENT
DISTORTION IN CLASS B AMPLIFIERS

LABORATORY EXPERIMENTATION

This experiment makes use of a program SPECTRUM developed especially for the Junior Laboratory. It was written in Turbo PASCAL and compiled into executable form on a diskette. After using the EE316 Master System Disk to boot the Disk Operating System (DOS), you are ready to invoke SPECTRUM by entering its name. The program is divided into three logical sections which must be executed in order. The first is an initialization step which obtains the parameters of the experiment (e.g., user names, sampling frequency, number of samples) through a dialog with the user. The second step does the sampling of a waveform and displays the waveform, the amplitude spectrum, or the phase spectrum on the lab oscilloscope. After an initial set of samples is taken, all subsequent operations are done on this set unless the space bar is used to request a new set. The third step is entered by typing a "d" (for "display") in step two. In this step you may display and obtain hard-copy plots of the waveform and spectra you observed in step two.

Note that you *must have seen* on the oscilloscope in step two anything you want to print or display in step three.

(1) Exercise the program SPECTRUM using as a guide the questions asked in Prep Question (1). Obtain your waveforms from the HP Function Generator (limit its output to between − 5v and + 5v!) via A/D channel 0. Observe your waveforms and spectra on the oscilloscope via D/A channel 0, with negative slope triggering supplied from D/A channel 1. Repeat for square wave and triangular wave inputs. Use DC coupling on oscilloscope input for all experiments. Sketch in your lab notebook the waveforms and spectra you observe, and make one or two well-chosen plots on the printer.

(2) Carry out the experiment you designed to demonstrate aliasing in response to Prep Question (2). Present your results and conclusions, accompanied either by sketches or a printer-plot.

(3) Carry out the experiment you designed to check the accuracy of the timing generator of the Lab Tender (and the correctness of the procedure TimingInit in SPECTRUM). Present your results and conclusions, accompanied by appropriate sketches.

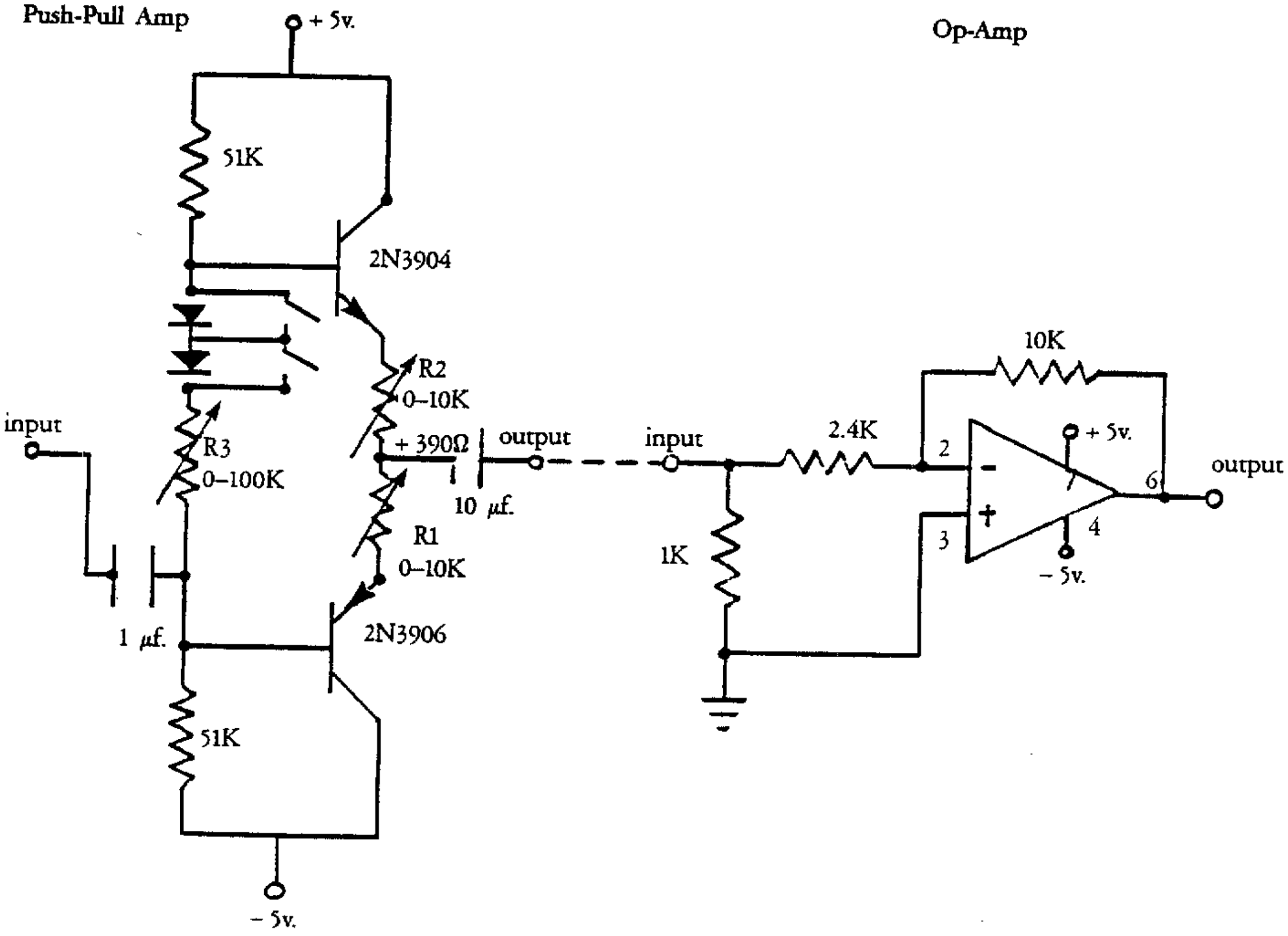
(4) A simple complementary-pair push-pull amplifier has been built for this experiment. External

resistors can be attached to alter the bias and change the effective transistor gain. Biasing diodes can be switched in or out of the circuit.

a) Experiment with this amplifier using the function generator and the oscilloscope, but not the computer. Use a + 5v and − 5v supply voltage. Make sure the 1K load resistor at the X4 op-amp input is connected. Bias the amplifier to show crossover distortion clearly, then try to remove it, both using and not using the biasing diodes. Use the multimeter to measure the quiescent collector current at all times, and at some point adjust the bias to obtain true Class A operation. Adjust the gain of one of the transistors to show beta-difference distortion clearly, then try to remove it. Increase the input to the point where clipping occurs. What is the maximum output voltage without clipping?

b) Repeat (a) using the program SPECTRUM. Display the spectrum showing crossover distortion on the printer-plotter and discuss. A small input signal and use of the X4 op-amp will be helpful. Display the spectrum showing beta-difference distortion on the printer-plotter and discuss. Display the spectrum showing clipping and discuss. Make adjustments to minimize all types of distortion and record on the printer-plotter.

(5) (If time permits) Using your knowledge of the triggering algorithm used in the procedure SampleSeries in SPECTRUM, perform experiments designed to exercise the algorithm. Include at least the results of experiments with zero-crossing triggering, triggering at or near the maximum of a sinusoid, and slope inputs other than + 1 or − 1. What do you do if the triggering is inadvertently set too high, so no triggering can take place? Experiment also with slow and fast waveforms. Does the algorithm need improvement? Record your tests and their results in your notebook.



ENGINEERING

EE316

Spring 1985(3)

EXPERIMENT C-2
THE COMPUTER AS A LABORATORY INSTRUMENT IMPURITY DISTRIBUTION IN JUNCTION DIODES

PURPOSE

This experiment is intended to provide further experience with the use of the small computer as a measuring and recording device. Of particular interest in this experiment is the computer's ability to carry out computations on the collected data (in the form of a least-squares fit) and to *control* the data-taking in the experiment via its D/A converter. The specific application is to the determination of the doping profile of a p-n junction diode via the measurement of its capacitance-vs-reverse-bias characteristic. Theory indicates that for an abrupt-junction diode, the inverse-squared-capacitance-vs-reverse-bias characteristic should be a straight line whose slope is proportional to the constant impurity concentration at any depletion width. This measurement may be automated using a small computer by a program which will step the reverse bias voltage through its range while measuring a voltage proportional to junction capacitance at each step.

PREPARATORY QUESTIONS

The following capacitance versus voltage data were taken on an abrupt alloy junction silicon diode, heavily doped in the p-region.

Reverse Bias (volts)	0.5	1.0	2.0	4.0	8.0
Capacitance (pf./cm^2)	4000	3270	2530	1890	1370

(1) Determine the built-in voltage of the diode from a plot. Confirm your result with a regression analysis if readily available.

(2) Determine the impurity density in the n-region.

(3) What capacitance might be expected for a bias of 25 volts?

(4) What would be the width of the depletion region at a reverse bias of 5 volts if the impurity density in the n-region were doubled? The built-in voltage is not strongly dependent on impurity density.

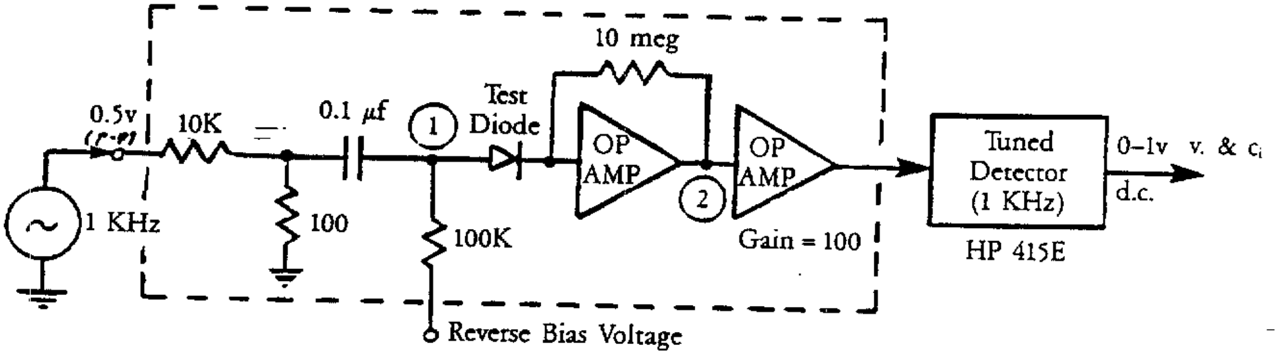
(5) Consider a specific diode with the above characteristics which has a junction area of 0.1 cm^2. Suppose our measuring equipment is arranged so that the voltage presented to the A/D converter is -5v for a capacitance of 0pf and $+5$v for a capacitance of 500pf. What change in capacitance will cause a change in the least significant bit of the Lab Tender's A/D converter? How much change in bias is required to cause this change in capacitance, if the reverse bias is

a) 0 volts
b) -10.0 volts?

Suppose now we are determining the impurity profile by measuring the *local* change in capacitance vs voltage; i.e., we are not assuming an abrupt junction. A change in voltage of less than that calculated above is likely to cause no change whatsoever in capacitance. What will we calculate the impurity density to be in this case? >From your results, comment on the advisability of taking many equal steps in reverse bias voltage to determine more accurately the impurity profile.

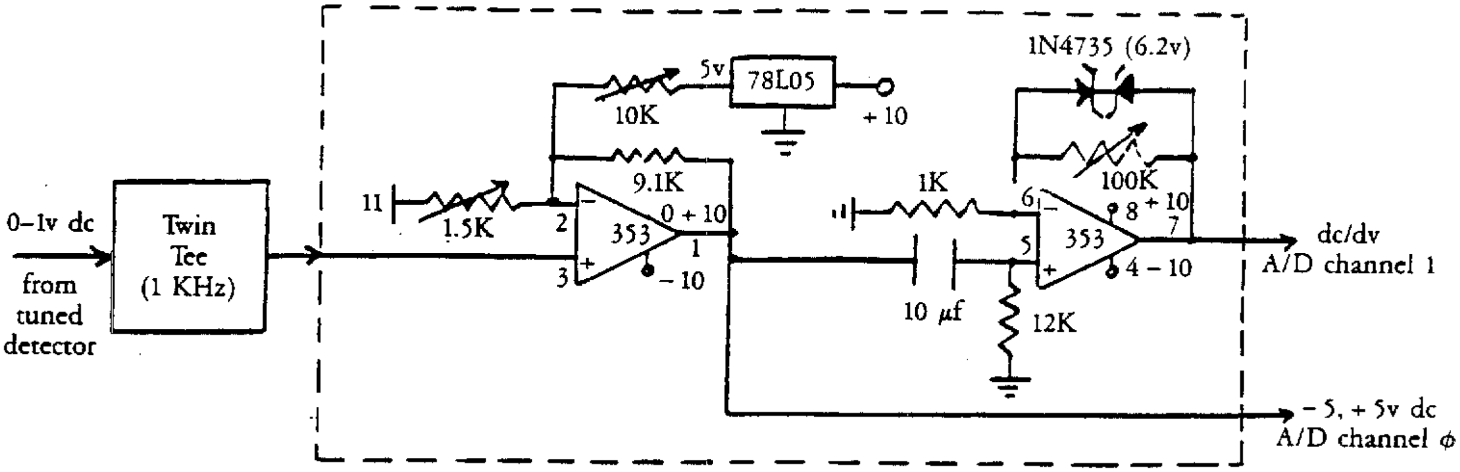
LABORATORY EXPERIMENTATION

The figure below provides a schematic diagram of an experimental setup for measuring junction capacitance. The AC measuring signal (1000 Hz) should be about 5mv peak-to-peak at point 1, or 0.5v peak-to-peak at the output of the signal generator; that is, large enough to drive the tuned detector, but small enough to stay within the small signal assumption. The tuned detector provides a DC voltage proportional to the magnitude of the 1000 Hz component of its input signal, thereby rejecting the noise which is inevitably present in a setup with such high gain. At point 1 the AC signal is superimposed on the negative DC voltage used to bias the diode to the desired operating point. Since the summing junction of the operational amplifier is at virtual ground, this bias appears entirely across the diode. The diode capacitance C, the feedback resistance R, and the operational amplifier form a differentiator. Thus, if the AC voltage at point 1 is $V \sin \omega t$, the voltage at point 2 is $-VRC\omega \cos \omega t$, which is proportional to the junction capacitance. This signal, after further amplification by a factor of 100, forms the input to the tuned detector. The diode C-V characteristic may be obtained manually with this setup. After noting the tuned detector meter reading from a known calibrating capacitor, a series of readings is taken with the diode in place and increasingly negative bias voltages applied.



Diode Capacitance Measurement Setup

Automating this experiment is made possible by the tuned detector, which delivers a DC voltage proportional to the meter deflection. This signal is designed to drive a chart recorder, has a range of only 0–1v, and has a large 1000 Hz leakage component superimposed on it. A Twin-Tee filter is used to suppress the leakage signal. An operational amplifier with a gain of 10 and voltage offset of −5v then maps the 0–1v input into the −5v, +5v range of the A/D converter. Another AC-coupled amplifier with a gain of ten is used to provide a peak signal proportional to dc/dv during a part of the experiment when the bias voltage is "dithered" a small amount by the computer and the resulting change in capacitance detected. This amplifier provides a direct measurement of dc/dv as an alternative to the highly undesirable approach of differencing almost equal values of capacitance in the computer.



Additional Circuitry For Obtaining A/D Input Data

(1) Using your D/A converter as a voltage source for biasing, examine the capacitance versus voltage characteristics of

a) A capacitor of known value;

b) An abrupt junction diode (No. 1).

The signal generator should be set up as stated above. Its frequency should be set to obtain maximum deflection of the tuned detector meter. The tuned detector gain should be set to cause near full deflection when the diode under test is inserted in its jig and zero bias applied. Observe the noise present at the input to the tuned detector. How large is it with no input signal applied? You should ascertain that the entire experimental setup is operating correctly before proceeding to the next step.

(2) Now automate the experiment by obtaining the biasing voltage from channel 0 of the Lab Tender's D/A converter, and by connecting the A/D converter's channel 0 & 1 to the output of the test setup. Run PROFILE and follow the directions given to calibrate the equipment with a known capacitance. The tuned detector gain must be set for a full-scale reading for the *larger* capacitance of the fixed capacitor and the zero-biased diode. Why? Experiment with the program to become acquainted with its properties. Notice the requests made, the default values assumed, and the displays provided. Observe and discuss the various signals present during a run, especially the effect of "dithering" the bias voltage during measurement of dc/dv.

(3) Run the program, this time obtaining plots and listings of capacitance versus voltage, $1/C^2$ vs V, and log N(x) vs junction depth. The built-in voltage is obtained by a least-squares fit, assuming the inverse-square capacitance vs voltage characteristic to be a straight line. You should comment on the plots you obtain. The plot of $1/C^2$ vs V is experimental data for V negative and the straight-line least-squares extrapolation to the built-in voltage for V positive.

(4) Repeat the experiment using diode No. 2, a linearly graded junction diode. Observe all the displays, but plot only $1/C^2$ vs V. Comment on the results obtained.

(5) For linearly graded junction diodes, the junction capacitance is proportional to $V^{-1/3}$. For this case, then, a plot of $1/C^3$ should be a straight line. With the EE316 Source Programs diskette in drive B:, type COPY B:PROFILE.PAS B:DOPING.PAS, enter TURBO and set up B: as your Logged disk. Then use DOPING as your work file. Edit this file so that it will generate a plot using this assumption. Compile the program and use it to repeat steps (2) and (3) using diode No. 2.

it will generate a plot using this assumption. Compile the program and use it to repeat steps (2) and (3) using diode No. 2.

EE316

Spring 1985(4)

EXPERIMENT C-3
THE COMPUTER AS A LABORATORY INSTRUMENT DIRECT MEASUREMENT AND SIMULATION OF CIRCUIT PERFORMANCE

PURPOSE

A small computer is a useful instrument for the measurement of the performance of circuits already in existence. If a *new* circuit is to be designed, the same methods may be applied to a breadboard realization of the design. But the computer can help us here in a quite different way, namely by *simulating* the performance of the circuit. If accurate mathematical models of the devices used in the circuit are available, a model of the entire circuit may be analyzed by the computer without the need for the presence of a physical circuit. For measuring real circuit behavior we will consider

(1) Providing an input signal to the circuit from the D/A converter, sampling the response with the A/D converter (time response);

(2) Using the D/A converter to sweep a function generator over a range of frequencies, measuring the response with the A/D converter operating as a peak detector (frequency response).

For simulating circuit behavior we will consider, after having obtained a set of equations representing the circuit model

(1) Direct evaluation of the circuit transfer function (frequency response);

(2) Numerical integration of the circuit equations for an arbitrary given input signal (time response);

(3) Inversion of the Laplace Transformation of the product of the transfer function and the transformed input signal via the partial fraction expansion (time response);

(4) Inversion of the Discrete Fourier Transform (DFT) of the product of the c_n of a periodic input signal and the corresponding values of the transfer function (time response).

PREPARATORY QUESTIONS

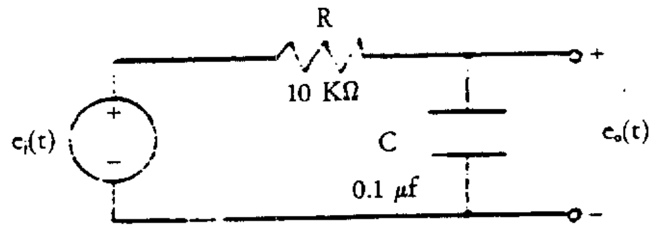
For the simple RC filter shown below

(1) Find the transfer function $E_o(s)/E_i(s)$. At what frequency is the gain reduced to 1/sqrt(2) of its DC value?

(2) If $e_i(t)$ is a step function, find $e_o(t)$ via the partial fraction expansion and Inverse Laplace Transform. Include the possibility that $e_o(0)$ is not zero; i.e., that C has an initial charge. For those not familiar with the Laplace Transform, solve the differential equations any way you wish.

(3) Find $e_o(t)$ in (2) via numerical integration using Euler's rule with a 0.2ms and a 0.4ms integration step size. Calculate only 3 or 4 steps and compare with the result found in (2).

(4) If $e_i(t)$ is a square wave with period 10.0ms, what are the c_n of the periodic $e_o(t)$?



LABORATORY EXPERIMENTATION

(1) The Function Generator as a Voltage-Controlled Oscillator (VCO) — Calibration

The HP function generator provides a frequency which is linearly dependent on a voltage applied through the back of the instrument. If the frequency dial is set to 1, the frequency may be raised by a factor of about 10.5 with a negative voltage of the same magnitude. Since the Lab Tender D/A converters operate over a range of [− 5, + 5], this voltage must be shifted by 5v and magnified a little. An operational amplifier circuit for accomplishing this shift is provided on a breadboard. The circuit diagram appears on this sheet. Supply it with + 12v and − 12v power, and input a − 5v signal from the Lab Tender. Adjust the + 12v supply for 0v out. A + 4.96v input should yield a negative voltage in excess of − 10v. Connect the shifter to the VCO input, the frequency counter to the function generator output, and set the frequency to about 1 on the 100 scale (100 Hz). Run the program VCOCAL. It will request several readings of the frequency read from the counter. It will then report the best straight-line fit to the voltage vs frequency characteristic along with the error in linearity found. Is this error in line with the resolution of the D/A converter? Can you think of a way to automate the experiment completely?

(2) Swept Frequency Response Using a VCO

With a twin-tee test circuit driven by a sinusoid from the VCO, and with the A/D converter channel 0 connected to the output of the filter, run the program FREQRESP. Observe the output of the test circuit on the oscilloscope. Obtain a printer-plot of the frequency response. Compare the results with those obtained by simulation and shown on this sheet. Repeat the experiment using the 10K resistor — 0.1 μf capacitor filter on the breadboard. Compare with your prep question results. Before carrying out this experiment, you must carefully remove any DC offset from the VCO, using the multimeter. Why?

(3) Time Response Measurements

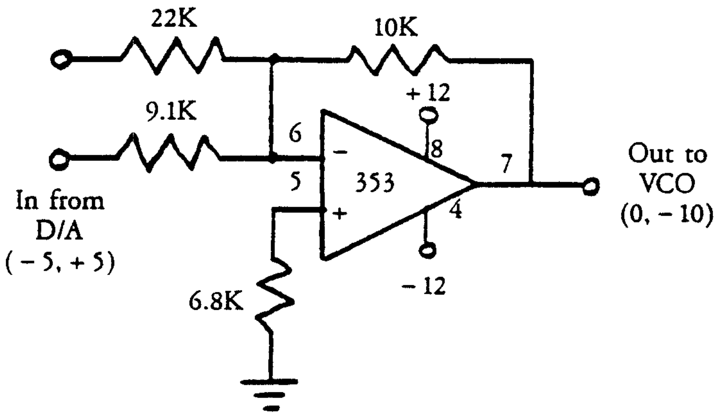
With D/A converter channel 2 connected directly to the input of the RC filter, and with the A/D converter channel 0 connected to its output, run the program STEPRESP and eventually obtain a plot of the step response of the circuit. Compare with your prep question results. Repeat the experiment with the twin-tee filter. You may observe the sampled step response obtained by the computer by connecting D/A channel 0 to your oscilloscope input, using D/A channel 1 as a negative-slope trigger as in earlier experiments. Results from a simulation appear on this sheet. You will need the highest sampling rate possible to catch the initial spike of the twin-tee response. The present program will allow a rate of about 15 KHz before A/D overrun (new sample request before last sample read) occurs.

(4) Time Response Simulation

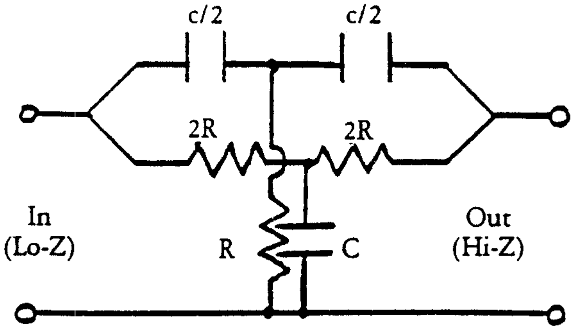
Simulate the RC filter in (3) by running STEPSIM, entering the circuit parameters when requested. Run the simulation with several different integration step sizes to measure the truncation error. Compare the results of the several runs with your prep question calculations. The computed step response may be observed as in (3).

(5) Frequency and Time Response Simulation with Periodic Input

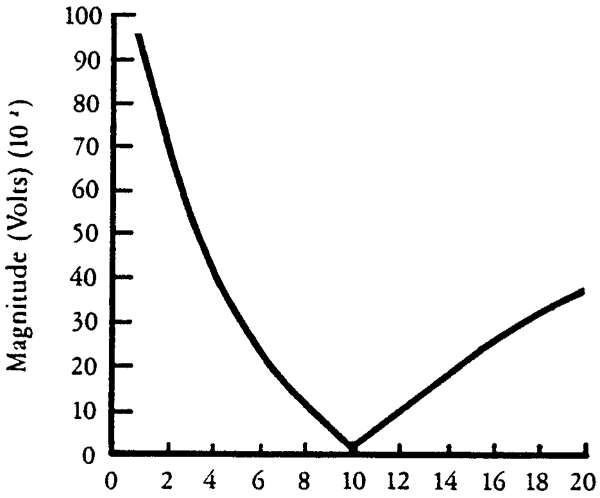
Repeat (4) using a periodic square wave input by running FOURSIM and entering the circuit parameters when requested. Obtain a printer-plot of the output amplitude spectrum and the output waveform, which is obtained in this program from an Inverse Discrete Fourier Transform of the output spectrum. Compare the output amplitude spectrum with your prep question results. Compare the output waveform with the previous runs. Be careful to choose the waveform parameters (sampling frequency, etc.) to give easily comparable results.



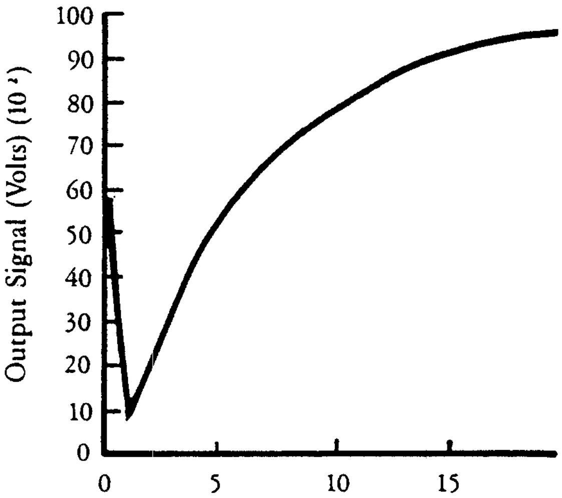
Matching D/A output to VCO input



Twin-Tee Filter
for 1 KHz Notch R(KΩ) C(μf) = 1/2π
R = 16.14KΩ C = 0.01 μf.



Frequency Hz (10^2)
Twin-Tee Frequency Response



Twin-Tee Step Response
Time (Sec.) (10^{-4})