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Optimization and testing of a counting rate circuit for nuclear reactor noise measurements

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OPTIMIZATION AND TESTING OF A COUNTING RATE CIRCUIT

FOR NUCLEAR REACTOR NOISE MEASUREMENTS

by

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I. INTRODUCTION

Reactor noise measurements are normally performed with an ionization chamber and micro-microammeter or a pulse type detector and a counting-rate circuit. In either method, time dependent neutron level variations are converted to voltage signals which are analyzed by standard random noise techniques (14).

The pulse detector-counting-rate circuit combination, when properly designed, exhibits a higher frequency response (1, 3, 5) and less electronic noise pick up than the ionization chamber. For these reasons it has become quite popular as a neutron level to voltage transducer for noise measurements. The standard application consists of a pulse neutron detector, linear pulse amplifier with discriminator, and the counting-rate circuit which converts the voltage pulses from the amplifier to a continuous voltage. This voltage depends on the input pulse rate to the counting-rate circuit (CRC). Although the CRC is considerably more efficient than the ionization chamber, its transfer function characteristic prohibits the detection of the reactor frequency response at high frequencies without appropriate corrections.

The purpose of this investigation was to develop a technique for testing and optimizing the CRC with respect to the frequency response and distortion of the output signal. It was, therefore, necessary to employ a device which would behave in a manner analogous to the detector-amplifier-pulse shaper detection system and produce a pulse rate proportional to its input voltage. An electronic circuit capable of converting voltage to pulse rate (6) seemed to satisfy the requirements for simulating the detection system. It was found in this investigation that it provided an excellent method for testing and optimizing the CRC. This pulse-producing circuit, justifiably given the name voltage-to-frequency converter (V-F-C), is shown in Figure 3 and is described in some detail in Part II, Section C.

The pulses generated by the V-F-C were fed to the input of the CRC for integration. The resulted output of the CRC was displayed on the oscilloscope and its voltage amplitude was recorded for different frequencies of the incoming pulses. The final result was interpreted by means of a "Bode" plot which is a plot of the gain of the system in decibels versus logarithmic frequency.

The frequency response of the CRC was studied in the frequency range from 1 to 1000 cps which is within the frequency range considered to be important for the reactor measurements. Thus by knowing the frequency response of the CRC, reactor noise measurements can be performed in a low band of frequencies within which the amplitude of the transfer function of the CRC remains constant. Beyond the "corner" frequency the amplitude of the transfer function decreases at a rate of approximately 15 decibels/decade and therefore the noise measurements must be corrected.

II. REVIEW OF LITERATURE

A. Reactor Noise Concept

The term noise as used in science and engineering is applied to any type of signal or information flow characterized by a random behavior.

A nuclear reactor, which under certain conditions is a linear physical system, can be expected to exhibit noise in a variety of ways. In most cases, reactor noise is due to the random nature of its neutron power. For example, when the neutron population is relatively low, the reactor power level can be expected to exhibit random fluctuations because the effects of individual neutrons are observed. However, when the neutron population is high the random fluctuations in the power level are more likely caused by other disturbances (14). Such a disturbance could be the temperature of the fuel or the coolant flow for example.

Noise analysis has been employed by many scientists and engineers to obtain information about reactor dynamics. A simple analysis of the random fluctuations in the power level of a nuclear reactor may provide a continuous report on operating variables of the reactor which are of great assistance to the operator (13). Noise level is frequently measured by the signal-to-noise ratio expressed in decibels as follows:

$$10 \log_{10} \frac{\text{signal power}}{\text{noise power}}$$

or

$$20 \log_{10} \frac{\text{signal voltage}}{\text{noise voltage}}$$

since electric power is proportional to voltage. The reactor signal to which the noise is referred may simply be the average neutron or power level of the reactor. It may also be a certain variation of the reactor power induced by positioning a control rod. In most cases a nuclear reactor is excited by a control rod. A step change in rod position gives a period for calibration at very low powers, while it gives the reactor response to a step reactivity function at high powers. The transfer function of the system may be obtained at discrete frequencies by using an oscillating control rod. In some measurements of the reactor transfer function, a control rod is moved in a random manner to encompass a wide continuous frequency range at one time.

Studies of noise analysis and descriptions of recent developed measuring techniques can be found in a book by Thie (14).

Noise research at Iowa State University consists of the work of Leribaux (9), Danofsky (2) and Paleocrassas (10). Part of the investigation carried out by Paleocrassas (10) utilized a CRC similar to the circuit that the present investigation is concerned with.

B. Counting-Rate Meter

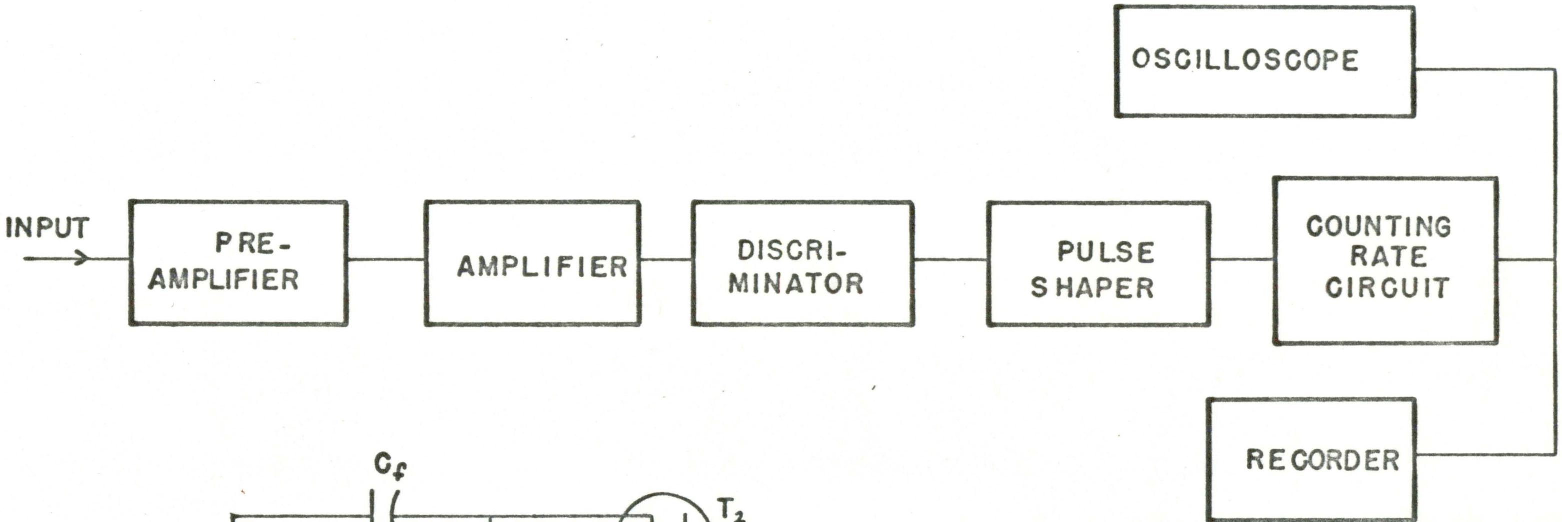
The counting-rate meter is a device for use with a Geiger-Muller detector or any other random or periodic counting instrument (3). It includes a simple electrical computing circuit, namely the counting-rate circuit, such that the output reads the average counting rate directly. It is to be distinguished from the counter, i.e., a scaler-impulse-register combination used in conjunction with a timer. The counting-rate meter has the advantage that the counting rate can be indicated and recorded continuously. A block diagram of a counting-rate meter is shown in Figure 1. The apparatus consists of a number of electronic instruments that assist in conditioning the detector signal (11), produced by means of a nuclear reaction, which is to be counted by the CRC.

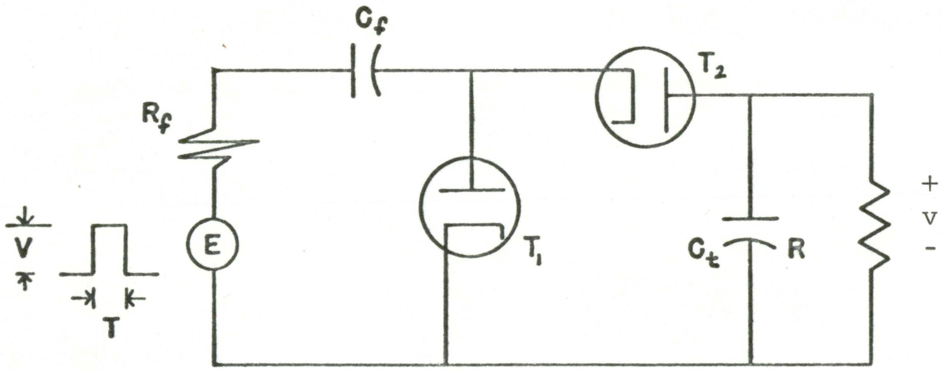
The basic operation of the counting-rate meter is as follows: When a nuclear particle interacts with a detector a charge is released at the input of a preamplifier which is an electronic circuit used to insure that the pulse will not be attenuated in the cable connected to the amplifier. The function of the amplifier is to amplify the signal approximately 100 times so that its magnitude will be large enough to register a count. The discriminator is connected in series with the amplifier and serves to select only those pulses that are desired for the counting process. These pulses enter the pulse shaper or pulse equalizer which is a conventional multivibrator circuit. This is used to insure that all the pulses passing the discriminator are made uniform in size and shape before they reach the CRC which is the prime concern of this investigation and is discussed in detail in the next section. The output of the integrating circuit or CRC may be continuously recorded on a recorder which is connected in series with the meter (3, 11).

1. <u>Counting-rate circuit</u>

A description of the design and operation of the CRC can be found in most standard textbooks on electronic circuits including Price's (11) and Elmore and Sands' (5). A very good description of the electronic

Figure 1. Simplified diagram of a counting-rate meter for pulse-type detectors (counting-rate circuit given by Cooke-Yarborough (1, p. 191))





OUTPUT OF COUNTING RATE CIRCUIT

circuits comprising the counting-rate meter, and the statistics of the system is given by Kip et al. (7). The CRC operates on a counting rate to voltage linear relationship. As shown in Figure 1 it consists of a diode-pump circuit that feeds a known charge for each input pulse into a tank capacitor C_t which is shunted by a resistor R. The voltage across the capacitor C_t builds up to an equilibrium value at which the rate of loss of charge through the shunt resistor equals the rate of input of the charge by the pulses. If the charge per pulse is a constant, the equilibrium value of the voltage v is:

$$v = rqR \,, \qquad (1)$$

where r is the average number of pulses per second

q is the charge fed into C_t

R is the shunt resistor.

Equation 1 can also be written as:

$$v = rVC_fR \quad \text{since} \quad q = VC$$

where C_f is the capacitor of the diode-pump or charge feeding circuit, and

V is the voltage amplitude of the incoming pulses.

If the incoming pulse rate is constant with time the voltage across the tank capacitor C_t is seen to be independent of the size of the capacitor as given by Equation 1. However, the capacity does affect the time required to reach equilibrium and the statistical accuracy as discussed in the next section.

The feeding of the charge to the integrator is accomplished by employing the diode-pump circuit which operates as follows: Consider a rectangular pulse of duration T and height V produced by the generator E with internal resistance R_f, Figure 1. The capacitor C_f is charged, through the resistance R_f in series with T_1, up to nearly the pulse voltage V, provided that the pulse duration T is greater than about five time constants or $5R_fC_f$. When the input pulse returns to zero, C_f discharges through T_2, placing a fixed charge VC_f per pulse on the tank capacitor C_t, provided that the following conditions hold:

$$C_f \ll C_t$$

$$v \ll V$$

and

$$\frac{1}{r} - T > 5R_fC_f \quad .$$

The first two conditions ensure that negligible charge remains on C_f in equilibrium, while the third condition ensures that sufficient time elapses for equilibrium to be nearly reached before the next pulse occurs. If the condition $v \ll V$ is not satisfied the charge per pulse becomes $(V - v)C_f$; therefore, Equation 1 becomes

$$v = \frac{VrC_fR}{1 + rC_fR} \quad . \qquad (2)$$

Equation 2 indicates that linear relationships between voltage and counting rate are obtained by properly choosing the circuit parameters.

2. Statistics of the counting-rate meter

The statistical treatment of counting-rate meter data differs from that for direct counting and for scaling circuits (7). For the counting-rate circuit (CRC) it is seen from Equation 1 that the average voltage across the RC_t tank resistance R is

$$v = rqR \quad .$$

Thus the time averaging parameter is introduced into the circuit by the tank resistance and any change in R will change the output proportionally. In parallel with this resistance is the smoothing capacitor C_t, which serves to average out the statistical fluctuations in the counting rate by imposing a time constant of RC_t seconds on the tank circuit. The random distribution of individual pulses with time, in accord with Poisson's distribution law will produce fluctuations from the average voltage output. The tank condenser merely smooths out these voltage fluctuations by introducing a time delay in the response and recovery of the integrating circuit. Changes in value of C_t can affect only the speed of response of the circuit to a change in average counting rate, and to the short-time statistical fluctuations.

Because of this time constant, the net output voltage at any instant involves an integration of all the previous counts, expressed exponentially according to the time elapsed since they occurred. Then successive closely or continuously spaced observations are not mutually independent. This interdependence of successive observations is the condition which requires a special statistical theory for evaluating the probable error directly in terms of the fluctuations observed in the continuous record.

The standard deviation σ from the equilibrium voltage of an instantaneous value taken at random is given in Price (11) as:

$$\sigma_v = \left[\frac{q^2 rR}{2C_t} \right]^{\frac{1}{2}} \qquad (3)$$

3. Determination of average counting rate and probable error

After the voltage across C_t has reached equilibrium any instantaneous reading of the output voltage caused by a purely random counting rate has a probable error identical with that inherent in a message register observation of the same counting rate over a time interval equal to $2RC_t$. This probable error is expressed in terms of the parameters of the CRC and the counting rate r. Each pulse counted excites the transient

$$e(t) = \left[\frac{C_f}{C_t} \right] V \exp \left[\frac{-t}{RC_t} \right] \qquad (4)$$

across C_t. The mean square fluctuation voltage for random counts can be computed using Campbell's theorem,

$$(\Delta v)^2 = \overline{(e(t) - v)}$$

$$= r \int_{-\infty}^{\infty} e^2(t)dt$$

giving $$(\Delta v)^2 = \frac{rC_f^2V^2R}{2C_t},$$

which yields Equation 3 when its square root is taken and VC_f is replaced by the charge q (3).

The fractional probable error is defined as

$$p = 0.67 \frac{\Delta v}{v} \qquad (5)$$

where

$$\Delta v = \sigma v = \left[\frac{q^2rR}{2C_t} \right]^{\frac{1}{2}} \qquad (3)$$

and

$$v = rqR \qquad (1)$$

Substitution leads to Equation 6

$$p = \frac{0.67}{(2rRC_t)^{1/2}} \quad . \tag{6}$$

For a given reading of the meter, Equation 6 shows that rR is constant so a certain value of C_t corresponds to a definite fractional probable error. The absolute probable error, s, of a single reading is (7)

$$s = pr = 0.477 \left[\frac{r}{RC} \right]^{\frac{1}{2}} \quad . \tag{7}$$

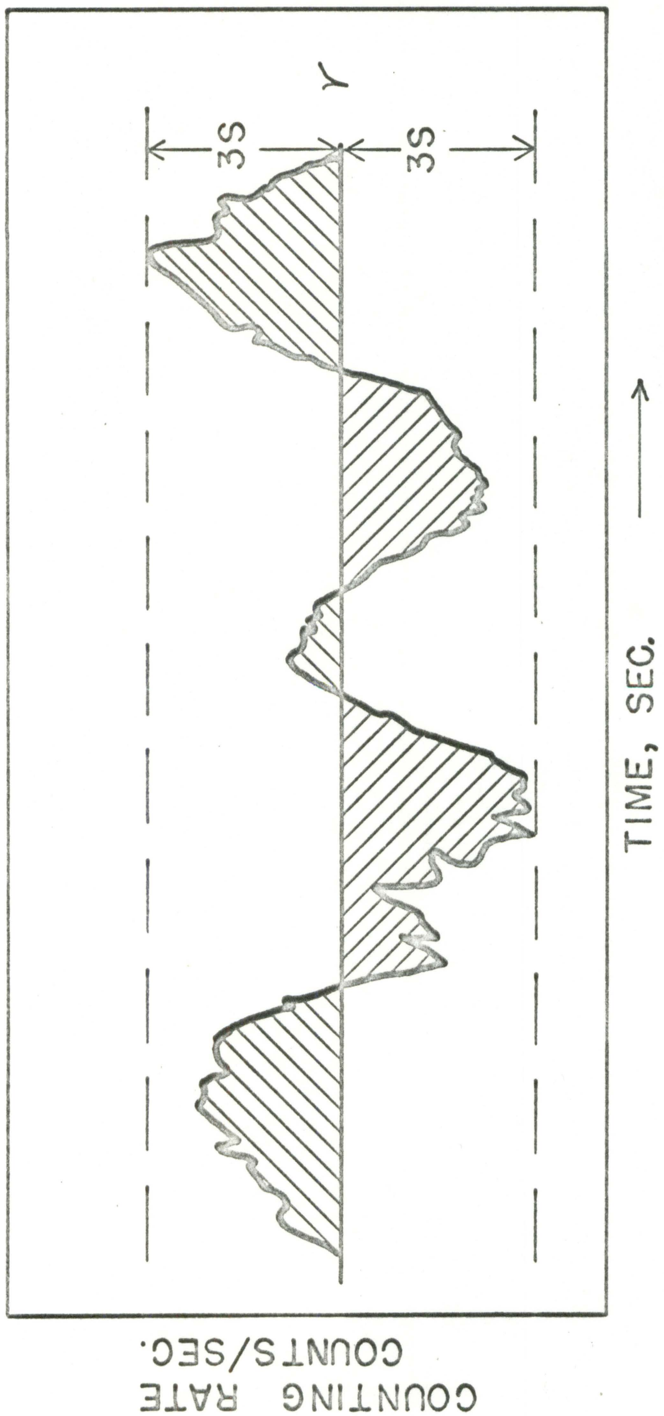
Continuous recording displays visually the average counting rate and, from the magnitude of the fluctuations, gives an index of the probable error of the mean. Figure 2 shows a schematic representation of the output voltage record as a function of time, displaying exaggerated statistical fluctuations for purposes of illustration. The average value r is determined by drawing a line through the record, such that the first moment of the individual variations from r is zero. This is seen to be a line which gives equal areas (shown cross shaded in Figure 2) above and below the average value.

In any Poisson distribution the statistical fluctuations in the random occurrence of individual events approach the normal law distribution as the average value increases. The difference between the two distribution laws is small for $r = 10$ and negligible for $r > 100$. Hence the well-known normal law property that states that the fractional number of individual fluctuations greater than three times the probable error of a single observation is 4.4 percent for fluctuations of both positive and negative sign may be utilized.

Taking any particular point on the output curve as an isolated

Figure 2. Schematic representation of counting-rate meter output showing statistical fluctuations (7, p. 329)

The heavy line locates the average value r, the equal shaded areas representing the observations above and below the average value. The dotted lines locate the region $r \pm 3s$, where s is the probable error of any single point on the curve.


γ
3S
3S
TIME, SEC.
COUNTING RATE
COUNTS/SEC.

observation, it is seen that its variation from the average should exceed 3s only 4.4 percent of the time (7). Thus if lines are drawn, as in Figure 2, which include all but 2 percent of the highest observations and 2 percent of the lowest observations, a reasonably accurate graphical evaluation of the probable error s of any single point will result.

4. Statistical equilibrium time

A finite time is required for the counting-rate meter output to reach a new equilibrium value when the average counting rate is changed suddenly. The new equilibrium is effectively reached when the theoretical instantaneous output current or voltage differs from the final average output by s or less. Starting with zero output current, this equilibrium time, t_o, is (12),

$$t_o = RC_t \left(1/2 \ln 2rRC_t + 0.394 \right) \qquad (8)$$

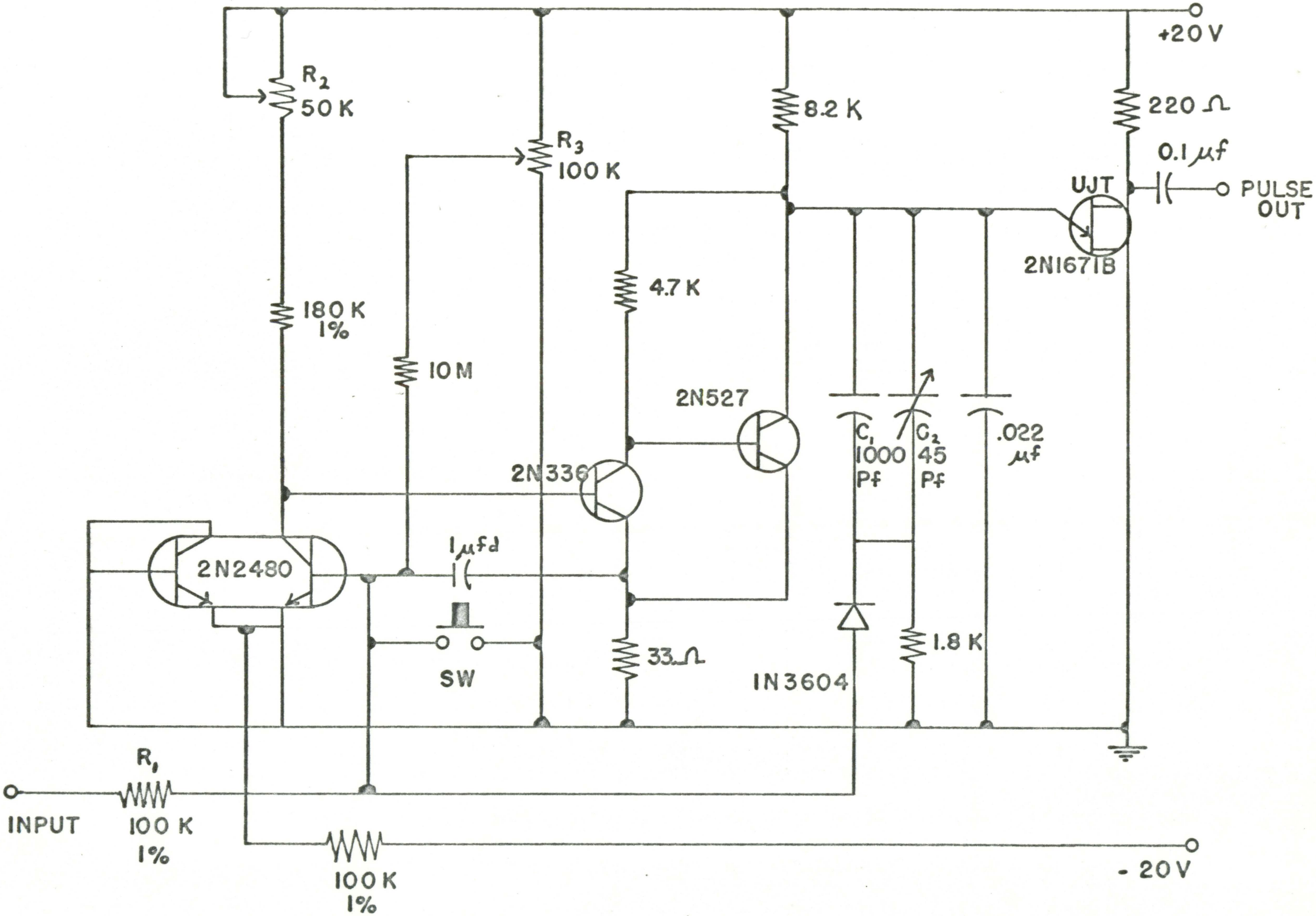
C. Voltage-to-Frequency Converter

The voltage-to-frequency converter (V-F-C) is an electronic circuit that gives an output frequency proportional to the input voltage. For the design and specifications given in the General Electric Transistor Manual (6) an input of 1 volt produces a frequency of 1 KC or 1000 pulses/sec. The circuit is shown in Figure 3 and was an important contributor to experimentally obtaining the response of the CRC.

It has an input impedance of 100 K and its linearity is better than 0.1 percent with a short term equivalent input voltage drift less than 0.5 millivolts. Overall negative feedback is used to achieve the high degree of linearity and stability. The transistors form an operational amplifier with an overall voltage gain of 5000 at the emitter of

Figure 3. Voltage-to-frequency converter given in Transistor Manual (6, p. 346)

The filtering of the D.C. level of the output is necessary in order to obtain the 2 volt pulse.


+20 V
R2
50 K
R3
100 K
8.2 K
220 Ω
0.1 μf
UJT
PULSE OUT
2N1671B
4.7 K
180 K
1%
10 M
2N527
C1
1000
Pf
C2
45
Pf
.022
μf
2N336
2N2480
1μfd
33 Ω
SW
IN3604
1.8 K
R1
INPUT
100 K
1%
100 K
1%
- 20 V

the unijunction transistor (UJT). Each time the UJT fires a fixed quantity of charge is fed back to the input of the operational amplifier through C_1, C_2, and the diode. The average current fed back to the input is proportional to the frequency so that the frequency must be proportional to the input voltage to maintain the summing point of the operational amplifier at zero potential.

To adjust the circuit the switch SW is closed and R_2 is set to the point where oscillations just start. Then SW is opened, one millivolt is applied at the input and C_2 is set to the point where the frequency is 1000 cps. If this setting is outside the range of C_2, capacitor C_1 must be replaced or trimmed. The voltage supplies used for biasing the transistors should be at least as stable as the required measurement accuracy. The filtering of the D.C. level of the output is necessary in order to obtain the desired pulse.

III. EXPERIMENTAL PROCEDURE AND EQUIPMENT

A. Characteristic Response and Performance of the Voltage-to-Frequency Converter

The need for utilizing the V-F-C in this investigation arose from the necessity of designing an electronic circuit which would produce a pulse rate proportional to its voltage input. If, for example, a positive sine wave were applied at the input of such circuit the output pulse rate should be expected to increase and decrease accordingly, following a sinusoidal distribution.

The design of a circuit that would respond as described above would involve a frequency modulator unit in conjunction with a multivibrator but its adjustment to produce a pulse rate within the desirable range would be rather difficult. Instead the V-F-C described previously seemed to work quite well, attaining a high degree of stability.

As it was mentioned in the introduction, the V-F-C behaves similarly to the radiation detection system, i.e., produces a pulse rate proportional to the input voltage just like the detector placed in a nuclear reactor gives a higher pulse rate when more neutrons are absorbed. Thus the counting-rate circuit may be tested for its frequency response for any time-varying signal by the generated pulses of the V-F-C. In this work the time-varying signal impressed at the input of the V-F-C was chosen to be a positive sine waveform.

The pulse obtained at the output of the V-F-C, Figure 3, when a positive voltage of any waveform was applied at its input had the following characteristics:

Height of pulse	V	= 2 volts
Delay time	T_D	= 2 μsec
Rise time	T_R	= 3 μsec
Decay time	T_F	= 4 μsec
Pulse duration	T	= 8 μsec

It is to be realized here that only inputs of positive polarity would produce a pulse. Pulses of uniform rate required a D.C. input voltage whereas pulses of variable rate required a time varying signal. In addition the V-F-C pulse was negative in polarity and therefore when applied to the CRC for integration the diodes of the pump-circuit, Figure 1, were properly arranged to satisfactorily feed the charge into the tank circuit. Obviously the polarity of the diodes should be reversed from their previous arrangement which was designed to count a positive pulse.

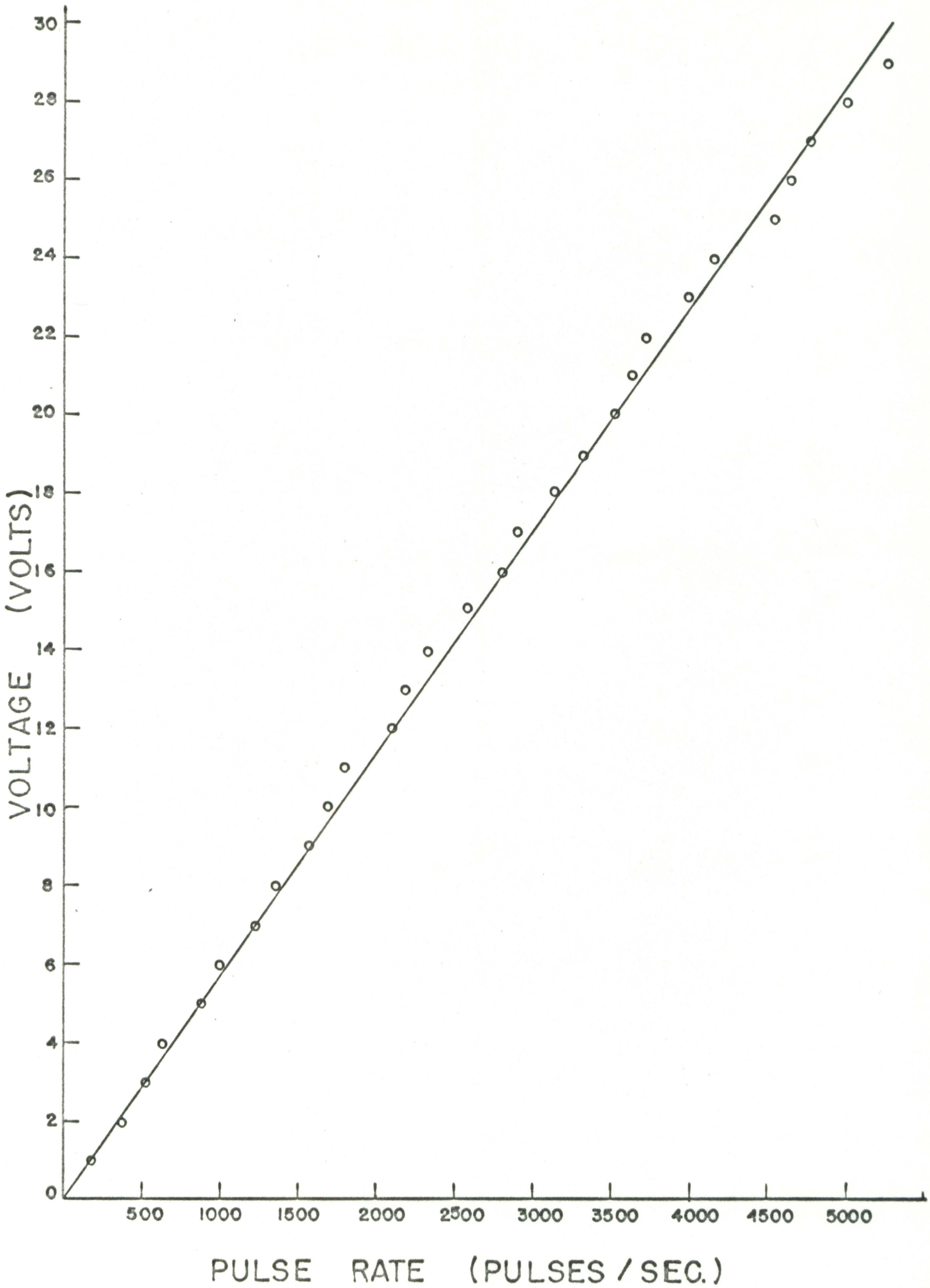
The counting rate obtained by the V-F-C used in this experiment was not quite as high as the one specified by the designer (6) but it was sufficiently high for the purpose of this investigation.

The input voltage-counting rate response was obtained for the V-F-C for a voltage input ranging from 1 to 30 volts taken in 1 volt increments. The resulting data are tabulated in Table 1 and shown as a graph in Figure 4.

Table 1. Voltage vs. counting rate characteristic of voltage-to-frequency converter

Voltage (volts)	Period (msec)	Frequency (counts/sec)
1	6.000	167
2	2.600	385
3	1.900	527
4	1.550	645
5	1.120	893
6	1.000	1000
7	0.810	1235
8	0.730	1370
9	0.640	1563
10	0.600	1670
11	0.540	1800
12	0.480	2082
13	0.460	2180
14	0.430	2325
15	0.390	2570
16	0.360	2780
17	0.345	2900
18	0.320	3130
19	0.300	3333
20	0.283	3530
21	0.275	3635
22	0.270	3710
23	0.250	4000
24	0.240	4170
25	0.220	4550
26	0.215	4650
27	0.210	4770
28	0.200	5000
29	0.190	5265
30	0.190	5265

Figure 4. Voltage versus counting rate response of the voltage-to-frequency converter


30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
VOLTAGE (VOLTS)
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
PULSE RATE (PULSES / SEC.)

B. Procedure

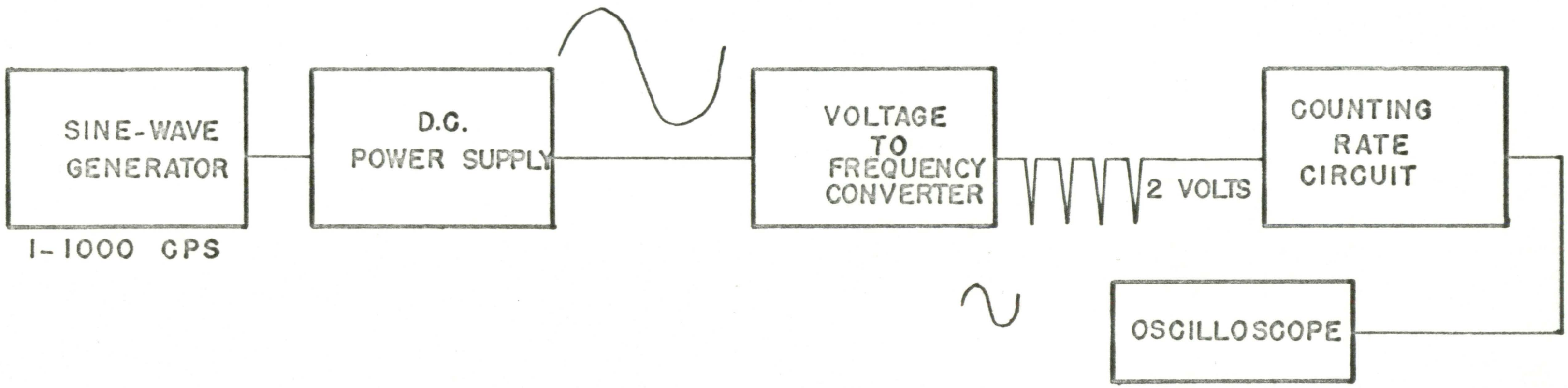
The instrumentation used for obtaining the frequency response of the CRC is shown in Figure 5 and is equivalent to that shown in Figure 1. The detector-amplifier-pulse shaper system has been replaced by the V-F-C whose pulses are large enough and well shaped to be ready for counting without any modifications.

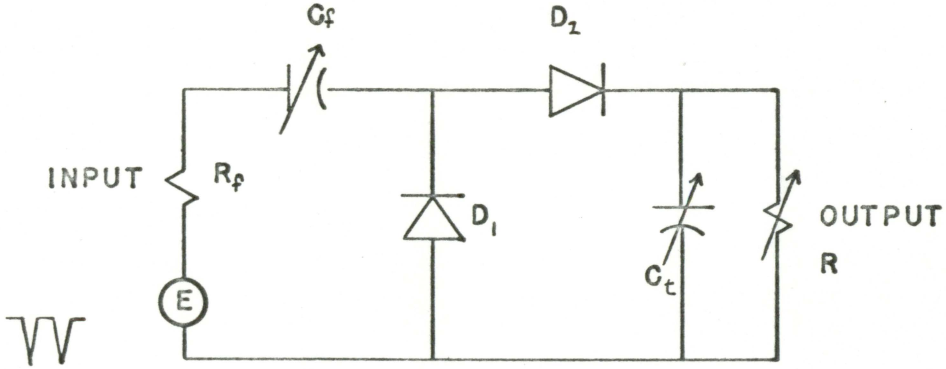
The sinusoidal waveform supplied by a low frequency function generator was superimposed on a D.C. level in such a manner that the resulting waveform was a sine wave with its minimum value at about +2 volts. The amplitude of the sine wave was varied for obtaining additional sets of data. However, most of the data were taken using a constant amplitude waveform and hence the same counting rate variation.

The desired positive waveform was fed into the V-F-C which transformed the time-varying voltage into the time-varying pulses which in turn were impressed across the input of the CRC. The result displayed on the oscilloscope was a positive sine wave whose amplitude is described by Equation 1. In this case, since the V-F-C produces pulses of 2 volts in magnitude the output of the CRC at low frequencies did not exceed 0.6 volts for a typical component setting of the circuit.

When only a D.C. voltage was applied at the input of the V-F-C the resulting output of the CRC was also a D.C. level. In addition its magnitude was independent of the changes in values of the tank capacitor C_t. The voltage obtained across R in this case denotes a uniform counting rate and is described by Equation 1. A check of an experimentally obtained counting rate with the one resulting from Equation 1 showed that the two values agreed within 20%.

Figure 5. A schematic representation of the instrumentation used to obtain the frequency response of the counting-rate circuit


SINE-WAVE GENERATOR
1-1000 CPS
D.C. POWER SUPPLY
VOLTAGE TO FREQUENCY CONVERTER
2 VOLTS
COUNTING RATE CIRCUIT
OSCILLOSCOPE


Cf
D2
INPUT
Rf
D1
E
Ct
OUTPUT
R

The frequency response of the CRC was obtained by varying the frequency of the sine wave from 1 to 1000 cps. As the frequency of the signal was increased the output of the CRC decreased according to the transfer function characteristic of the circuit.

A photograph of the output pulses from the V-F-C is shown in Figure 6 for a constant input voltage and in Figure 7 for an input frequency of 300 cps.

Data were taken for different parameter settings of the CRC, subject to conditions given in Price (11) with the purpose of optimizing the circuit response and still maintaining an undistorted signal. In order to provide a wide choice of parameter settings, variable components were used for C_f, R and C_t. The input resistor, R_f, was held constant at 1 K throughout the experiment. The other components of the CRC were varied over a wide range of values to study their effect on the size and distortion of the output signal of the CRC. All results of this investigation were interpreted by means of Bode diagrams in which magnitude in decibels is plotted versus logarithmic frequency.

C. Equipment

The present investigation utilized the following equipment:

1. A Hewllet Packard low frequency function generator model 202 A
2. An Electro D.C. power supply model 612-D
3. Two transistor power supplies
4. A Tektronix dual-beam oscilloscope model 502A
5. A Tektronix oscilloscope camera model C-12

Figure 6. Characteristic output of the voltage-to-frequency converter when a D.C. voltage is applied at its input

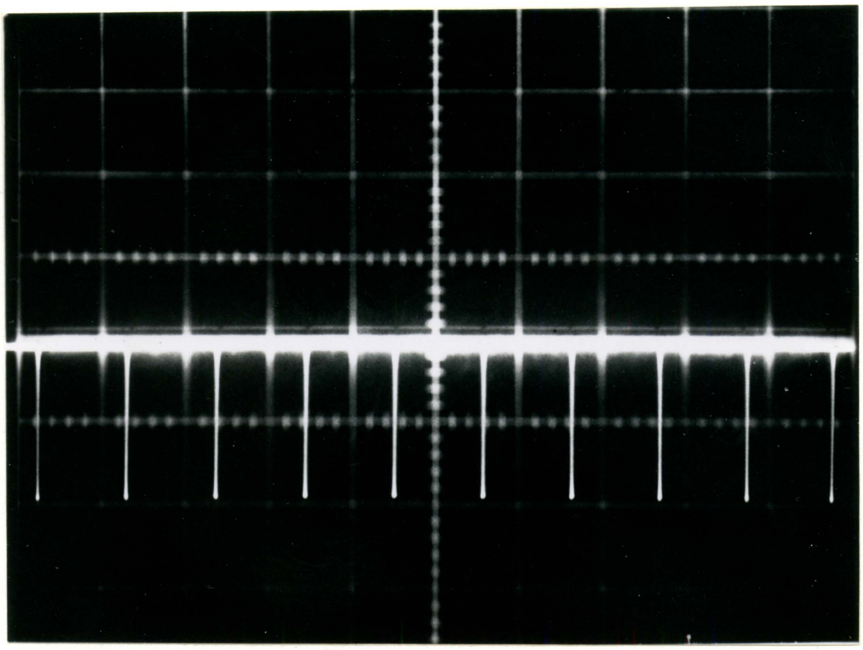
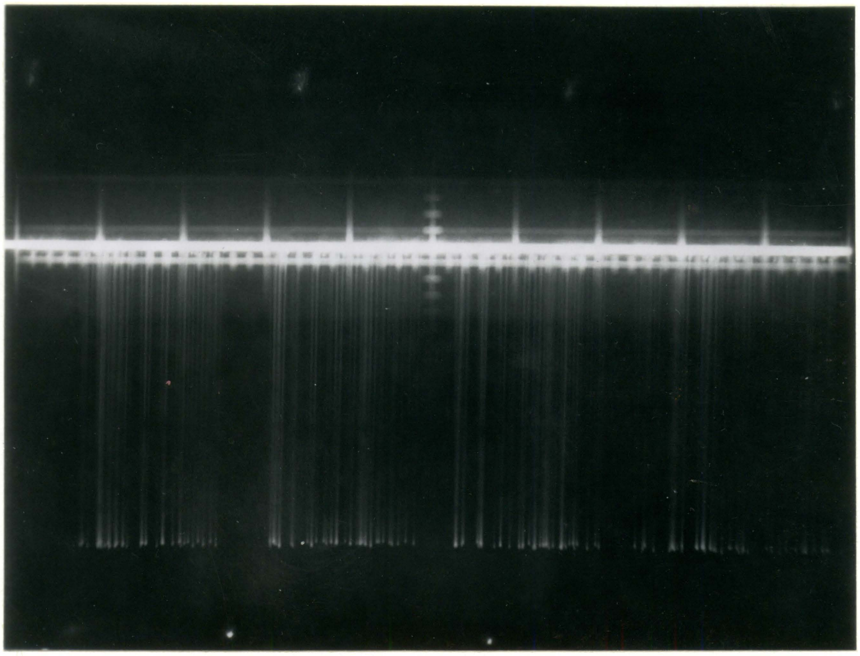


Figure 7. Characteristic output of the voltage-to-frequency converter when a 300 cps positive sine wave is applied at its input



IV. RESULTS

The amplitude of the transfer function of the CRC has been plotted for different parameter settings of the circuit and these results are presented and discussed in this section. The purpose is to show the variation of the "corner" frequency (the frequency at which the magnitude of the output of the circuit is 0.707 times the magnitude of the output at low frequencies) of the CRC with respect to different circuit components and counting rate inputs. An attempt has been made to provide useful data on the CRC and to describe a method of testing for future work.

The most common input employed to test the CRC was a pulse rate varying in a sinusoidal manner from a maximum 3130 pulses/sec to a minimum of 385 pulses/sec. Under the best design and performance conditions of the CRC the corner frequency obtained was approximately 40 cps. For each Bode plot the amplitude of the transfer function of the CRC was found to decrease at 15 decibels/decade for frequencies above the corner frequency. A simple RC circuit exhibits a corner frequency at $\frac{1}{2\pi RC}$ cps and its transfer function amplitude decreases at 20 decibels/decade. The fact that the slope of the transfer function of the CRC is different than 20 decibels/decade may be due to the action of the switching diodes.

The variation of the corner frequency due to different values of the tank capacitor C_t, with all other components the same, is shown in Table 2. Figure 8 shows the Bode plots for the two parameter settings of Table 2. Figures 9 and 10 exhibit the effect of the time constant RC_t on the corner frequency. As the time constant RC_t increases, the corner frequency decreases.

Figure 8. Amplitude of the transfer function of the counting rate circuit at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum

Curve A. Parameter setting of the counting-rate circuit: $C_f = 0.002\ \mu f$, $R_f = 1$ K, $C_t = 0.5\ \mu f$, R = 50 K

Curve B. Parameter setting of the counting-rate circuit: $C_f = 0.002\ \mu f$, $R_f = 1$ K, $C_t = 1\ \mu f$, R = 50 K

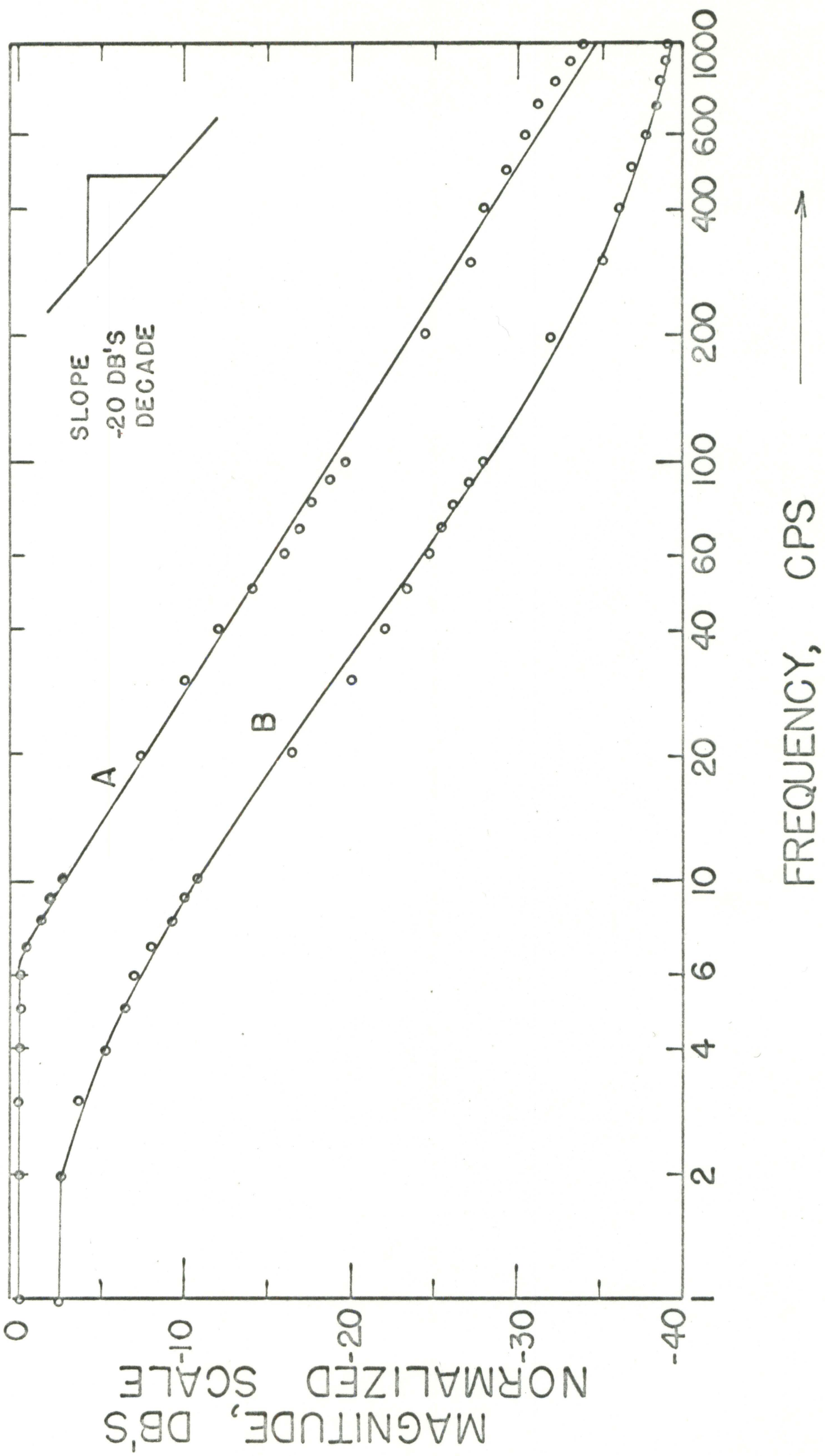

SLOPE
-20 DB'S
DECADE
A
B
0
-10
-20
-30
-40
MAGNITUDE, DB'S
NORMALIZED SCALE
2
4
6
10
20
40
60
100
200
400
600
1000
FREQUENCY, CPS

Figure 9. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: $C_f = 0.01\ \mu f$, $R_f = 1$ K, $C_t = 0.2\ \mu f$, $R = 100$ K. The input to the circuit was a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum

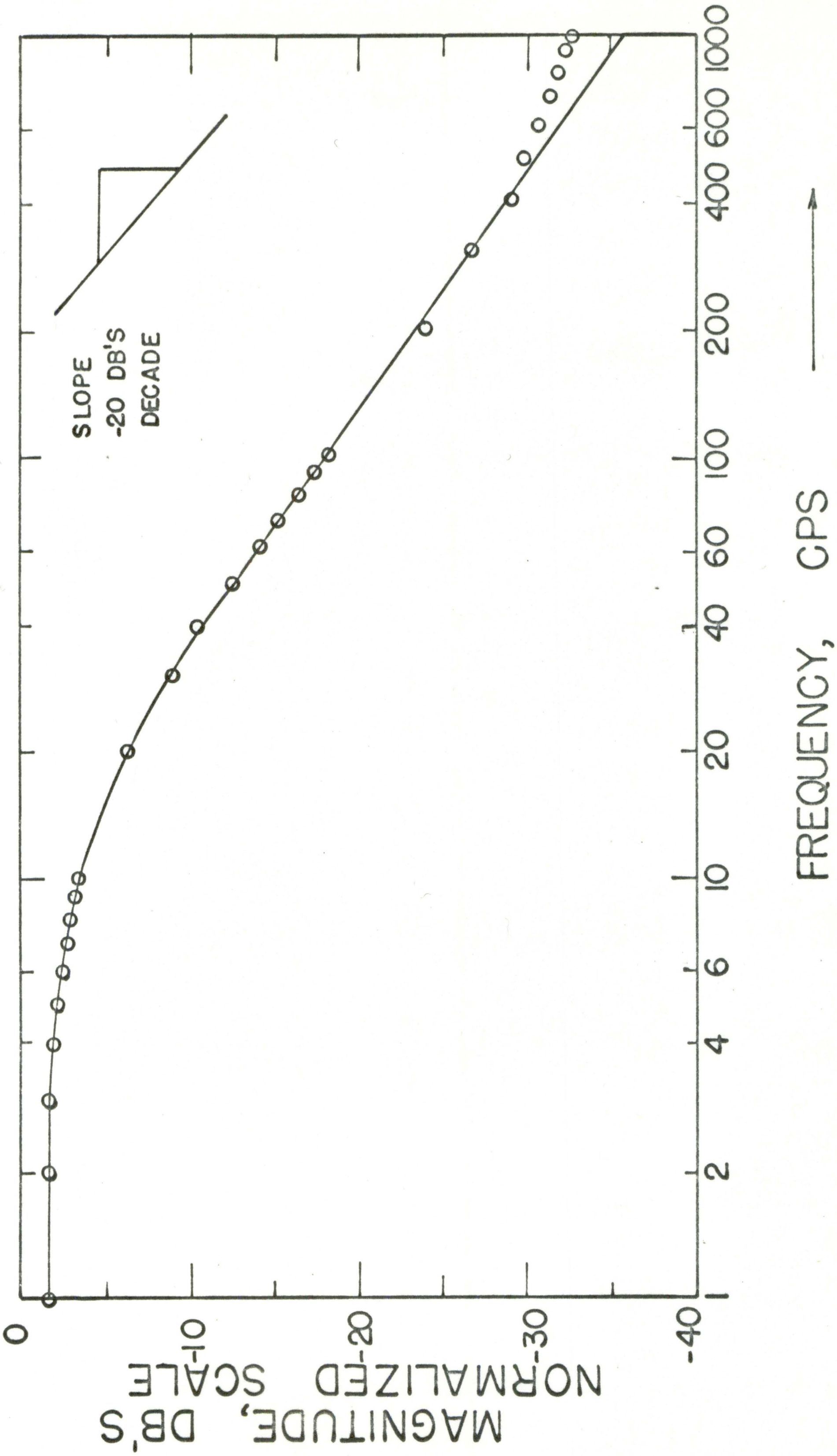
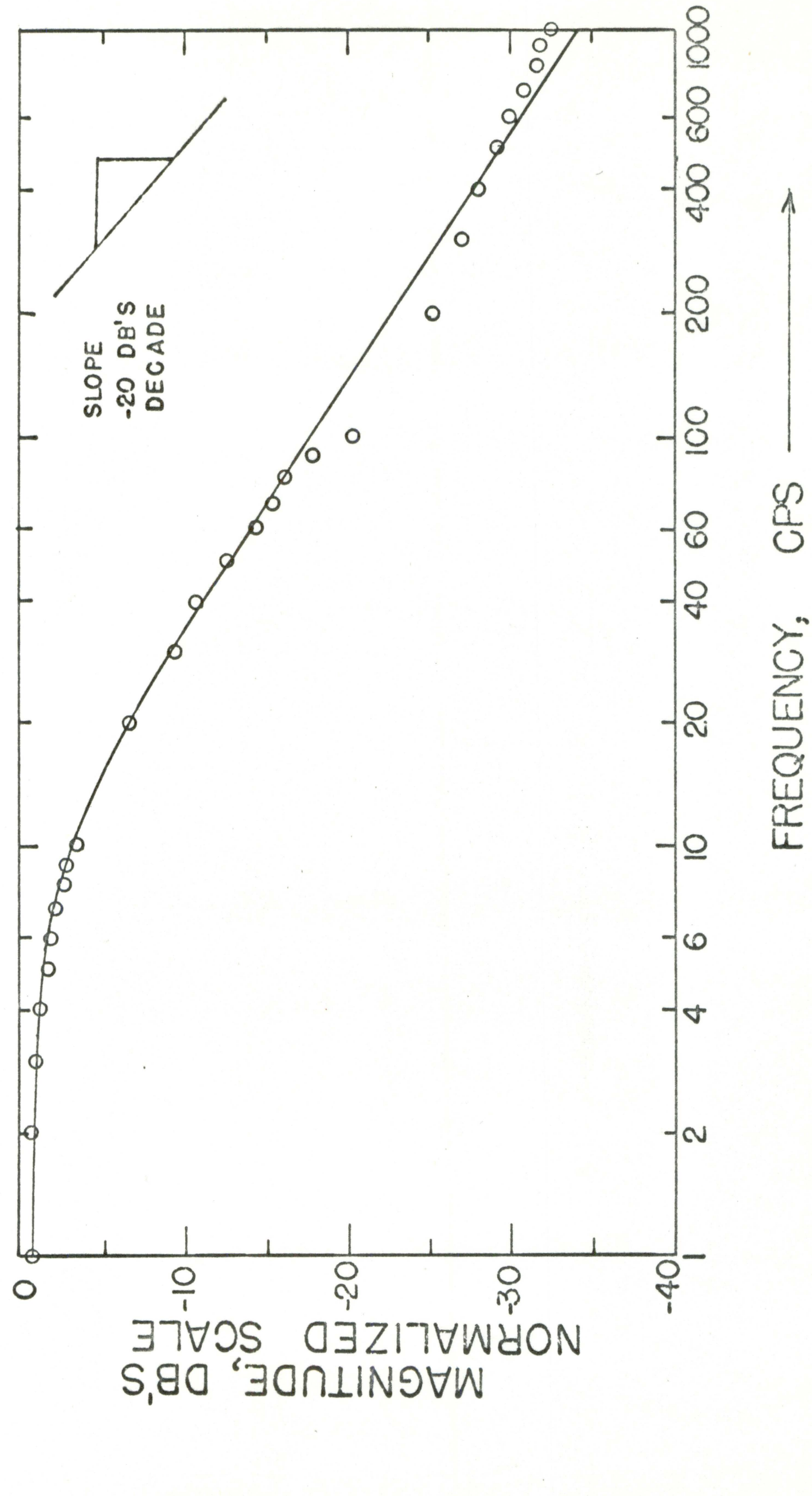

SLOPE
-20 DB'S
DECADE
0
-10
-20
-30
-40
NORMALIZED SCALE
MAGNITUDE, DB'S
1
2
4
6
10
20
40
60
100
200
400
600
1000
FREQUENCY, CPS

Figure 10. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: C_f = 0.001 μf, R_f = 1 K, C_t = 0.05 μf, R = 900 K. The input to the circuit was a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum



SLOPE
-20 DB'S
DECADE
0
-10
-20
-30
-40
MAGNITUDE, DB'S
NORMALIZED SCALE
1
2
4
6
10
20
40
60
100
200
400
600
1000
FREQUENCY, CPS

Table 2. Corner frequency comparison

C_f μf	R_f K	C_t μf	R K	Corner frequency cps
0.002	1	0.5	50	11
0.002	1	1	50	4

Efforts were made to optimize the corner frequency of the CRC by varying its components while a non-distorted signal was maintained. The need for a well integrated output signal with its pulsating fluctuations smoothed out requires a large tank capacitor C_t. As can be seen from the Bode plots the corner frequency decreases with increasing values of the capacitor C_t. Therefore a compromise has to be made in choosing a set of parameters which would offer an optimum response of the CRC.

In order to present exact information on the output signal of the CRC an oscilloscope polaroid camera was used to photograph the desired output for different parameter settings and input signal frequencies. Therefore, a comparison of the quality of the output signal can be made with respect to different frequencies and or different parameter settings. Figure 11 shows a photograph of the CRC at a frequency of 100 cps whereas Figure 12 exhibits the output at 40 cps. The magnitude of the output at the lower frequency is larger than the magnitude of the output at the higher frequency as would be expected from the frequency response of the CRC. However, the photographs were obtained for outputs displayed at different voltage sensitivities and therefore a comparison of the magnitudes of the

Figure 11. Output of the counting-rate circuit obtained with a 100 cps positive sine wave applied at the input of the voltage-to-frequency converter. Parameter setting of the counting-rate circuit as follows:

$$C_f = 0.001\ \mu f$$

$$R_f = 1\ K$$

$$C_t = 0.05\ \mu f$$

$$R = 900\ K$$

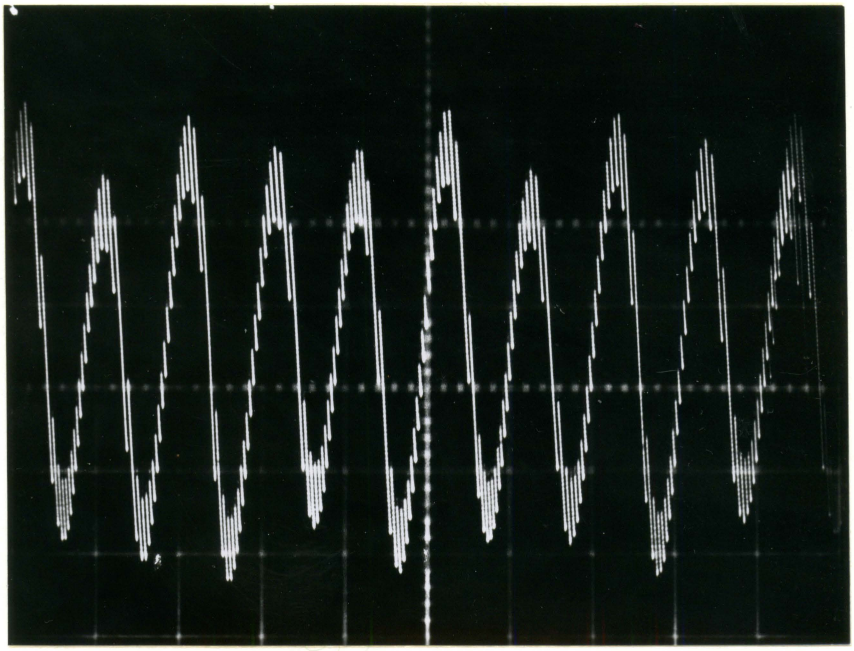


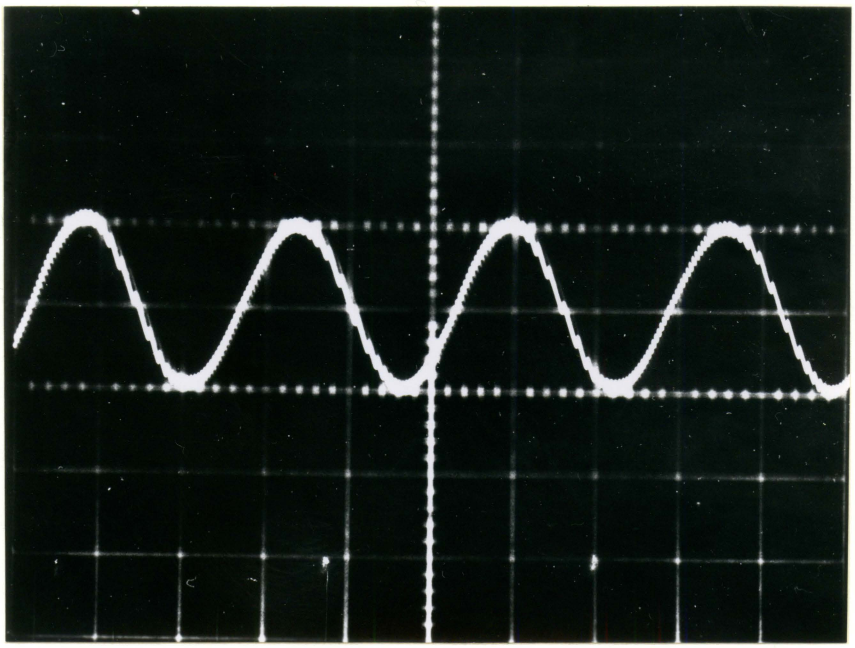
Figure 12. Output of the counting-rate circuit obtained with a 40 cps positive sine wave applied at the input of the voltage-to-frequency converter. Parameter setting of the counting-rate circuit as follows:

$C_f = 0.01\ \mu f$

$R_f = 1\ K$

$C_t = 1\ \mu f$

$R = 100\ K$



waveforms shown in the pictures is not to be made. Specifically, the objective of the illustrative photographs (Figures 13, 14, and 15) is to indicate the dependence of the output signal's quality on the incoming frequency. It was found that as the frequency of the input signal increases the output is distorted in addition to being reduced in amplitude. Thus when the frequency of the sine wave input is increased to about 200 cps the output signal begins to become distorted and at 500 cps as shown in Figure 16 the distortion is almost at its maximum.

The corner frequency of the transfer function of the CRC also varies with respect to counting rate inputs. Figures 17, 18, and 19 exhibit the transfer function of the CRC for the same parameter setting but different pulse rate inputs. A comparison of the corner frequencies obtained from Figures 17, 18 and 19 is made in Table 3.

Table 3. Corner frequency comparison

Counting rate, r pulses/sec	C_f μf	R_f K	C_t μf	R K	Corner frequency cps
300 to 5880	0.001	1	0.03	300	31
385 to 3130	0.001	1	0.03	300	36
200 to 1800	0.001	1	0.03	300	40

Figure 13. Output of the counting-rate circuit obtained with a 20 cps positive sine wave applied at the input of the voltage-to-frequency converter. Parameter setting of the counting-rate circuit as follows:

$C_f = 0.01\ \mu f$

$R_f = 1\ K$

$C_t = 0.1\ \mu f$

$R = 300\ K$

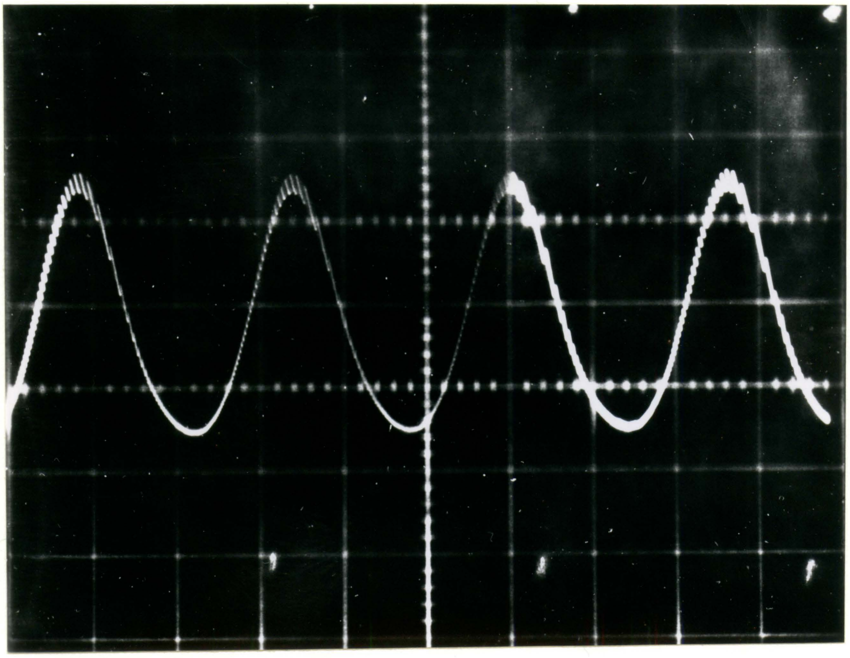


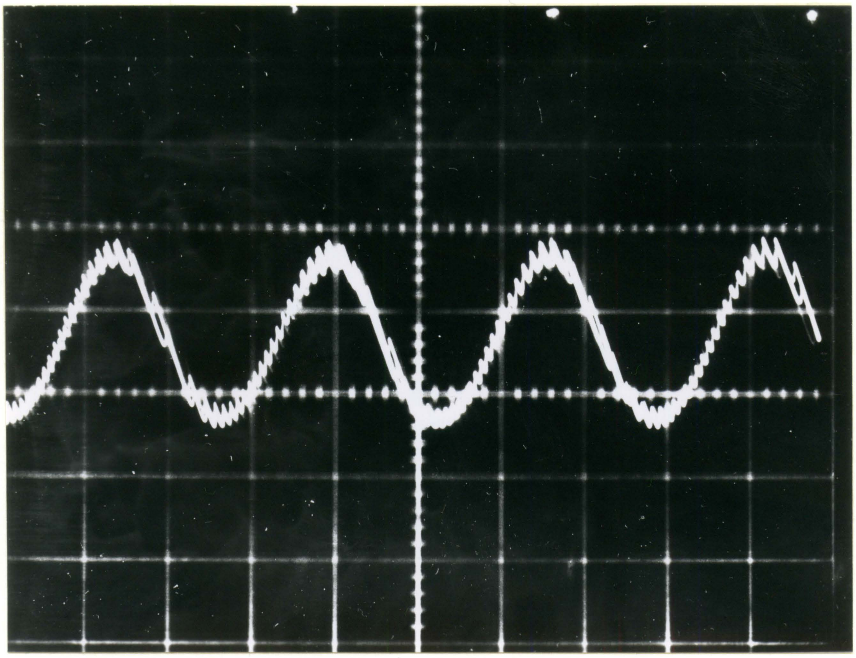
Figure 14. Output of the counting-rate circuit obtained with an 80 cps positive sine wave applied at the input of the voltage-to-frequency converter. Parameter setting of the counting-rate circuit as follows:

$C_f = 0.01\ \mu f$

$R_f = 1\ K$

$C_t = 0.1\ \mu f$

$R = 300\ K$



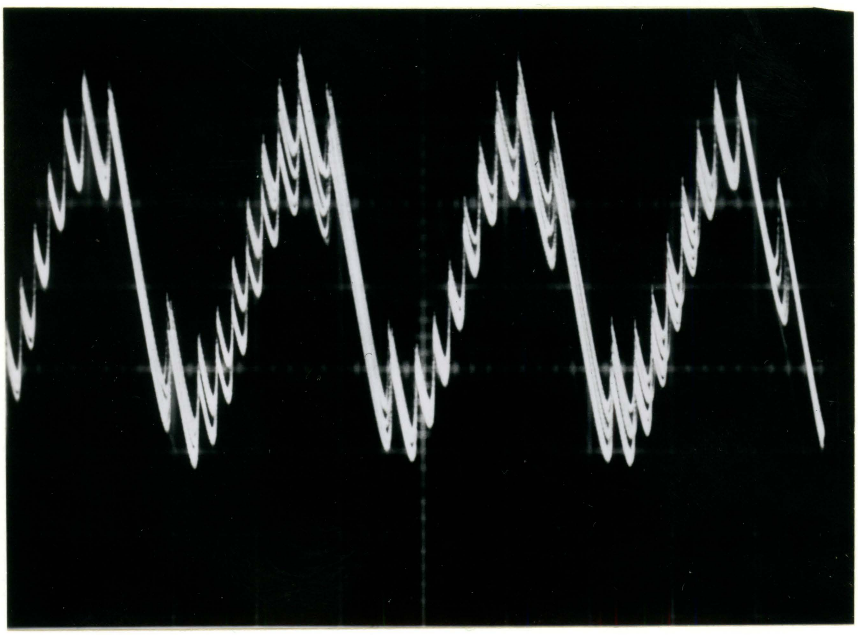


Figure 16. Output of the counting-rate circuit obtained with a 500 cps positive sine wave applied at the input of the voltage-to-frequency converter. Parameter setting of the counting-rate circuit as follows:

$C_f = 0.01\ \mu f$

$R_f = 1\ K$

$C_t = 0.1\ \mu f$

$R = 300\ K$

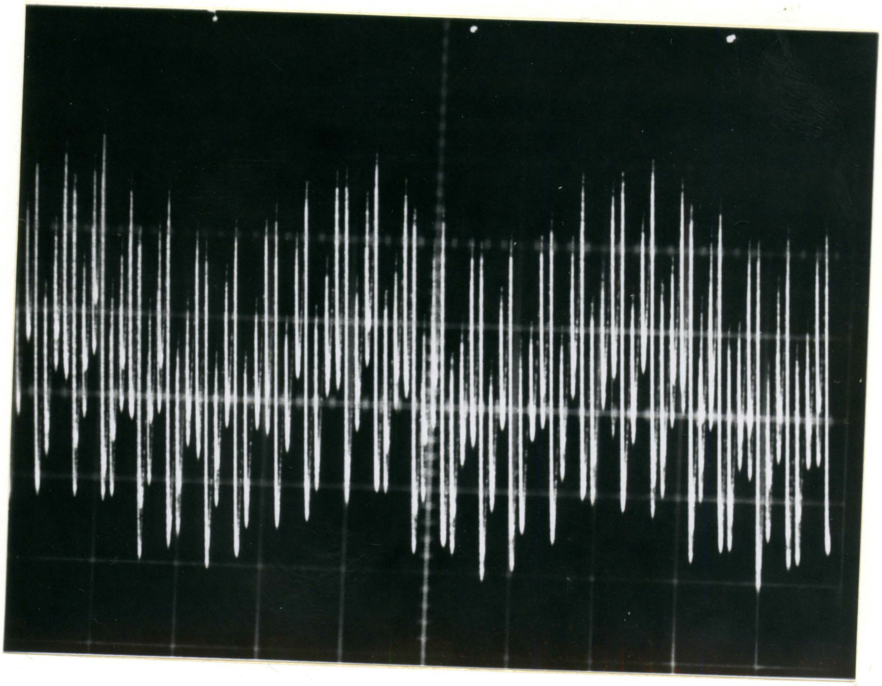


Figure 17. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: $C_f = 0.001$ μf, $R_f = 1$ K, $C_t = 0.03$ μf, R = 300 K. The input to the circuit was a sinusoidally varying pulse rate of 5880 pulses/sec maximum to 300 pulses/sec minimum

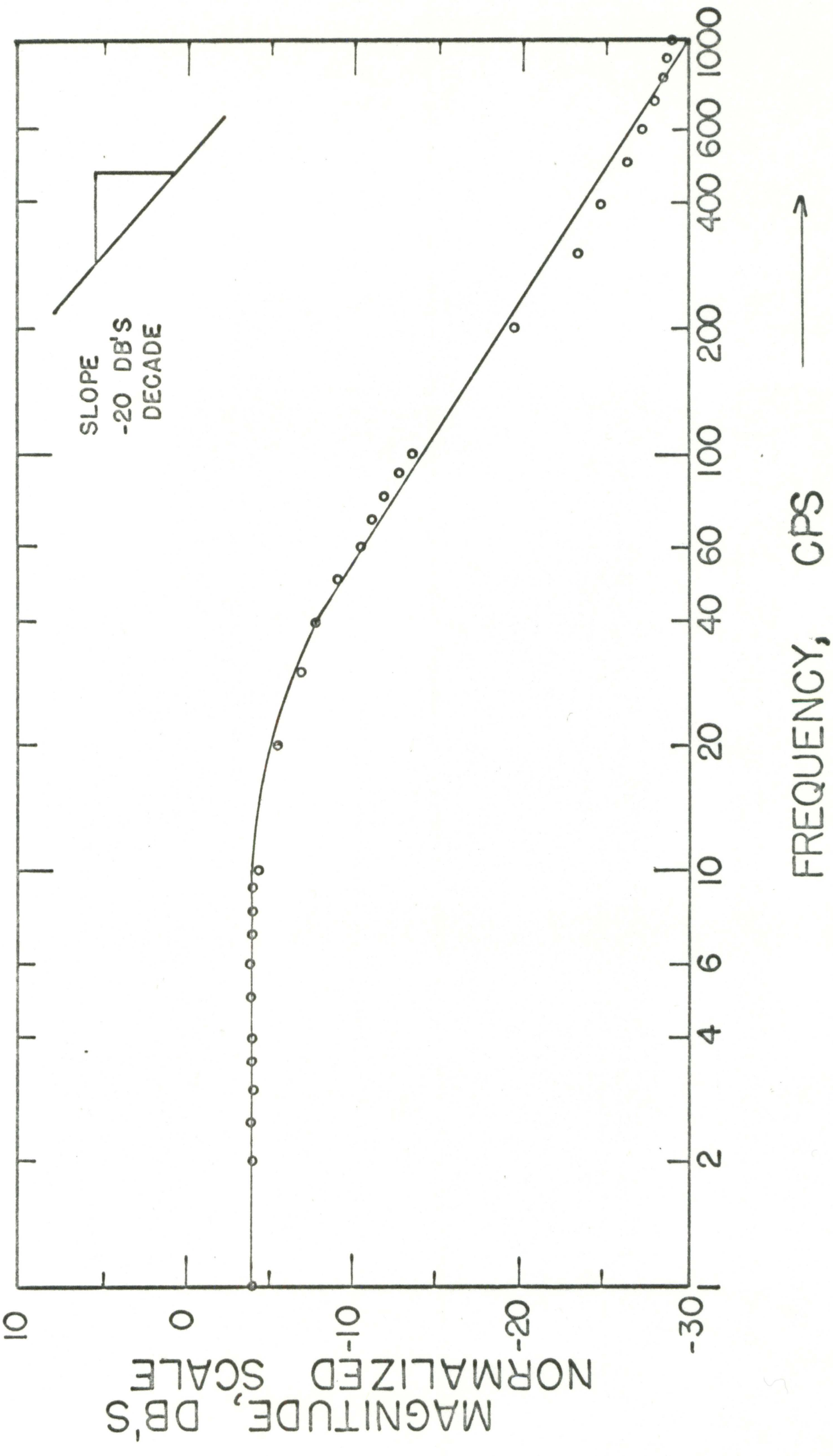

SLOPE
-20 DB'S
DECADE
MAGNITUDE, DB'S
NORMALIZED SCALE
10
0
-10
-20
-30
2
4
6
10
20
40
60
100
200
400
600
1000
FREQUENCY, CPS

Figure 18. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: C_f = 0.001 μf, R_f = 1 K, C_t = 0.03 μf, R = 300 K. The input to the circuit was a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum

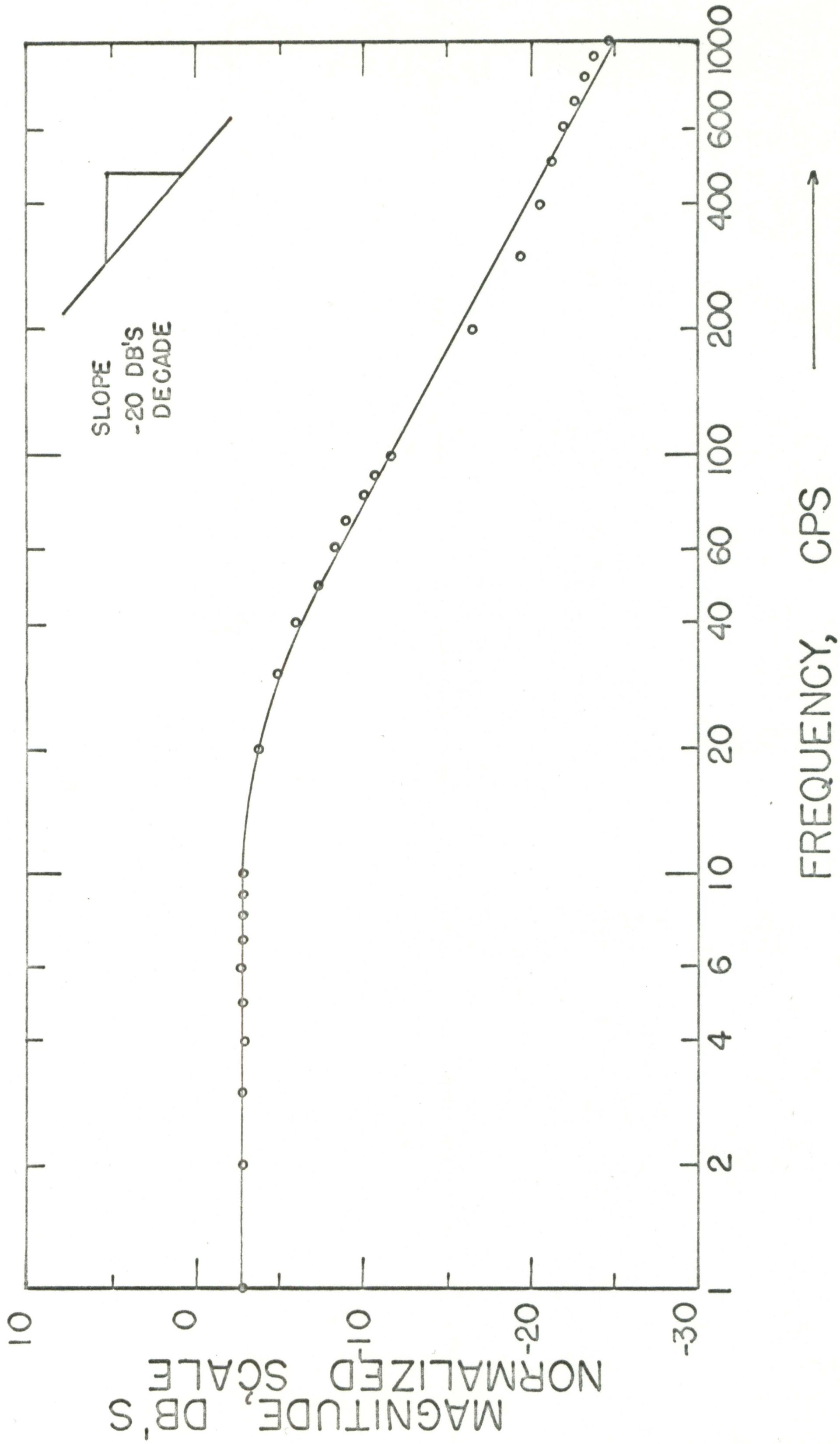
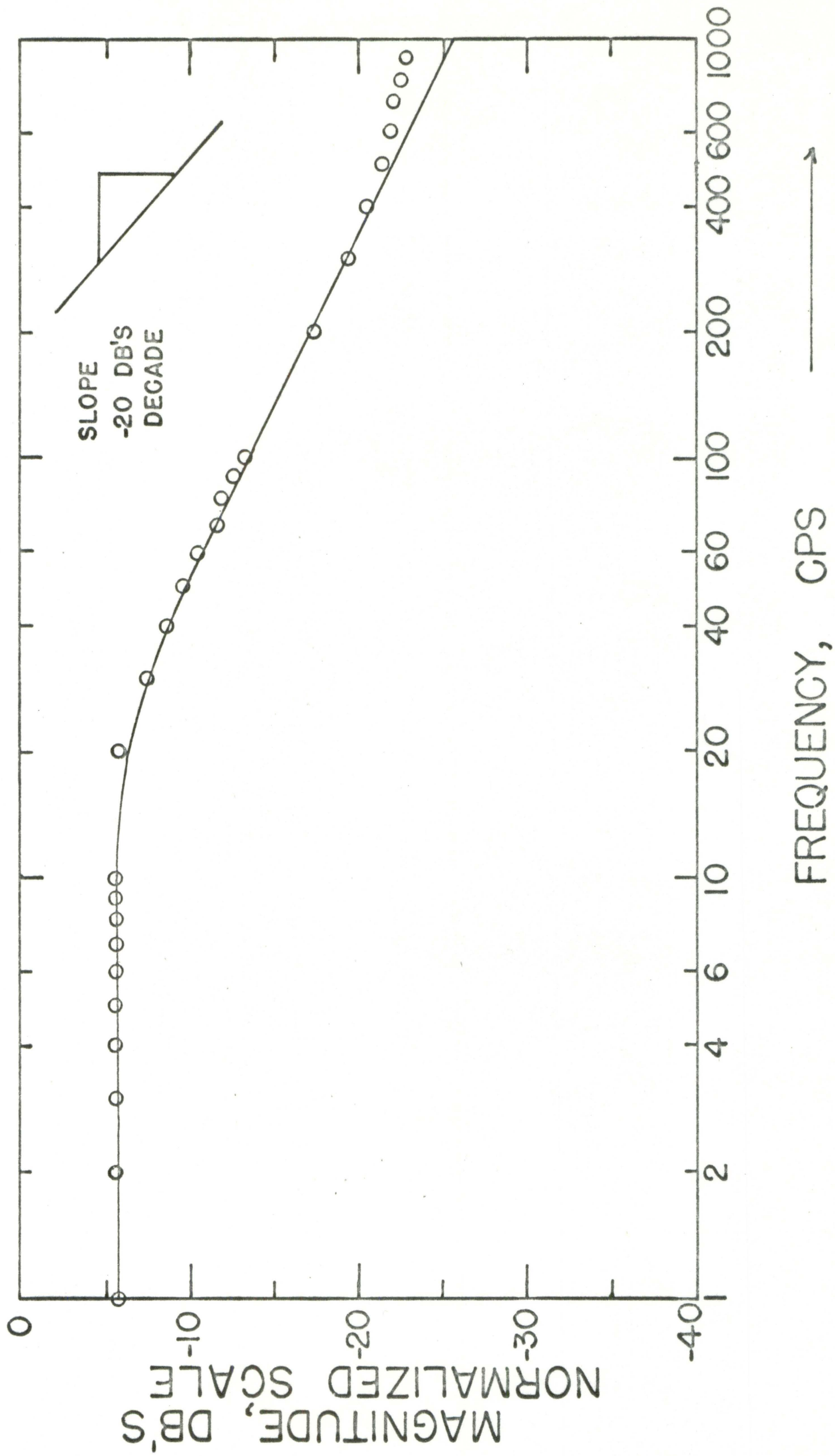

SLOPE
-20 DB'S
DECADE
FREQUENCY, CPS
MAGNITUDE, DB'S
NORMALIZED SCALE
10
0
-10
-20
-30
1
2
4
6
10
20
40
60
100
200
400
600
1000

Figure 19. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: C_f = 0.001 μf, R_f = 1 K, C_t = 0.03 μf, R = 300 K. The input to the circuit was a sinusoidally varying pulse rate of 1800 pulses/sec maximum to 200 pulses/sec minimum


SLOPE
-20 DB'S
DECADE
MAGNITUDE, DB'S
NORMALIZED SCALE
0
-10
-20
-30
-40
2
4
6
10
20
40
60
100
200
400
600
1000
FREQUENCY, CPS

From Table 3 it can be seen that the corner frequency varies with respect to counting rate. As the counting rate increases the corner frequency decreases. This is due to the fact that the elapsing time between pulses decreases with increasing counting rate, thus requiring smaller time constants R_fC_f and RC_t for the pulses to be efficiently counted by the CRC.

Another Bode plot of a typical parameter setting is shown in Figure 20. Figure 21 shows the Bode plot of the CRC for a choice of parameters that were found to provide an optimum response and performance of the counting rate circuit at the given pulse rate input. This result is summarized in Table 4.

Table 4. Optimum design of CRC for the employed input

Counting rate input, r pulses/sec	C_f μf	R_f K	C_t μf	R K	Corner frequency cps
385 to 3130	0.001	1	0.1	50	40

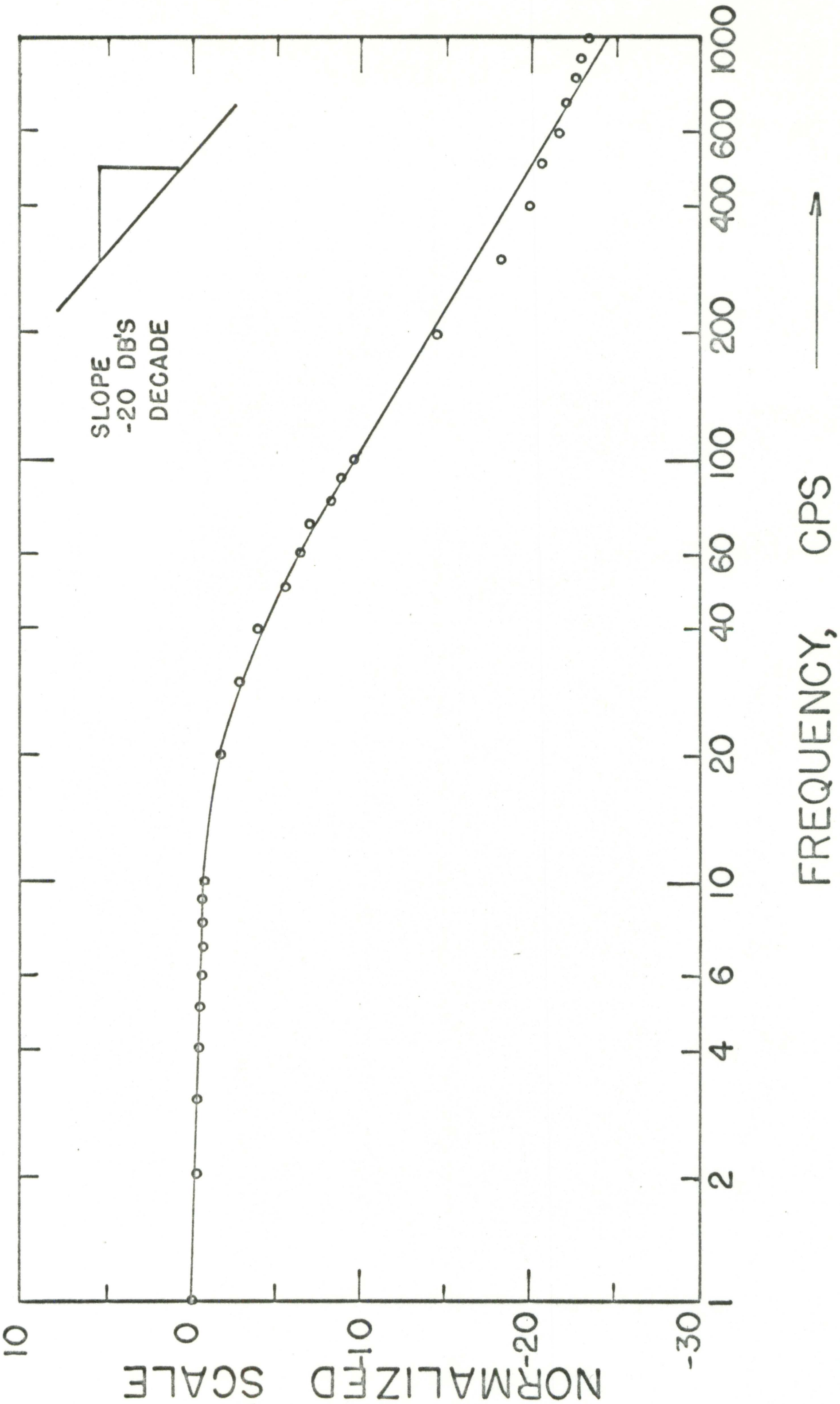
In Figure 22 the transfer function of the CRC is shown for inputs consisting of an average counting rate plus a small fluctuating pulse rate.

Because in reactor noise measurements the frequency response of the reactor at frequencies up to a 1000 cps is often investigated, it is apparent that the results obtained by the CRC in such a case should have to be corrected to account for the characteristic transfer function of the circuit.

A CRC slightly modified from the one used in this work was described in an unpublished thesis by Kylstra (8) with the claim of achieving a corner frequency of 350 cps at an input of 4,000 to 10,000 pulses/sec. This circuit was tested with the aid of the V-F-C and its transfer function was obtained. It was found that its corner frequency was approximately 43 cps, which is not greatly different than the one obtained for optimum design in this investigation.

Finally, all data describing the shown Bode plots are tabulated in the appendix.

Figure 20. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: C_f = 0.01 μf, R_f = 1 K, C_t = 0.1 μf, R = 100 K. The input to the circuit was a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum



SLOPE
-20 DB'S
DECADE
1 2 4 6 10 20 40 60 100 200 400 600 1000
FREQUENCY, CPS
10 0 -10 -20 -30
MAGNITUDE, DB'S
NORMALIZED SCALE

Figure 21. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: $C_f = 0.001$ µf, $R_f = 1$ K, $C_t = 0.1$ µf, $R = 50$ K. The input to the circuit was a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum

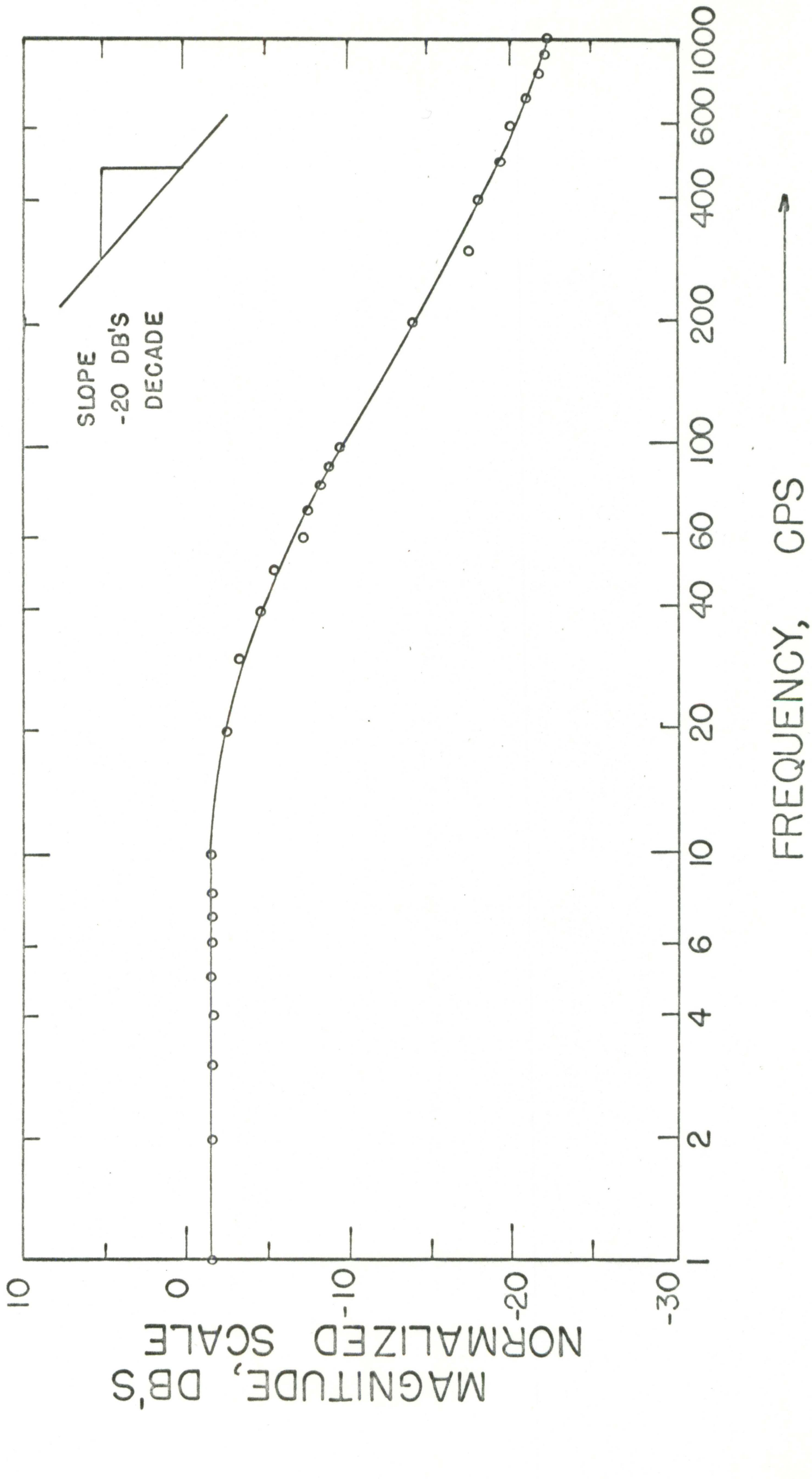
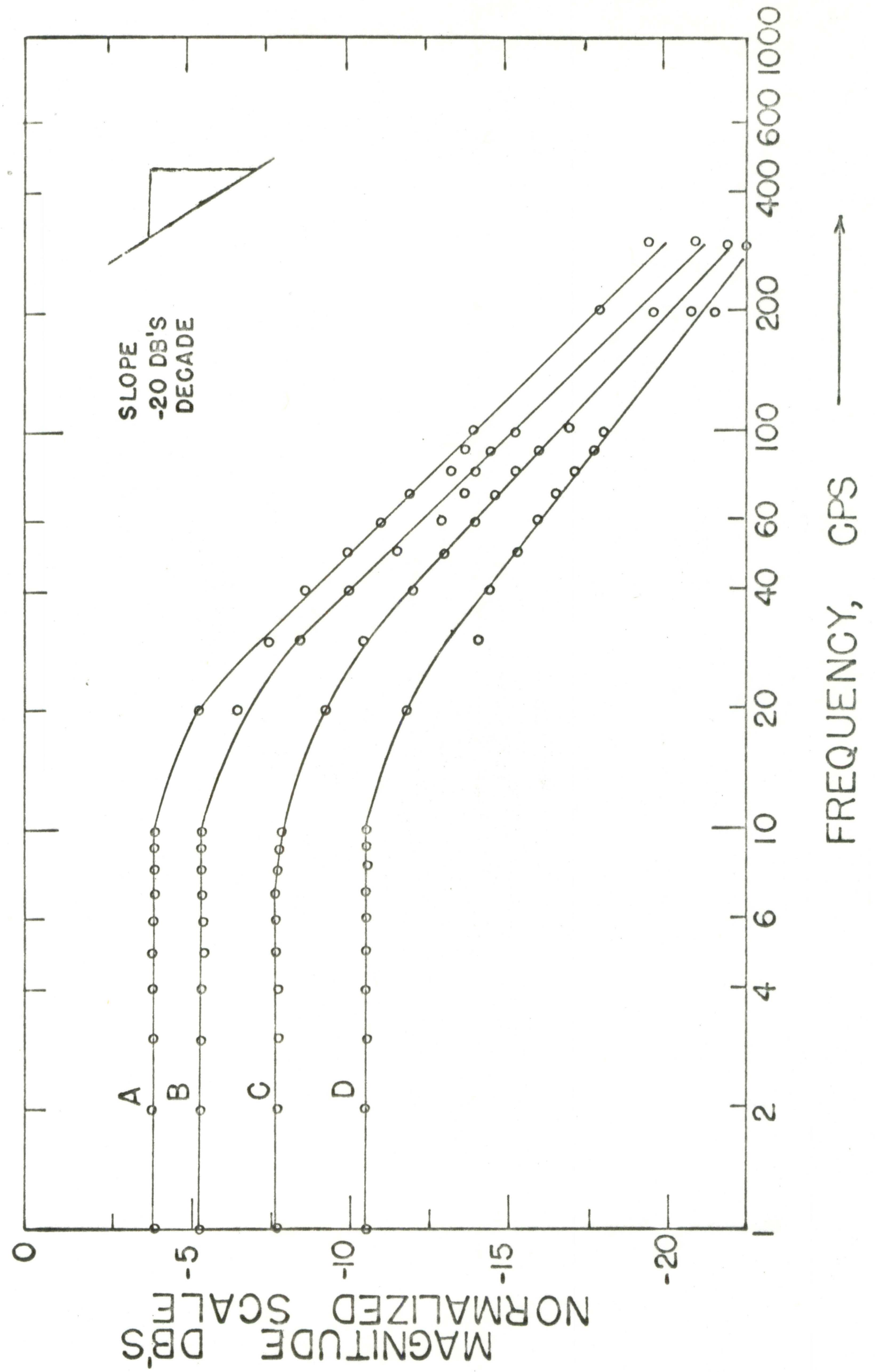

SLOPE
-20 DB'S
DECADE
FREQUENCY, CPS
1
2
4
6
10
20
40
60
100
200
400
600
1000
MAGNITUDE, DB'S
NORMALIZED SCALE
10
0
-10
-20
-30

Figure 22. Amplitude of the transfer function of the counting-rate circuit for the following parameter setting: C_f = 0.001 μf, R_f = 1 K, C_t = 0.1 μf, R = 100 K. The input to the circuit was a sinusoidally varying pulse rate of 4550 pulses/sec maximum to 2570 pulses/sec minimum for curve A, 4170 pulses/sec to 2780 pulses/sec for curve B, 4000 pulses/sec to 2900 pulses/sec for curve C, and 3170 pulses/sec to 3130 pulses/sec for curve D


SLOPE
-20 DB'S
DECADE
A
B
C
D
0
-5
-10
-15
-20
MAGNITUDE DB'S
NORMALIZED SCALE
1
2
4
6
10
20
40
60
100
200
400
600
1000
FREQUENCY, CPS

V. CONCLUSIONS

The present investigation justifies the following conclusions.

1. The CRC can be tested for its frequency response and its overall performance by employing a V-F-C or a similar pulse producing electronic circuit. Such circuits, as the one used in this work, can transform any positive voltage waveform to a pulse rate that varies according to the magnitude of the waveform. Thus, a known time varying pulse rate may be applied at the input of the CRC for testing purposes.
2. The results of this investigation indicate that it is feasible to optimize the CRC with respect to the frequency response and distortion of its output signal. It should be noted, however, that the optimum choice of the CRC components depends primarily on the counting rate and the frequency band of interest. For example, a low counting rate requires a large time constant RC_t and a large capacitor C_t if an undistorted signal is to be obtained. On the other hand when a high pulse rate is to be counted, the time constant RC_t and the output resistor R should be small enough to effectively integrate the closely spaced pulses. Also when the CRC is to be used for noise measurements at low frequencies, i.e., below the corner frequency of the CRC, the time constant RC_t and the capacitor C_t should have large enough values to insure the best

quality of the output signal.

3. The optimum corner frequency of the CRC for the best choice of the circuit parameters insuring an undistorted output signal was found to be 40 cps.

VI. SUGGESTIONS FOR FUTURE WORK

The author believes that the technique employed in this investigation to test the CRC has not been used before. Because the CRC is of great importance to pulse type detection systems employed in nuclear reactor noise measurements the following future work possibilities are suggested.

1. Investigate the frequency response for randomly varying pulse rates generated by a V-F-C.
2. Correlate the CRC calibration data with the results of reactor noise measurements.
3. Improve the design of the CRC with respect to its frequency response.

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Finally the author wishes to express his deep gratitude to his parents for their spiritual help and deep concern that made his college years possible.

IX. APPENDIX: TABULATION OF EXPERIMENTAL DATA

Table 5. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: $C_f = 0.002$ μf, $R_f = 1$ K, $C_t = 1$ μf, R = 50 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	22.20	2.20
2	22.50	2.50
3	23.80	3.80
4	25.20	5.20
5	26.40	6.40
6	27.00	7.00
7	28.00	8.00
8	29.10	9.10
9	30.00	10.00
10	30.40	10.40
20	36.40	16.40
30	40.00	20.00
40	42.00	22.00
50	43.10	23.10
60	44.40	24.40
70	45.20	25.20
80	46.00	26.00
90	47.00	27.00
100	48.00	28.00
200	52.00	32.00
300	55.00	35.00
400	56.00	36.00
500	56.60	36.60
600	57.40	37.40
700	58.00	38.00
800	58.60	38.60
900	58.80	38.80
1000	59.00	39.00

Table 6. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: $C_f = 0.002\ \mu f$, $R_f = 1$ K, $C_t = 0.5\ \mu f$, R = 50 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	20.00	0.00
2	20.00	0.00
3	20.00	0.00
4	20.00	0.00
5	20.00	0.00
6	20.00	0.00
7	20.40	0.40
8	21.40	1.40
9	22.00	2.00
10	22.60	2.60
20	27.10	7.10
30	30.00	10.00
40	32.00	12.00
50	34.00	14.00
60	36.00	16.00
70	36.60	16.60
80	37.40	17.40
90	38.40	18.40
100	39.60	19.60
200	44.40	24.40
300	47.00	27.00
400	48.00	28.00
500	49.20	29.20
600	50.40	30.40
700	51.00	31.00
800	52.20	32.20
900	53.00	33.00
1000	54.00	34.00

Table 7. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: C_f = 0.01 μf, R_f = 1 K, C_t = 0.2 μf, R = 100 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	11.70	1.70
2	11.70	1.70
3	11.70	1.70
4	12.00	2.00
5	12.20	2.20
6	12.40	2.40
7	12.80	2.80
8	13.00	3.00
9	13.20	3.20
10	13.60	3.60
20	16.40	6.40
30	19.20	9.20
40	20.90	10.90
50	22.50	12.50
60	24.20	14.20
70	25.20	15.20
80	26.70	16.70
90	27.82	17.82
100	28.50	18.50
200	34.20	24.20
300	37.00	27.00
400	39.30	29.30
500	40.00	30.00
600	41.00	31.00
700	41.40	31.40
800	42.00	32.00
900	42.50	32.50
1000	43.10	33.10

Table 8. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: C_f = .001 μf, R_f = 1 K, C_t = 0.05 μf, R = 900 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	10.40	0.40
2	10.41	0.41
3	10.70	0.70
4	11.00	1.00
5	11.40	1.40
6	11.70	1.70
7	12.00	2.00
8	12.40	2.40
9	12.80	2.80
10	13.22	3.22
20	16.41	6.41
30	19.20	9.20
40	20.90	10.90
50	22.50	12.50
60	24.20	14.20
70	25.20	15.20
80	26.00	16.00
90	28.00	18.00
100	30.40	20.40
200	35.10	25.10
300	37.00	27.00
400	38.00	28.00
500	39.20	29.20
600	40.00	30.00
700	40.80	30.80
800	41.50	31.50
900	41.90	31.90
1000	42.40	32.40

Table 9. Frequency response of CRC at a sinusoidally varying pulse rate of 5880 pulses/sec maximum to 300 pulses/sec minimum (parameter setting of CRC: $C_f = 0.001\ \mu f$, $R_f = 1$ K, $C_t = .03\ \mu f$, R = 300 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	8.86	3.86
2	8.86	3.86
3	8.86	3.86
4	8.86	3.86
5	8.86	3.86
6	8.86	3.86
7	8.86	3.86
8	8.86	3.86
9	8.86	3.86
10	9.10	4.10
20	10.20	5.20
30	11.70	6.70
40	12.60	7.60
50	14.00	9.00
60	15.12	10.12
70	15.92	10.92
80	16.81	11.81
90	17.70	12.70
100	18.42	13.42
200	24.40	19.40
300	28.02	23.02
400	29.81	24.81
500	31.20	26.20
600	32.00	27.00
700	32.80	27.80
800	33.20	28.20
900	33.50	28.50
1000	34.00	29.00

Table 10. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: $C_f = 0.001\ \mu f$, $R_f = 1$ K, $C_t = .03\ \mu f$, $R_t = 300$ K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	12.52	2.52
2	12.56	2.56
3	12.56	2.56
4	12.56	2.56
5	12.56	2.56
6	12.56	2.56
7	12.56	2.56
8	12.56	2.56
9	12.56	2.56
10	12.57	2.57
20	13.60	3.60
30	14.90	4.90
40	15.90	5.90
50	17.10	7.10
60	18.04	8.04
70	18.80	8.80
80	20.00	10.00
90	20.50	10.50
100	21.40	11.40
200	26.80	16.80
300	29.10	19.10
400	30.40	20.40
500	31.00	21.00
600	32.00	22.00
700	32.60	22.60
800	33.00	23.00
900	33.82	23.82
1000	34.55	24.55

Table 11. Frequency response of CRC at a sinusoidally varying pulse rate of 1800 pulses/sec maximum to 200 pulses/sec minimum (parameter setting of CRC: $C_f = 0.001$ μf, $R_f = 1$ K, $C_t = .03$ μf, $R_t = 300$ K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	15.40	5.40
2	15.40	5.40
3	15.40	5.40
4	15.40	5.40
5	15.40	5.40
6	15.40	5.40
7	15.40	5.40
8	15.40	5.40
9	15.40	5.40
10	15.40	5.40
20	15.80	5.80
30	17.40	7.40
40	18.40	8.40
50	19.60	9.60
60	20.40	10.40
70	21.40	11.40
80	21.90	11.90
90	22.50	12.50
100	23.10	13.10
200	27.40	17.40
300	29.10	19.10
400	30.40	20.40
500	31.20	21.20
600	31.85	21.85
700	32.00	22.00
800	32.42	22.42
900	32.80	22.80
1000	33.10	23.10

Table 12. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: C_f = .01 μf, R_f = 1 K, C_t = .1 μf, R = 100 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	10.00	0.00
2	10.20	0.20
3	10.22	0.22
4	10.22	0.22
5	10.50	0.50
6	10.51	0.51
7	10.60	0.60
8	10.61	0.61
9	10.62	0.62
10	10.80	0.80
20	11.60	1.60
30	12.81	2.81
40	14.00	4.00
50	15.40	5.40
60	16.21	6.21
70	17.00	7.00
80	18.02	8.02
90	18.82	8.82
100	19.60	9.60
200	24.40	14.40
300	28.03	18.03
400	29.82	19.82
500	30.40	20.40
600	31.42	21.42
700	32.00	22.00
800	32.40	22.40
900	32.80	22.80
1000	33.05	23.05

Table 13. Frequency response of CRC at a sinusoidally varying pulse rate of 3130 pulses/sec maximum to 385 pulses/sec minimum (parameter setting of CRC: C_f = 0.001 μf, R_f = 1 K, C_t = 0.1 μf, R = 50 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	21.40	1.40
2	21.40	1.40
3	21.40	1.40
4	21.40	1.40
5	21.40	1.40
6	21.40	1.40
7	21.40	1.40
8	21.40	1.40
9	21.40	1.40
10	21.40	1.40
20	22.20	2.20
30	23.40	3.40
40	24.40	4.40
50	25.20	5.20
60	27.10	7.10
70	27.40	7.40
80	28.20	8.20
90	28.80	8.80
100	29.60	9.60
200	34.00	14.00
300	37.40	17.40
400	38.00	18.00
500	39.20	19.20
600	40.00	20.00
700	41.00	21.00
800	41.80	21.80
900	42.20	22.20
1000	42.70	22.70

Table 14. Frequency response of CRC at a sinusoidally varying pulse rate of 4550 pulses/sec maximum to 2570 pulses/sec minimum (parameter setting of CRC: $C_f = 0.001\ \mu f$, $R_f = 1\ K$, $C_t = 0.1\ \mu f$, $R = 100\ K$)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	23.80	3.80
2	23.80	3.80
3	23.80	3.80
4	23.80	3.80
5	23.80	3.80
6	23.80	3.80
7	23.80	3.80
8	23.80	3.80
9	23.80	3.80
10	23.80	3.80
20	25.20	5.20
30	27.50	7.50
40	28.50	8.50
50	30.00	10.00
60	31.00	11.00
70	32.00	12.00
80	33.20	13.20
90	33.60	13.60
100	34.00	14.00
200	38.00	18.00
300	39.60	19.60

Table 15. Frequency response of CRC at a sinusoidally varying pulse rate of 4170 pulses/sec maximum to 2780 pulses/sec minimum (parameter setting of CRC: $C_f = 0.001$ μf, $R_f = 1$ K, $C_t = 0.1$ μf, R = 100 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	25.20	5.20
2	25.20	5.20
3	25.20	5.20
4	25.20	5.20
5	25.20	5.20
6	25.20	5.20
7	25.20	5.20
8	25.20	5.20
9	25.20	5.20
10	25.20	5.20
20	26.40	6.40
30	28.40	8.40
40	30.00	10.00
50	31.50	11.50
60	33.00	13.00
70	33.60	13.60
80	34.00	14.00
90	34.40	14.40
100	35.20	15.20
200	39.60	19.60
300	41.00	21.00

Table 16. Frequency response of CRC at a sinusoidally varying pulse rate of 4000 pulses/sec maximum to 2900 pulses/sec minimum (parameter setting of CRC: $C_f = 0.001\ \mu f$, $R_f = 1$ K, $C_t = 0.1\ \mu f$, R = 100 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	27.60	7.60
2	27.60	7.60
3	27.60	7.60
4	27.60	7.60
5	27.60	7.60
6	27.60	7.60
7	27.60	7.60
8	27.80	7.80
9	27.80	7.80
10	28.00	8.00
20	29.10	9.10
30	30.40	10.40
40	32.00	12.00
50	33.00	13.00
60	34.00	14.00
70	34.40	14.40
80	35.20	15.20
90	36.00	16.00
100	36.40	17.40
200	41.00	21.00
300	42.00	22.00

Table 17. Frequency response of CRC at a sinusoidally varying pulse rate of 3710 pulses/sec maximum to 3130 pulses/sec minimum (parameter setting of CRC: C_f = 0.001 μf, R_f = 1 K, C_t = 0.1 μf, R = 100 K)

Frequency (cps)	Experimental magnitude, -db	Normalized magnitude, -db
1	30.40	10.40
2	30.40	10.40
3	30.40	10.40
4	30.40	10.40
5	30.40	10.40
6	30.40	10.40
7	30.40	10.40
8	30.40	10.40
9	30.40	10.40
10	30.40	10.40
20	31.80	11.80
30	33.00	13.00
40	34.10	14.10
50	35.20	15.20
60	36.00	16.00
70	36.40	16.40
80	37.00	17.00
90	37.60	17.60
100	37.80	17.80
200	40.00	20.00
300	41.00	21.00