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APPLICATION OF NEGATIVE FEEDBACK TO REDUCTION OF GLOW DISCHARGE NOISE

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ABSTRACT

Several researchers have studied the problem of discharge current modulation noise in the output radiation intensity of a d-c excited He-Ne laser. Work presented herein uses an analog circuit to demonstrate the feasibility of using negative feedback to reduce the discharge current noise and thereby reduce noise in the output radiation intensity.

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I. INTRODUCTION

A number of researchers have studied the amplitude stability of the output radiation intensity of He-Ne lasers.[1,2,3,4] These studies have shown that in DC excited lasers amplitude fluctuations exist which are partially correlated with fluctuations in the discharge current. The fluctuations in the light intensity are of sufficient magnitude to cause problems in laser instrumentation and communication systems.

The fact that the light noise is correlated with the discharge current noise suggests the possibility of reducing the light noise by applying conventional feedback techniques to reduce the noise in the current. In order to pursue this idea it was determined to use an analog circuit where a voltage regulator tube functions as an analog to the laser discharge tube. This approach was used for the following reasons:

1) the voltage regulator tube is a "glow discharge" tube and has similar plasma conditions to the laser discharge tube,

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2) considerable work has been reported in the literature on models or equivalent circuits for VR tubes[5,6,7,8,9]. This work provides a basis for an analytical study of feedback problems associated with the analog circuit,

3) voltage regulator tubes are readily available and inexpensive. This allowed experimental work on stability problems to proceed while a laser system suitable for noise studies was being designed and assembled.

II. DESCRIPTION OF FEEDBACK SYSTEM

Figure 1 shows the schematic diagram of the proposed feedback system. This scheme uses a signal proportional to the discharge current for control of the discharge current.

Fluctuations that arise in the discharge current will be reduced due to the negative feedback. This feedback scheme is termed current-to-current feedback and is to be contrasted with future work on light-to-current feedback wherein the laser output power is stabilized by control of the laser current. It is clear that current-to-current feedback (II-FB) can be regarded as making the bias supply for the plasma tube appear more like a current source.

Since the eventual purpose of this work is to reduce fluctuations in laser power, the negative feedback techniques employed will be termed "stabilization" and the circuitry will be called "stabilizer."

In order to predict the noise reduction and stabilization performance for the stabilizer it was necessary to have a small-signal equivalent circuit for the discharge tube. One approach represented in the literature is to measure the impedance versus frequency characteristics and then synthesize an equivalent lumped-parameter network that would give the same shape and magnitude impedance versus frequency curve. Some selection in the large number of possible circuits can be made on the basis of knowledge of the plasma conditions. It has been pointed out that if no appreciable space charge builds up in the anode region, then the impedance of a discharge is essentially that of the cathode region.[6]

For example, Figure 2 shows a plot of impedance as a function of frequency for an OA2 discharge tube. This figure shows that the impedance has the same shape as that of a parallel R-L-C network which has a low Q. A possible equivalent circuit is shown in Figure 3. The parameters shown can be qualitatively related to phenomena in the plasma. r corresponds to the slope of the voltage-current characteristic. In a VR tube this has a small positive value by design which is contrasted with the usual negative resistance of glow discharges as, for example, with laser tubes. Yeh has suggested that the delay represented by L can be related to the transit time of the ions across the cathode-fall region.[5] C is the capacitance of the cathode-fall region and is of the order of magnitude of $A\epsilon/d$, where A is the area of the discharge, ϵ is the permittivity of free space, and d is the length of the cathode-fall region.[9] R is a damping term which determines the Q of the equivalent circuit and is related to collisions between ions and neutrals in the cathode-fall.[8]

Values for the parameters were obtained from experimental measurements. r was determined from the low frequency resistance and is 600 ohms. R is the resistance at resonance and was found to be 10,000 ohms. C = 10 pf was determined from the literature.[9] L = 2.5 millihenries was determined from the measured resonance frequency and the value of C. Figure 2 shows measured and calculated values of impedance as a function of frequency. From this Figure it was concluded that the equivalent circuit is adequate for analysis purposes.

III. CALCULATION OF NOISE REDUCTION AND STABILITY ANALYSIS

For calculation of noise reduction and stability analysis the equivalent circuit shown in Figure 4 was used. In the analysis the following assumptions are made:

1. r_p for the pentode can be neglected;

2. The voltage transfer function of the feedback amplifier can be described by

$$K = \frac{K_m}{(1 + s\tau_1)^2} \quad ; \qquad (1)$$

3. The input resistance of the amplifier is lumped with R_o;

4. I_n represents the equivalent noise current generator of the discharge.

For these conditions the open-loop transfer function G is

$$G = \frac{I_L}{I_n} = \frac{R_s}{R_s + Z_{eq} + R_o} \quad . \qquad (2)$$

Reference to Figure 3 shows that Z_{eq} is

$$Z_{eq} = \frac{1}{C} \frac{s + \frac{r}{L}}{s^2 + s(\frac{r}{L} + \frac{1}{RC}) + \frac{1}{LC}(1 + \frac{r}{R})} \quad . \qquad (3)$$

Combining equations (2) and (3) gives

$$G = \frac{s^2 + s(\frac{r}{L} + \frac{1}{RC}) + \frac{1}{LC}(1 + \frac{r}{R})}{\frac{R_s+R_o}{R_s} \{s^2 + s(\frac{r}{L} + \frac{1}{RC} + \frac{1}{(R_s+R_o)C}) + \frac{1}{LC}(1+\frac{r}{R} + \frac{r}{R_s+R_o})\}} \qquad (4)$$

The feedback factor H can be expressed as

$$H = \frac{K_m\, g_m\, R_o}{(1 + s\tau_1)^2(1 + s\tau_2)} \quad . \qquad (5)$$

In this expression τ_2 accounts for the frequency response of the pentode. Equations (4) and (5) can be combined to give

$$GH = \frac{K_m\, g_m\, R_o[s^2 + s(\frac{r}{L} + \frac{1}{RC}) + \frac{1}{LC}(1 + \frac{r}{R})]}{(\frac{R_s+R_o}{R_s})(1+s\tau_1)^2(1+s\tau_2)[s^2+s(\frac{r}{L}+\frac{1}{RC})+\frac{1}{(R_s+R_o)C}+\frac{1}{LC}(1+\frac{r}{R}+\frac{r}{R_s+R_o})]} \qquad (6)$$

The order of magnitude of reduction in noise can be determined by looking at the low frequency closed-loop transfer function, $\frac{G}{1+GH}$. For this case, the approximation is made that s approaches zero. The closed-loop function then becomes

$$\frac{I_L}{I_n} = \frac{1}{1 + \frac{R_o}{R_s} + \frac{r}{R_s(1 + \frac{r}{R})} + K_m\, g_m\, R_o} \quad . \qquad (7)$$

With typical values of $R_s = 10^4$ ohms, $R_o = 10^3$ ohms, $K_m = 3$, and $g_m = 4000$ micro-mhos, $\frac{I_L}{I_n} = 1/13.16$. This can be compared to the open loop value of I_L/I_n which is,

$$\frac{I_L}{I_n} = \frac{1}{1 + \frac{R_o}{R_s} + \frac{r}{R_s(1 + \frac{r}{R})}} = \frac{1}{1.16} \quad . \qquad (8)$$

Thus the feedback reduces the noise by a factor of approximately eleven.

The stability analysis was done by using a root locus plot of GH given by Equation (6). Figure 5 shows this plot where measured values of $\tau_1 = 10^{-7}$ and $\tau_2 = 0.565 \times 10^{-7}$ were used. This plot shows a frequency of instability of 2.55 MHz at a K_m of 2.66.

From this plot it can be seen that if the double poles due to the amplifier or the pole due to the shunt pentode are moved closer to the origin, the frequency of oscillation becomes lower and the system becomes unstable at a lower value of amplifier gain, K_m, and vice versa.

IV. EXPERIMENTAL RESULTS

The system described by Figure 1 was studied experimentally. The following data have been obtained.

Figure 6 shows the discharge current noise in the bandwidth 10^3 - $5(10^5)$Hz without feedback.

Figure 7 shows the current noise with feedback. A comparison of Figures 6 and 7 shows the noise has been reduced by approximately a factor of seven. The experimental value of K_m which gave this reduction was 3. As noted earlier, the calculated value of reduction was 11. One source of error was instrumentation. Figure 7 contains a significant amount of noise from the oscilloscope amplifier. There was a stray noise pulse riding on the ground of the whole system. Also, the calculated noise reduction assumed the low frequency model whereas the measured noise included components with frequencies up to 5×10^5 Hz.

Figure 8 shows the experimental frequency of oscillation to be $2MH_z$ when K is increased beyond the point of stability. This compares favorably with the 2.55 MHz determined from the root-locus plot. Experimental verification of the effects of the poles of the feedback amplifier was obtained by increasing the amplifier roll-off frequency to one MHz. The system then became unstable at a value of gain of 15 and oscillated at a frequency of 3MHz. This qualitatively agrees with the results of the root-locus plot.

Further experimentation verified the utility of the physical model and the root locus plot.

V. CONCLUSIONS

It has been shown that the feedback system of Figure 1 can be used to reduce the discharge current noise. From a stability standpoint it has been shown that greater stabilization and/or noise reduction obtained when the bandwidth of the feedback loop is made as wide as possible. Further, and most important, the agreement of experiment and calculation indicates that the equivalent circuit used for the discharge tube is adequate to describe its behavior.

It is anticipated that similar results will be obtained when this technique is applied to the laser. One major change will be that r will be negative for the laser tube. This may aggravate stability problems if r is large enough to cause zeroes in the right half plane.

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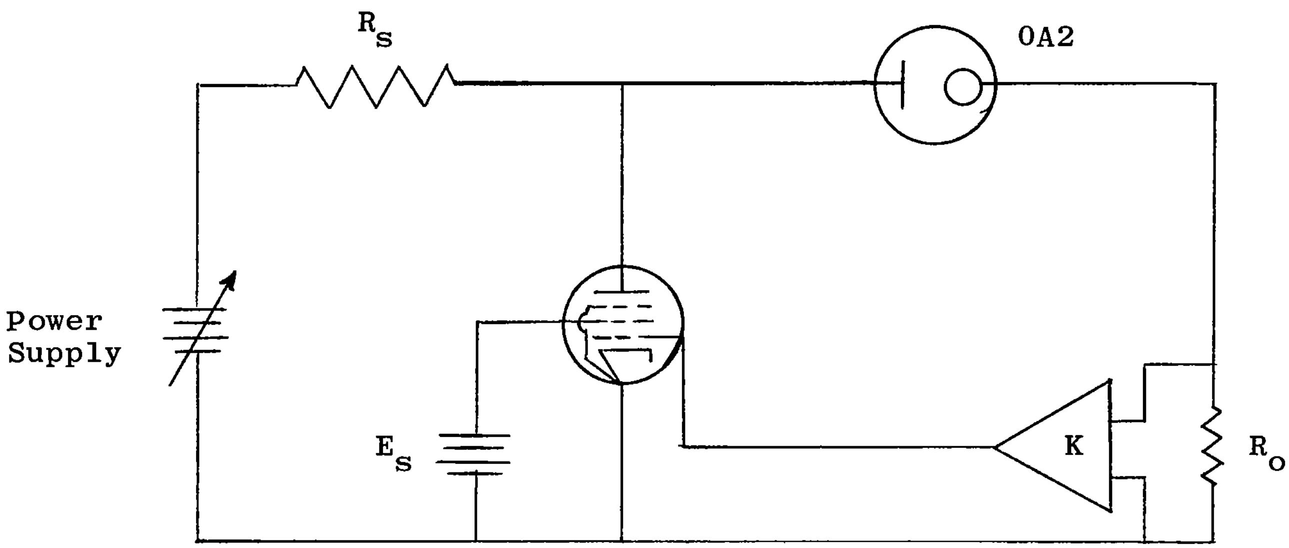


Fig. 1. Schematic Diagram of Feedback System

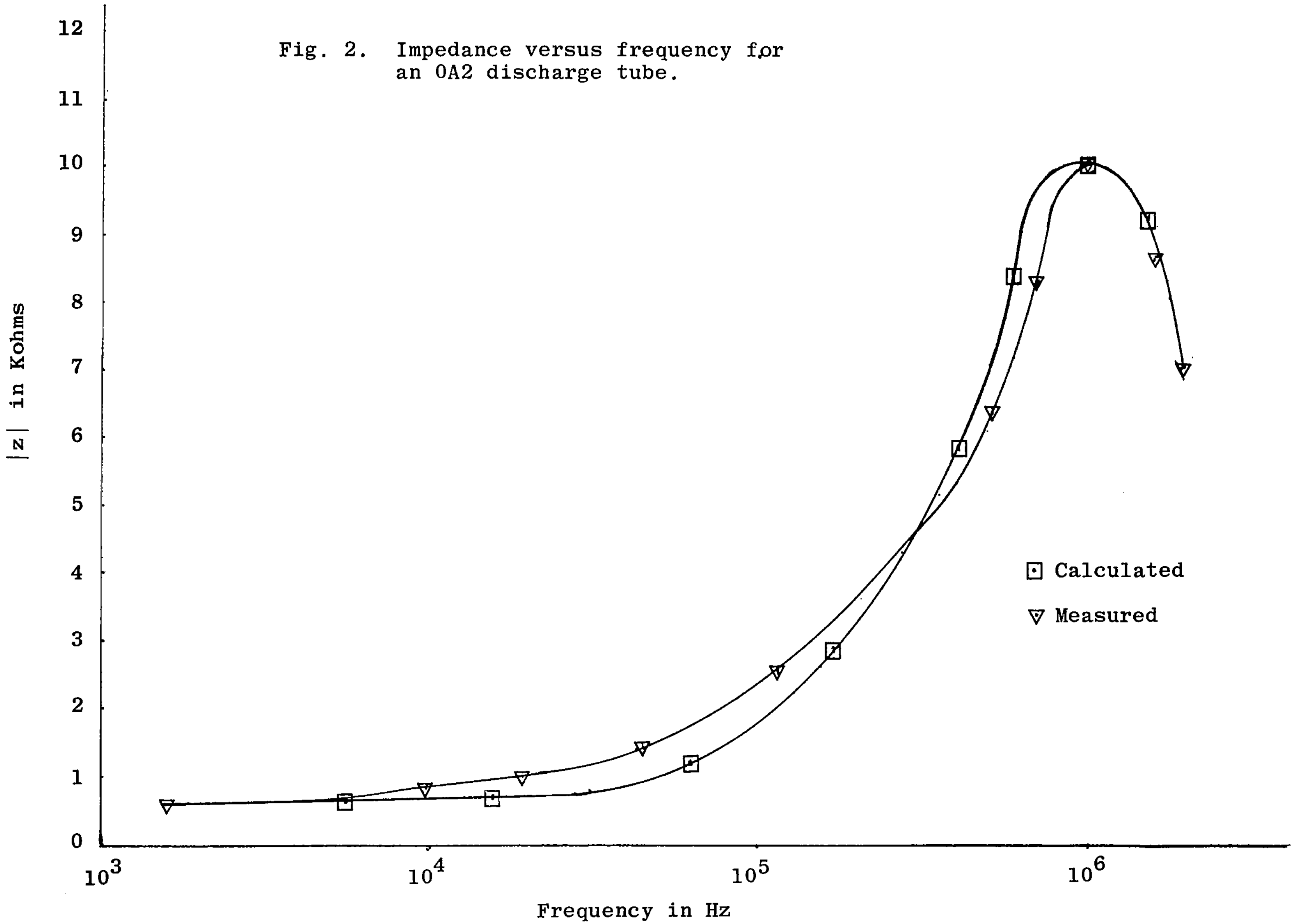


Fig. 2. Impedance versus frequency for an OA2 discharge tube.

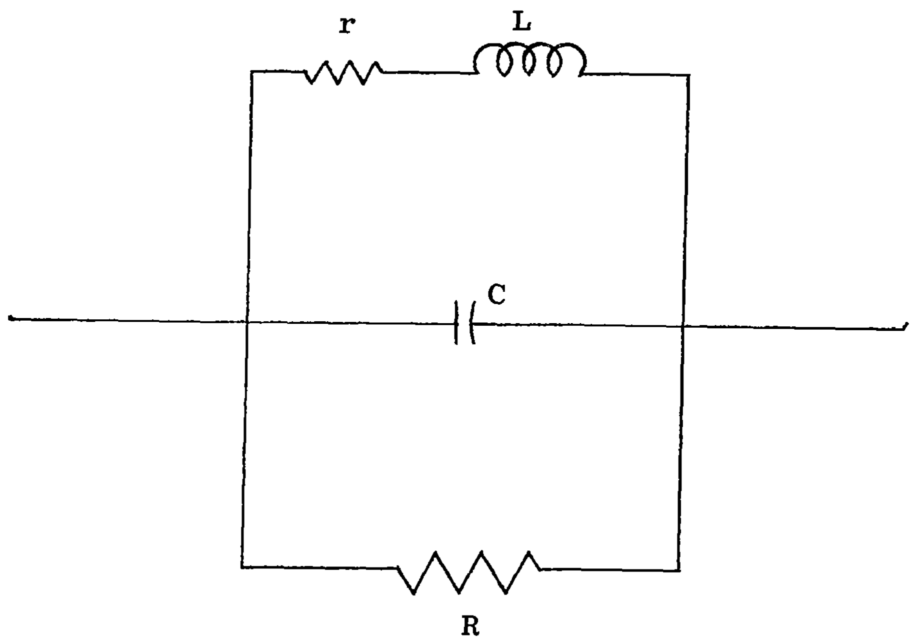


Fig. 3. Small-signal equivalent circuit for an 0A2 discharge tube.

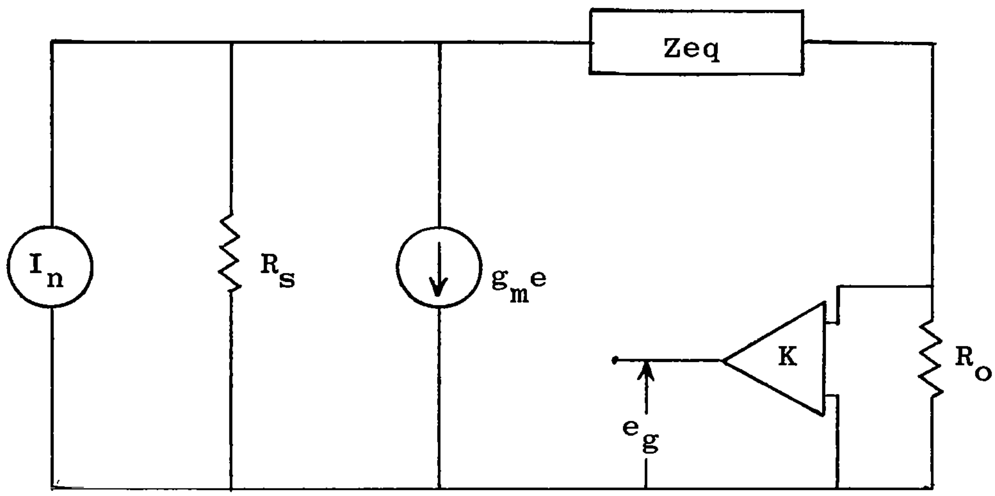


Fig. 4. Small-signal equivalent circuit for "current-current" feedback.

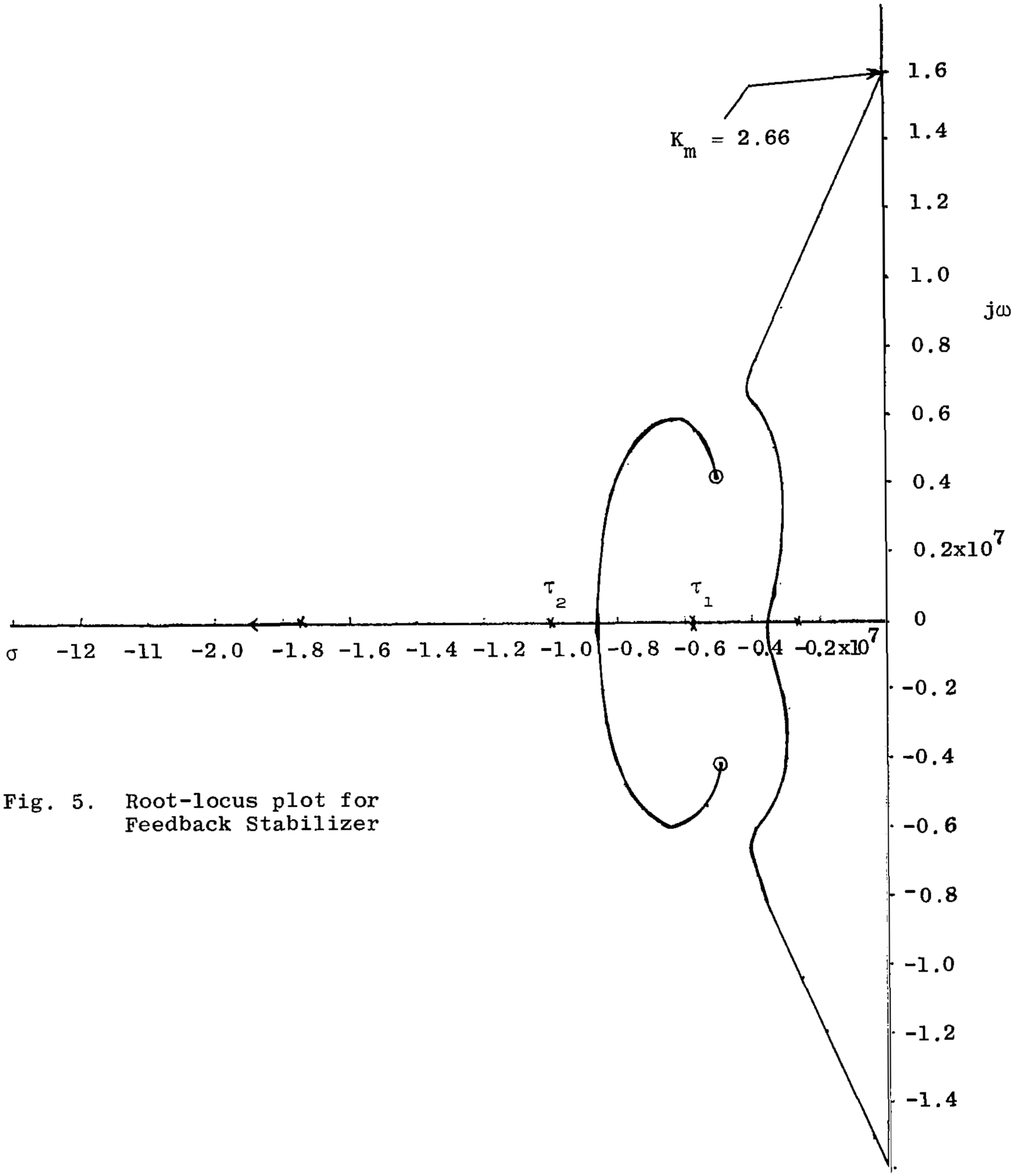
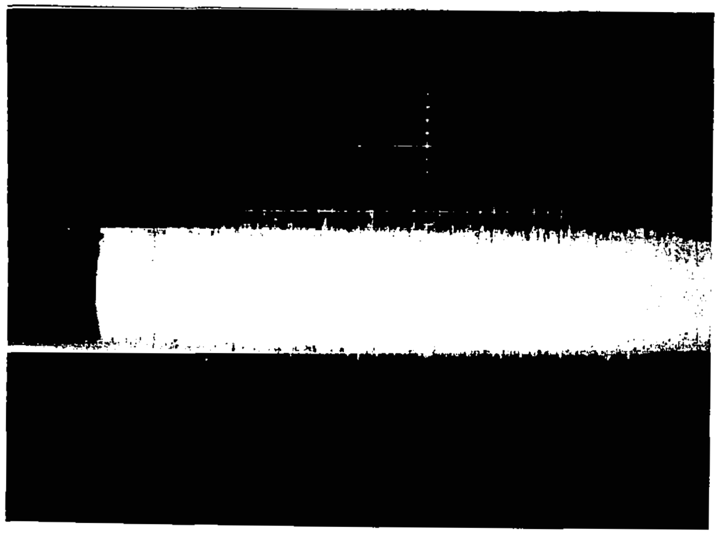


Fig. 5. Root-locus plot for Feedback Stabilizer



Scales: Current - 0.2 μ amps/cm

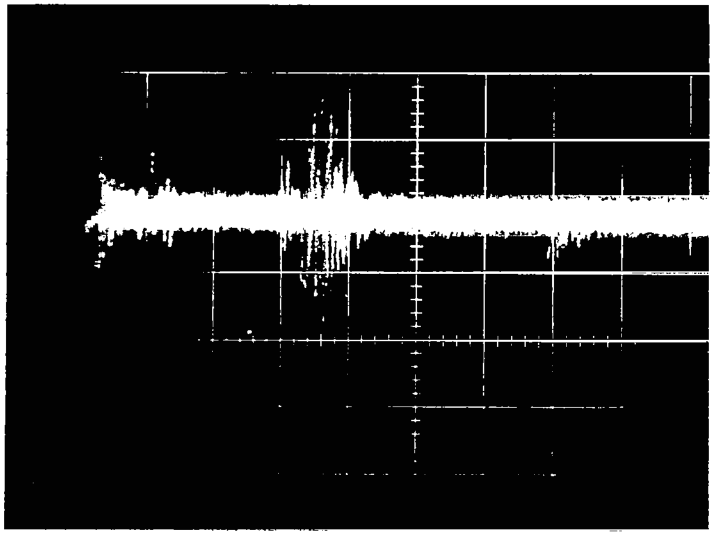
Sweep - 50 m sec/cm

Cutoff frequencies of Scope Amplifier:

$$\nu_L = 10^3 Hz$$

$$\nu_H = 5(10^5) Hz$$

Fig. 6. Current noise without feedback.



Scales: Current - 0.2 μ amps/cm

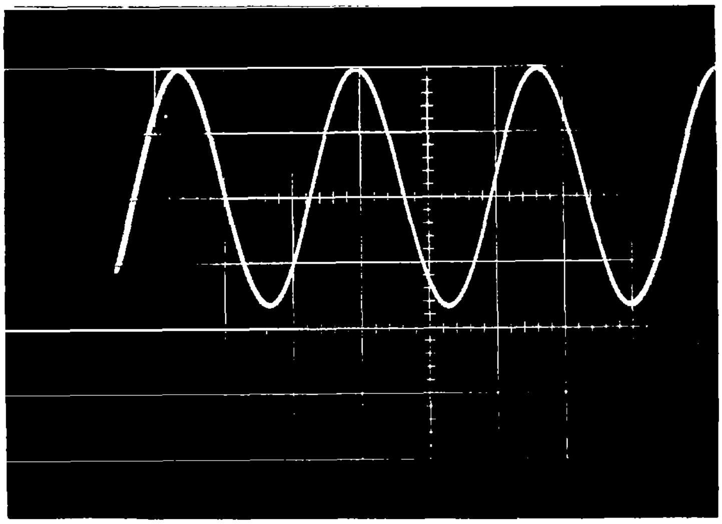
Sweep - 50 m sec/cm

Cutoff frequencies of Scope Amplifier:

$$\nu_L = 10^3 Hz$$

$$\nu_H = 5(10^5) Hz$$

Fig. 7. Current noise with feedback.



Scale: Sweep - 0.2 μ sec/cm

Fig. 8. Current waveform for unstable system.

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