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HIGH SPEED DEFLECTION AMPLIFIER FOR CRT FLYING SPOT SCANNERS

A deflection system for precision cathode ray tubes is described which permits a point by point scanning of less than one microsecond. The linearity of this system is at least 0.02%, and its drift better than 0.001% per degree C.

A. INTRODUCTION

As the performances of flying spot scanners become more sophisticated, there is a need for more flexible deflection systems. An interesting mode of operation in the horizontal direction could be, for instance, a combination of sweep and point by point scans. This results in high linearity and large bandwidth requirements for the deflection amplifier.

Commercially available amplifiers do not meet these requirements at the present time. That is the reason for this design, which aims at eliciting the best performance from the deflection yokes currently on the market.

B. SPECIFICATIONS

The amplifier should be a voltage-to-current converter, accepting an input signal of $\pm$ 5 volts.

Assuming the use of a 1 Mc logic and 12 bit registers, steps equal to 1/4000 of the maximum deflection should be possible in one microsecond, thus requiring a bandwidth of 700 Kc and a linearity of one part in 4000.

To allow for interpolations in the case of sweep scans, and to avoid too frequent calibrations, short term drift should be of the order of one part in 40,000.

C. DESIGN LIMITING FACTORS

1. Coils

The critical parameter of deflection coils is their resonant frequency. In fact one should include the driving cables capacitance, which is in parallel with the coils distributed capacitance. The over-all resonant frequency should be as high as possible, since as one approaches this frequency, the current starts flowing into the capacitance, thus producing no magnetic field and no deflection. The choice of the smallest coil inductance, resulting in a low distributed capacitance and a larger current to produce a certain field, is recommended, if one can handle the current.

The coils selected have the following characteristics:

CELCO No.	HD 428-P670	
L @ 1 Kc	25	microhenry
C	60	picofarad
R	0.1	ohm
Current for 21^{o} deflection @ 20 kV anode voltage:	6.0	ampere

Using 6 foot RG22 cables, the resonant frequency is $f_o = 3$ Mc.

2. Power Transistors

The use of such coils was made possible because of the availability of excellent power transistors. The current gain-bandwidth product is clearly a determining factor and one has to compromise between this product and the coils resonant frequency when selecting yoke and transistors.

Output stage transistor:

Honeywell MHT 6316 $\quad I_{max} = 5$ A

$P_{max} = 30$ Watt

current gain × bandwidth $= 30$ Mc

$C_{bc} = 90$ pf @ $V_{cb} = 10$ Volt

The effects of C_{bc}, the collector-base capacitance are multiple and depend strongly on the load impedance. Figure 1, Eq. 1, with $Z_N = \infty$, indicates the stage current gain modification occuring when the collector-base impedance is taken into account.

I_2	output current
I_1	input current
β	transistor current gain
Z_{bc}	collector-base impedance
Z_{be}	base-emitter impedance
Z_L	load impedance

In a common emitter configuration, a single transistor circuit would require a transformer to obtain a feedback signal with the proper phase, capable of neutralizing the effect of Z_{bc}.

However a differential amplifier lends itself to neutralization since an in-phase signal is always available at the output. Compensation can be achieved (Fig. 1) by connecting an impedance Z_N (usually a capacitor of the same order of magnitude as C_{bc}) between input and in-phase output.

Over-neutralization can even provide an overshoot of the response, at a certain frequency, accompanied by a phase lead. The different parameters of this kind of "lead network" are hard to define since they depend on the value of β and the nature of Z_L at the frequencies of interest (Eq. 2). Furthermore this type of circuit is equivalent to the application of positive feedback and violent oscillations are very likely to occur if the value of ΔC is too large.

3. Lower Stages

Since the amplifier will be operated as a voltage-to-current converter with a voltage gain of unity, as far as drift is concerned, one then relies on the characteristics of the first stage.

Feedback cannot improve drift, except in the case of chopper stabilization; but this technique has several unpleasant features and has been avoided.

The transistor selected for the input circuit (Motorola MD 1125) is a Si matched pair for which the manufacturer guarantees a differential drift of the order of 10 microvolt per degree C, referred to the input. For an ambient temperature change of 10° C, this would represent a drift of one part in 50,000.

The two most important limiting factors in the design of such a deflection system are the coil-cable resonant frequency f_o, and the power transistors current gain-bandwidth product.

Since f_o was found to be 3 Mc, it is obvious that the Nyquist diagram should go through the unity circle at a frequency lower than 3 Mc, but higher than 700 Kc, if the specifications are to be met.

D. OPEN LOOP AMPLIFIER

The circuit used is described on Fig. 2, page 8 , omitting all capacitors. The two first stages are made of the familiar "long tail pair" which insures a true differential amplification. The 3 dB point of these pairs is around 5 Mc.

The output stage is differential too, and comprises two power transistors in parallel in each leg; their collectors drive the coils, thus increasing their roll-off frequency considerably.

A gain of 82 dB can be achieved with a frequency dependance as shown on Fig. 3, page 9. The curve is flat up to 650 Kc, then falls quite rapidly. The first objective of the frequency correction will be to try to obtain a gain of one at 700 Kc or higher, crossing the 0 dB line with a slope not larger than 20 dB per decade.

E. FREQUENCY COMPENSATION

This can be very simply accomplished with two so-called "lag networks" on the output of the lower stages, and a "lead network" operating in the emitters of the output stage.

The effect of these networks, as well as the expected open loop response, are indicated on Fig. 3.

This will not by any means guarantee stability, nor will it yield the desired closed loop response, since nothing has been said about the phase characteristic so far.

But this approach does give an excellent introduction for plotting a first Nyquist diagram which will show how oscillatory the system is, and in which direction further compensation must be applied.

F. CLOSED LOOP RESPONSE

Given a transfer function $\overline{AB}$, the general expression for the gain of a feed-back system is

$$\overline{A}' = \frac{1}{\overline{B}} \frac{\overline{AB}}{1 + \overline{AB}}$$

In our case $\frac{1}{\overline{B}}$ is real and represents the desired response, whereas

$$\frac{\overline{AB}}{1 + \overline{AB}}$$

represents the departure of $\overline{A}'$ from $\frac{1}{\overline{B}}$ as frequency varies. This quantity can be represented in magnitude and phase in the complex plane. It can be shown that the locus of

$$\left| \frac{\overline{AB}}{1 + \overline{AB}} \right| = M \quad \text{for all positive integer values of } M$$

is a family of circles centered at $s = \pm \dfrac{M^2}{1 - M^2}$ on the real axis, and of radii

$$r = \pm \frac{M}{1 - M^2} \quad .$$

The locus of $\operatorname{Arg}\left(\dfrac{\overline{AB}}{1 + \overline{AB}}\right) = \theta$ for all positive integer values of θ

is represented by a family of circles too; it will not be used here.

The interesting property of these constant M loci is that when they are superimposed on a Nyquist diagram, they readily indicate what the closed loop response will be like. Therefore a criterium of quality is added to the stability criterium.

Figure 4, page 10 is a Nyquist diagram, as modified by the compensation networks discussed above. The amplifier is stable, has a sufficient phase margin ($\pi - \phi$ when $|\overline{AB}| = 1$), and its 3 dB bandwidth, i.e., the frequency at which the curve intersects with the $M = 0.7$ circle, is 825 Kc. But an overshoot of 25% can be observed at 600 Kc; this is confirmed by the step response as shown on picture no. 1 page 13. Damping alone would not be a desirable solution, since it would reduce the bandwidth, whereas a phase lead at that particular frequency will decrease the overshoot and provide a larger bandwidth.

Modification of the phase response was attempted by over neutralizing the output stage in the way discussed on Fig. 1; the exact value of C_N was found experimentally, providing about 45° of phase advance at 600 Kc. ($\Delta C \approx 20$ pF.) At higher frequencies, 18° at 1.2 Mc and 30° at 3 Mc, could be obtained by shunting the base resistors of the output stage with a capacitor.

The result of these two corrections is the curve of Fig. 5, where the 3 dB bandwidth has been increased to 1.2 Mc. However, a resonance can be observed at 6 Mc which seems to be associated with the coils' stray inductance; but at this frequency we know that little magnetic field can be produced and as long as the amplifier stability is not threatened, there is no reason for damping this resonance.

A final adjustment of the response can be performed by varying the stage 1 lag network upper corner frequency. Photographs 2,3 and 4, page 13 represent respectively two underdamped solutions and an optimum step response, for different positions of the network potentiometer.

In the case of picture 4, the open and closed loop transfer function frequency responses have been plotted in amplitude and phase, on Fig. 6.

It should be noted that the closed loop phase does not exceed 130° up to 3 Mc. This feature is important if the amplifier is to be included in an optical feedback loop as will be necessary for a "line following" type of flying spot scanner.

G. DRIFT

Two types of drift have been measured. The first type is a long term drift and is essentially a function of temperature. Over a period of 8 hours the output drift was found to be smaller than 50 μvolt/$^{\circ}$C or 1 part in 100,000 per $^{\circ}$C.

The second type of drift (or low frequency noise) is the one that would occur during the scan of a single frame; over periods of less than 4 seconds, the peak-to-peak drift was within 1 part in 50,000.

Changes of 0.1% in the output of any of the power supplies could not produce a variation of the amplifier output, larger than the drifts measured above.

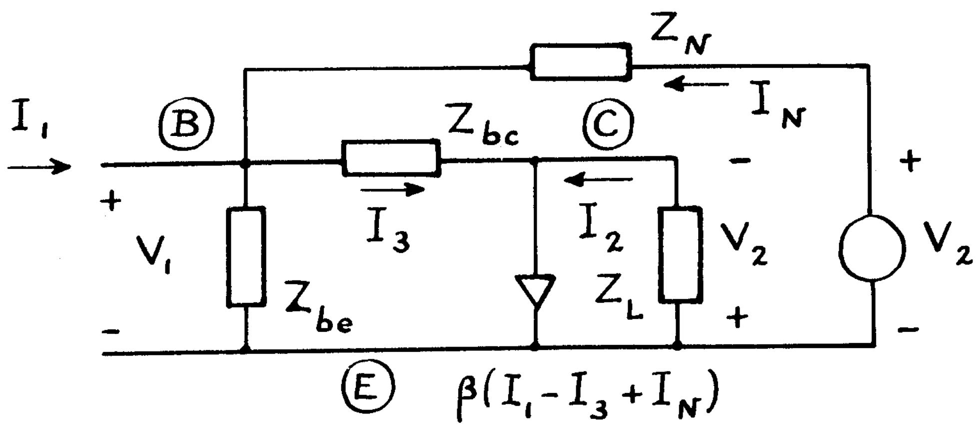
H. CONCLUSION

This design will allow for incremental scans with steps of one microsecond, provided the input waveform has a total rise time of less than 0.3 microseconds. This figure is limited by the coils' distributed capacitance only.

In the case of linear sweep scans, a linearity of one part in 5,000 can be achieved. For a higher value the stability problem would have to be reconsidered and might turn out to be impractical.

EFFECT & NEUTRALIZATION of C_{bc}

neglecting the base spreading resistor $r_{bb'}$



$$I_2\left[1 + (\beta+1)\frac{Z_L}{Z_{bc}} - \beta\,\frac{Z_L}{Z_N}\right] = I_1\left[\beta - \frac{\beta+1}{Z_{bc}}\, Z_{be} /\!/ Z_N /\!/ (Z_{bc}+Z_L)\right]$$

assuming $\dfrac{Z_{be} /\!/ Z_N /\!/ (Z_{bc}+Z_L)}{Z_{bc}} \ll 1$

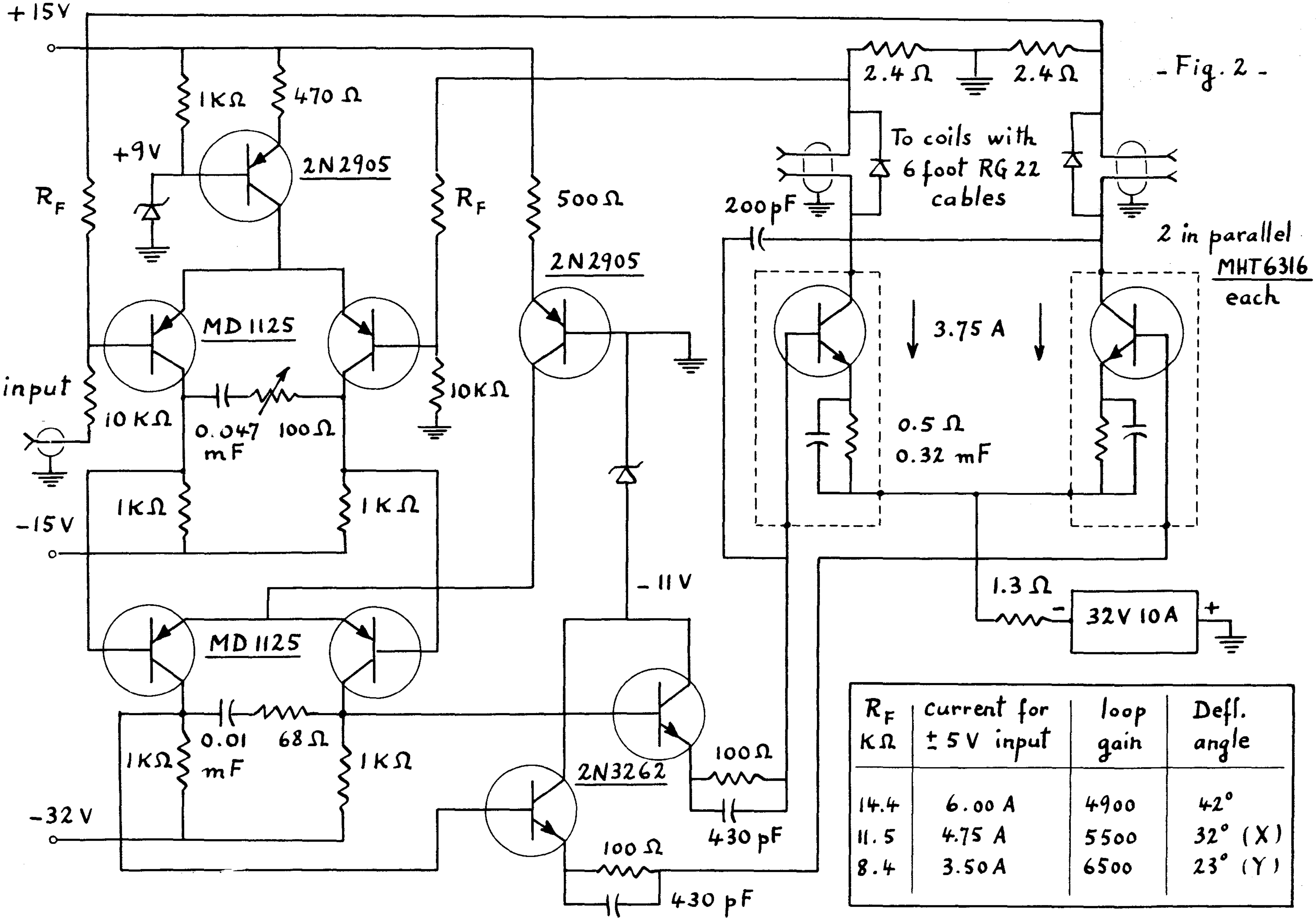
$$\frac{I_2}{I_1} = \frac{\beta}{1+(\beta+1)\dfrac{Z_L}{Z_{bc}} - \beta\,\dfrac{Z_L}{Z_N}} \qquad (1)$$

Neutralization for $Z_N \approx Z_{bc} = \dfrac{1}{j\omega C_{bc}}$

Lead network for $Z_N < Z_{bc}$ or $C_N - C_{bc} = \Delta C > 0$

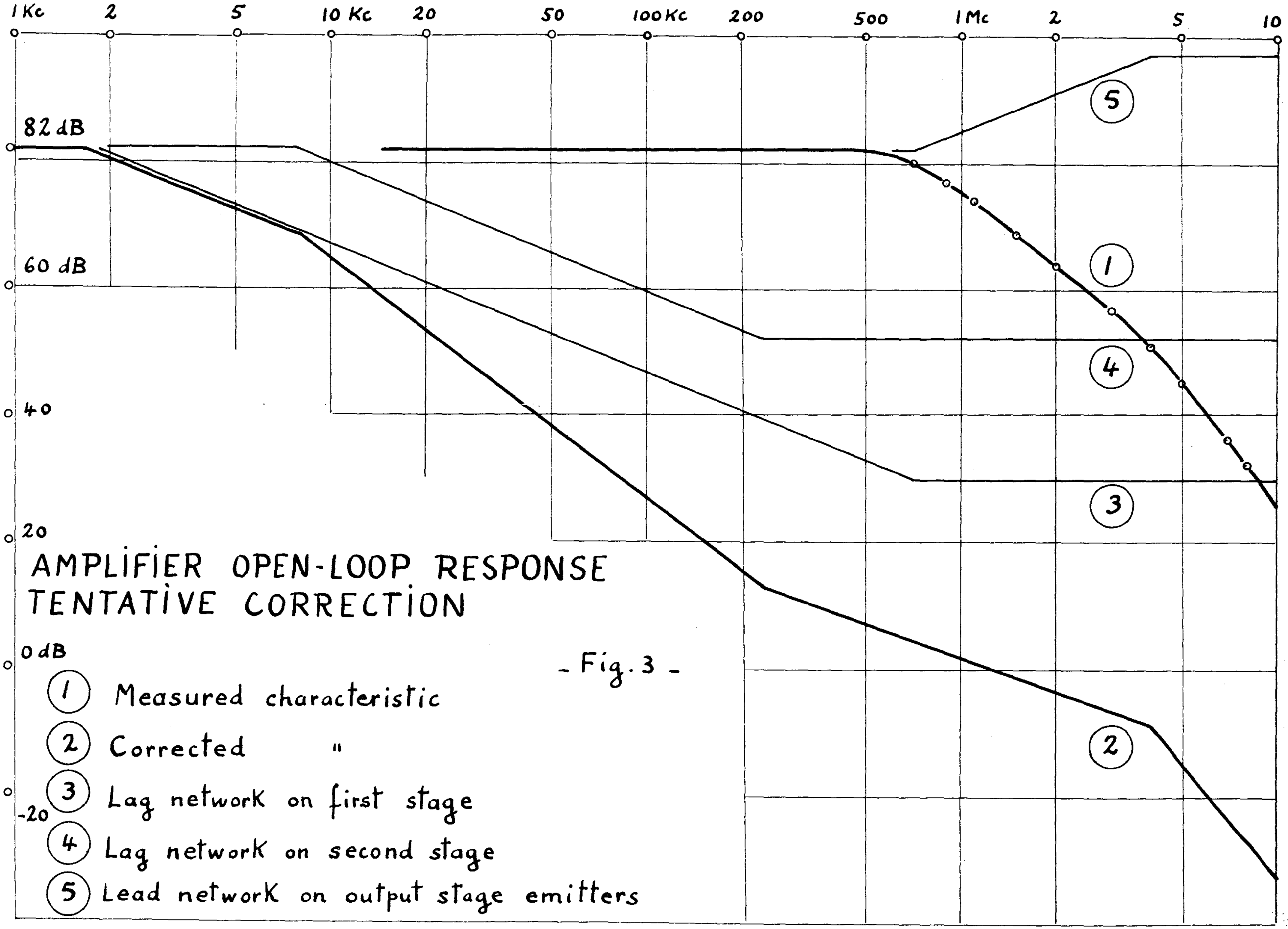
$$\frac{I_2}{I_1} \approx \frac{\beta\left[1 + j\omega\beta Z_L \Delta C\right]}{1 + (\beta Z_L \omega \Delta C)^2} \qquad (2)$$

- Fig. 1 -



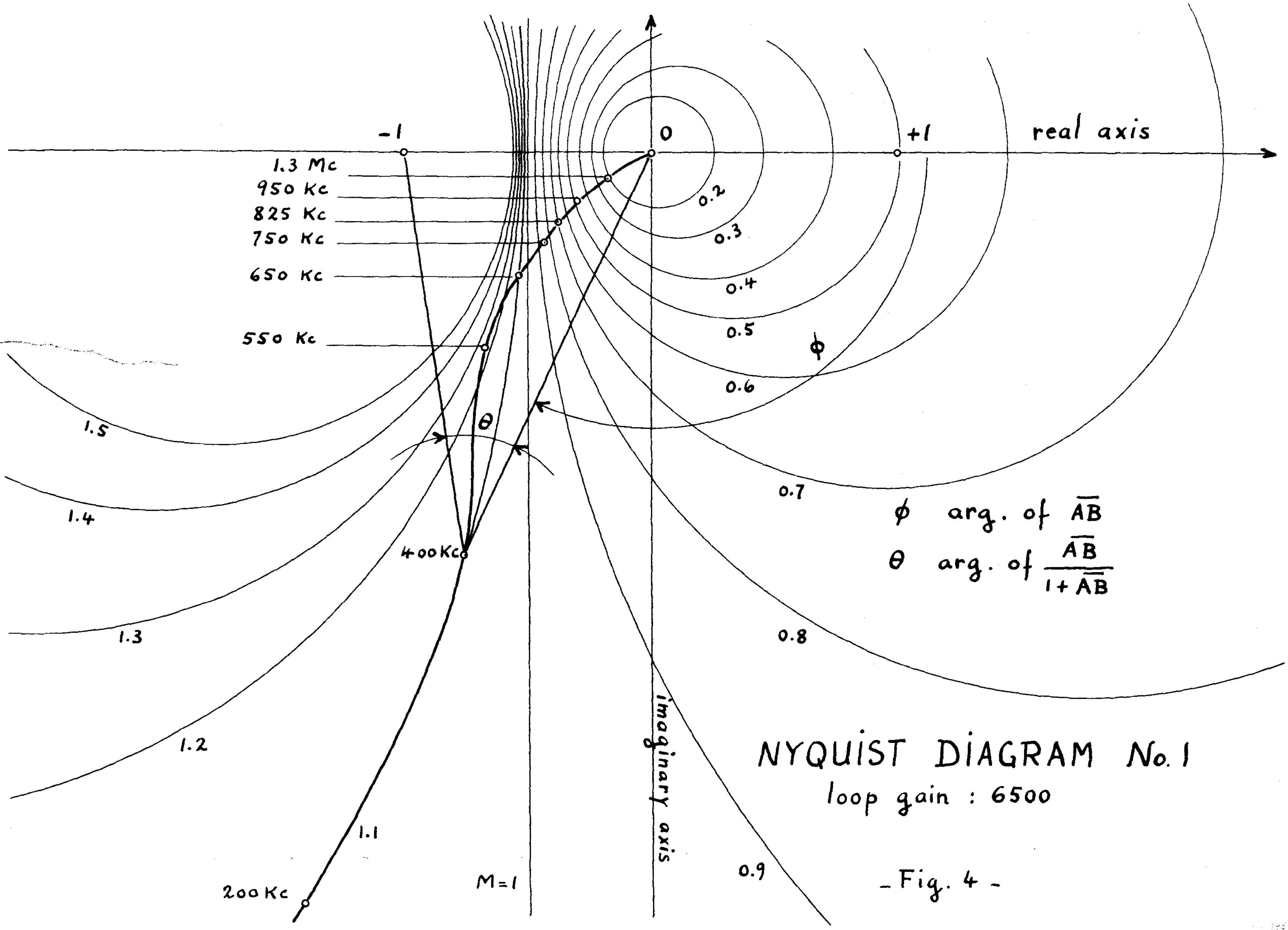
- Fig. 2 -

R_F KΩ	current for ± 5 V input	loop gain	Defl. angle
14.4	6.00 A	4900	42°
11.5	4.75 A	5500	32° (X)
8.4	3.50 A	6500	23° (Y)



AMPLIFIER OPEN-LOOP RESPONSE
TENTATIVE CORRECTION

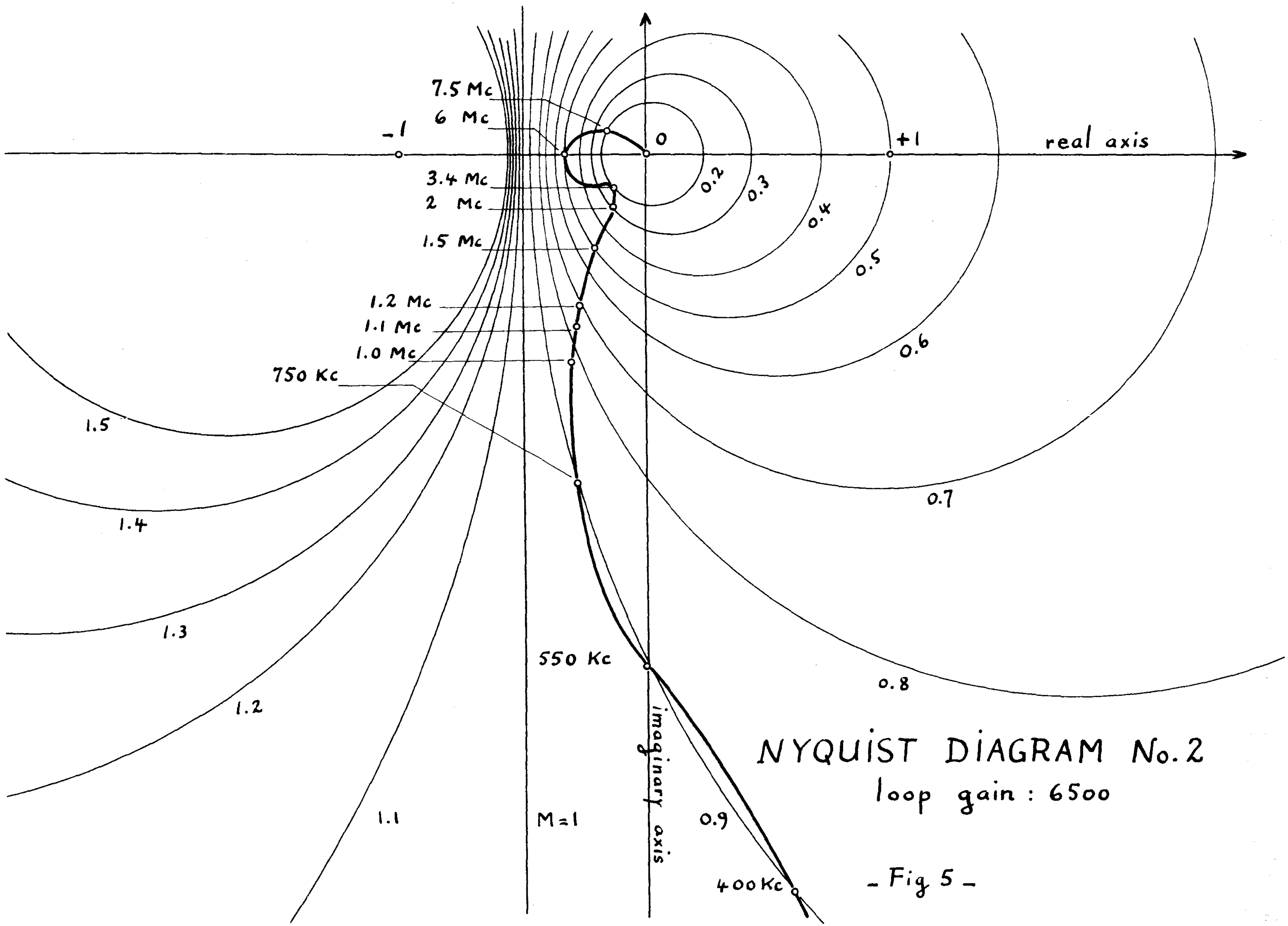
- Fig. 3 -



NYQUIST DIAGRAM No. 1

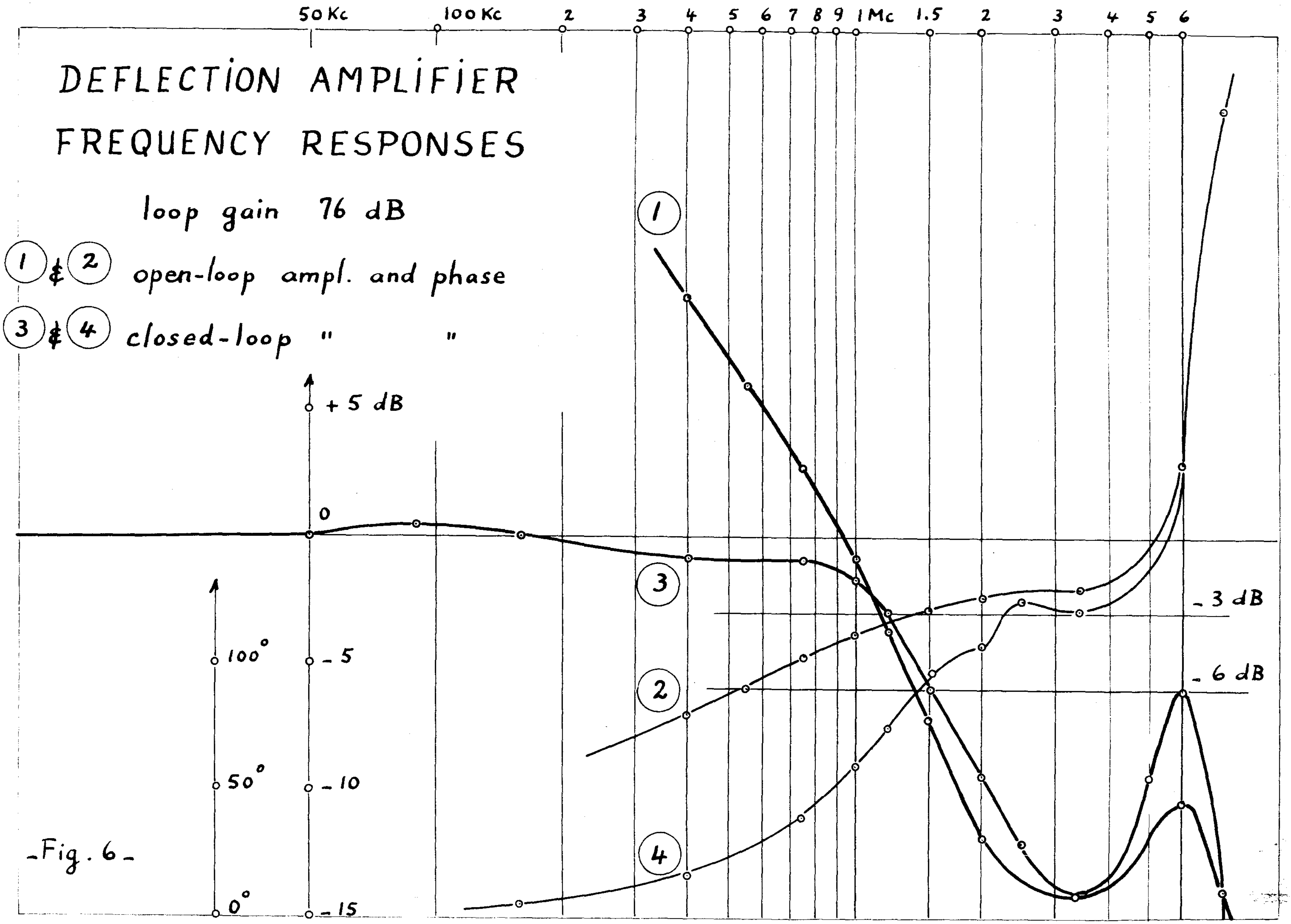
loop gain : 6500

- Fig. 4 -

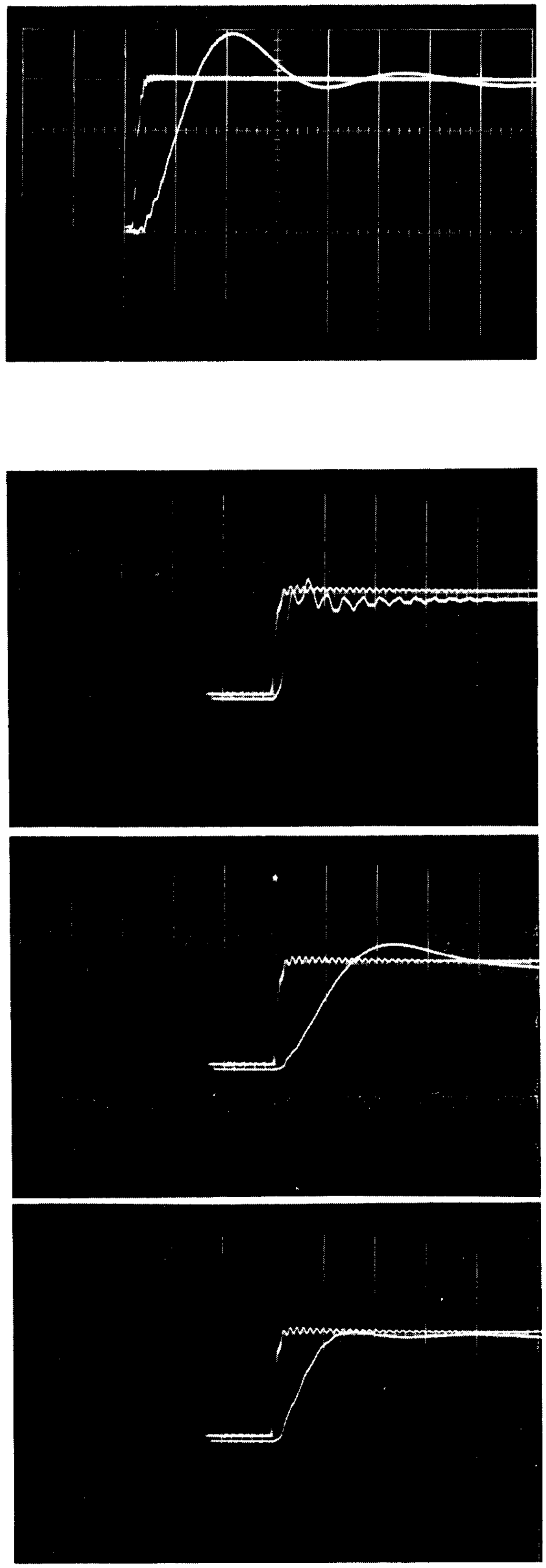


NYQUIST DIAGRAM No. 2
loop gain : 6500

- Fig 5 -


DEFLECTION AMPLIFIER
FREQUENCY RESPONSES
loop gain 76 dB
1 & 2 open-loop ampl. and phase
3 & 4 closed-loop " "
50 Kc
100 Kc
2
3
4
5
6
7
8
9
1 Mc
1.5
2
3
4
5
6
+ 5 dB
0
- 5
- 10
- 15
100°
50°
0°
- 3 dB
- 6 dB
1
2
3
4

- Fig. 6 -



-1-

-2-

-3-

-4-

Response to step of 150 mv
Time base 0.5 μsec / cm

- Fig. 7 -