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SOME VOLTAGE FEEDBACK LOOPS FOR RF SYSTEM OF THE AGS BOOSTER

AD
BOOSTER TECHNICAL NOTE
NO. 130

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Abstract

As the accelerator beam intensity increases, the loading of RF system becomes a serious problem and one typical solution is to utilize the proper control of amplifier-cavity combination, using some feedback techniques.

Some voltage feedback loops are suggested for the RF system of the BNL Booster, which is required to work over a frequency range of 2.4 to 4.2 MHz for the acceleration of protons. A fast response loop leads to a factor of about ten reduction of the output impedance in the final amplifier, that impedance is paralleled with the shunt impedance of the cavities. In addition,an Automatic Voltage Control (A.V.C) loop ensures that the gap voltage follows the voltage program generated by the computer and be stable enough against the variations from the power supplies. The peak-to-peak noise level on the gap voltage of less than 0.5% is expected within the acceleration period.

Introduction

The simplified block diagram of this system is shown in Fig.1.

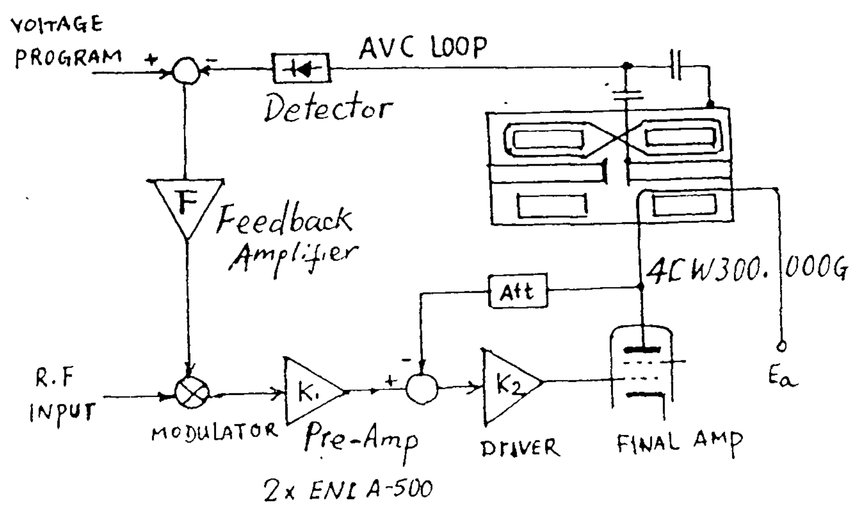


Fig.1 Block diagram of voltage feedback loops

A final amplifier EIMAC 4CW300.000G with the voltage gain of 45 excites an accelerating voltage of 22.5 Kv on each gap of the cavity. The pre-amplifier consists of two ENI A-500 commercial amplifiers for the first stage with a voltage gain of 60 db. A suitable driver amplifier inserted between the two stages is desirable for the compensation of the power loss caused by the use of the feedback.

Some schemes and considerations about the design of the feedback system for proton acceleration are described here.

Choice of driver tube

The amplifier circuit can be assembled by using a transistor and some types of commercial wideband amplifier available now. But experience in the past indicated that semi-conductor components may display a degraded performance after large exposure to radiation near a high energy accelerator as experienced in CERN. For this reason an electronic vacuum tube may be a better selection.

To choose the tube to satisfy output power and lower output impedance requirements, various types of tubes including triode and tetrode were investigated. Some main specifications about these tubes are listed in TABLE.1.

For the triode, owing to the large value of the capacitance between the plate and the grid, it is very easy to have self-exciting oscillations occur at certain frequencies and too troublesome to neutralize the positive feedback. Otherwise, the gain of the triode is comparably low with the tetrode.

Some results indicated that the output load resistance of the circuit using the tube such as QB3/750 or QB4/1100 is too big to match the impedance of the wideband transformer.

After the comparison with each other, a SIEMENS YL-1056 is the referred one and it has been chosen for the same purpose as at CERN. Its static characteristic curve is shown in Fig.2.

Fast feedback loop

The primary purpose of the fast feedback loop is to reduce the output impedance of the final amplifier with stability in RF system.

For the output impedance reduction factor of 10 in the final amplifier and keeping the original voltage gain constantly, the following relationship hold,

$$\frac{Z_o}{Z_f} = 1 - K_1 K_2 \beta$$

$$K_f = \frac{K_1 K_2}{1 - K_1 K_2 \beta}$$

where

Z_o, Z_f--output impedance of final amplifier without feedback and with feed-feed

K_f--voltage gain of the feedback loop

K_1, K_2--voltage gain of driver and final amplifier

β--feedback factor

for $Z_o/Z_f=10$, $K_f=K_2=45$, thus, $K_1=10$, $\beta=-0.02$.

A 20 db open loop gain and same output peak voltage as that without feedback at the grid of final amplifier can be obtained.

A driver amplifier over such range can be obtained in several ways, such as wideband amplifier, tuned amplifier and so on. However,due to the large input capacitance of the final amplifier tube,it is necessary to select carefully a suitable type and to design the network for matching the next stage.

Two schemes with different types of driver for the fast loop are discussed.

Driver using Push-pull amplifier

In the circuit of Fig.3 a wideband push-pull amplifier is used as a driver. The even harmonics are balanced out in the output circuit and,thus,a greater output may be obtained without exceeding a given permissible distortion. A d-c saturation of the output transformer is avoided and no signal frequency component of current flows through the plate supply to produce feedback problem.

The amplifier using this tube working in ground-cathode push-pull arrangement is designed. Class AB operation is used with consideration of balance of the linear gain characteristics and the plate efficiency.

The 9-point harmonic analysis method is adopted for the calculations of the amplifier with given d-c current(I_0), fundamental current (I_a).

From these values, we have

output power	$P_{\sim} = \frac{1}{2} V_a I_a$
input power	$P_o = E_a (I_0 + I_Q)$
plate dissipation	$P_a = P_o - P_{\sim}$
plate efficiency	$\eta = P_{\sim}/P_o$
plate load resistance	$R_a = V_a/I_a$

where

E_a--the d-c plate voltage

V_a--the peak signal voltage on the plate

I_Q--the quiescent plate current

Some numerical examples are listed in TABLE.2.

In this circuit, internal feedback takes place from the plate through resistor Rf setting up a voltage across the R1 , the phase of plate voltage exactly oppose to that of grid voltage. Since the feedback is proportional to the plate voltage, this circuit gives a reduction in both amplitude and frequency distortion thereby setting up a voltage of such polarity as to tend to restore the balance. R2 is additional resistor to improve the balance between the two tubes. Any imbalance between the tubes will produce a current through this resistance, thereby setting up a voltage of such polarity as to tend to restore the balance.

For the transformer in the circuit, some Wideband Balun Transformer are commercially available now, its cutoff frequency can be extended to about 32 MHz. The input transformer may be made with a small ferrite toroid such as PHILIPS -4M2, because the power losses in it is not high.

In order to reduce the phase shift, a resonant circuit with low Q-value (Q=0.8) is adopted at the input of final amplifier.

Driver using tuned amplifier

In the circuit of Fig.4, a tuned amplifier with low Q-value resonant tank circuit is used as a driver to pass the desired band of frequency and reject the harmonics. Such amplifier with internal feedback has been successfully adopted at CERN.

Because the plate voltage of this circuit uses parallel-feed,the tank inductance coil is at ground or low potential and therefore less insulation is required. The block condenser is normally of sufficient size,that is,its drop voltage does not vary appreciably from its average value throughout the rf cycle. Owing to the presence of this condenser, the flow of power to the tank circuit is much more uniform than the series-feed circuit.

The plate load of the first stage is a low pass filter with 50 Ohm input impedance and cutoff frequency of 32 MHz.

Taking the damp resistance of 50 ohms and the turns ratio of 0.5 (n1/n2) at the autotransformer coil,then, the load resistance of 200 ohms [$\frac{Z_1}{Z_2}=\left(\frac{n_1}{n_2}\right)^2$] is given at the grid of final amplifier. The value of the resistor is so low, that two tubes are needed.

The feature of this circuit is that there will be a little phase shift at resonance, but the resonator control have to synchronize with the cavity fequency by changing the biasing current of the ferrite.

The calculations about this amplifier is similar to that mentioned above.Some parameters calculated are also listed in TABLE.2.

Fast loop stability

As designed already, the output of final amplifier is tightly coupled to the cavities through an inductance loop around these ferrites. Figure 5 shows its equivalent circuit. The impedance ($R_p + jX_p$) reflected from the cavity to the plate of final amplifier can be written:

$$R_p = \frac{R_f(1 - X_f\omega C_p - \omega^2 L_p C_p) + \omega C_p R_f (X_f + \omega L_p)}{(1 - X_f\omega C_p - \omega^2 L_p C_p)^2 + \omega^2 C_p^2 R_f^2}$$

$$X_p = \frac{(X_f + \omega L_p)(1 - X_f\omega C_p - \omega^2 L_p C_p) - \omega C_p R_f^2}{(1 - X_f\omega C_p - \omega^2 L_p C_p)^2 + \omega^2 C_p^2 R_f^2}$$

where

$$R_f = \frac{\omega m^2 R_s}{(R_s^2 + X_s^2)} + \frac{R_s}{1 - \frac{4X_s L_m}{\omega m^2} + \frac{4L_m^2(R_s^2 + X_s)}{\omega^2 m^4}}$$

$$X_f = \frac{-\omega^2 m^2 X_s}{(R_s^2 + X_s^2)} + \frac{\omega^2 m^2 X_s - 2\omega L_m (R_s^2 + X_s^2)}{\omega^2 m^2 - 4X_s\omega L_m + 4L_m^2(R_s^2 + X_s^2)}$$

$$X_s = \omega L_2 - \frac{1}{\omega C_2}$$

R,C,L,m--resistance,capacitance,inductance and mutual inductance in circuit (see Fig.5)

Its characteristic curve on the plate of final amplifier at different frequencies can be found from :

$$G(\omega) = 20 \log_{10}\sqrt{R_o^2 + X_o^2} \quad ; \quad \varphi(\omega) = tg^{-1}\left(\frac{X_o}{R_o}\right)$$

where

$$R_o = K_1 K_2 \frac{R_p(r_p + R_p) + X_p^2}{(r_p + R_p)^2 + X_p^2} \quad ; \quad X_o = K_1 K_2 \frac{X_p(r_p + R_p) - R_p X_p}{(r_p + R_p)^2 + X_p^2}$$

rp--plate resistance of final amplifier (see Fig.5)

The curve indicates that the phase shift caused by remaining parts of this system must be less then 60 degree when the open loop gain equals 1, therefore some networks with large phase shift is not to be allowed.

In order to reduce the additional phase shift, some solutions are considered.

A capacitor divider is the best way to get the feedback signal from the output of final amplifier,because there is no phase change in it.

Some resonant circuit with very low Q-value can be used between each two stages, especially for the tube with a large input capacitance.

In the driver, the phase shift caused by the lowpass filter at the plate of the first tube is small, because it has a wideband of 31 MHz. The gain and phase curve of this network are shown (Fig.6).

The main transfer functions of the feedback loop consists of several parts as follows:

the cavity circuit
$$G_1(S) = \frac{R_p(\omega)+jX_p(\omega)}{r_p + R_p(\omega)+jX_p(\omega)}$$

the lowpass filter
$$G_2(S) = \frac{1}{1+ST_1+\frac{1}{A+\frac{S}{T_2}}} \; ; \; A=\frac{R_2}{r_{p1}} \; ; \; T_1 = r_{p1}\cdot C_4 \; ; \; T_2 = \frac{r_{p1}}{L_1}$$

the tuned tank in amplifier
$$G_3(S) = \frac{1}{1+A+ST_1+\frac{T_2}{S}} \; ; \; A=\frac{r_{p2}}{4R_3} \; ; \; T_1 = r_{p2}\cdot C_5 \; ; \; T_2 = \frac{r_{p2}}{L_2}$$

the capacitance divider
$$G_4(S) = \frac{1+ST_1}{1+ST_1+ST_2+B_1+B_2} \; ; \; T_1 = R_1C_1 \; ; \; T_2 = R_1\frac{C_1C_2}{C_3} \; ; \; B_1 = C_1/C_3 \; ; \; B_2 = C_2/C_3$$

where $S = j\omega$

r_p --plate resistance of final amplifier

r_{p1} --plate resistance of first stage amplifier in driver

r_{p2} --plate resistance of second stage amplifier in driver

R, C, L--resistance,capacitance and inductance in these circuit(see Fig.3 and Fig.4)

Bode plot can be used for the stability analysis, any feedback loop will become unstable if the open-loop gain equals 0 db and a total phase shift of 180° occurs. Here,an extra about 40° phase margin is allowed, some Bode plots about two types of driver are shown (Fig.7 and Fig.8), the system is stable.

Fig.9 shows the Bode plot of closed loop.

In the push-pull driver,some additional phase shifts may come from the wide-band transformer, here the time delay arising from these transformers is neglected.

These curves show that these feedback loops are stable, but there is little phase margin remaining. For improvement,some internal feedbacks are available for adjustment.

A.V.C loop

The scheme of this loop is shown in Fig.10. It consists of modulator,pre-amplifier,driver,final amplifier,capacitor divider,detector and feedback amplifier.

The rf input signal exciting the pre-amplifier is regulated at a 250mV level via the modulator and the modulator is controlled by a signal proportional to the difference between the program voltage (Fig.11) and the feedback signal from the cavity. Some balanced mixer and analog multiplier can be used for this modulator.The mixer is to provide the attenuation between the input and the output and this attenuation is about 10 db when the control current is changed from 1 ma to 10 ma at the control port.

A linear multiplier following an operational amplifier presents the same function for use of the modulator.

The feedback signal is taken from a capacitor divider mounted in the cavity and through a cathode follower (such as tube 6146) to the detector.

A feedback amplifier is made of some IC operational amplifiers and networks. Due to the high gain characteristics of the ENI A-500,relatively little signal gain is required in this amplifier.

The voltage gain of the open loop ($K\cdot\beta$) can be given by

$$\frac{\Delta u_f}{u_f} = \frac{1}{|1-K\beta|}\cdot\frac{\Delta u}{u}$$

where

$\Delta u/u$ --the stability of the system without feedback

$\Delta u_f/u_f$ --the stability of the feedback loop

K --whole voltage gain of the loop

β --feedback factor

for

$$\frac{\Delta u_f}{u_f} = 0.5\%, \quad \frac{\Delta u}{u} = 50\% \text{ (extremely condition)}, \quad K\beta \cong 100.$$

In contrast with the fast feedback loop,the response speed of the signal is very slow and only for an envelope of modulating voltage.

Because the parts of loop is a carrier system employing some resonant circuits,the response of a tuned tank operating at resonance,to a modulating signal of frequency Fm is equal to $\frac{1}{1+jF_m\frac{2Q}{f_c}}$,where fc is the resonant frequency.

The main time delay concerning some parts are given as follow:

Cavity tank with beam loading	3.8 us
Resonant circuit	0.73 us
Detector	0.3 us

It shows that the whole delay of this system is small compared with the front edge of the program voltage and it can be neglected or easily corrected by using some simple networks in the feedback amplifier.

These transfer functions about the AVC loop includes:

the cavity circuit

$$G_1(s) = \frac{1}{1+\frac{sQ_1}{\pi f}}$$

the tuned tank in amplifier

$$G_2(s) = \frac{1}{1+\frac{sQ_2}{\pi f}}$$

the detector

$$G_3(s) = \frac{A}{1+sT} \; ; \; A = \frac{R_2}{R_1+R_2} \; ; \; T = \frac{R_1 R_2}{R_1+R_2}\cdot C_1$$

the compensation circuit

$$G_4(s) = \frac{\left(1+\frac{s}{2\pi f_{c1}}\right)\left(1+\frac{s}{2\pi f_{c2}}\right)}{\left(1+\frac{s}{2\pi f_{j1}}\right)\left(1+\frac{s}{2\pi f_{j2}}\right)}$$

the cable delay

$$G_5(s) = e^{-s t_d}$$

where

Q_1 --the quality factor of cavity

Q_2 -- the quality factor of the tuned tank in the driver

R, C --the resistance and capacitance in the circuit(see Fig.10)

f_{c1}, f_{c2} --the frequency at "zero" point of compensation function

f_{j1}, f_{j2} --the frequency at "pole" point of compensation function

t_d --time delay (Cable)

Fig.12 is the Bode plot about AVC loop without compensation and no time delay ($t_d=0$), this loop is unstable. After compensations, some Bode plots with different time delay caused by the cable are shown in Fig.13. These curves indicated that the time delay (t_d) bigger the loop gain (G) must lower for keeping the system stable (a 45° phase margin has taken).

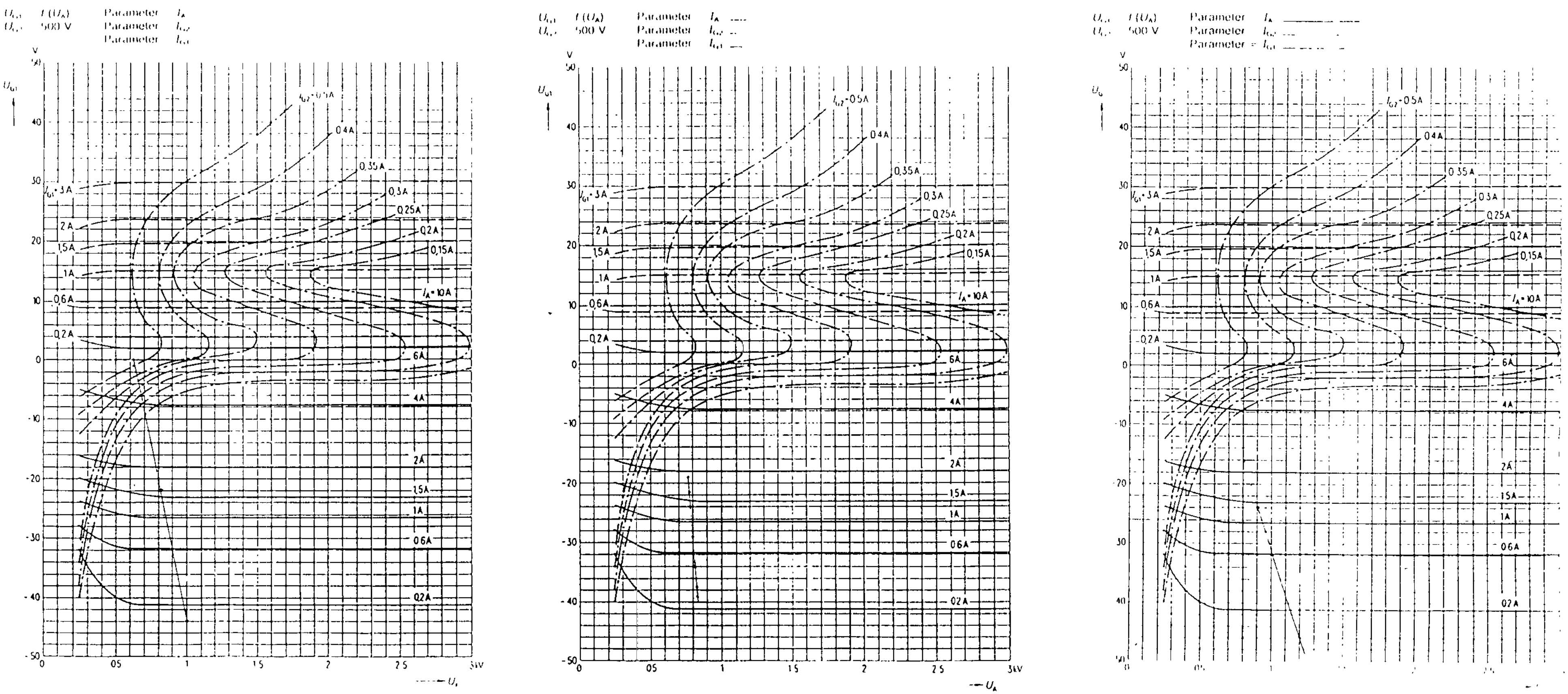
TABLE 1. Main Technical Data of Some Tube

TYPE		Po (kw)	Pa (kw)	Uam (kv)	Dia (mm)	Hig (mm)	cooling
SIEMENS (TETRODE)	YL-1056	1.17	2	3.5	95	103	FAC
	YL-1057	1.1	2	3.6	95	103	FAC
	RS-1072	1.2	1.8	2.9	95	103	FAC
	YL-1058	1.44	2.2	3.6	95	103	FAC
PHILIPS (TETRODE)	QB3/750	1.0	0.25	4	87	151	NC
	QB4/1100	1.1	0.4	4	87	151	NC
	YL-1440	2.4	1.5	4	63	125	FAC
	YL-1541	2.1	2	4.5	63	122	FAC
	YL-1590	1.1	2	4	73	109	FAC
PHILIPS (TRIODE)	TB3/750	1.55	0.35	4	87	151	NC
	TB4/1250	2.29	0.45	4	118	213	NC
	TB2/400	0.7	0.15	2.5	62	132	NC

Po - Plate output power
Pa - Plate dissipation
Uam - Maximum plate d-c voltage
Dia - Diameter of the tube
Hig - Height of the tube
FAC - Force air cooling
NC - Natural cooling

TABLE 2. Summary of tube perfirmance

		Push-pull	First stage	Tuning stage
(1) Plate d-c voltage	(v)	1000	800	1200
(2) Peak signal voltage on plate	(v)	375	40	400
(3) Grid bias voltage	(v)	-44	-29	-46
(4) Peak signal voltage on grid	(v)	44	10	30
(5) Zero signal plate current	(A)	0.1	0.8	0.1
(6) Plate average current	(A)	1.45	1.63	0.61
(7) Peak fundamental componenet of plate current	(A)	2.45	0.81	1.02
(8) Plate power input	(W)	1550	1304	733
(9) Power output	(W)	459	16	204
(10) Plate dissipation	(W)	1090	1272	519
(11) Plate efficieny	(%)	30	1.3	27.8
(12) Plate load resistance	(OHM)	153	49.5	392



(a) Push-pull amplifier

(b) First stage of driver

(c) Tuning amplifier

Fig.2 Characteristicc curve of tube YL-1056

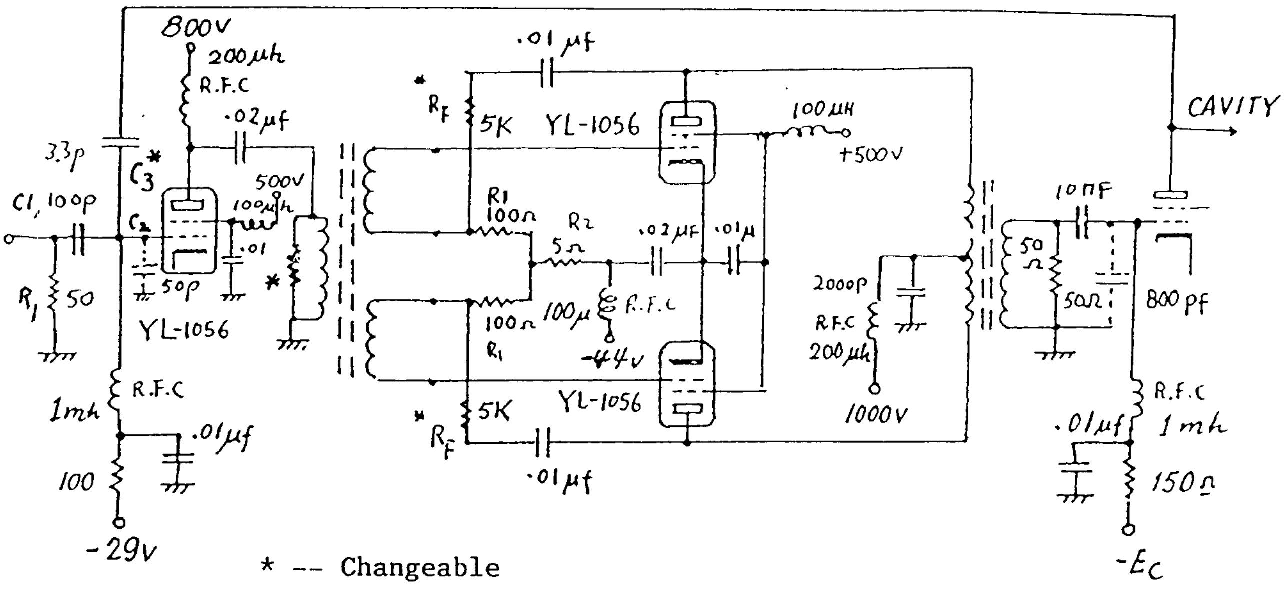


Fig.3 Fast loop with push-pull amplifier

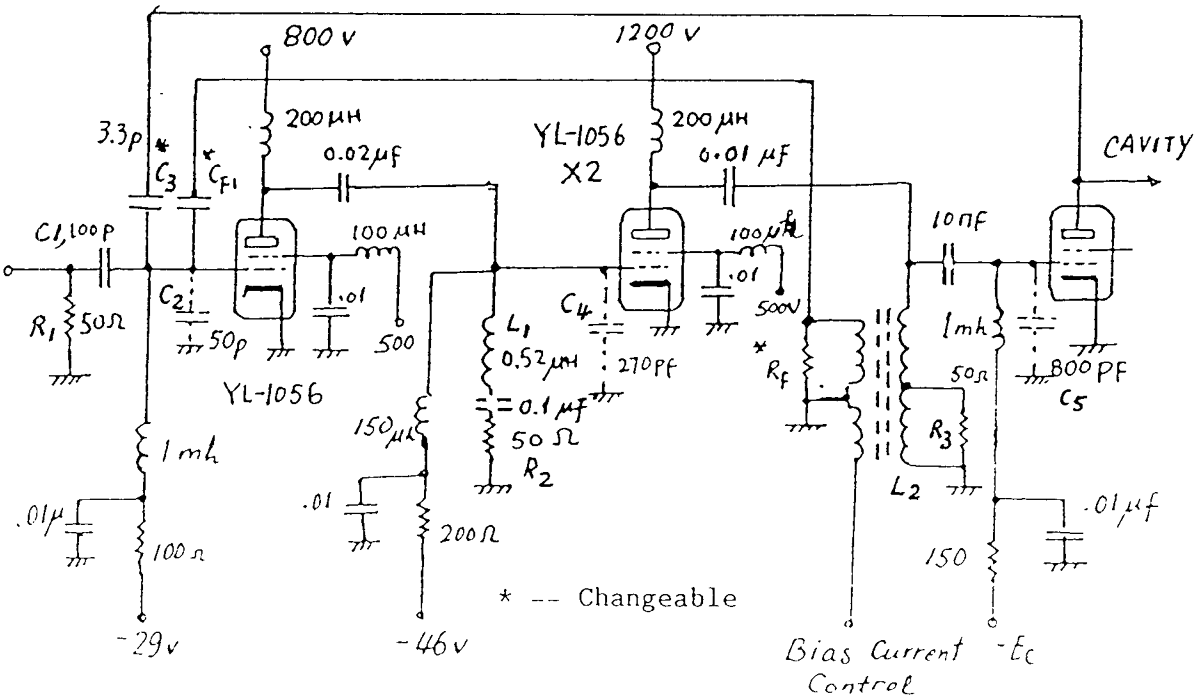


Fig.4 Fast loop with tuning amplifier

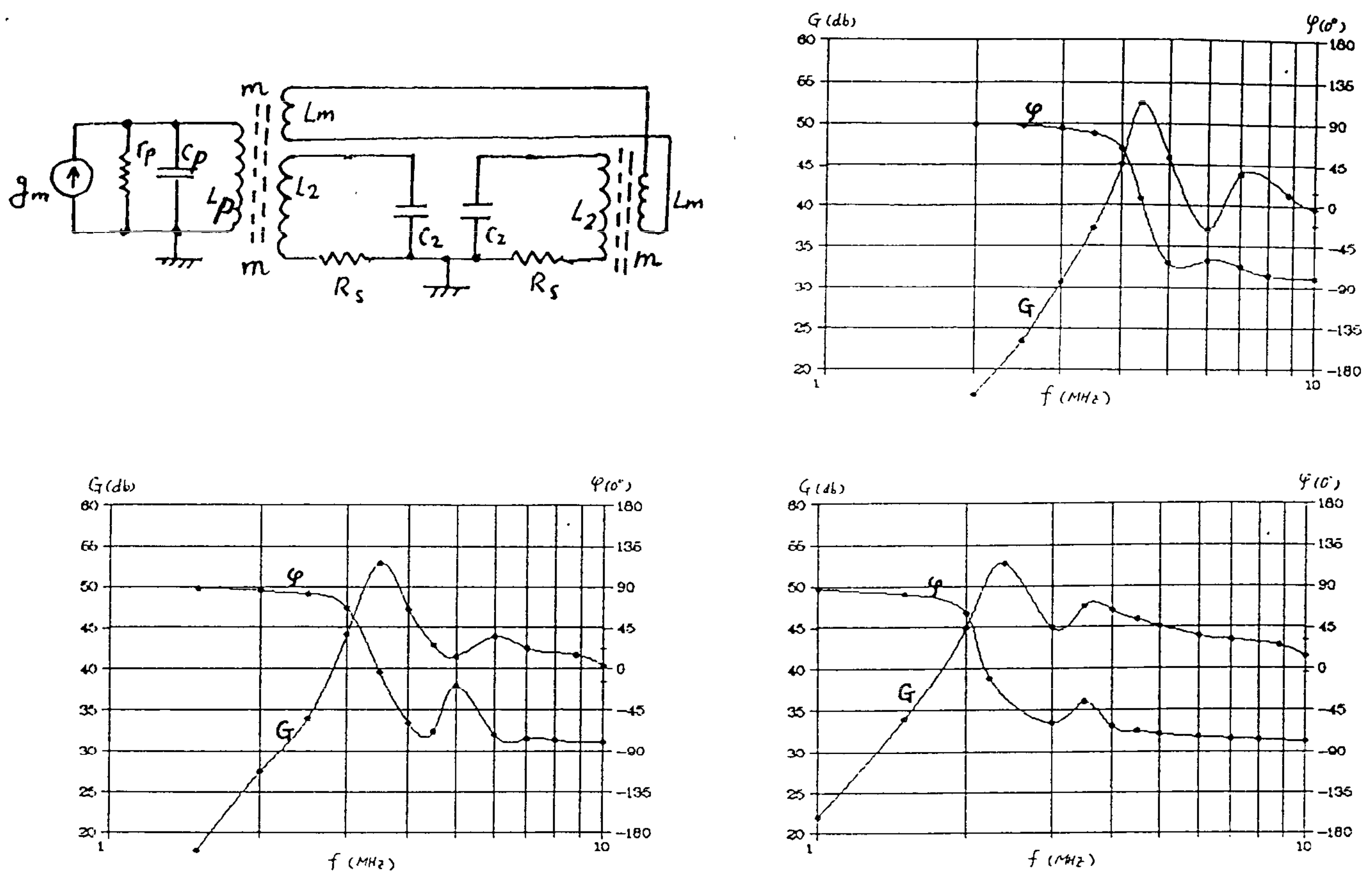


Fig.5 Equivalent circuit and resonant curve of the cavity

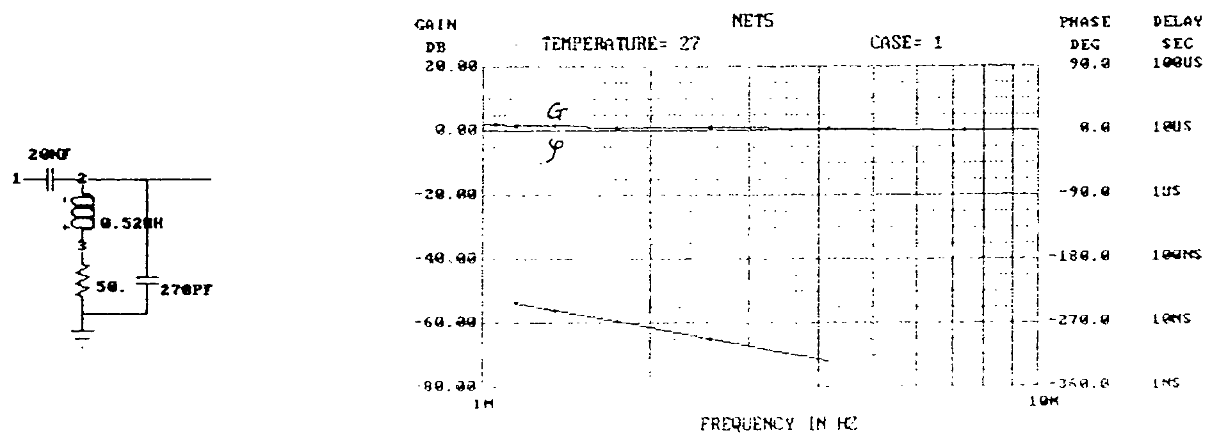


Fig.6 Gain and phase curve of lowpass network

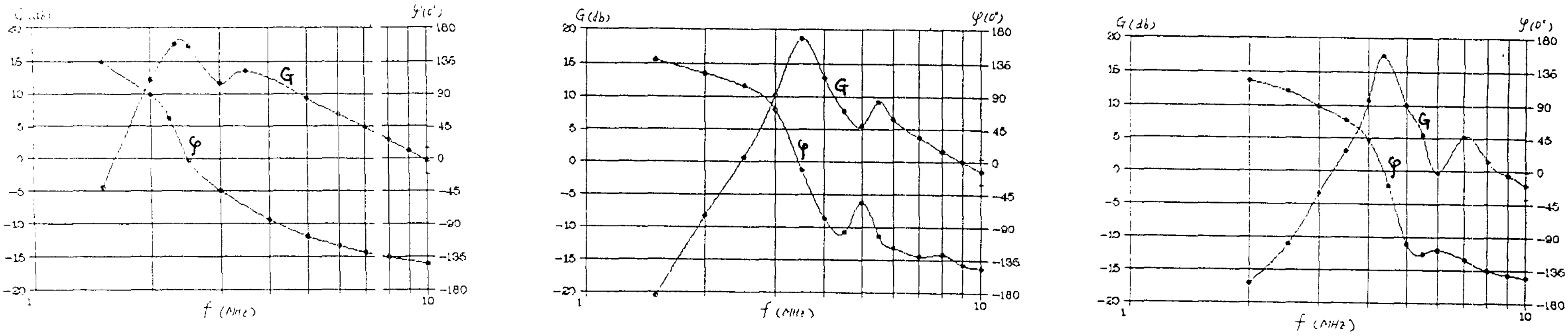


Fig.7 Bode plots Of fast loop with push-pull amplifier

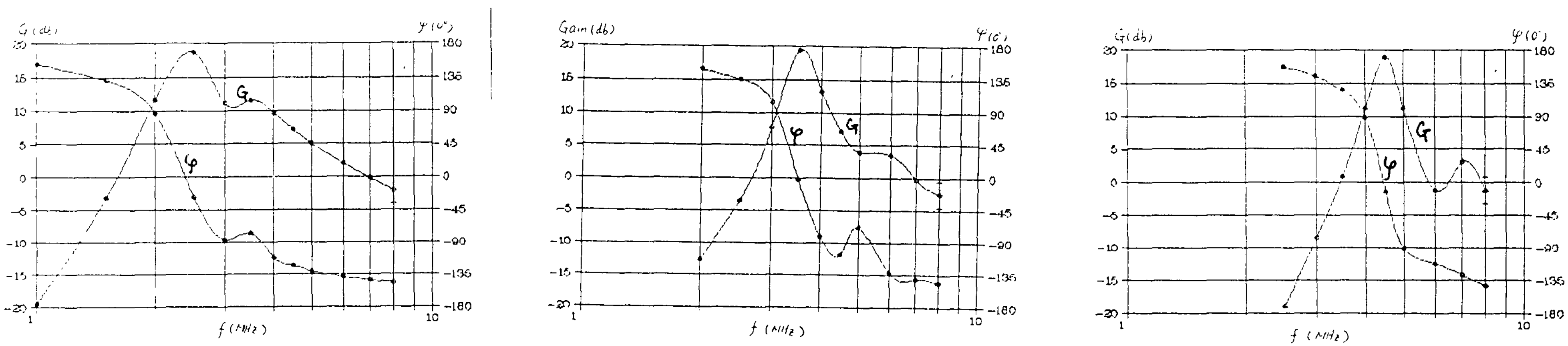


Fig.8 Bode plot of fast loop with tuning amplifier

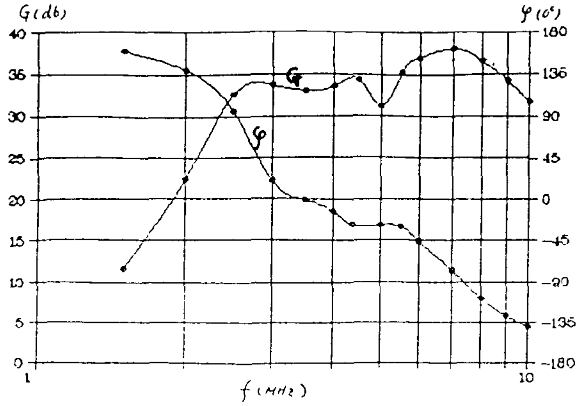


Fig.9 Bode plots of closed loop

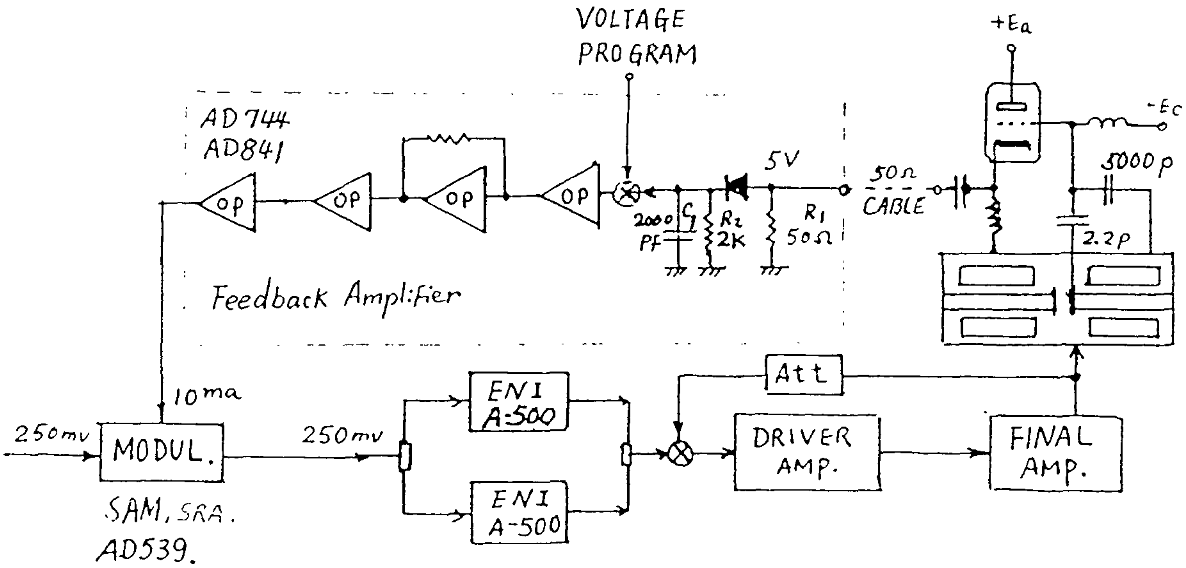


Fig.10 Black diagram of AVC loop

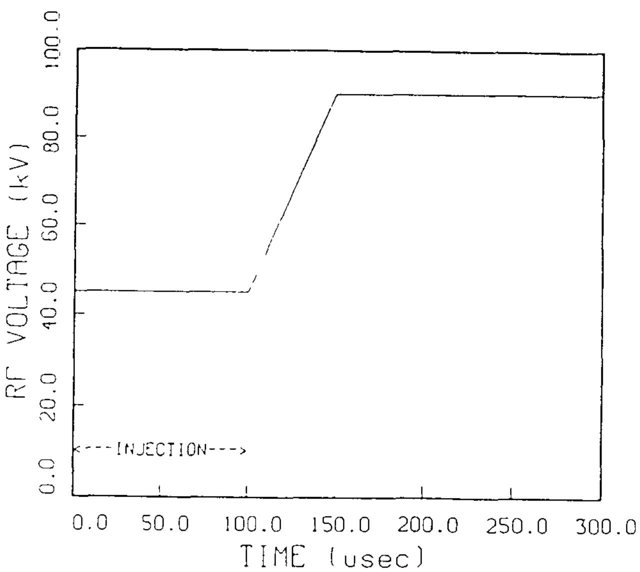


Fig.11 Voltage program for proton

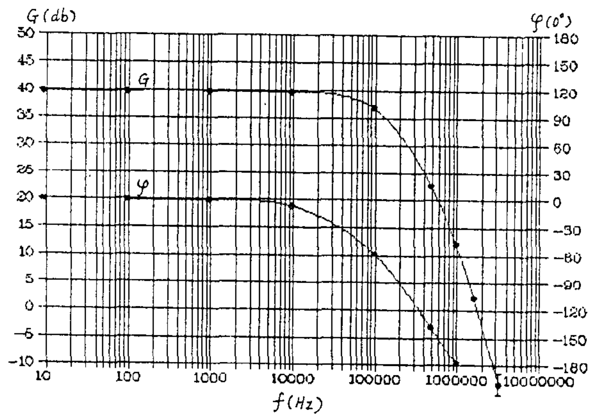


Fig.12 Bode plot of AVC loop
without compensation

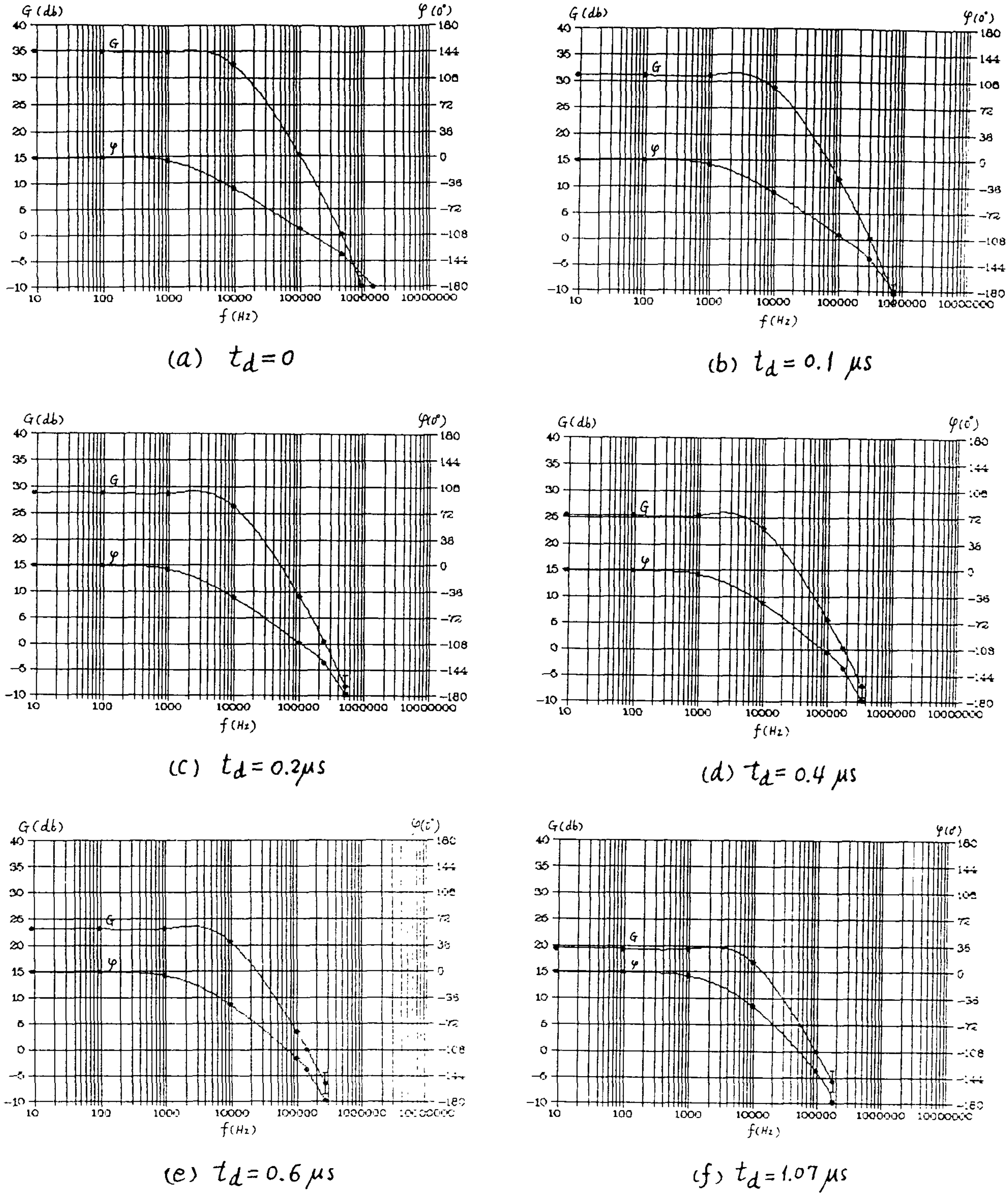


Fig.13 Bode plots of AVC loop compensated with different time delay (t_d)

Acknowledge

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Reference

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