

Okio Ozawa and Kikuo Ishikawa
Pioneer Electronic Corporation
Ohmori, Japan

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SUPER LINEAR CIRCUIT

Okio Ozawa, Kikuo Ishikawa
PIONEER ELECTRONIC CORPORATION
Amplifier Designing Section
Ohmori, Japan

INTRODUCTION

Almost all the hi-fi audio amplifiers at present use semiconductors such as transistors and FETs as their active devices. However, these semiconductors have their peculiar non-linearities in input-output characteristics. Thus they are by no means ideal active devices for hi-fi amplifiers. Fundamental characteristics required for hi-fi amplifiers are the following:

1. Flat frequency response in the audio band.
2. Low distortion.
3. Wide dynamic range (high S/N)
4. Stability against any external loads.
5. Stability of required input and output impedances.

To satisfy the above conditions, most of the hi-fi amplifiers apply overall negative feedback which returns a portion of the output signal back to the input as shown in Fig. 1. This is done to reduce distortion generated by non-linearities of the semiconductors, to improve frequency response and S/N ratio and to secure the desired input and output impedances. It has been believed that negative feedback was indispensable for amplifiers to realize distortion of less than 0.01%. However, the stability against external loads becomes worse when negative feedback is applied. The Super Linear Circuit is really a new amplifying circuit which not only satisfies the performance required of audio amplifiers but also achieves stable operation and extremely low distortion without applying overall negative feedback.

NON LINEARITIES OF SEMICONDUCTOR DEVICES AND THE DISTORTION PRODUCED IN THE AMPLIFIERS THEREBY:

What kind of input-output characteristics do transistors and FETs used as amplification devices have?

Transistors have the following direct current exponential characteristics between the input voltage, V_{BE} , and the output current, I_c .

$$(1) \quad I_c = I_s \left\{ \exp \left(\frac{q V_{BE}}{k T} \right) - 1 \right\}$$

Where	I_s	=Leakage current
	q	=Electron charge
	k	=Boltzmann's constant
	T	=Temperature (°K)

Considering the signal transfer in a common emitter circuit as shown in Fig. 2a, the output signal waveform consists of many harmonics mainly the 2nd and therefore the amplifier would have the high distortion shown in Fig. 2b.

FETs have the following direct current transfer characteristics between the input voltage V_{GS} and the output current I_D

$$(2) \quad I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P}\right)^2$$

where I_{DSS} = Drain-source current with the gate shorted
 V_P = Pinch off voltage

In the case of FET amplifiers, harmonic distortion consists only of the 2nd harmonic. To lessen distortion caused by the non-linearities of semiconductors and to linearize the transfer characteristics, hi-fi amplifiers have been designed with differential amplifiers, using current mirror circuits or with large resistors in series with emitters.

First let us examine the distortion of an amplifier using a resistor in the emitter circuit. Fig. 3 shows that circuit.

If V_B is the quiescent base voltage, I_{ES} caused by a superimposed sine wave input voltage, V_i , is analyzed as follows:

$$(3) \quad I_E = f(V_B) + \sqrt{2} f'(V_B) V_i \sin \omega t + \frac{1}{2} f''(V_B) V_i^2 (1 - \cos 2\omega t) + \frac{\sqrt{2}}{12} f'''(V_B) V_i^3 (3 \sin \omega t - \sin 3\omega t) + \dots$$

The 2nd and 3rd harmonic distortion become:

$$(4) \quad D_2 \div \frac{V_i}{2\sqrt{2}} \frac{h}{R_E^2 I_E^2} \times 100 \quad [\%]$$

$$(5) \quad D_3 \div \frac{V_i^2}{12} \left(\frac{-\frac{2R_E h}{I_E^3} + \frac{3h^2}{I_E^4}}{R_E^4} \right) \times 100 \quad [\%]$$

when $R_E \gg \frac{h}{I_E}$ where $h = \frac{KT}{q}$

Fig. 4 shows harmonic distortion vs input level using parameters of common use. Fig. 5 shows the distortion of the differential amplifier. In the circuit using a series emitter resistor, the 2nd harmonic distortion is remarkably small and the level of the 3rd harmonic becomes equivalent to 2nd harmonic distortion near the clipping point. In the case of the differential amplifier, theoretically it generates no 2nd harmonic distortion but many odd harmonics.

CHARACTERISTICS AND PROBLEMS CAUSED BY OVERALL NEGATIVE FEEDBACK

A fundamental block diagram of overall negative feedback amplifiers is shown in Fig. 6. Here A_o represents the DC amplification of the amplifier without feedback. The effective amplification for a negative feedback

amplifier is, typically:

$$(6) \quad A = \frac{A_o}{(1 + A_o \beta) \left(1 + S \frac{T}{1 + A_o \beta}\right)}$$

If $A_o \beta \gg 1$

the closed loop amplification, A, as shown in Fig. 7 becomes:

$$(7) \quad A \doteq \frac{1}{\beta + \frac{T_s}{A_o}}$$

and if β has a flat response, frequency response is improved by $A_o \beta$ times in frequency range below $f = \frac{1}{2\pi T}$.

As to the distortion as illustrated in Fig. 8, distortion is reduced by negative feedback. The distortion D_o of the amplifier becomes D through the negative feedback β -circuit for $\beta \gg \frac{T_s}{A_o}$

$$(8) \quad D_o - \beta A_o D = D$$

Where D_o = distortion generated in amplifier, and then

$$(9) \quad D = \frac{D_o}{1 + A_o \beta}$$

This shows the low frequency distortion generated in open loop is reduced by negative feedback in the same proportion that the amplification is reduced.

Feedback also reduces the low frequency open loop noise in the same way that the distortion is reduced. Therefore:

$$(10) \quad N = \frac{N_o}{1 + A_o \beta}$$

Where N = Noise generated at the output with negative feedback
 N_o = Noise generated at the output in the absence of negative feedback.

Also both the input and output impedances of an amplifier are either increased or decreased depending on the form of the feedback used. As negative feedback has various merits in designed amplifiers, it is broadly applied to audio use hi-fi amplifiers at present and results in high performance devices.

However, negative feedback has some weak points. One is caused by the phase difference between input and output signals as shown in Fig. 6. The subtraction of the input V_i and β times the output V_o , that is $(V_i - \beta V_o)$, is the input of the amplifier. If the phase shift between

input and output exceeds 90° in the open loop, the normally subtractive feedback signal would become additive positive feedback, and when the phase shift exceeds 180° , the amplifier will cause oscillation trouble.

Semiconductors, resistors and other component parts of amplifiers have their own frequency responses. Moreover, there are many elements which cause phase shift in the high frequency range, such as stray capacitance and inductance in wiring, and phase characteristics of audio components connected outside of the amplifier (for example, cartridges and speakers). If the negative feedback is operated in the region where phase shift exceeds 90° there would be a peak in the frequency response and the amplifier could become unstable in the frequency range. Fig.9 shows these conditions. Thus designers of amplifiers compensate the phase in open loop in order to apply negative feedback.

Fig. 10 shows the results of negative feedback mentioned above. On account of phase compensation in open loop, the amount of negative feedback is reduced in the high frequency range in comparison with the previous condition. Therefore, the improvement of distortion, S/N ratio and both input and output impedance are disturbed, and the high frequency performance will be sacrificed.

The second problem is concerning TIM distortion shown in Fig. 11. When a transient step signal is applied to the input, the output will not appear initially due to the time delay of the amplifier. The level of the input signal to the amplifier at this moment is transiently V_i . The level of the input signal of the amplifier is the difference between input signal and negative feedback signal i.e. $V_e = (V_i - \beta V_o)$. Therefore, the allowable input level at the input stage would be V_e . However, it becomes a very large signal at the transition period of the step signal. If the quiescent current at the input stage is small, the signal current is saturated transiently and the small high frequency signal which is added to the step signal is broken off as in Fig. 13.

This is one cause for generating TIM distortion. Amplifiers of recent design eliminate TIM distortion by increasing the input stage allowance or by positioning a low-pass filter before the input of the amplifier to restrict high frequencies. Fig.14 shows a block diagram with the low-pass filter is located in front of the amplifier. ω_0 is the angular cutoff frequency of the input low pass filter, and ω_1 the angular cutoff frequency of the amplifier in closed loop. The input V_e of the amplifier is:

$$(11) \quad V_e = \frac{V_{ip}}{s} \cdot \frac{s \frac{1}{\omega_1}}{(1 - s \frac{1}{\omega_0}) (1 + s \frac{1}{\omega_1})}$$

where V_{ip} is the maximum value of the step input signal.

To transform into time field, it becomes:

$$(12) \quad V_e(t) = \frac{\omega_0}{(\omega_1 + \omega_0)} \left[e^{-\omega_1 t} - e^{-\omega_0 t} \right] V_{ip}$$

This state of affairs is shown in Fig. 15. The quiescent current I_a required at the input stage of the amplifier is:

$$(13) \quad I_a = G_a \cdot V_{ep}$$

where G_a is the transfer conductance at the input stage
 V_{ep} is the peak of the signal at the input stage of the amplifier.

Although negative feedback amplifiers have prominent characteristics for improving distortion and S/N ratio, and controlling both input and output impedance, they become unstable by TIM or oscillation and their performance deteriorates at high frequencies.

THE PRINCIPLE OF THE SUPER LINEAR CIRCUIT

The fundamental thought of the Super Linear Circuit is that this circuit cancels the non-linearity of transistors by using the same characteristics of the transistors in a reverse mode. Fig. 16 shows the fundamental circuit of the Super Linear Circuit. In the diagram, I_a is a base current in the current mirror circuit and the same currents I_1 and I_2 flow in the mirror circuit.

When the signal voltage V_i is delivered at the input, emitter voltage V_{E2} of the transistor Q_2 is:

$$(14) \quad V_{E2} = V_i + V_{BE1} - V_{BE2} = R_E I_{E2}$$

where V_{BE1} = Base-emitter voltage of transistor Q_1 .

V_{BE2} = Base emitter voltage of transistor Q_2 .

R_E = Emitter resistance of transistor Q_2 .

I_{E2} = Current flows in R_E

Here

$$(15) \quad V_{BE1} = \frac{kT}{q} \ln \left(\frac{I_{C1}}{I_{S1}} - 1 \right)$$

$$(16) \quad V_{BE2} = \frac{kT}{q} \ln \left(\frac{I_{C2}}{I_{S2}} - 1 \right)$$

If the transistors Q_1 and Q_2 are developed for complimentary use, each saturation current is usually equal. As I_{C1} and I_{C2} are equal at any moment on account of the current mirror, V_{BE1} is equal to V_{BE2} on the condition that $I_{C1} = I_{C2}$, $I_{S1} = I_{S2}$. Then:

$$(17) \quad V_i = R_E I_{E2}$$

In case h_{FE} of each transistor is large

$$(18) \quad I_{E2} \div I_{C2} \quad I_{C2} = I_{C3}$$

Therefore

$$(19) \quad V_i = R_E I_{C3}$$

Output voltage V_o becomes

$$(20) \quad V_o = I_{C3} R_L = \frac{V_i}{R_E} R_L$$

and the voltage gain becomes

$$(21) \quad V.G. = \frac{V_o}{V_i} = \frac{R_L}{R_E}$$

In short, the Super Linear Circuit performs linear amplification by theoretically cancelling the non-linearity of the transistors and in principle, it becomes a no-distortion circuit.

Let's consider the Super Linear Circuit from another point of view. Transfer conductance is the current to voltage gain of an amplifier. The transfer conductance G_m is expressed as the ratio of the output current to the input voltage:

$$(22) \quad G_m = \frac{I_o}{V_i} = \frac{I_{C3}}{V_i} = \frac{1}{R_E}$$

Therefore:

$$(23) \quad V.G. = \frac{V_o}{V_i} = \frac{I_{C3} R_L}{V_i} = G_m R_L = \frac{R_L}{R_E}$$

Since the Super Linear Circuit is considered a linear conductance amplifier which generates no distortion, the transfer conductance is $(1/R_E)$.

CHARACTERISTICS OF THE SUPER LINEAR CIRCUIT MODULE

To make good use of the Super Linear Circuit many careful considerations are given to the module. The internal circuit and outer circuit of the Super Linear Circuit are shown in Fig. 17. As shown in the diagram, the Super Linear Circuit is fundamentally of push-pull construction. Therefore, extremely low distortion which is generated by the typical tolerance of parts used is cancelled by this push-pull circuit and a low distortion circuit is realized. The input stage is also a push-pull construction using low noise P channel and N channel FETs that have nearly equal characteristics. An input capacitorless amplifier is realized with high input impedance.

The output impedance of the Super Linear Circuit is very high. As the output impedance is the load resistance, R_L , the characteristics change with the external load. The output impedance is reduced by applying an SEPP common collector circuit outside of the Super Linear Circuit. Also, this module has regulated power supplies to strengthen the stability of the quiescent point and to suppress drift which occurs because of no overall negative feedback. By controlling the reference voltage point from outside the module, we are able to adjust the output DC offset.

By sending the output of the DC-detecting circuit, which is shown in the diagram, back to the reference voltage point of the module, the DC voltage at the output terminal is suppressed to 0V and we are able to realize an output-capacitorless amplifier.

Figs. 18 through 20 show the characteristics of a flat amplifier when the Super Linear Circuit is normally applied. As shown in the data, although applying no overall negative feedback, the distortion is less than 0.01%. The remarkable thing is that the distortion at high frequency (100kHz) is not so large compared with that at middle frequencies. Fig.21 shows the distortion characteristic of a common negative feedback amplifier. The distortion at middle frequencies is low, but as the frequency becomes high, the distortion increases rapidly.

Thus, the Super Linear Circuit can satisfy the performance covering all the items required of audio amplifiers. By molding the circuits, thermal stability, reliability and shielding from external noise are obtained. Moreover, parts used inside are carefully examined not only on physical performance but also on tonal quality in order to realize a worthy audio amplifier.

APPLICATION OF THE SUPER LINEAR CIRCUIT TO THE PRODUCT LINE

Fig. 22 shows a block diagram of a conventional audio amplifier system. Basic amplification stages are equalization amplifier, flat amplifier and power amplifier. The power amplifier includes the power stage required to drive the speakers. The Super Linear Circuit can be applied to any of the amplification stages.

Fig. 23 shows 3 methods of equalization, (a) is an active equalization network which is employed in ordinary amplifiers (b) is a passive equalization network which is employed in high grade amplifiers, and (c) is a current equalization network which fully uses the characteristics of the Super Linear Circuit. As mentioned before, the Super Linear Circuit can be considered as a linear conductance amplifier.

The gain of the circuit is proportional to the load R_L . By setting the RC network load of the Super Linear Circuit as shown in Fig. 24, the gain of the circuit versus frequency is shown in Fig. 25. The equalization amplifier employed in the Super Linear Circuit (level diagram in Fig. 26b) can provide high input allowance at high frequencies compared with the passive equalization (level diagram shown in Fig. 26 a). Also, the new circuit has no instability factor like the oscillation from active equalization. Here, an ideal equalization amplifier for audio use has been realized.

Fig. 27 shows the block diagram of the flat amplifier applied to the Super Linear Circuit and its frequency response for capacitance loads. No peak appears due to no overall negative feedback. Fig. 28 shows the frequency response of a typical flat amplifier applying overall negative feedback for several capacitance loads. The peaks appear at high frequencies because the phase of the feedback signal is shifted by the capacitance loads.

Since the Super Linear Circuit is a current generator it cannot be connected directly to drive a loudspeaker load. A push-pull class A three stage Darlington emitter follower stage is therefore used to couple the Super Linear amplifier to loudspeaker loads as shown in Fig. 29. Since no overall negative feedback is used in the output stage, the final Darlington stage contains several parallel connected transistors. The final output impedance is very nearly equal to 0.1 OHMs. Problems typical in amplifiers using overall negative feedback do not appear in this design.

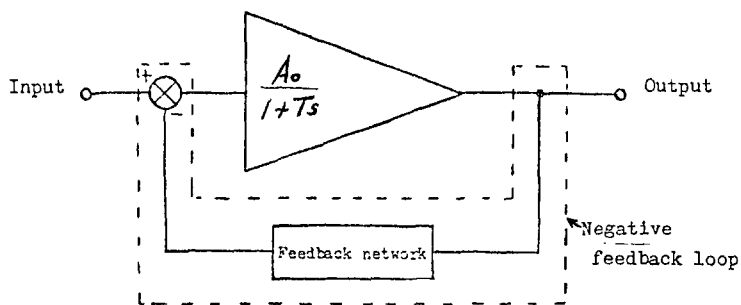
A stereo preamplifier C-41 and 60 watt mono power amplifier M-41 using the Super Linear Circuit have been in production for over 6 months and are currently being sold in Japan.

CONCLUSION

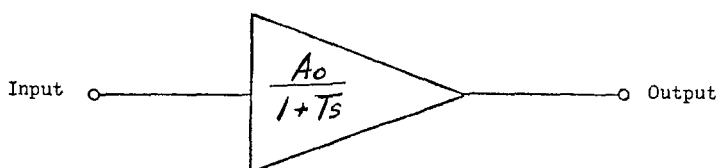
Several decades have passed since negative feedback technologies have been applied to audio amplifiers. It has become an inevitable technology especially for transistor amplifiers. On account of the developments in circuit technology and feedback technology, distortion and other performance characteristics of audio amplifiers have reached the limit of measurement. However, there are still problems in the design of overall negative feedback amplifiers. The newly developed Super Linear Circuit has taken off the overall negative feedback loop and has eliminated the problems caused by overall negative feedback. By doing so we have produced an amplifier of superior characteristics which we believe has started a new design philosophy and the beginning of a new era in high fidelity audio amplifiers.

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Proceedings of the IREE, Australia, October 1977.
- 2) M. Otala- "Transient Distortion in Transistorized Audio Power
Amplifiers" Trans. IEEE, Vol. AU-18, No.3
September 1970.

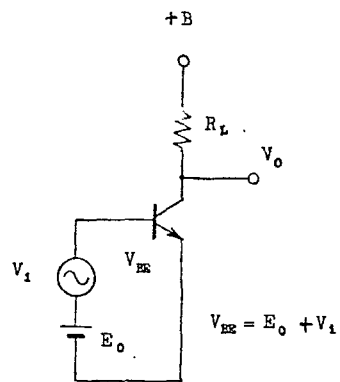


(a) Amplifier, overall negative feedback applied

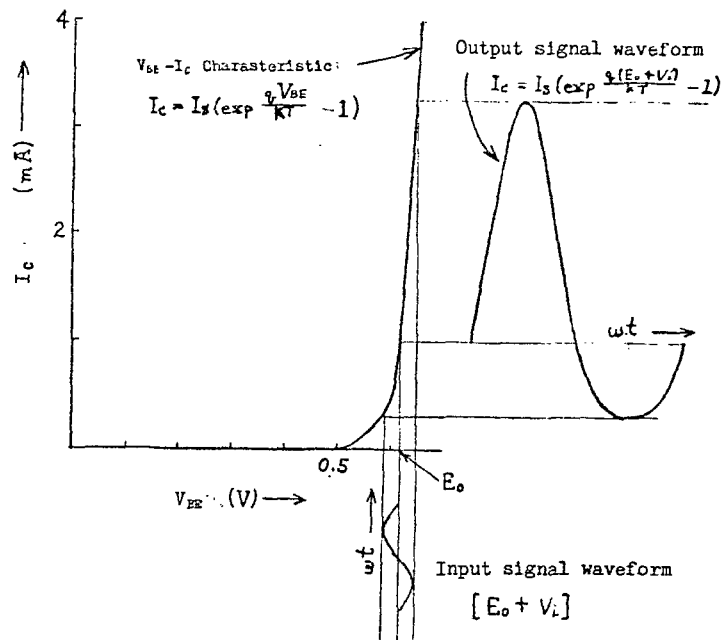


(b) Amplifier, no overall negative feedback applied

Fig.1 Form of the amplifiers



(a) Common emitter circuit



(b) Input-output characteristics

Fig.2 Distortion caused by non-linearity of transistors

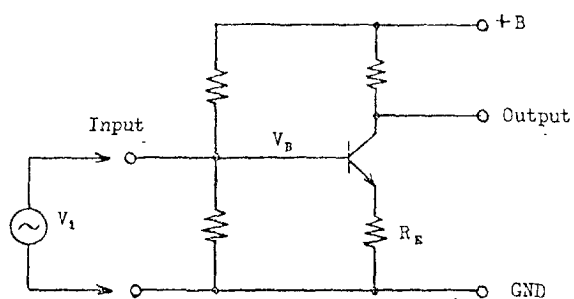


Fig.3 Common emitter circuit for practical use

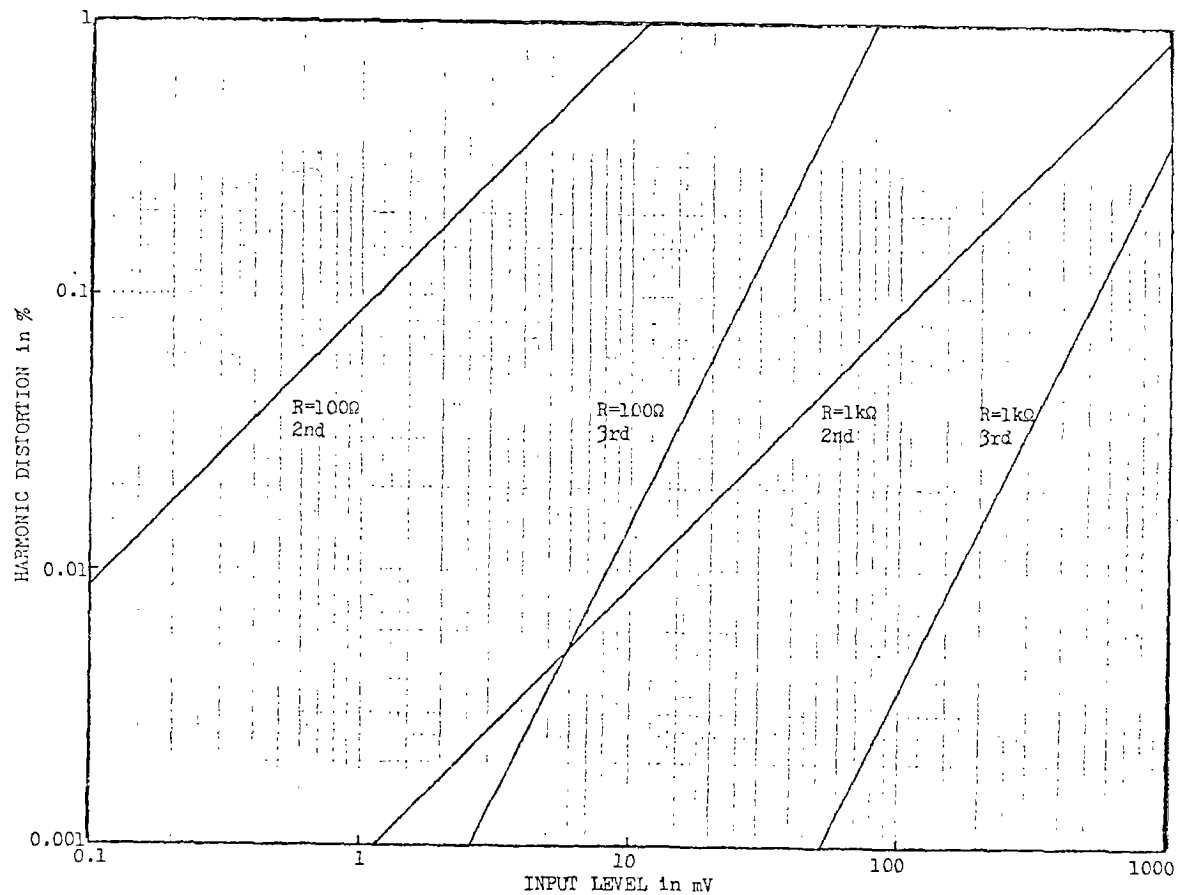


Fig. 4 Harmonic Distortion VS Input Level For Several Values
Of Emitter Resistor

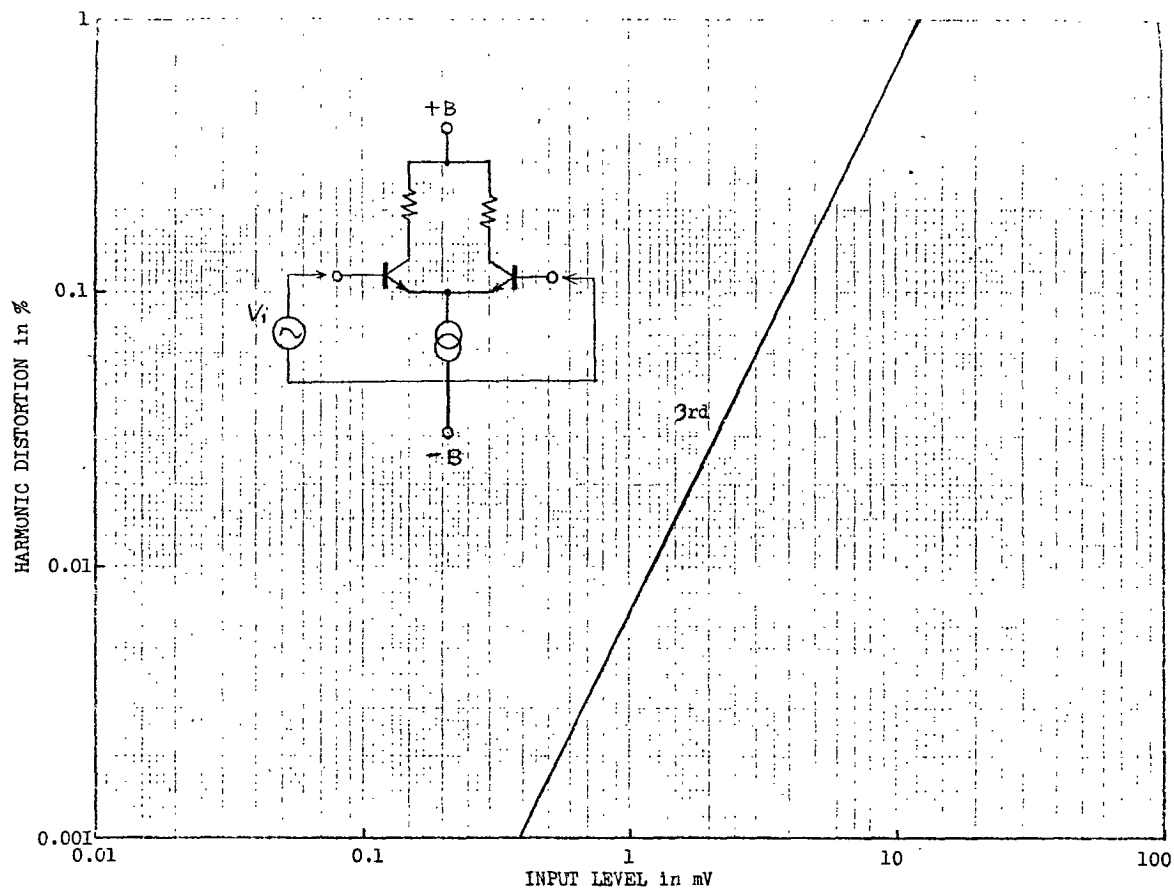


Fig.5 INPUT LEVEL vs. HARMONIC DISTORTION

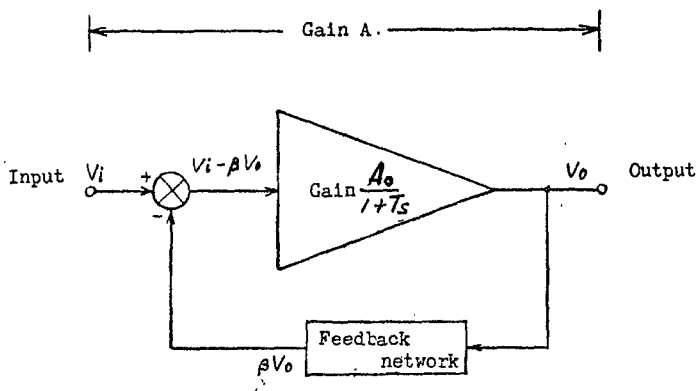


Fig.6 Block diagram of amplifier using overall negative feedback.

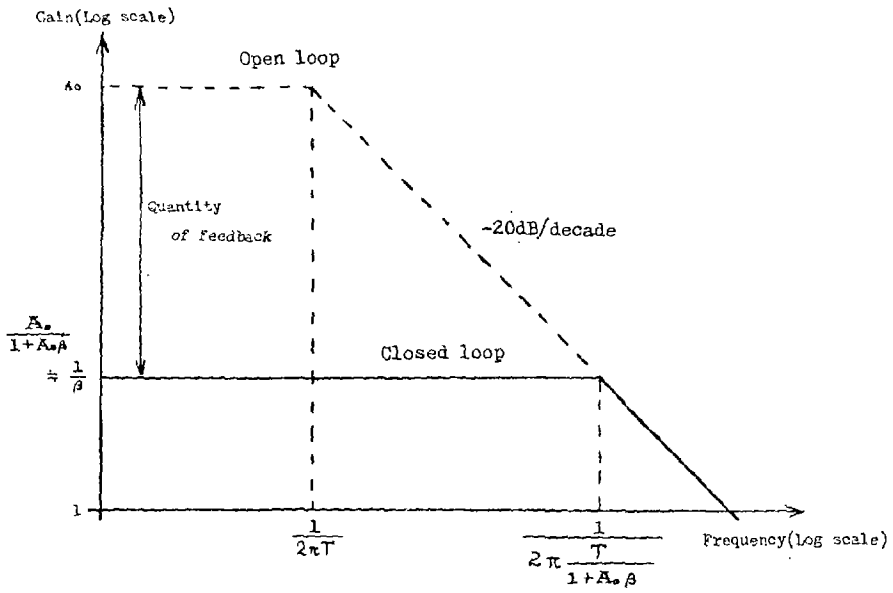


Fig.7 } Characteristic of negative feedback amplifier

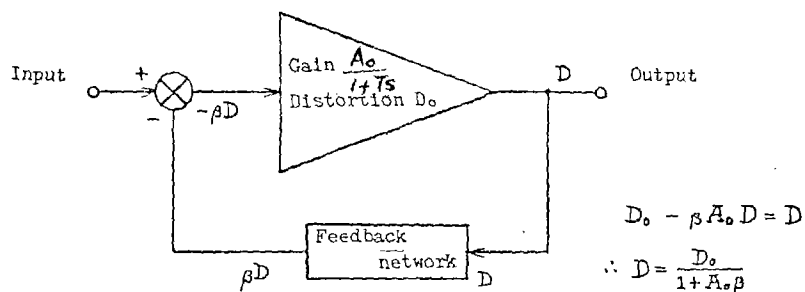


Fig.8 Distortion reduction by *negative* feedback

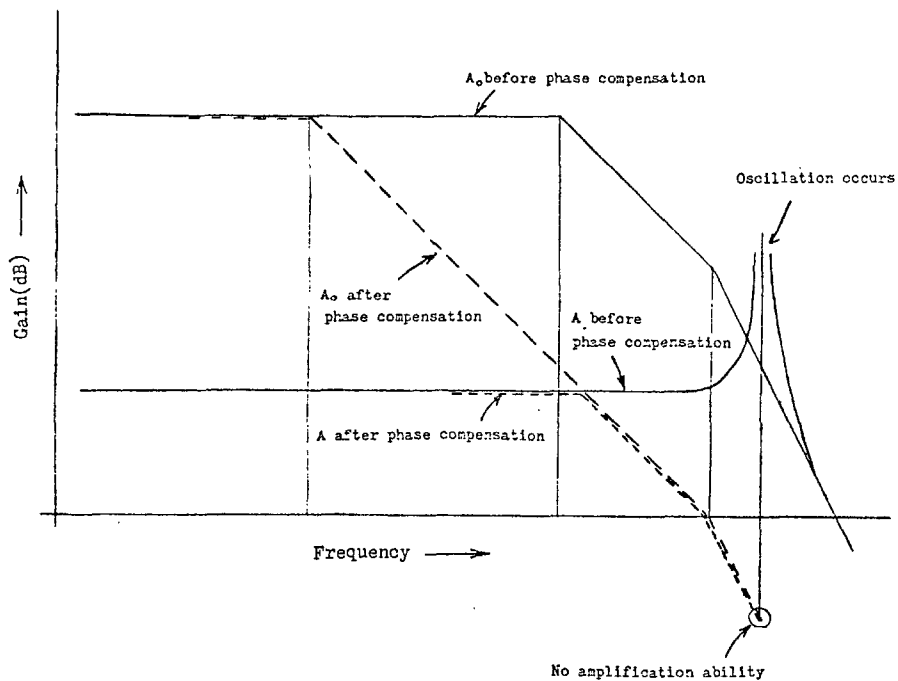


Fig.9 Frequency response of negative feedback amplifier

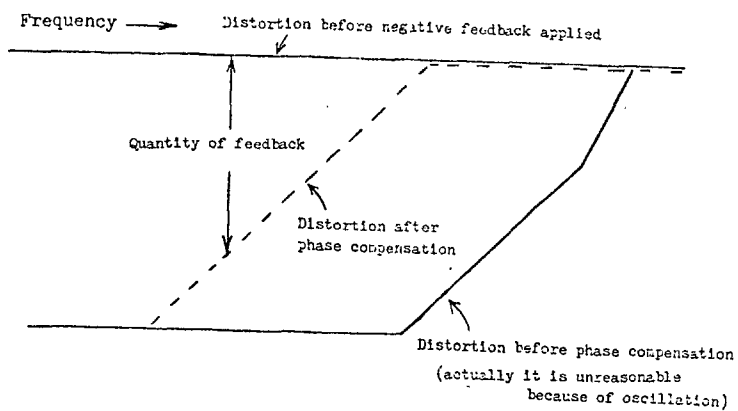


Fig.10 Distortion depends on negative feedback

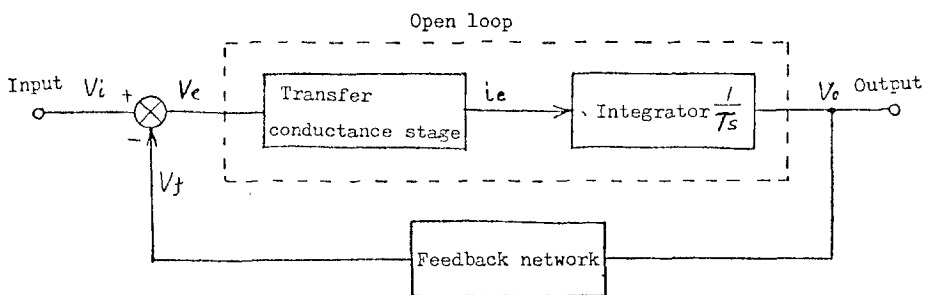


Fig.11 Model amplifier with negative feedback applied

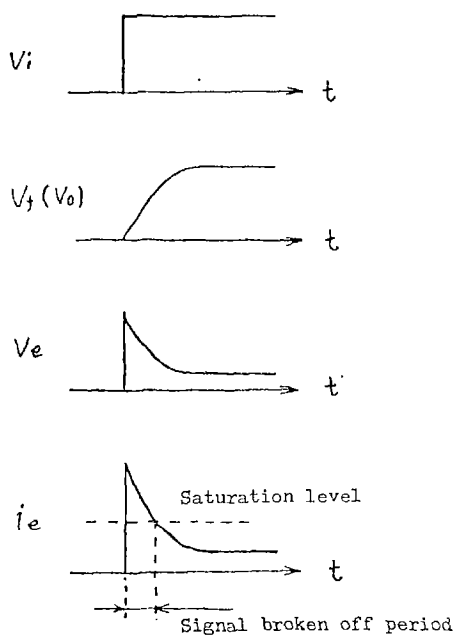


Fig.12 Response of step signal

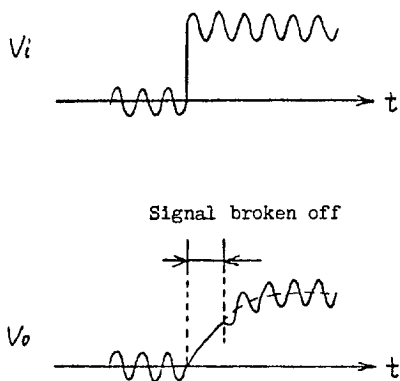
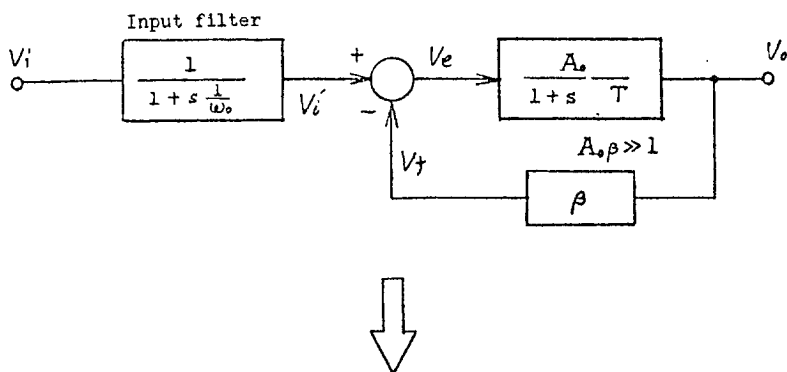


Fig.13 Principle of TIM generation



$$A \cong \frac{1}{\beta} \quad , \quad \omega_1 \cong \frac{\beta}{T} A_o$$

ω_o : Angular cut off frequency of preamplifier (Input filter)

ω_1 : Angular cut off frequency of the amplifier (closed loop)

Fig.14 Block diagram of amplifier with preamplifier

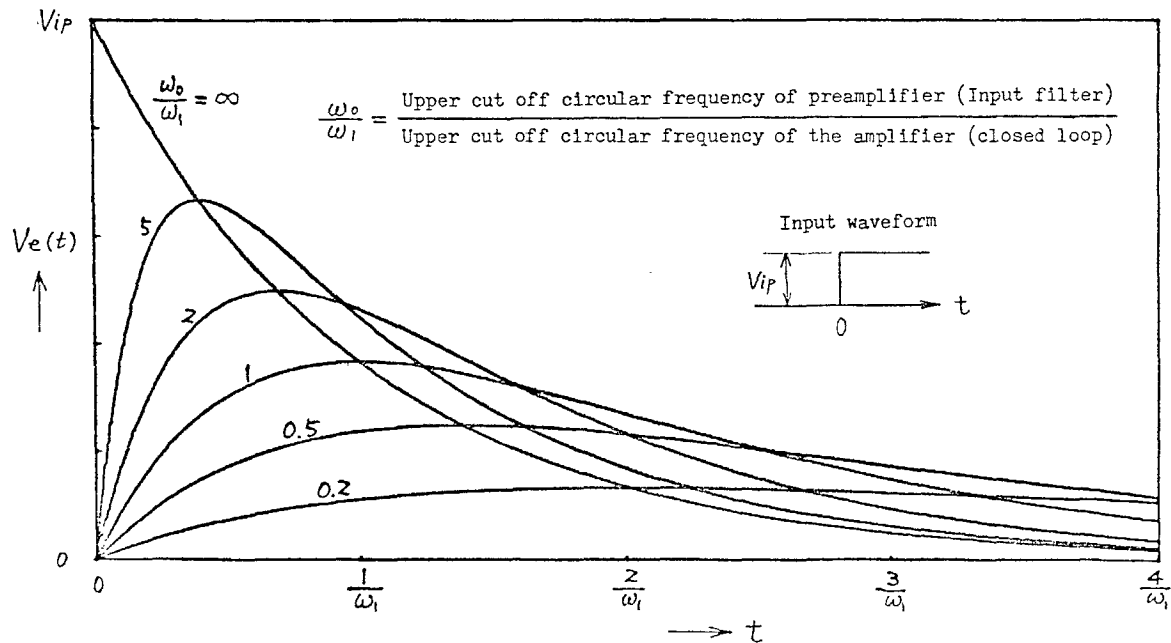


Fig.15 Error signal voltage as a function of the normalized time for several sets of parameters

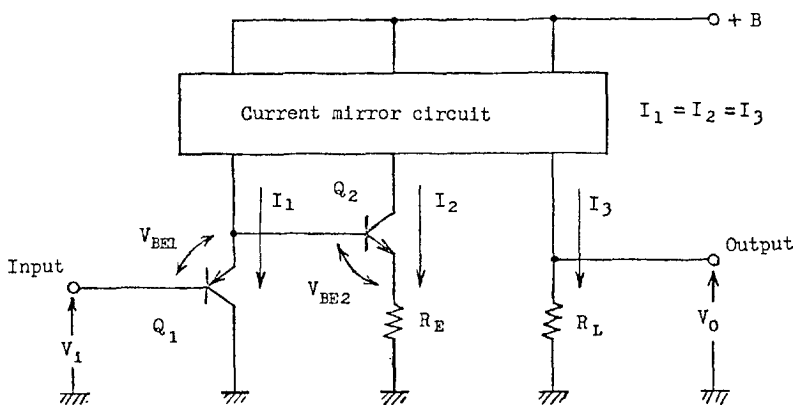


Fig.16 Fundamental circuit of Super Linear Circuit

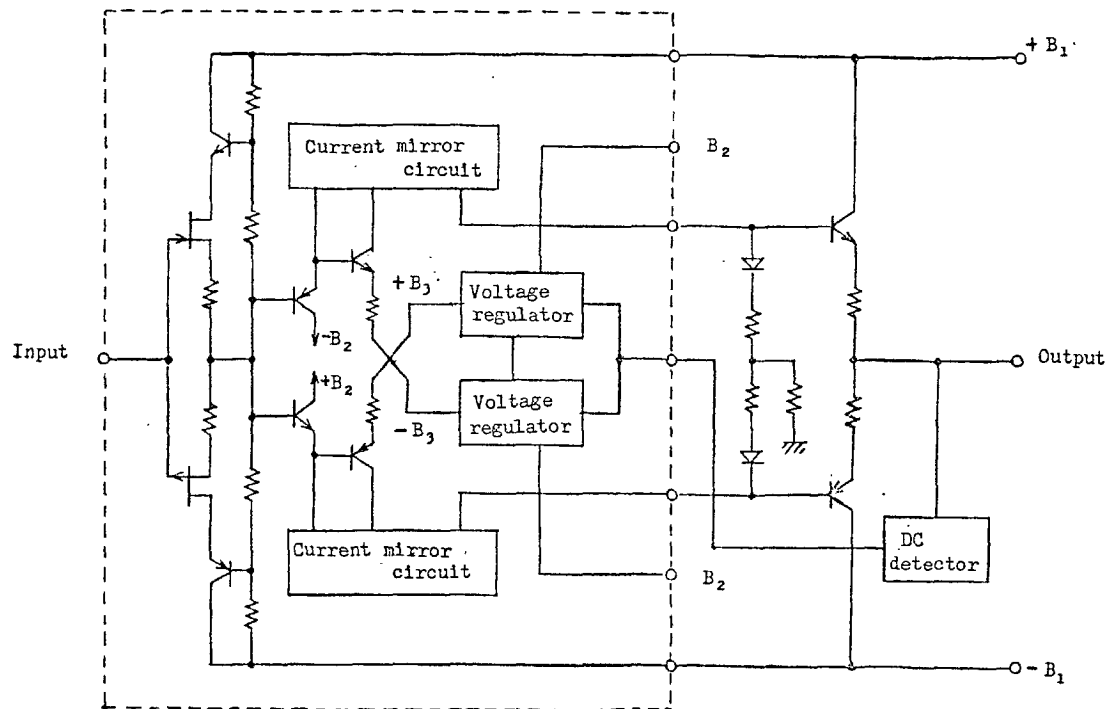


Fig.17 An example of employing Super Linear Circuit

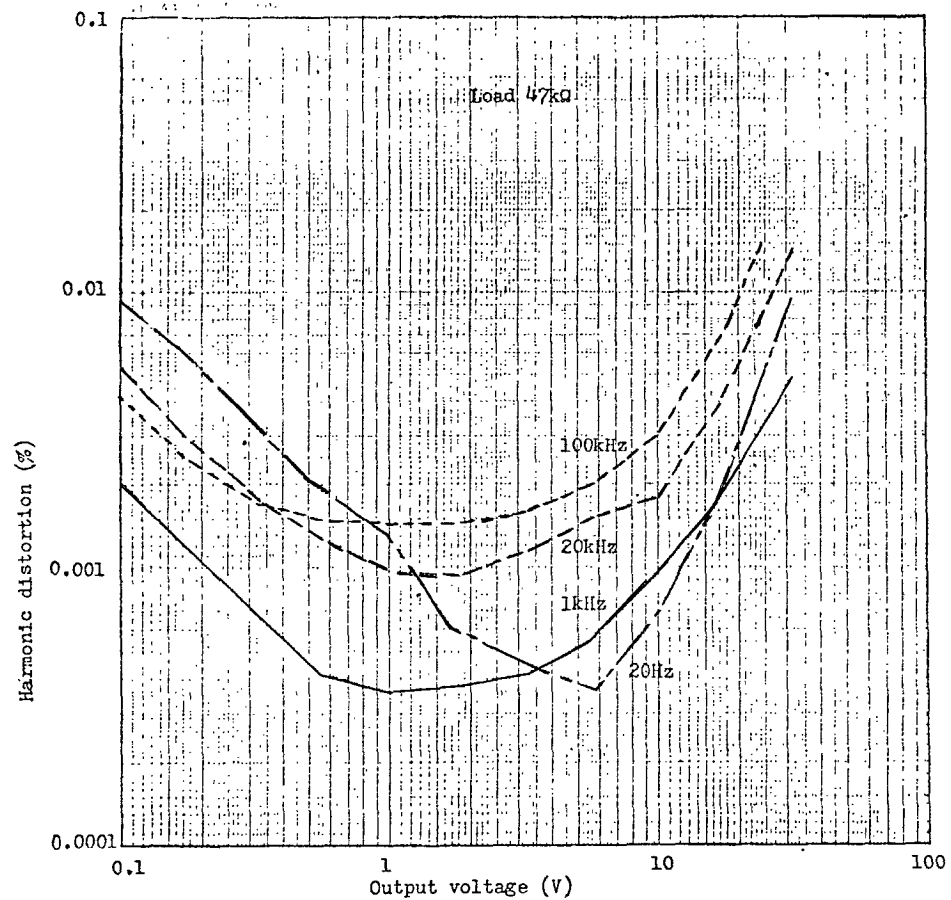


Fig. 18 Harmonic Distortion VS Output Voltage

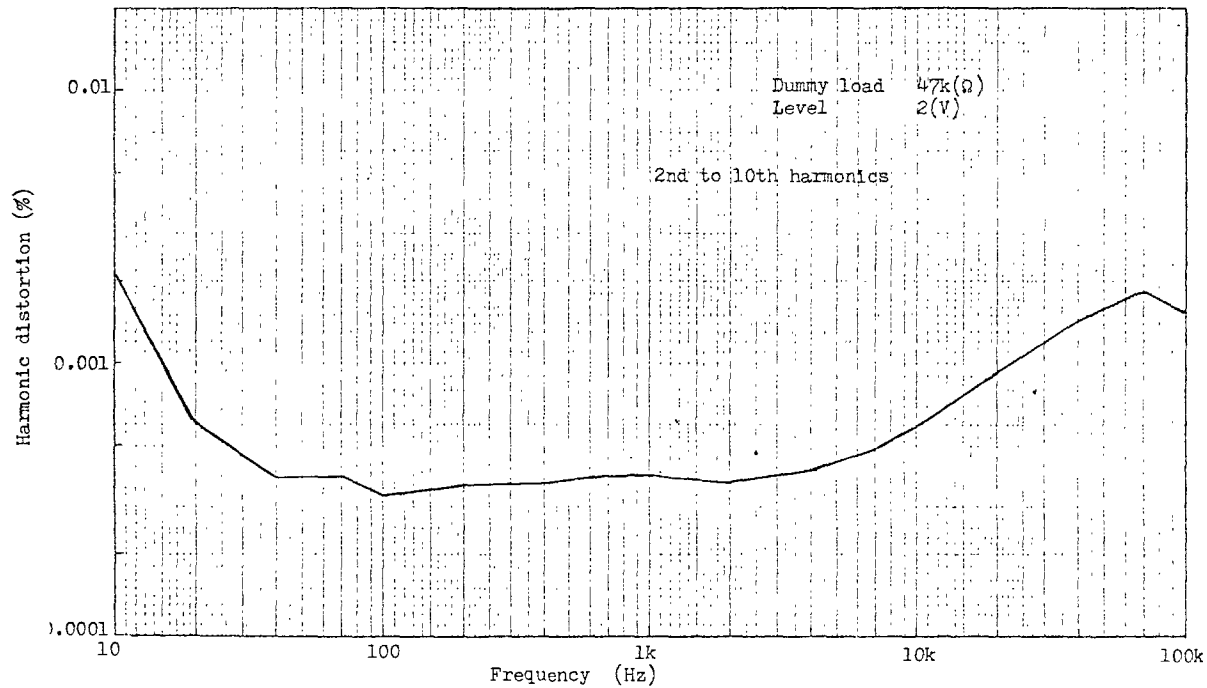


Fig.19 Frequency vs. Harmonic distortion (Super Linear Circuit)

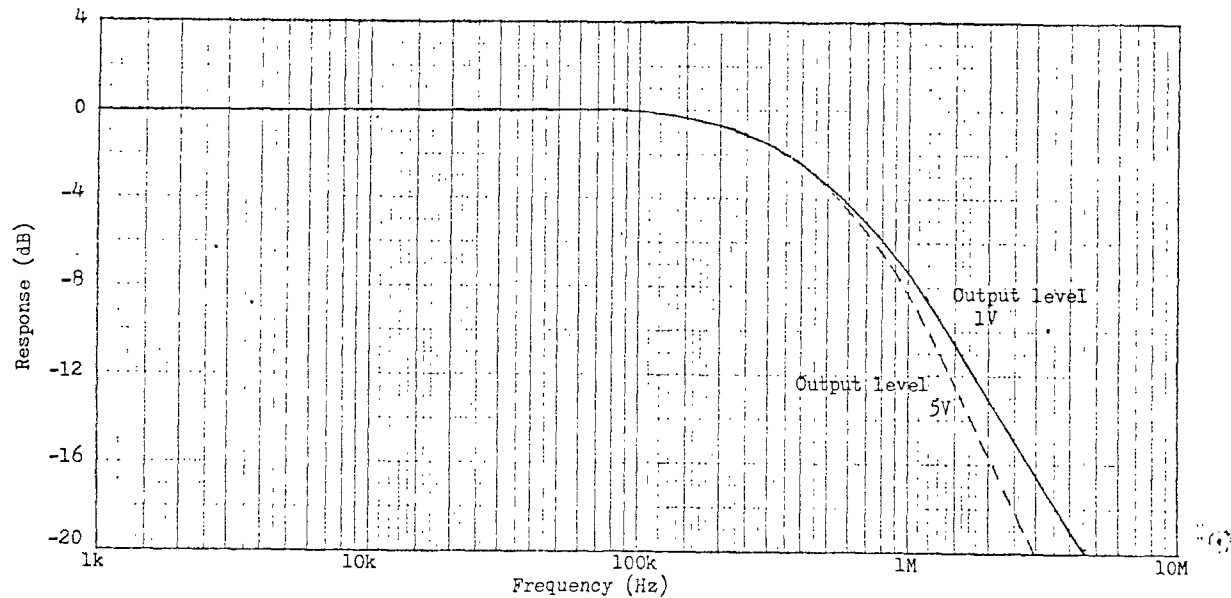


Fig.20 Frequency Response (Super Linear Circuit)

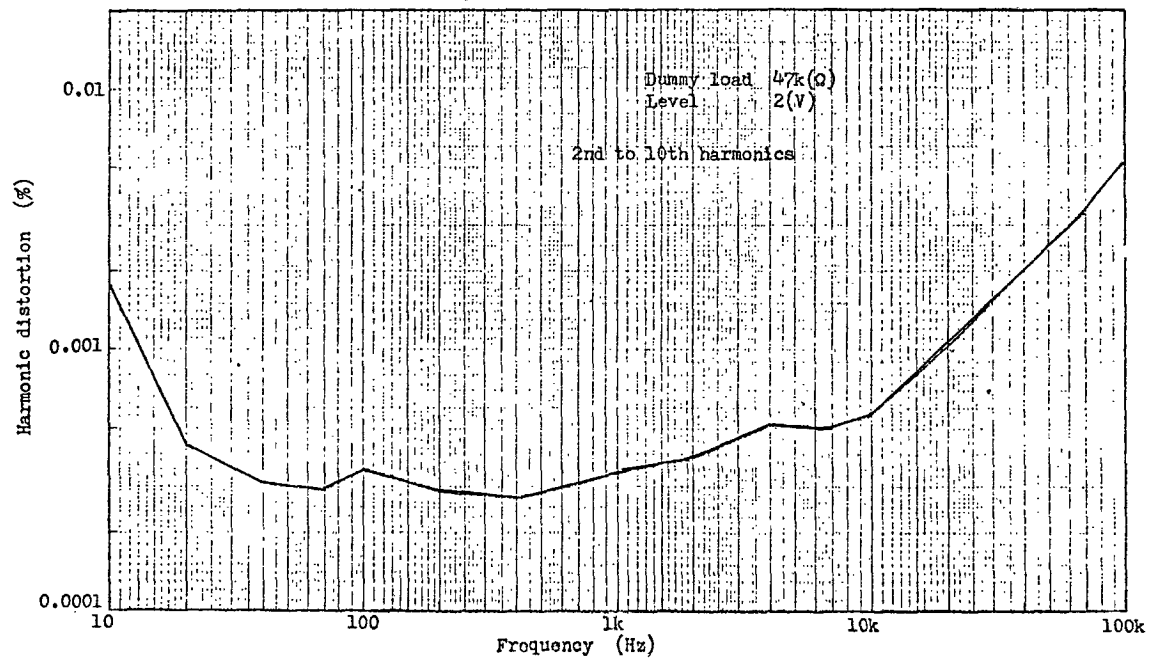


Fig. 21 Harmonic Distortion VS Frequency (Conventional Amplifier)

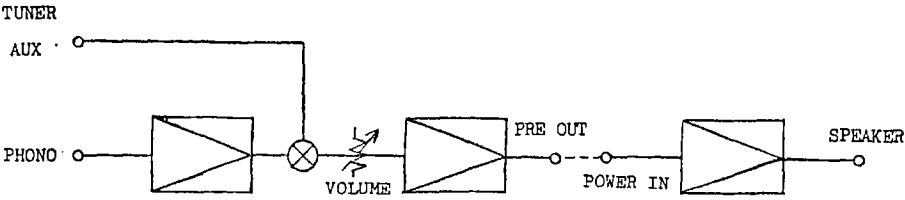
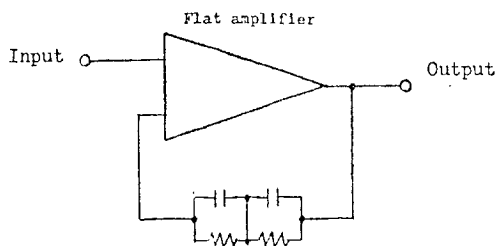
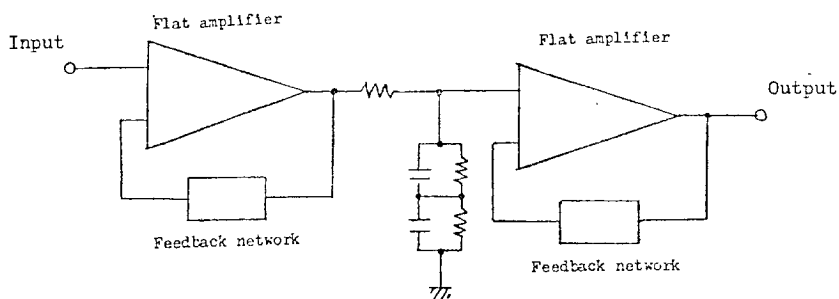


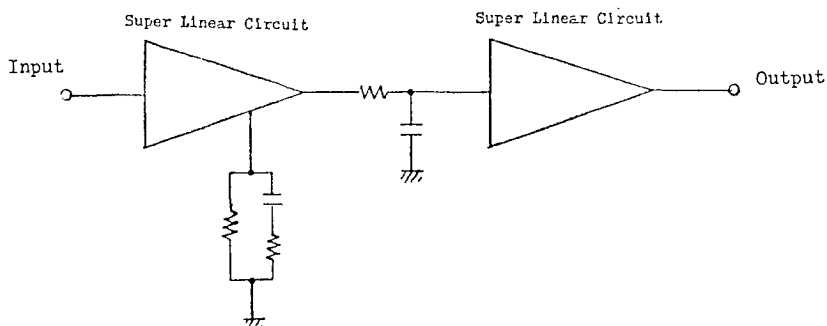
Fig.22 Block diagram of general audio amplifier



(a) General active equalization



(b) Passive equalization



(c) Current equalization

Fig.23 Three Methods of Equalization

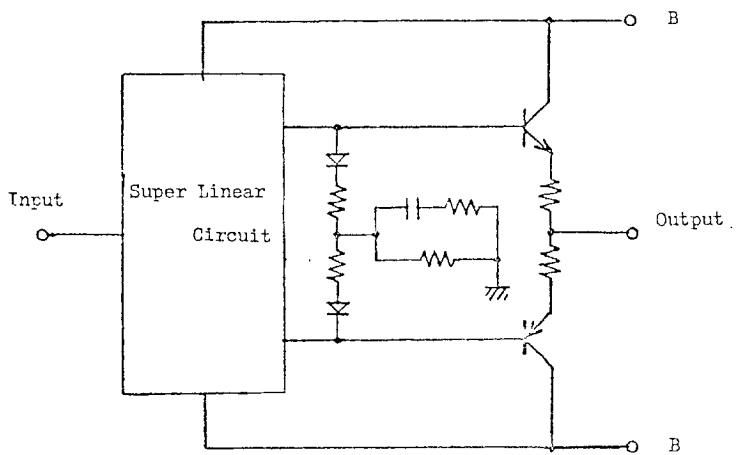


Fig.24 CR network as a load of Super Linear Circuit

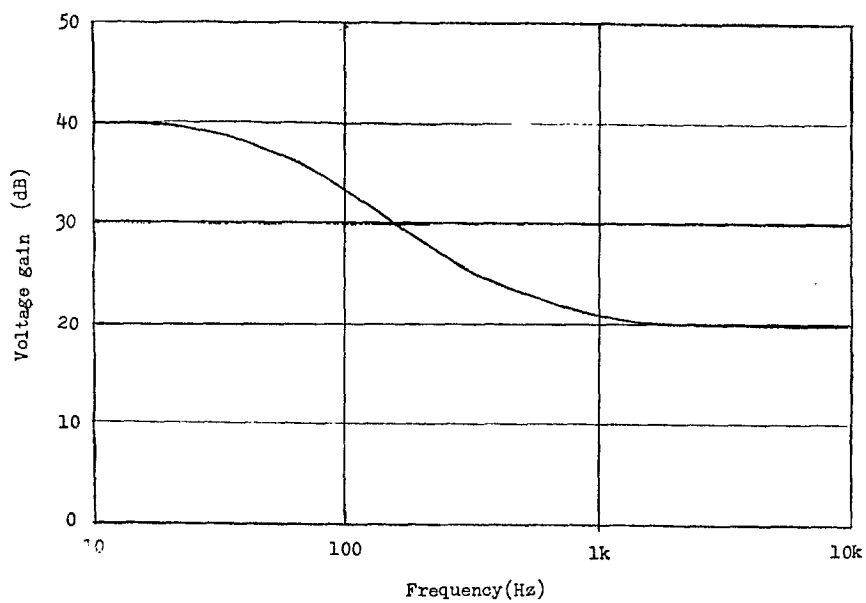
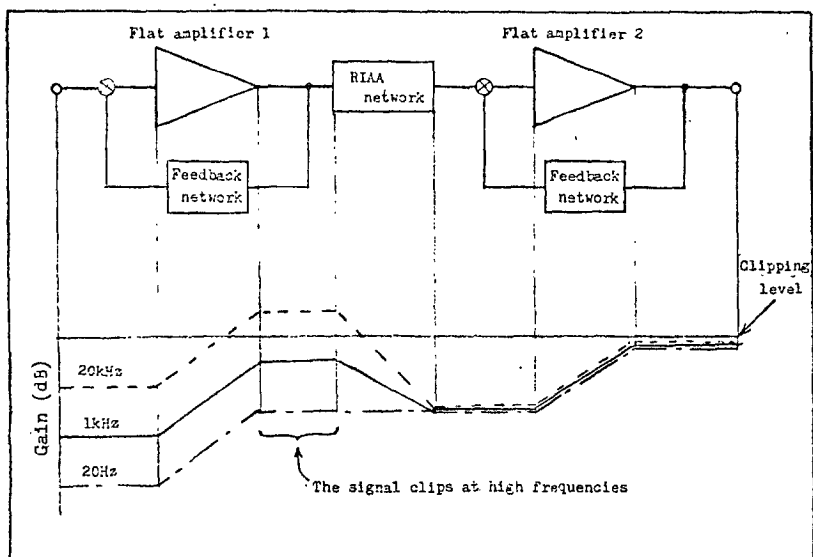
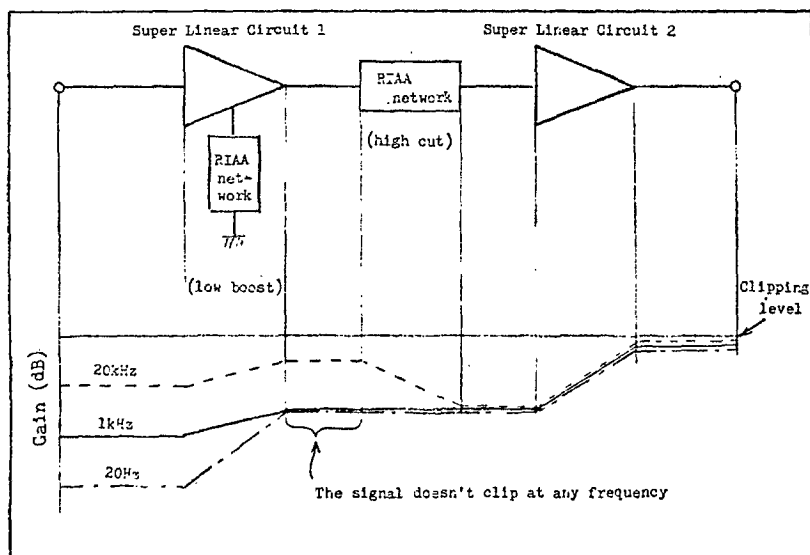


Fig.25 Frequency response of Fig.24



(a) Level diagram of passive equalization



(b) Level diagram of current equalization

Fig.26 The level of equalization

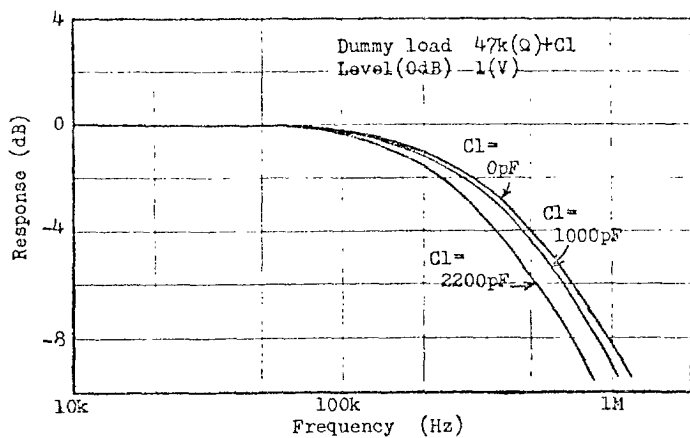


Fig.27 Frequency response of Super Linear Circuit with a capacitance load

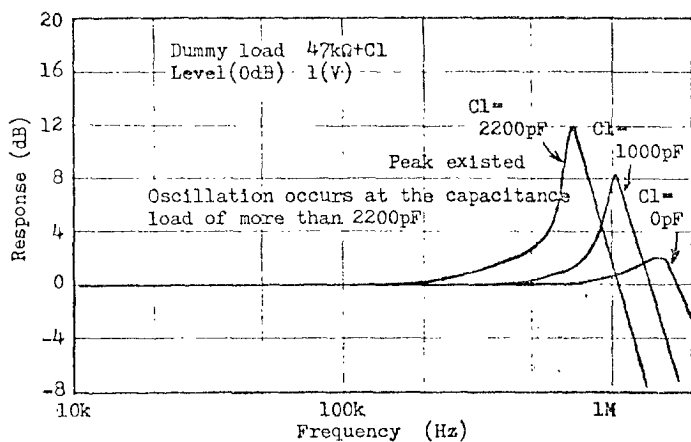


Fig.28 Frequency response of instability amplifier applied negative feedback

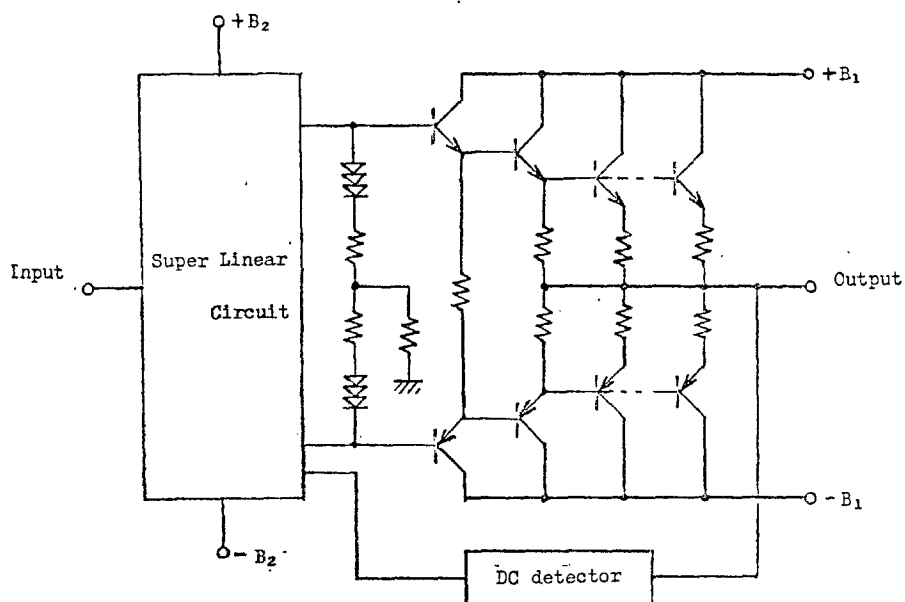


Fig.29 Power amplifier employing Super Linear Circuit