AMPLIFIER TRANSIENT CROSSOVER DISTORTION RESULTING FROM TEMPERATURE CHANGE OF OUTPUT POWER TRANSISTORS

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ABSTRACT:

The fluctuation of the idle current resulting from temperature increases of power transistors in class-B amplifiers becomes the cause of transient crossover distortion when dynamic input signals such as music sources are applied.
This paper explains the cause of this transient crossover distortion and suggests a counter-measure using a bias control circuit with a built-in microprocessor.

INTRODUCTION

For class-B amplifiers using a single-end push-pull power amplifier stage, the idle current in the power transistors has a great effect upon the generation of crossover distortion.
The crossover distortion which is inevitably generated in class-B amplifiers is held to such a low level by increasing the amplifier negative feedback and maintaining a suitable idle current value, that it can virtually be ignored.
However, when music signals, which constantly fluctuate in level, are amplified, the value of the idle current deviates from the most suitable level, resulting in the generation of a great amount of crossover distortion.
It is thus possible, even for amplifiers which show a very good steady state value the conventional method, to confirm the presence of a great amount of crossover distortion when transient type signals are measured.
Crossover distortion which occurs with signal level fluctuation is known as Transient Crossover Distortion (T.C.D.). This paper looks at the cause of T.C.D and suggests a countermeasure for it.

1. Idle current and crossover distortion in class-B amplifiers

Crossover distortion is caused by nonlinearities at the connection point between the PNP transistor and NPN transistor

of the output stage.
The transfer characteristic of each transistor is determined by the V_{BE} characteristic (which has an exponential function characteristic), and, because there is no operation until the base voltage reaches approximately 0.6 V, bias is applied and current flows through each transistor emitter. This current is called the idle or quiescent current.
Figure 1 shows the relationship between idle current and linearity at the junction.
The three figures show the changes in linearity at the junction of PNP and NPN transistors as a function of the idle current value. Distortion increases if the idle current is less than or more than the optimum value of the idle current.
Because the idle current is determined by the bias voltage, it is necessary to control the idle current at the optimum value under any operation condition of the amplifier.
Formula 1 shows the relationship between the idle current and bias voltage in the circuit of Figure 2.

$$I_{CQ} = \frac{V_B - (V_{BE1} + V_{BE2})}{2Re}$$

I_{CQ} = Idle current
V_B = Bias voltage
Re = Emitter resistance

V_{BE1} and V_{BE2} represent thermal characteristics, and these values change in response to temperature changes in the power transistor.
In order to maintain the idle current at a specified value, bias voltage must be changed in response to changes in the V_{BE1} and V_{BE2} values caused by temperature change.
The bias circuit is also known as the thermal-compensation circuit, and, in order to precisely follow the thermal changes of the power transistor, its heat generation must be checked.

2. Effect on idle current by the heat generation of power transistors

The usual composition of a class-B SEPP circuit is shown in Figure 3. In this figure, Q1 and Q2 are power transistors, and transistor Q3 and resistors R1 and R2 make up the bias circuit. If we then investigate the relationship between the junction temperature (Tj) of power transistors Q1 and Q2 and the base-base bias voltage (Vb) necessary to maintain the proper value of idle current to, the characteristics generally become as shown in Fig. 4.
That is:

$$Vb = Vo - K\ (Tj - To) \ .... \ (1)$$

where K: is dependent upon the transistor.
When the junction operating temperature Tj rises, the necessary base-base bias voltage Vb becomes smaller accordingly.
If we then investigate the bias voltage Vb' applied to base-base of Q1 and Q2 by the bias current of transistor Q3 and resistors R1 and R2 in Figure 3, we find:

$$Vb' = \frac{R_1 + R_2}{R_2} Vbe$$

Here Vbe represents the voltage between the base and emitter of Q3, and has the thermal characteristics shown in Figure 5, in the same way as Vb:

$$Vbe = Vo' - K' (Tj' - To)$$

$$Vb' = \frac{R_1 + R_2}{R_1} Vo' - K' (Tg' - To) \quad .....(2)$$

Consequently, because R1 = R2, Vo = 2Vo' and K = 2K', when R1, R2 and Q3 are set,

$$Vb' = Vo - K (Tj' - To) \ .... \ (3)$$

When the junction temperature of Q3 is the same as the output transistor, a constant idle current will result.
There are, however, two factors which can be considered to effect the change of the junction operating temperature of Q1 and Q2. One is the change in air temperature, and the other is the device dissipation. As for the former, the change of the junction operating temperature of Q1, Q2 and Q3 are exactly the same. Concerning the latter, however, Q1 and Q2 themselves generate heat, and, because there is sure to be some thermal resistance somewhere between Q1/Q2 and Q3, a thermal difference occurs. This is shown in Figure 6. As the device dissipation Pc of Q1 and QC becomes larger, so does the thermal difference ΔTj of Q1, Q2 and Q3 become larger. The difference is in proportion to the thermal resistance θ between Q1/Q2 and Q3.

$$\begin{aligned} \Delta Tj &= Tj - Tj' \\ &= Pc \ \theta \ .... \ (4) \end{aligned}$$

If we substitute this for formula (3):

$$\begin{aligned} Vb' &= Vo - K (Tj - Pc\theta - To) \\ &= Vb + KPc\theta \end{aligned}$$

resulting in an error of KPcθ between Vb' and Vb.
Consequently, in the circuit in Figure 3, bias voltage cannot completely compensate for both of the afore mentioned conditions.

3. Bias response to sudden changes in device dissipation of power transistors

In the ordinary class-B SEPP circuit shown in Figure 3, output device dissipation is changed greatly by the output signal level, resulting in the characteristic shown in Figure 7. Thus, when the source is a music signal output device, dissipation is constantly changing. Let us examine the changes in bias requirements brought about by dynamic dissipation in the output devices.

Shown in Figure 8 are heat sinks as used for the circuit in Figure 3. Figure 9 shows just how the junction temperature of Q1, Q2 and Q3 changes over a period of time by device dissipation of Q1 and Q2.

In Figure 9, the junction temperature (Tj) of Q1 and Q2 suddenly changes at t1, it increases gradually until T2 and stabilizes thereafter. The thermal increase time-constant to t1 differs from that of t1 to t2. The time-constant to t1 depends upon the transmission speed of heat from the Q1 and Q2 junction to the collector, so that, because the transmission speed is fast, the time-constant to t1 is short. In the same way, the time-constant from t1 to t2 depends upon the transmission speed of the heat of the Q1 and Q2 heat sinks, so that, because this speed is slow, the time-constant from t1 to t2 becomes long, and Q3 junction operating temperature Tj' increases gradually to t2. This is because heat is transmitted from Q1 and Q2 to Q3 via the heat sinks, and thus the thermal rise time-constant of Q1 and Q2 from t1 to t2 becomes the same.

Figure 10, the reverse of Figure 9, shows just how the junction operating temperature of Q1, Q2 and Q3 is changed over a period of time when device dissipation of Q1 and Q2 is changed from a certain value to 0. It can be seen that the result is the same as that shown in Figure 9.

The thermal resistor Θ used in formula 5 between Q1/Q2 and Q3 is the junction operating temperature difference Tj - Tj' of Q1, Q2 and Q3 (stabilized at a constant level beyond t2 in Figure 9) divided by device dissipation Pc of Q1 and Q2:

$$\Theta = (Tj - Tj')/Pc \qquad ({}^{\circ}C/W)$$

Consequently, although the junction operating temperature difference ΔTj of Q1, Q2 and Q3 was expressed in formula 5 as Pc Θ, this is the temperature difference after device dissipation has reached a steady stage value. Formula 5 does not satisfy the conditions when a transient signal is applied.

$$Tj - Tj' = Pc \, . \, \Theta$$

Under this condition, each constant of the Q3, R1 and R2 bias circuit becomes

$$R1 = R2 \qquad Vbe = \frac{Vo - KP_{C1\theta}}{2} - \frac{K}{2}(Tj' - To)$$

and thus

$$Vb' = \frac{R_1 + R_2}{R_2} \, \frac{Vo - KP_{C1\theta}}{2} - \frac{K}{2}(Tj' - To)$$

$$= Vo - K\,(Tj' + KP_{C1\theta} - To)$$

$$= Vo - K\,(Tg - To)$$

$$= Vb$$

so that the proper idle current flows to Q1 and Q2.

With the bias circuit as described above, let's then look at the changes of the idle current and the junction operating temperatures of Q1, Q2 and Q3 for a music source with a mean value of Q1 and Q2 device dissipation of Pc1.

For a continuous signal (Pc = Pc1), the idle current is appropriate up to tx in Figure 11. Beyond tx, the source is music and the mean value of Pc is Pc1, but Pc changes violently with time because the source is music. Then, as was understood from Figures 9 and 10, the junction operating temperatures of Q1 and Q2 have a very short time-constant, and also change sharply together with the changes in Pc. The Q3 junction operating temperature, however, because the time-constant is long, does not change sharply in response to the violent changes in Pc resulting from the music source, and the temperature corresponds to the mean value of Pc (in this instance Pc1).

As a result, the idle current beyond tx in Figure 11 changes sharply together with the changes in the Q1 and Q2 junction operating temperatures.

In this way then, because Pc changes violently for a music source, the Q1 and Q2 junction operating temperatures change sharply even if the mean value of Pc is a value which will result in an appropriate flow of idle current, and, because the Q3 junction operating temperature does not follow, the appropriate idle current does not flow.

4. Measurement of transient crossover distortion

Figure 12 shows a circuit which has transient crossover distortion. The output stage does not apply negative feedback, and distortion can be easily confirmed.

The input signal uses a square-wave-modulated sine wave (tone burst). Because the amount of heat generated by the power transistor changes, a sine wave of fixed amplitude cannot be used.

Because the distortion meter also measures modulated signals, a distortion meter with a bandpass filter cannot be used. An I/O distortion meter which compares the difference between input

and output distortion is used.
Photo 1 shows the I/O distortion of an ordinary class-B amplifier. The output signal level is about 1 W at the low level and 10 W at the high level. Photo 2 is an enlarged photo of the point of change from low level to high level, and the crossover distortion generated at the junction of the NPN and PNP transistors can be clearly recognized.
In a circuit in which the idle current is a fixed signal of output level 10 W and which has bias voltage adjusted to obtain minimum crossover distortion, a large amount of crossover distortion occurs at the moment the output level changes, and temperature increases as a result of power transistor collector loss, so that the power transistor temperature shows a decreasing curve until the value becomes that of the bias adjusted by the output level 10-W fixed signal.
In other words, it can be seen that bias which will result in the optimum idle current is not applied to the power transistor V_{BE} at the moment when the output level of the NPN and PNP transistors changes from 1 W to 10 W.
The opposite movement occurs when the output level changes from 10 W to 1 W.
For music signals which do not have a constant fixed amplitude level, the crossover distortion which can be seen in photo 3 occurs when there is a change from fortissimo to pianissimo or vice versa.

5. An amplifier which generates no transient crossover distortion

The following methods might be considered as a countermeasure to transient crossover distortion resulting from inadequate thermal tracking under dynamic conditions:

a) Eliminate the dependance upon idle current by squaring the transmission characteristic at the junction point of NPN and PNP transistors.
b) In order to follow the thermal changes of power transistors, detect bias circuit temperature from the power transistor chip.
c) Calculate power transistor collector loss from the output signal, determine the value of V_{BE} change by determining heat generation, and then control bias voltage in order to correct that value.

Proposition a) is impossible, because the V_{BE} vs IC characteristic of the silicon power transistor has an exponential function.
Proposition b), in which a bias circuit thermal-detection element is included on the same chip as the power transistor is possible, but is not included on the same chip for transistors in wide use.
Proposition c) is the optimum method for power transistors currently designed and available.

The bias voltage is controlled, and the idle current can be constantly maintained at a fixed level by a bias circuit which follows the thermal changes of power transistors.

Figure 13 shows the circuitry of an amplifier which can control the bias voltage externally.

Resistance is connected in series with the conventional constant-voltage circuit so that the bias circuit voltage is dependent upon the current in the voltage amplifier stage.

A current-mirror circuit is used for coupling so that the voltage amplifier stage current is dependent upon the differential amplifier stage.

The bias voltage can be controlled by varying the current flow in the differential amplifier.

When, in figure 12, the signal level becomes low in an amplifier in which the bias voltage has been adjusted by a high signal level in order to minimize cross over distortion, which is basically the same as a circuit which confirms the transient cross over distortion of a class-B amplifier, it is necessary to increase the bias voltage because the V_{BE} value for the power transistor becomes large, as stated before.

When, in experimental circuits, the signal level is changed from high to low, and when the signal level which amplifies the differential amplifier current is changed from low to high, the current control which attenuates the differential amplifier current has a time-constant provided by the integrating circuit. This time-constant has the same value as the thermal time-constant of the power transistor and heat sink.

The power transistor V_{BE}, changed by signal level fluctuations as a result of bias control, is corrected. Photo 3 shows the I/O distortion waveform which results from the subtraction of output and input and the output signal of the amplifier controlled so that there is a constantly optimum idle current. The transient crossover distortion which occurs at the moment the signal level fluctuates, such as seen in photo 1, cannot be discerned.

Photo 4 is an enlarged view of the moment of fluctuation shown in photo 3. Even at the moment of signal level fluctuation, the appropriate bias voltage is applied, and, because a certain fixed idle current is maintained, there is no generation of a large amount of transient crossover distortion, thus maintaining a condition of stability.

6. Bias control by 4-bit microprocessor

Figure 14 shows the block diagram of a bias-control circuit using a 4-bit microprocessor. The analog input signals of heat sink temperature and output signal level are converted to digital by a 4-bit A/O converter.

The heat sink temperature and output signal level are calculated by the microprocessor, and the amount of bias voltage compensation is determined. This amount of bias voltage compensation is outputed to the output port, and converted to the analog amount by the D-A converter. The bias-compensation voltage, changed to an analog amount, passes through an integrated circuit which has a time-constant which agrees with the power transistor time-constant, and is connected to the bias voltage control circuit of the amplifier. By making the integrated circuit time-constant about 0.5s in this circuit, it matches the power transistor thermal time-constant.

There must be programming so that the emitted value is a combination of temperature data and output level data. Naturally the compensation amount calculated by the microprocessor varies if the power transistor thermal resistance or heat sink capacity changes.

The advantage to compensating bias by using the microprocessor is very great if two or more data must be combined or if it is necessary that the compensation be non-linear with respect to the input data.

For bias control of the amplifier, both are necessary.

In addition, the power transistor heat time-constant is comparatively long at 0.5s, and there is no problem with the microprocessor response speed.

CONCLUSIONS

Audio amplifier distortion has reached a truly amazing low level in conjunction with technological developments, but there are many instances in which this value can be measured by using a T.H.D. (Total Harmonic Distortion) meter which uses a constant amplitude level input.

Although it is difficult to measure distortion using a signal with a fluctuating amplitude level, it is necessary for research into audio amplifiers, when the objective is the amplification of music signals.

Transient crossover distortion explained in this paper is distortion caused by power transistor heat generation, and we believe it to be one of the first types of distortion which can be confirmed by measurement of amplitude-level-fluctuated signals.

We feel that using more complex signals or music signals in order to more precisely understand the operation of audio amplifiers will play an important role in future amplifier design.

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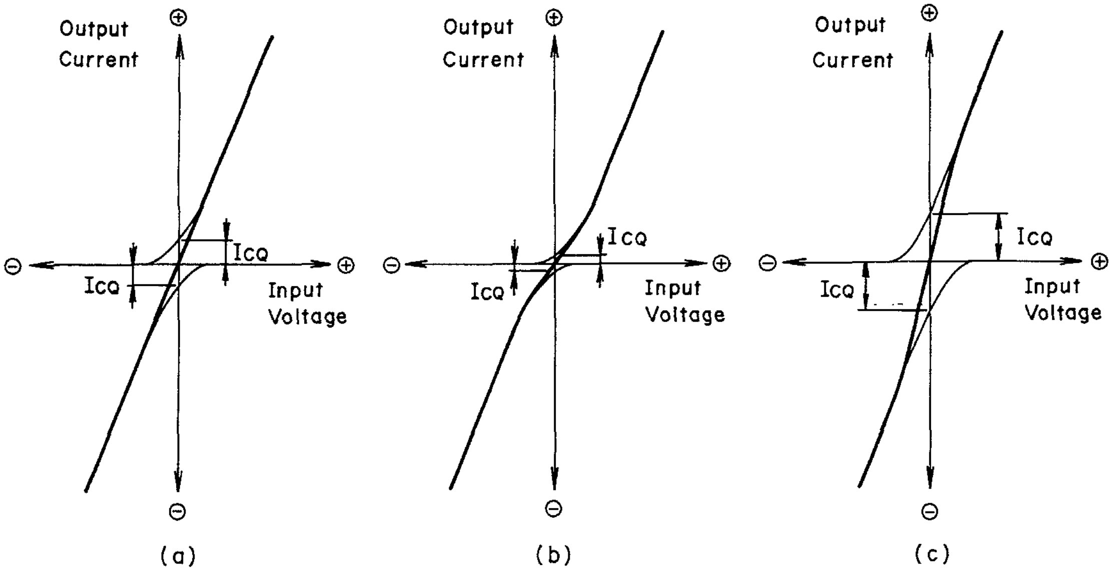
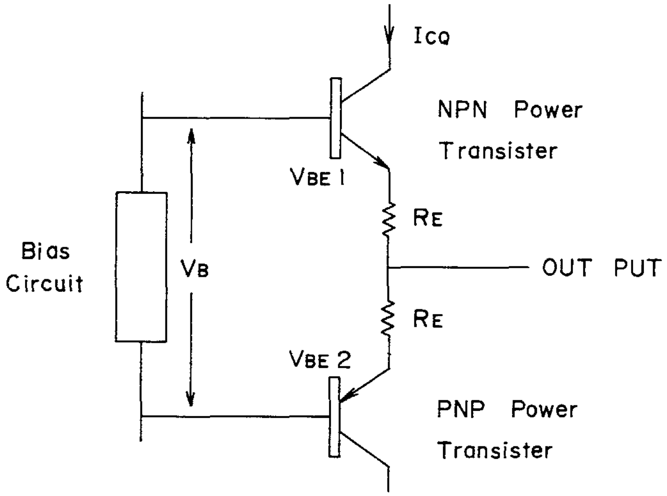
(3) K. Sato and A. Yoshida, Design of ICs and Transistor Circuits for Reliability



Icq = Idle Current

Fig.(1) Relation between the idle current and the linearity.



$$I_{CQ} = \frac{V_B \quad (V_{BE1} \quad V_{BE2})}{2R_E}$$

R_E = Emitter Resistance

V_{BE} = Base Emitter

V_B = Bias Voltage

I_{CQ} = Idle Current

Fig.(2) Bias Voltage V.S Idle Current .

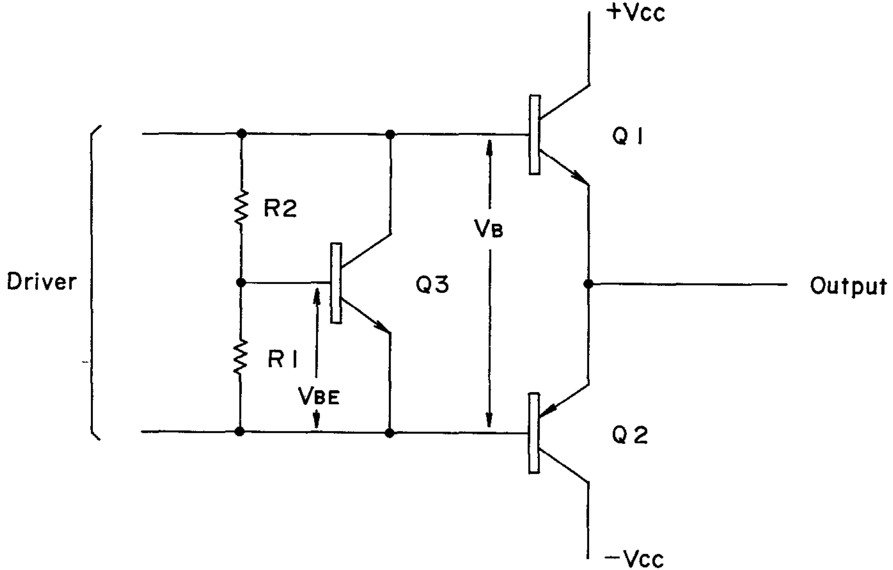


Fig. (3) The usual composition of a class−B SEPP circuit.

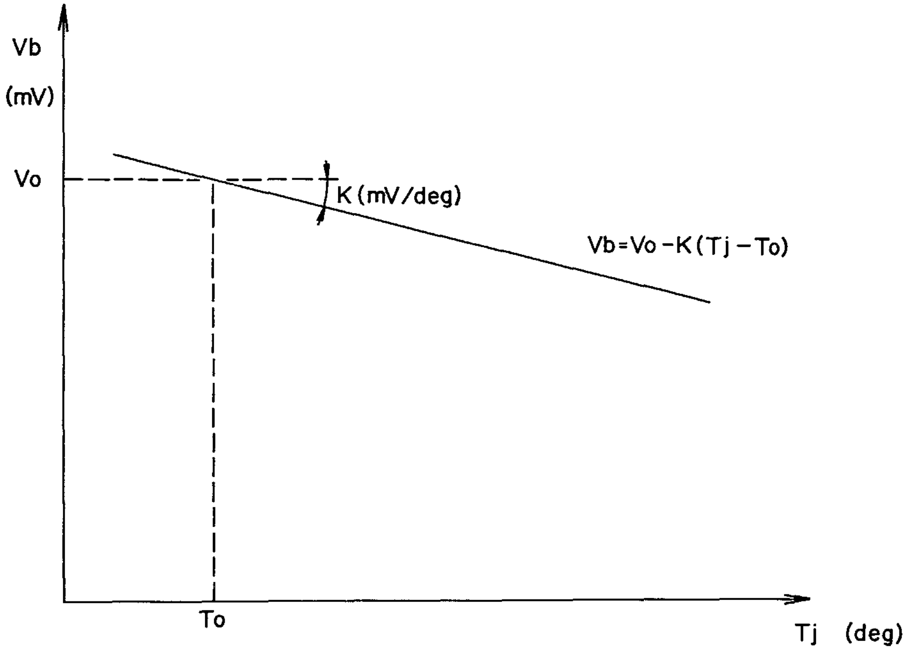


Fig.(4) The proper bias voltage (Vb) versus junction temperature (Tj) of Q1 and Q2.

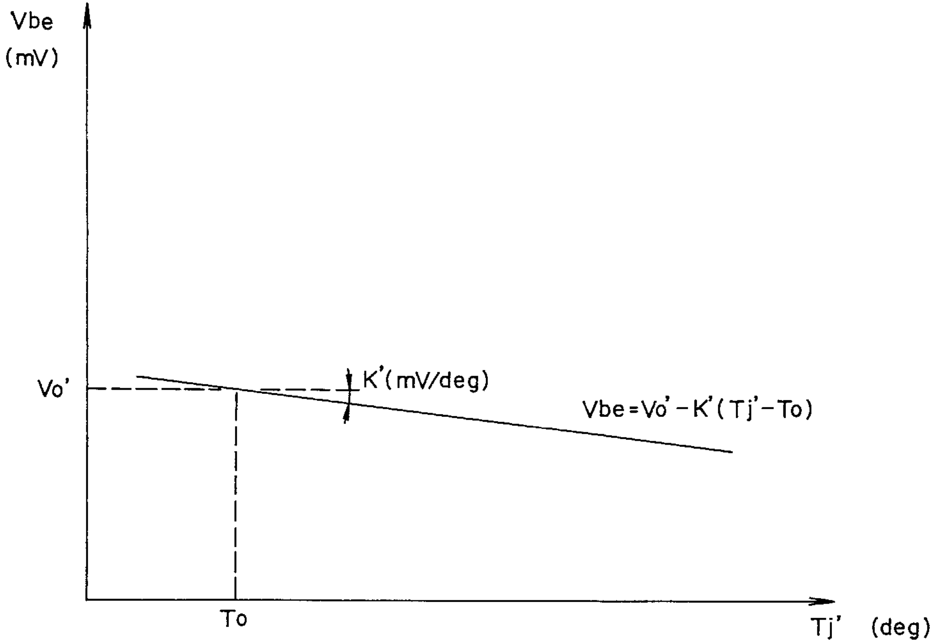


Fig. (5) The voltage (Vbe) between the base and emitter of Q3 versus junction temperature (Tj') of Q3 .

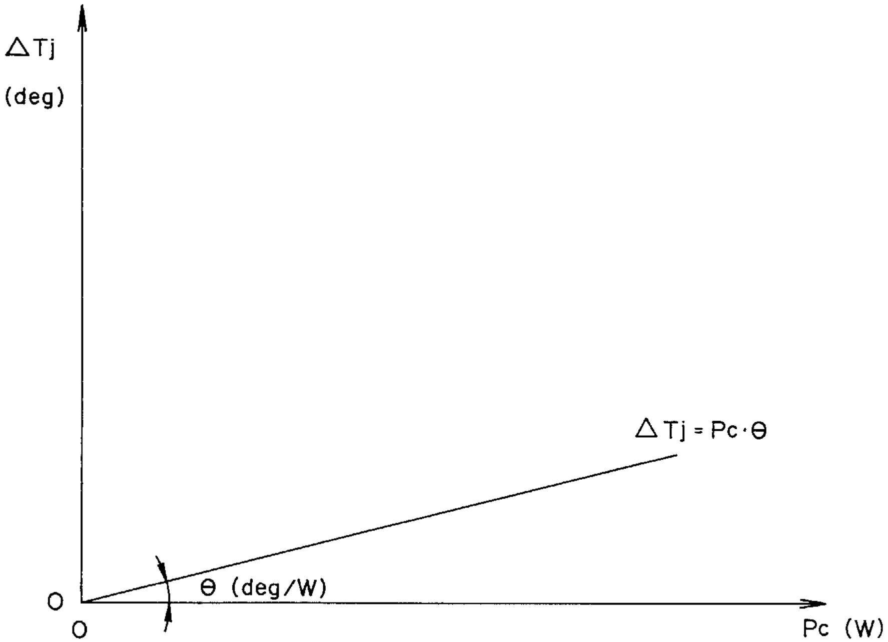


Fig.(6) A thermal difference (ΔTj) between Q1,Q2 and Q3 versus.

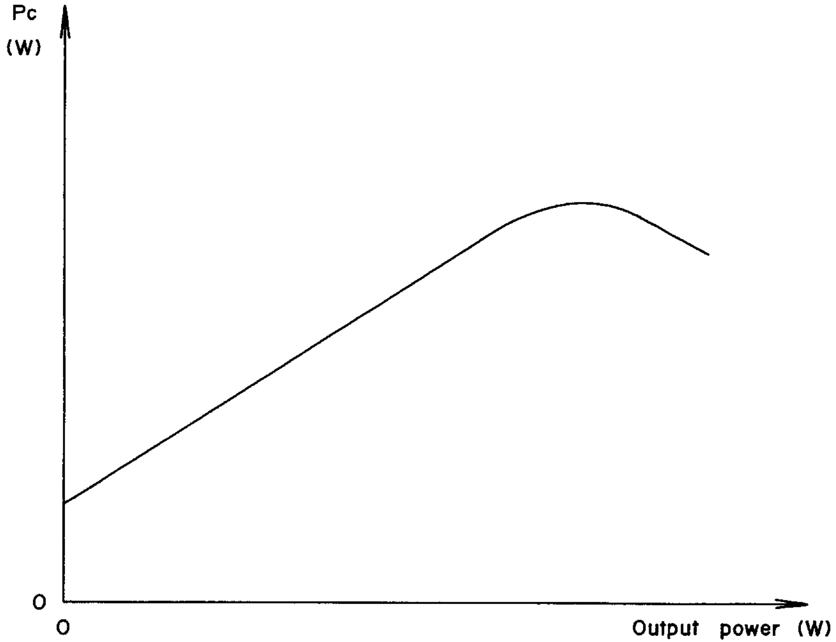


Fig. (7) Output device dissipation (Pc) versus output power.

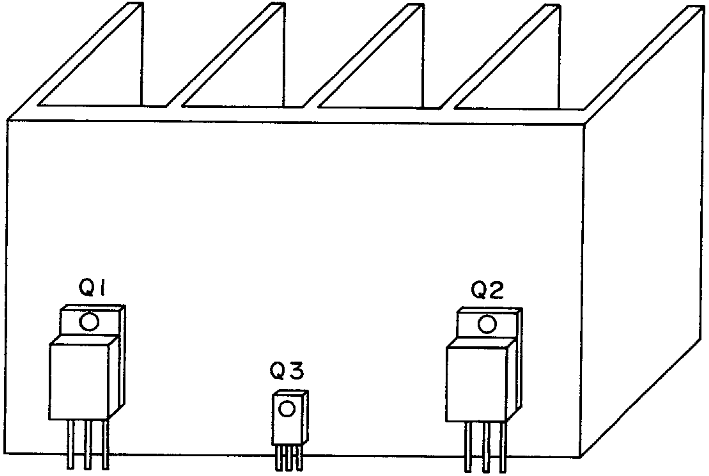


Fig. (8) Locational view attached Q1, Q2 and Q3 the heat sink.

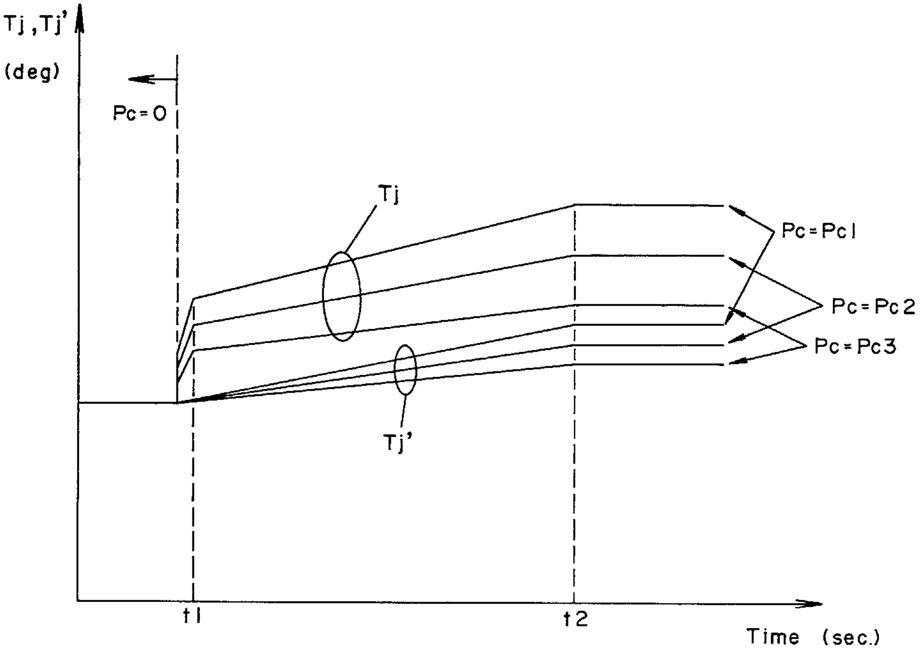


Fig.(9) Jumction temperature comparison between Q1, Q2 and Q3 due to various time.

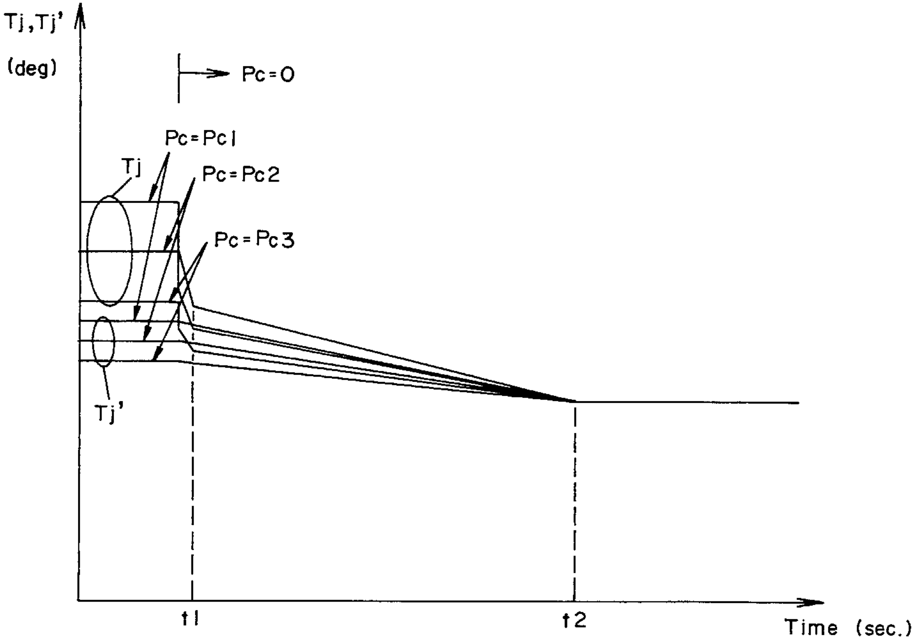


Fig. (10) Junction temperature comparison between Q1, Q2 and Q3 due to various time.

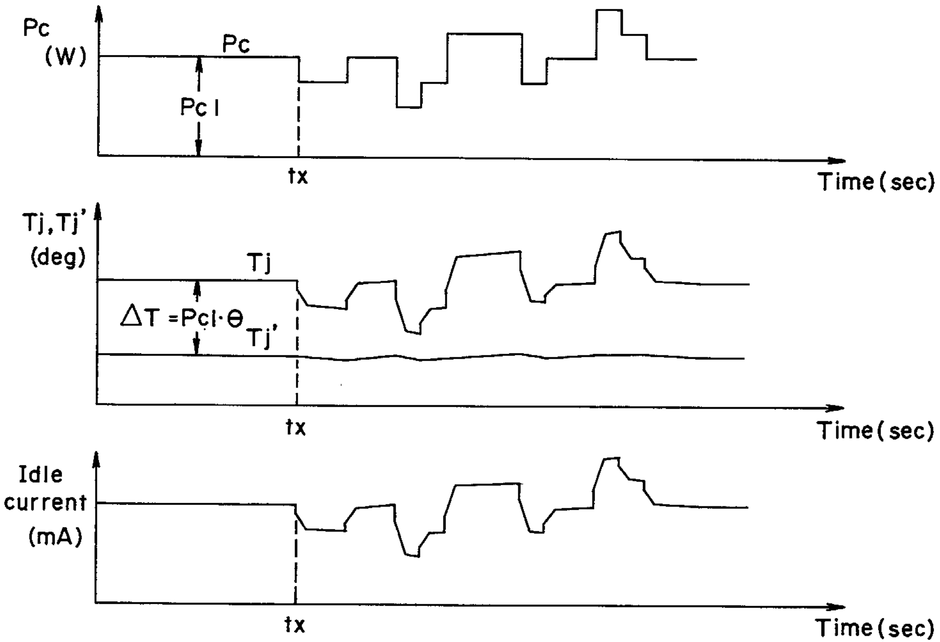


Fig. (11) Characteristics of junction temperature change of Q1, Q2 and Q3 and idle current change characteristics caused by the device dissipation (Pc) change of Q1 and Q2.

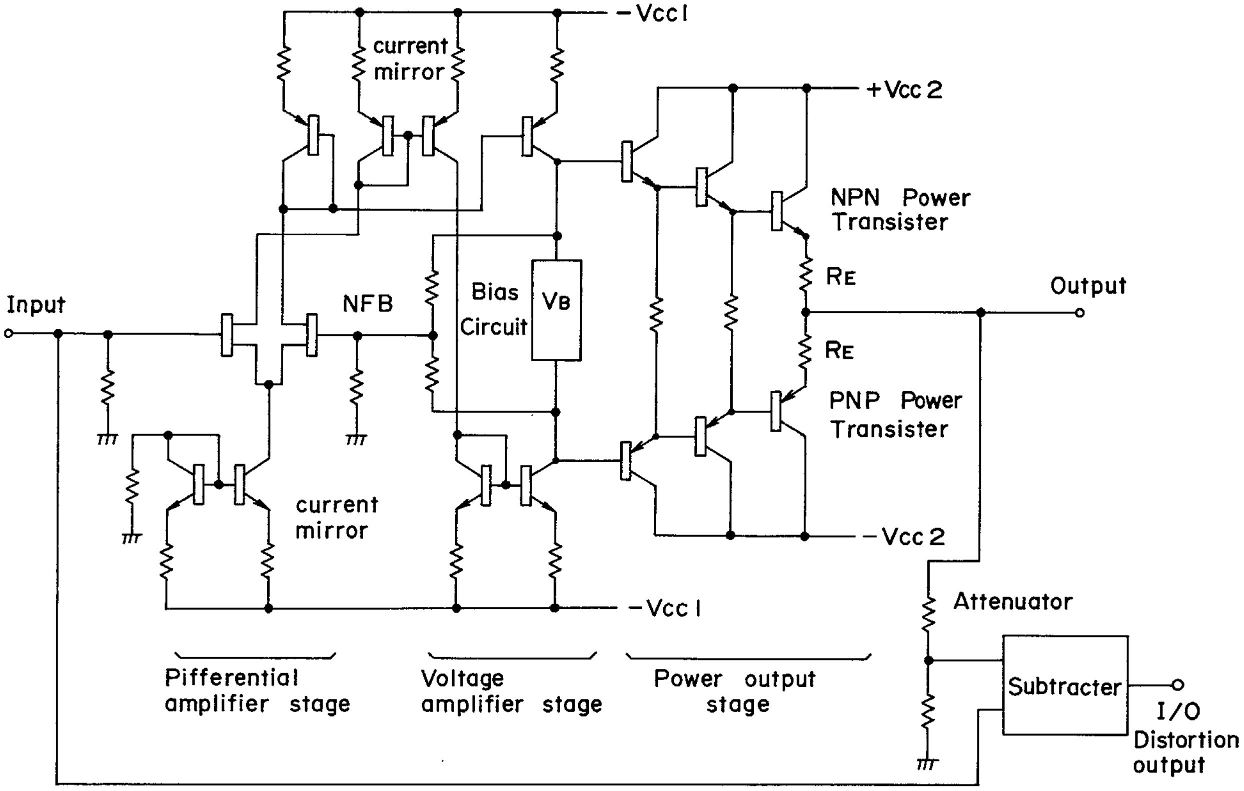


Fig.(12) Measuring circuit of the Transient Cross over Distortion in an ordinary B class Amplifier.

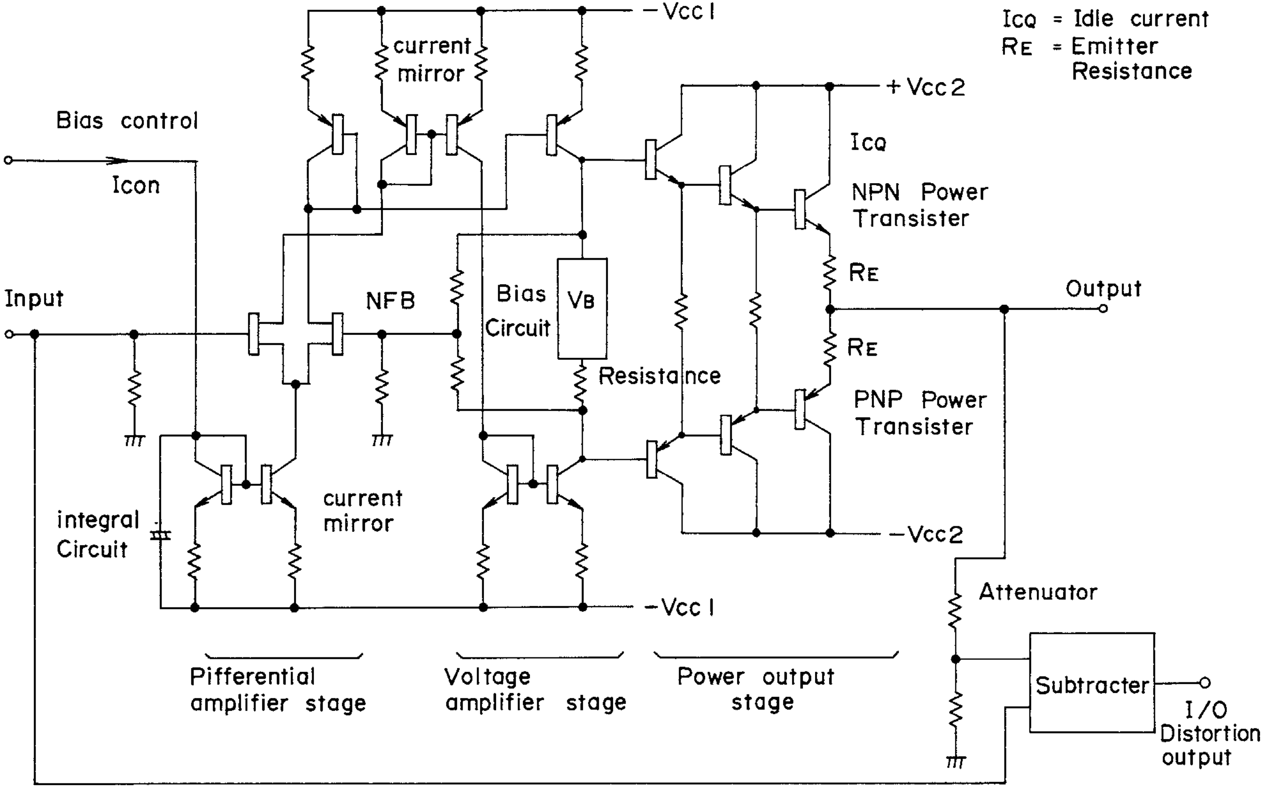


Fig.(13) Measuring circuit of the Transient Cross over Distortion in the B class Amplifier with the controlled bias circuit.

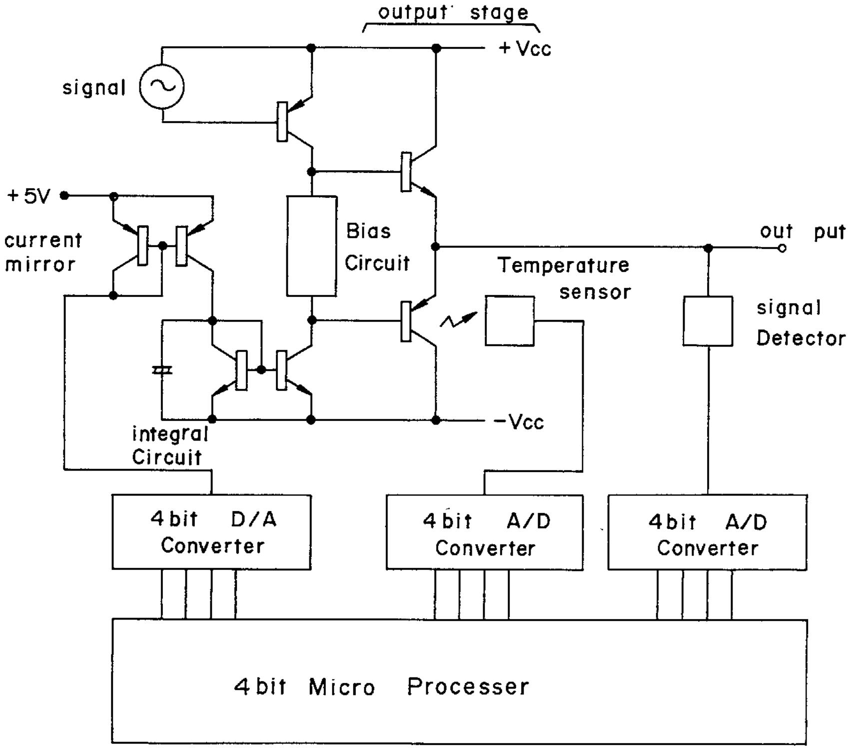
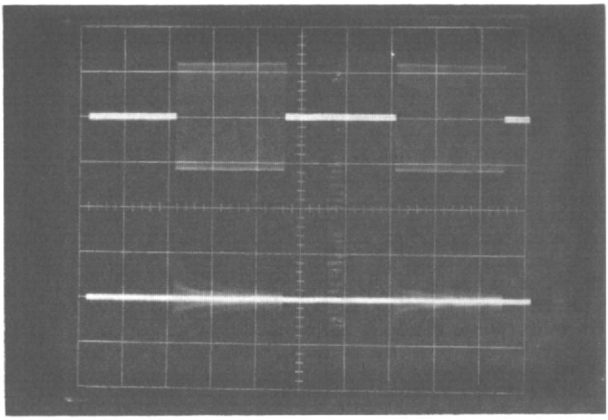


Fig.(14) Bias control circuit with a micro-processor.

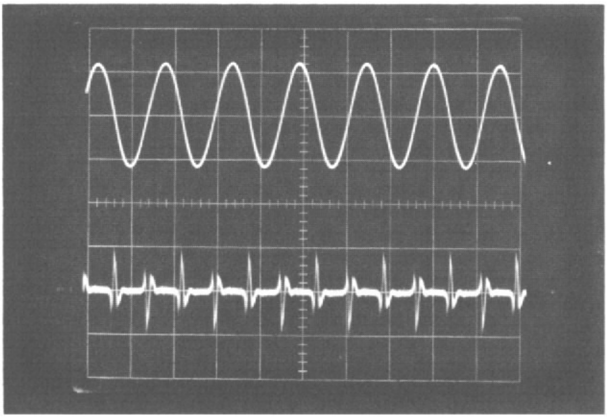


output signal waveforms

I/O Distortion waveforms

H 0.5s/div

(photo 1)

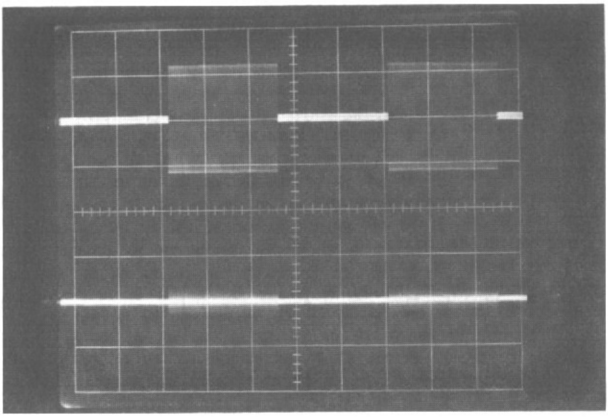


output signal waveforms

I/O Distortion waveforms

H = 2ms /div

(photo 2)

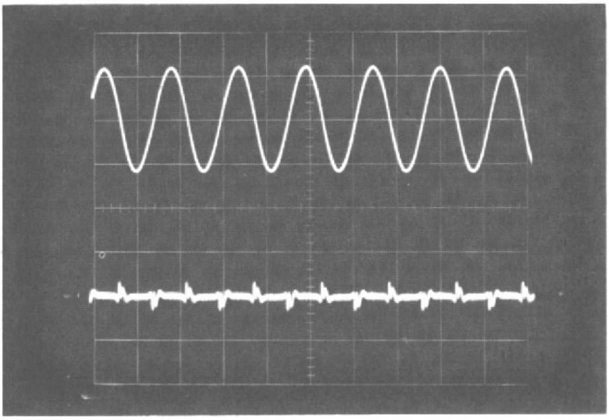


output signal waveforms

I/O Distortion waveforms

H 0.5 s/div

(photo 3)



output signal waveforms

I/O Distortion waveforms

H = 2 ms/div

(photo 4)