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# Feed Forward Linearization of Power Amplifiers

**Group-D16**

Nachiket Gajare ( 04d07015) < nachiketg@ee.iitb.ac.in>
Aditi Dhar ( 04d07030) < aditi@ee.iitb.ac.in>
Prakash Sutradhar ( 04d04016) < prakashs@ee.iitb.ac.in>
Nikhil C.Tambolkar ( 04d07014) < nikhilct@ee.iitb.ac.in>

Supervisor : Jayanta Mukherjee

## Abstract

This report discusses the method of raising the point of saturation of a highly distorted power amplifier. Due to non-linear distortions in the transistors in a power amplifier, the range of linearity of power amplifier is very small. Due to this early saturation point we have to face losses in power amplifier circuit. So, We have to increase the range of linearity. This report gives the qualitative as well as quantitative comparison between the readings of power amplifier before and after feed forward linearization.

## 1. Problem Statement:

**To increase the saturation voltage of power amplifier using Feed Forward linearization technique.**

## 2. Introduction:

In the transmission of signal from one point to another point, the transmitter usually contains a power amplifier. If the power amplifier is non-linear, then there is loss of power at the receiver due to distortion in the power amplifier at transmitter. These losses are significant in high frequency operation .The problem requires us to build a circuit which removes the distortion in the output voltage of power amplifier and after adjusting all gains and delays inside the circuit gives back the previous output without distortion.

### 3. Components :

The main components include :-

1. Distorted Power Amplifier ( CTC 810 audio amplifier)
2. OP 37 (Low Distortion Difference Amplifier)
3. LM 741 (Operational Amplifier)
4. One 4 ohm 5 watt speaker
5. Resistors
6. Capacitors.
7. Inductors.

**4. Method Of Linearization :**

There are various methods of linearization of power amplifier such as
-Feed Forward
-Feedback
-Power Cutoff
-Pre distortion
-Adaptive Pre distortion
-Envelope Elimination and Restoration
-Linear Amplification with non-Linear Components

**5. Advantages of Feed Forward Method over other methods:**

Feed Forward Method provides higher stability at the output than that of other method. This method is also simple to implement. Comparing with Feed Back method, it has greater advantages because in the Feed Back method output needs to be compared with the input in the each step.

**6. Feed Forward Method:**

Since distortion is in the output voltage of the power amplifier, so we shall use all the mathematical equations on voltages. There are many methods of linearization; we have used the most reliable and simplest one *Feed Forward Method*.

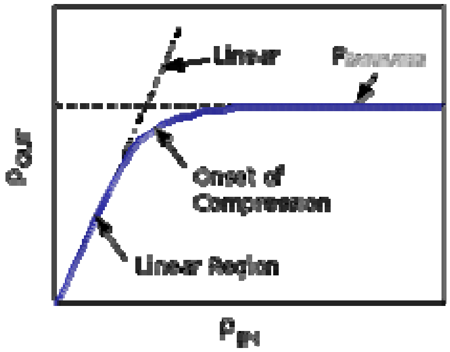
Feed Forward method, output of a distorted power amplifier can be considered as

$$V_{out} = A_v V_{in} + V_d$$

(This is the basic assumption on which the whole method stands)
Where $V_{in}$ is the input , $A_v$ is the power amplifer gain and $V_d$ is the amount of distortion.
We have to remove the distortion $V_d$.

**7. Types of Non-Linearity:**

When operating within the linear region of a component, gain through that component is constant for a given frequency. As the input signal is increased in power, a point is reached where the power of the signal at the output is not amplified by the same amount as the smaller signal.




$$P1dB_{output} = P1dB_{input} + (Gain - 1)\ dBm$$

***1 db Compression point :***

At the point where the input signal is amplified by an amount 1 dB less than the small signal gain, the 1 dB Compression Point has been reached. A rapid decrease in gain will be experienced after the 1 dB compression point is reached. If the input power is increased to an extreme value, the component will be destroyed

***Total Harmonic Distortion :***

Total harmonic distortion (THD) is an important figure of merit used to quantify the level of harmonics in voltage and current waveforms. Two different definitions for THD may be found in the literature. According to one definition, the harmonic content of a waveform is compared to its fundamental. By the second definition, the harmonic content of a waveform is compared to the waveform's rms value . In order to distinguish between the two, the former is occasionally denoted by $THD_F$ and the second by $THD_R$ . For instance, current THDs are defined a

$$THD_F = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1}; \quad THD_R = \sqrt{\frac{\sum_{n=2}^{\infty} I_n^2}{\sum_{n=1}^{\infty} I_n^2}}$$

where are either the rms values or the amplitudes of the harmonics. At low values of THD, there is not much difference between the two. However, the two definitions may cause ambiguity, confusion, and misinterpretation when measuring waveforms of high harmonic content. We shall use the harmonic power level definition to compare the results.

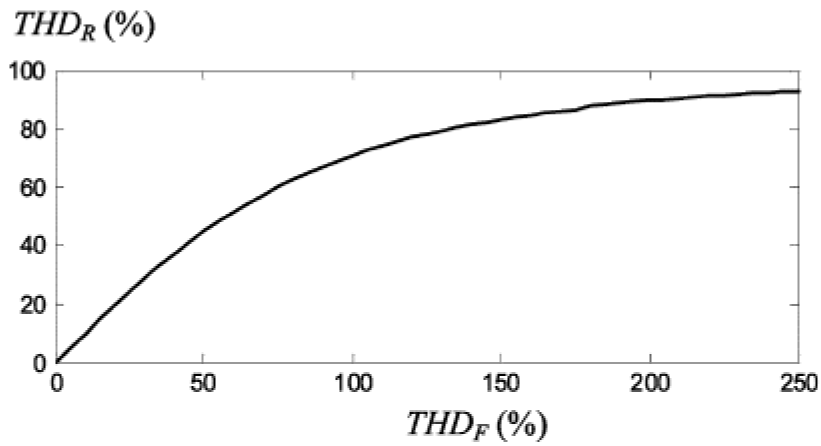



Fig. 1. Total harmonic distortion in percent of the signals rms versus its basic definition (in percentage of the fundamental) yields (4).

$$\mathrm{THD_R} = \frac{\mathrm{THD_F}}{\sqrt{1+\mathrm{THD_F^2}}}.$$

**Circuit Diagram :**

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**Main Circuit**

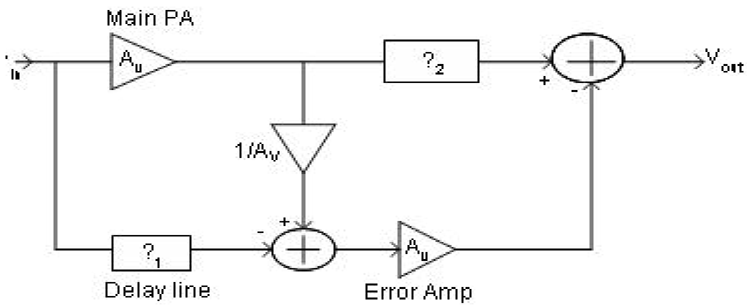


**Fig-1**

**Feed Forward Linearization Method**

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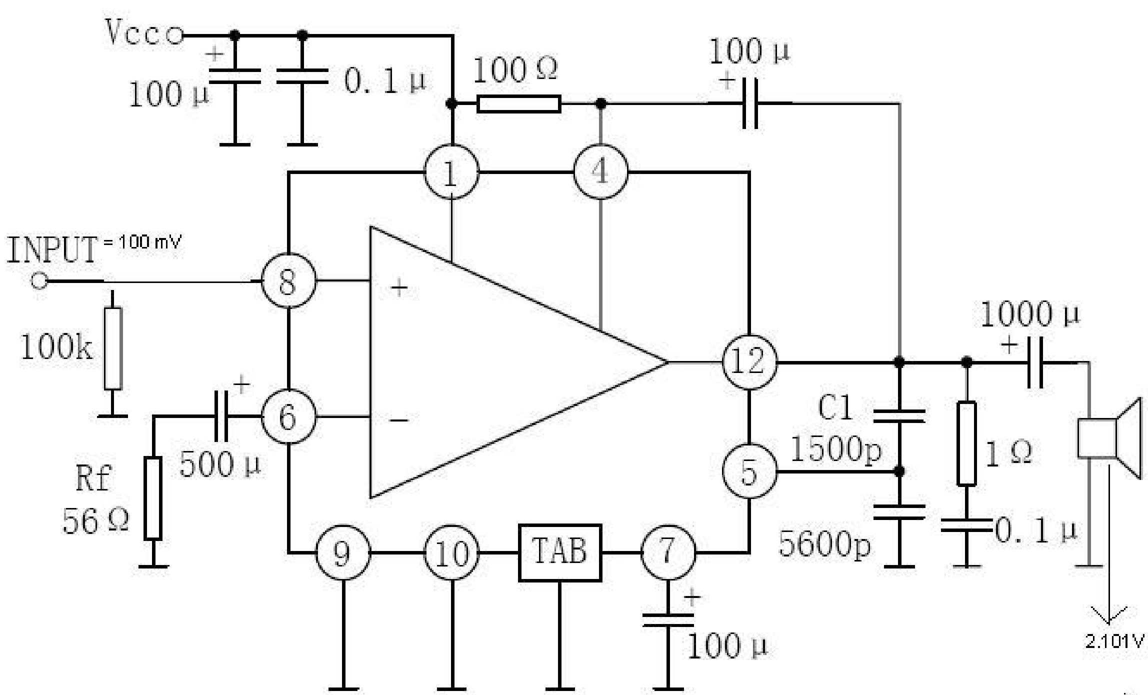
**8. Important Blocks :**

**Main Power Amplifier :** We using CTC 810 as main power amplifier, which is a low frequency Class B amplifier. It is a highly distorted audio amplifier with single supply up to 20 V.

*Charateristics of CTC 810 Class B Power Amplifier:*

A wide range of supply voltages (4 to 20V)
-High output current (up to 2.5A)
-High efficiency (75% at 6W output)
-Very low harmonic and cross-over distortion about 10% .
-Built-in thermal shut down protection circuit
-Power Dissipation (PD) = 1.7 W (No Heat Sink)
- Ambient operating Temperature Range -20 ℃ ~ +75 ℃
- Storage Temperature Range -40 ℃ ~ +150 ℃
-Lead Temparature Range (Soldering, 60 Sec) 310 ℃

After analyzing this circuit with a load of 4 ohm 5 watt speaker, we got the following characteristics :
Supply voltage = 10 V, $I_{min}$ = 0.05 A , $R_L$ = 8 Ohm and Freq. of Operation = 9.5 KHz,




Input Of Main Power Amplifier = 100 mV (Peak-Peak Sine Wave of Frequency 9.5KHz)
Output Of Main Power Amplifier =2.101 V (Peak-Peak Sine Wave of Frequency 9.5KHz with some amount of phase delay)
Gain Of Main Power Amplifier = 19 V/V (25dB)

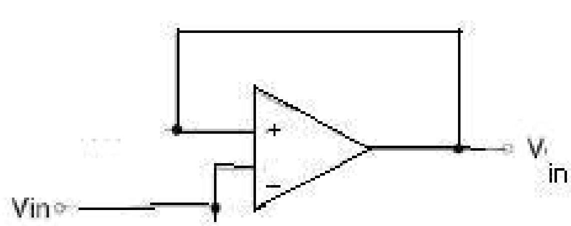
**Voltage Follower:** This is circuit which is made of operational amplifier to provide infinite impedance at the output ,i,e to follow the same voltage at input to output. Here we have used either OP37 or LM 741.

*Characteristics of OP 37 Voltage Amplifier:*

-Low Noise, 80 nV p-p (0.1 Hz to 10 Hz)
3 nV/÷Hz @ 1 kHz
-Swing of 10 V into 600 W and low output distortion make the OP37 an excellent choice for professional audio applications.
-Low Drift, 0.2  V/ C
-High Speed, 17 V/ micro-sec Slew Rate
-63 MHz Gain Bandwidth
-Low Input Offset Voltage, 10  micro V
-Excellent CMRR, 126 dB (Common-Voltage @ 11 V)
-High Open-Loop Gain, 1.8 Million
-Supply voltage + 22 V
-Internal voltage + 22 V
-Differential Input Voltage + 0.7 V
-Differential Input Voltage 25 mA
- Storage Temperature  Range -65 ℃ ~ + 150 ℃
-Operating Temperature Range -55 ℃ ~ + 125 ℃
-Lead Temperature Range (Soldering, 60 Sec) 300 ℃
- THD= 0.01%

*Characteristics of LM 741 Operational Amplifier:*

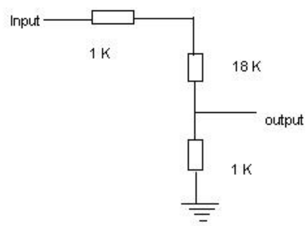
-Supply voltage + 22 V-(-) 22 V
-Power Dissipation 500 mW
-Differential Input Voltage + 30 V-(-) 30 V
-Output short Circuit Duration Continuous
-Operating Temperature Range -55 ℃ ~ + 125 ℃
- Storage Temperature Range -65 ℃ ~ + 150 ℃
-Lead Temperature Range (Soldering, 60 Sec) 260 ℃
- THD= 0.01%
From the above Characteristics we can see that if we use OP37 or LM741 in making different essential parts of circuit ,then it won't affect the properties the CTC 810.



**Attenuator :**We need to attenuate the output that we got directly from the main Power amplifier. We operated the circuit in the linear region at an input of 110 mV and at a frequency of 9.5 KHz.

From the power amplifier we got $V_{out} = 19V_{in} + V_d$

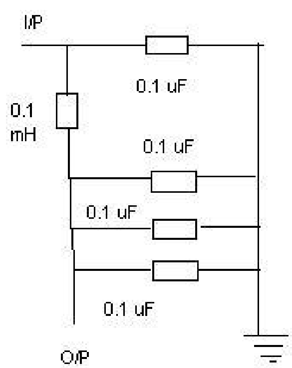
So, we **attenuated** the out by a factor of 19 with the help of resistor network .




In between them we needed an voltage follower , to nullify the effect of the impedance at the output of the main PA circuit on the voltage output.


**Delay Lines :** Delay lines are needed because when signal passes through the amplifier then the phase of the output shifts. Since the inputs to the difference amplifier must be in phase so we need a delay line to match the two signal one from the attenuator and other directly from power amplifier circuit.

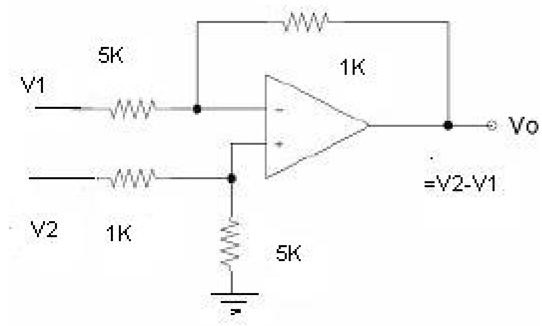
We have used a delay line made of capacitors and an inductor. The phases were matched by trial and error. The **delay line** circuit is shown in fig below :



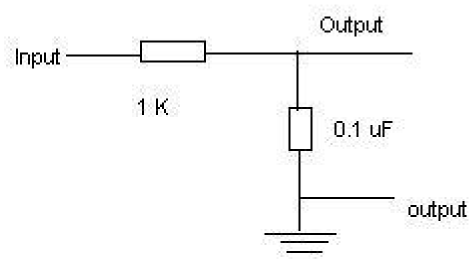

There is a gain due to delay to (since it is a LC circuit),so the gain has to be compensated for as well.

**Difference Amplifier :** Difference amplifier is a circuit made up of operational amplifier. It takes two signal input of exactly same phase and output is the difference of these two signals amplitude having same phase and same frequency. We need here a low distortion amplifier, because if it contains significant amount of distortion then it will add up to the distortion of main power amplifier and our calculation won’t match with the output. We use OP 37 low distortion operational amplifier to made differential amplifier.

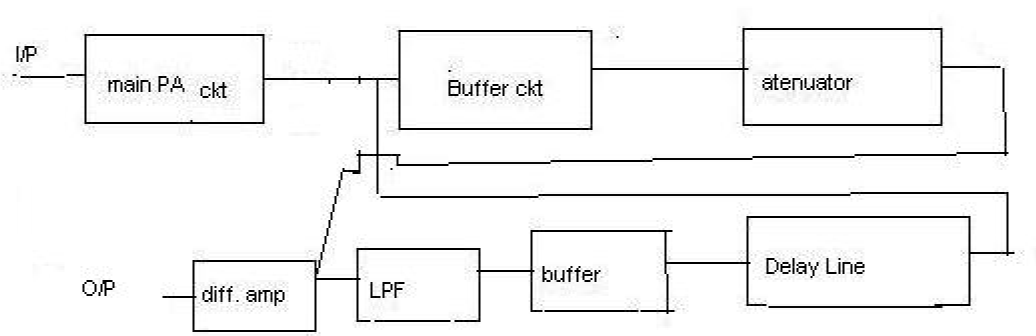
The circuit diagram of **difference amplifier** is shown in fig below :




To connect we need another buffer and Low Pass filter at the output of the buffer, because at the output of the buffer a band (distortion) is obtained ,to avoid it we needed to use a **LPF** as shown in fig :

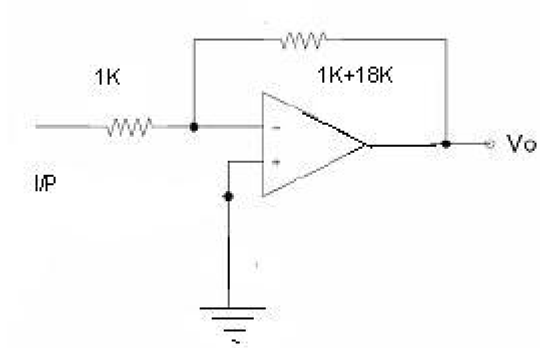



The overall first loop is as follow:

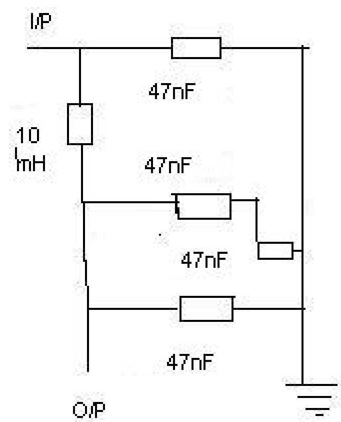



The output then is just Vd/Av .This is the error that we need to remove.
We also need to adjust for the gain of LPF and delay line.

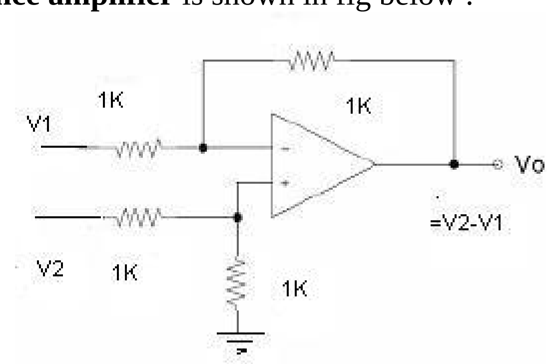
**Error Amplifier :** The error above we got is very small so to match its phase with the original output directly from the main power amplifier before going to the final difference amplifier we need to amplify. The **error amplifie**r circuit with a gain of **19** is shown in fig below:




Another signal from the output of main power amplifier is given directly to the **delay line** as shown in fig below:

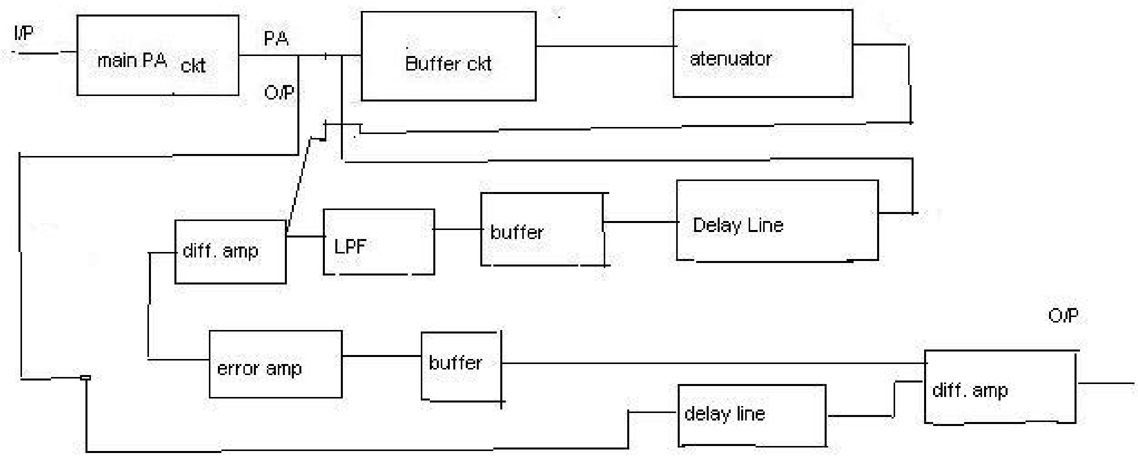



After matching the phases from the delay line it was given to the difference amplifier and another input of difference amplifier is from the output of error amplifier. The final **difference amplifier** is shown in fig below :

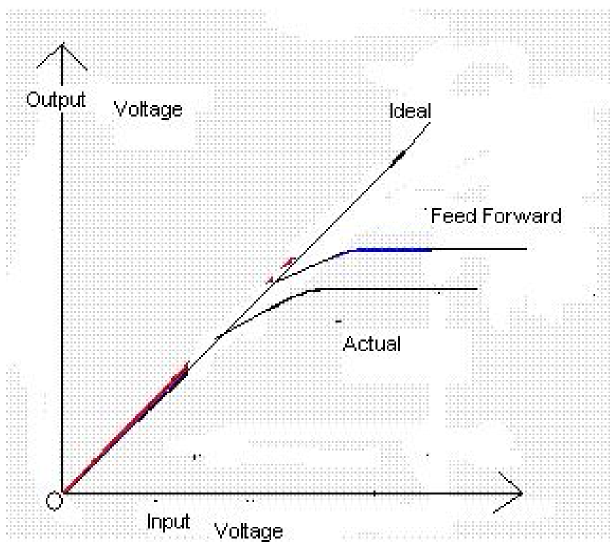



The input to the differential amplifier are $A_vV_{in} + V_d$ and $V_d$. Finally output the circuit is $A_vV_{in}$ + delta , delta is very small than Vd.

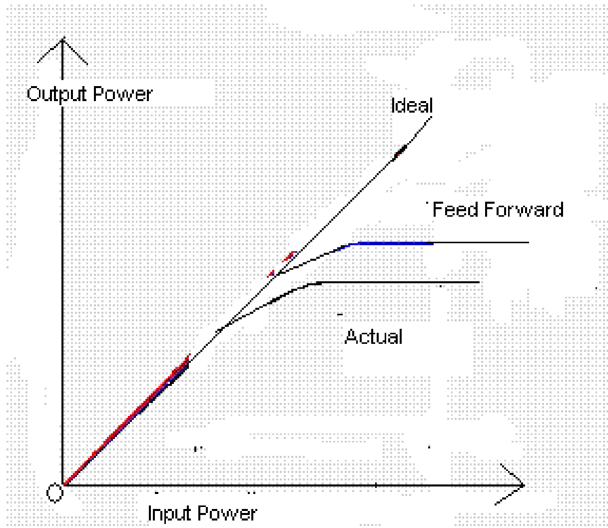
Thus the **overall circuit** diagram is as follows :




Final Output we got has larger range of linearization than that of direct output of audio amplifier. It also has to be noted that the output remains a sinusoid for a range of the input much larger than the original power amplifier.  The change in **output** is shown in fig below.




**Output Voltage vs Input Voltage of power amplifier is shown before and after Feed Forward Linearization.**




**Output Power vs Input Power of power amplifier is shown before and after Feed Forward Linearization.**

## 9. Readings:

The readingS for the measurement of non-linearities of main power amplifier CTC 810 are given below.
We have applied sinusoidal signal of frequency 9.5 KHz from signal generator .
[All the readings are dependent on signal frequency]

**-Measurement of 1 dB Compression Point :**
**<u>(*Before* Feed Forward Linearization)</u>**

All the reading are peak-peak value of sinusoidal signal .

| $V_{in}$ (mV) | | $V_{out}$ (Volts) |
|---|---|---|
| 25 | | 0.400 |
| 40 | | 0.637 |
| 60 | | 1.020 |
| 80 | | 1.426 |
| 90 | | 1.596 |
| 100 | | 1.860 |
| **110** | **(Operating Point)** | **2.101** |
| 120 | | 2.348 |
| ***130*** | **(Saturation Point)** | ***2.620*** |
| 140 | | 2.625 |
| 150 | | 2.630 |
| 160 | | 2.630 |
| 170 | | 2.630 |
| 180 | | 2.630 |

| | |
|---|---|
| 190 | 2.620 |
| 200 | 2.620 |

All the above readings are obtained using Digital Scope.
Now from the above readings we can find the aproximate voltage gains (considering distortions are in mili volt.in the linear region) using equation

$$V_{out} = A_v V_{in} + V_d$$

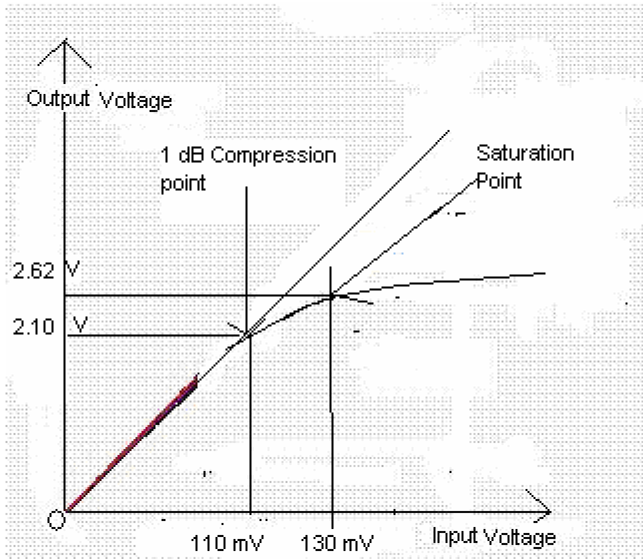
Since we have assumed distortions are in mili volt in the linear region,hence

$$V_{out} \sim A_v V_{in}$$

| $V_{in}$ (mV) | Gain ($A_v \sim V_{out} / V_{in}$) |
|---|---|
| 25 | 15 |
| 40 | 15.8 |
| 60 | 17 |
| 80 | 17.5 |
| 90 | 18.2 |
| 100 | 18.6 |
| 110 | 19 |
| 120 | 19.5 |
| 130 | 20 (saturation) |

Table shows that the measured voltage gain is not exactly a constant; it depends on input signal and signal's frequency. In the linear region gain is almost constant as also will be seen in the graph sheets attached, but after a certain input, distortion keeps on increasing as the input signal increases.

On plotting graph Output Voltage Vs Input Voltage we can find *1 dB compression point* at an input voltage of **110 mV** and *Saturation Voltage* at **130 mV**




**Output Voltage Vs Input Voltage at 9.5 KHz**

Since gain is varying with input signal, so we choose our range of operation in the linear region tipicaly at 110 mV (*1 dB compression point*)

**-Total Harmonic Distortion (THD):**
**(*Before* Feed Forward Linearization)**

| Frequency (KHz) | Power in the output signal (scalable by a factor k due to the reference settings of the spectrum analyser ) |
|---|---|
| 9.5 | 72.5 micro W |
| 19.5 | 225 nW |
| 29.5 | 125 nW |
| 39.5 | 57.7 nW |
| 49.5 | 25.5 nW |
| 59.5 | 14.4 nW |

THD can be calculated using equation

$$THD = \{(P_{19.5K} + P_{29.5K} + \ldots\ldots\ldots\ldots\ldots\ldots + P_{59.5K})/P_{9.5k}\ \} \quad \%$$

$$= 0.617\ \%$$

-**Measurement of 1 dB Compression Point :**
**(*After* Feed Forward Linearization)**

| $V_{in}$ (mV) | $V_{out}$ (Volts) |
|---|---|
| 25 | 0.400 |

| | |
|---|---|
| 40 | 0.637 |
| 60 | 1.020 |
| 80 | 1.426 |
| 90 | 1.596 |
| 100 | 1.860 |
| 110 | 2.101 |
| 120 | 2.348 |
| *130* | *2.620* |
| 140 | 2.780 |
| 150 | 3.061 |
| 160 | 3.281 |
| 170 | 3.583 |
| 180 | 3.881 |
| 190 | 4.188 |
| 200 | 4.505 |
| 210 | 4.835 |
| 220 **(New Op. Point)** | 5.187 |
| 230 | 5.530 |
| 240 | 5.901 |
| **250 (New Saturation point)** | 6.260 |
| 260 | 6.270 |
| 270 | 6.275 |
| 280 | 6.275 |
| 290 | 6.275 |
| 300 | 6.275 |

We can find 1 dB Compression Point is at 220 mV input and it saturates at 250 mV. This there is a significant increase in the 1db compression point which is also shown in the graph sheets attached.

| $V_{in}$ (mV) | Gain ($A_v \sim V_{out} / V_{in}$) |
|---|---|
| 25 | 15 |
| 40 | 15.8 |
| 60 | 17 |
| 80 | 17.5 |
| 90 | 18.2 |
| 100 | 18.6 |
| 110 | 19 |
| 120 | 19.5 |
| 130 | 20 |
| 140 | 20.4 |
| 150 | 20.9 |
| 160 | 21.4 |
| 170 | 21.8 |
| 180 | 22.3 |

| | |
|---|---|
| 190 | 22.7 |
| 200 | 23.2 |
| 210 | 23.6 |
| ***220*** | ***24.1*** |
| 230 | 24.5 |
| 240 | 25.0 |
| ***250*** | ***25.5 (saturation)*** |

Gain remains fixed as before for a particular input voltage at a particular frequency.

**-Total Harmonic Distortion (THD):**
**(*After* Feed Forward Linearization)**

| Frequency (KHz) | Power in the output signal (scalable by a factor k as per reference settings of the spectrum analyzer) |
|---|---|
| 9.5 | 2.58 mW |
| 19.5 | 50.4 micro W |
| 29.5 | 25.4 micro W |
| 39.5 | 8.32 micro W |
| 49.5 | 4.72 micro W |
| 59.5 | 2.24 micro W |

THD can be calculated using equation

$$THD = \{(P_{19.5K} + P_{29.5K} + \ldots\ldots\ldots\ldots + P_{59.5K})/P_{9.5k}\}\ \%$$

$$= 0.051\ \%$$

Thus we see that the linearization method increases the level at all the harmonic frequencies but the increase in the signal level at the main frequency is much significant compared to the harmonics which leads to a tremendous reduction in the THD.

**Gain Due To 1$^{st}$ Delay Line :**

| Input To Delay Line | Output To Delay Line | Gain due to delay line |
|---|---|---|
| 80 mV | 340 mv | 23.25 |
| 95 mV | 384 mV | 19.73 |
| 110 mV | 420 mV | 17.89 |

**Reading in the different parts of the circuit are given below :**

Main Power Amplifier Input = 110 mV
1$^{st}$ Buffer Input = 2.0 V

1st Buffer Output = 2.0 V
1st LPF Input = 66 mV
1st Delay Line Output = 245 mV
Output of Main Power Amplifier = 2.101 V
Output of Next Buffer = 2.101 V
Output Of Attenuator = 1.14 V
Output of Next Buffer (next after attenuator) = 1.26 V
Main Power Amplifier Gain = (2.101 V) / (110 mV) = 25 dB
2st Delay Line Output = 800 mV
Last Buffer Output = 800 mV
2nd Difference Amplifier Input = 800 mV
1st Delay Line Input = 110 mV
1st Delay Line Output = 420 mV
Gain due to delay line = 17.89 = 24.9 dB
Input To 1st Difference Amplifier = 420 mV
Output Impedence of main power amplifier circuit= 8 K
Final Output After Feed Forward Linearization = 2.101 V
Output Impedence of the circuit= 8 K

## 10. Problems Encountered :

**Selecting Power Amplifier :** We were suggested by Prof. J. Mukherji to use audio amplifier which is also a power amplifier. The characterization of the power amplifier had to be done properly.We then zeroed on CTC 810 which satisfies our requirement. Then we again had problem in characterizing CTC 810,initially we weren't getting a fixed saturation point and output power at the desired frequency, after consulting with TAs and checking the circuit again at last we got the characteristic of it.

**Supply Problem (ground Problem) :** : CTC 810 needs single power supply and OP 37 or LM 741 needs dual power supply, so these two circuits had different grounds, when we interconnected the two grounds externally , the output of the attenuator got distorted. Then we used + 15 V and -15 V supply having one ground and attenuated +15 V to 0 V for CTC 810 and thus we solved the problems of different grounding.

**Giving input to the difference amplifier :** We took a supply from signal generator and tried to get another input of magnitude halved from resistor divider to give input to difference amplifier. The resistor network was working separately but it doesn't work when we connect it to the difference amplifier. It was due to the output impedance of op amp. So, we had to use a voltage follower.

**Connecting main power amplifier and attenuator :** We made the main PA and attenuator circuit separately working but when we tried to connect them the output of the attenuator got changed, after thinking about it finally we came to know that it is the problem of output impedance. The overall impedance of main PA is changed due to connecting attenuator circuit which results a deviation of result, after connecting voltage follower circuit we had solved the problem of output impedance.

**Adjusting second delay line :** In the second loop we had only distortion signal (Vd) which was very tough to measure due to its irregular appearance. However, to use it as input for difference amplifier we need that the phase of that attenuated error (distortion) signal to be matched with the direct output of the main PA .Then we used another delay line which showed some changes in the error signal's waveform, then we fixed the problem in trial and error method.

**Voltage Regulator Problem :.** After completing the linearization of power amplifier in breadboard, we took the next task of soldering on PCB. We made two PCBs, one for only main power amplifier and another for the *feed forward* part. After completing soldering when we went for final checking, we found that voltage regulator in main power amplifier PCB was not working in desired way, output of voltage regulator was only 6.8 which was due to the lowering of its output as its temperature increased. The solution lay within using a heat sink Then we provided direct supply through two 1K resistors circuit.

**Short Circuit Problem:** After desoldering voltage regulator from main Power amplifier PCB, the circuit short circuited at some point between the supply and the ground in main Power amplifier PCB, we consulted with TA's and checked all the way to short out it but it was very difficult to find out the actual point of short circuit

**11. Important Outcomes :**

Any Power amplifier can be linearized with regards to its voltage waveform output using above method. In doing so we need to match the output impedance of the power amplifier for maximum power transfer.

We have seen that in making the above circuit we need to make the individual part of the circuit working properly separately and every part is to be designed depending on the characteristics of previous or other part. Finally, every part of the circuit is to be characterized properly because output of one part is dependent on the properties of other part.

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