EXPERIMENT NO. 5: POWER AMPLIFIERS AND FEEDBACK ANALYSIS

1.0 AIM:

The primary aim of this experiment is to thoroughly investigate the characteristics and performance of different classes of power amplifiers (specifically Class A, Class B Push-Pull, and optionally Class AB) and to comprehensively analyze the profound effects of negative feedback on various parameters of an amplifier.

2.0 OBJECTIVES:

Upon successful completion of this experiment, you will be able to:

- **Understand Power Amplifier Classes: Distinguish between Class A, Class B, and Class AB power amplifiers based on their operating principles, conduction angles, and efficiency characteristics.**
- **Design and Construct Power Amplifiers: Build and test basic Class A and Class B (and optionally Class AB) power amplifier circuits using discrete components.**
- **Characterize Class A Amplifier: Measure output power and calculate the efficiency of a Class A amplifier for a given load. Observe and analyze waveform distortion at high input signal levels.**
- **Observe Crossover Distortion: Identify and explain crossover distortion in Class B push-pull amplifier output waveforms.**
- **Mitigate Distortion: Understand and practically demonstrate how biasing (e.g., in Class AB) helps to reduce or eliminate crossover distortion.**
- **Implement Negative Feedback: Design and implement a voltage-series negative feedback amplifier using either an operational amplifier (Op-Amp) or discrete components.**
- **Quantify Feedback Effects: Measure and compare the voltage gain, input resistance, output resistance, and bandwidth of an amplifier *without feedback* and *with negative feedback*.**
- **Analyze Feedback Impact: Discuss and explain the significant impact of negative feedback on the amplifier's performance parameters, including gain reduction, bandwidth extension, impedance modification, and distortion reduction.**
- **Qualitative Stability Observation: If feasible, qualitatively observe the improvement in amplifier stability when negative feedback is applied, particularly in scenarios prone to oscillation.**
- **Instrumentation Skills: Effectively utilize laboratory equipment such as DC power supply, AC function generator, oscilloscope, and DMM for amplifier characterization and analysis.**

3.0 APPARATUS REQUIRED:

A comprehensive list of components and equipment necessary for performing this experiment.

S. No.	Component/Equipment	Specifications/Value	Quantity
1.	DC Power Supply (Variable)	Dual Output (e.g., +/- 15V, or 0-30V)	1
2.	AC Function Generator	Sine wave, Adjustable Amplitude, Wide Frequency Range	1
3.	Digital Multimeter (DMM)	Multi-function (Voltage, Current, Resistance)	1
4.	Oscilloscope	Dual Trace, Minimum 20MHz Bandwidth	1
5.	Breadboard	Standard Size, for circuit prototyping	1
6.	NPN Bipolar Junction Transistor	BC547 (for small signal), 2N2222 or similar (for Class A/B, higher current capability)	2-3 (at least one for each type)
7.	PNP Bipolar Junction Transistor	BC557 (for small signal), 2N2907 or similar (for Class B/AB, higher current capability)	1 (for Push-Pull)

8.	Operational Amplifier (Op-Amp)	e.g., LM741, TL082 (if using Op-Amp for feedback section)	1
9.	Resistors (Carbon Film, 1/4W or 1/2W)	Various values (100 Ω, 1 kΩ, 2.2 kΩ, 4.7 kΩ, 10 kΩ, 47 kΩ, etc.)	Assorted
10.	Load Resistors (Low Wattage)	8 Ω, 16 Ω (for power amplifier output), 100 Ω, 1 kΩ (for general loads)	2-4
11.	Capacitors (Electrolytic)	Coupling Capacitors: 1 μF, 10 μF (25V or 50V rating)	Assorted
12.	Diodes	1N4001 or 1N4148 (for Class AB biasing)	2
13.	Connecting Wires	Breadboard jumper wires, various lengths	Assorted

4.0 THEORY AND FUNDAMENTALS:

This section provides a detailed theoretical background for power amplifier classes and the principles of negative feedback, including all necessary formulas and explanations.

4.1 Power Amplifiers: Amplifying Power for Loads

Unlike small-signal amplifiers that primarily focus on voltage or current gain, power amplifiers are designed to deliver significant power to a load (e.g., a loudspeaker). Their primary concerns are power efficiency, output power capability, and thermal management. Power amplifier classes are defined by the conduction angle of the active device (transistor) during one cycle of the input signal.

4.1.1 Class A Power Amplifier

- **Operating Principle: In a Class A amplifier, the transistor is biased such that it conducts current for the entire 360 degrees of the input AC cycle. The Q-point** is typically set near the center of the DC load line. This ensures that the transistor is always in the active region, never cutting off or saturating for the full signal swing.

- Efficiency: Class A amplifiers are known for their linear operation and low distortion. However, they are highly inefficient. Even with no input signal, the transistor continuously draws quiescent current, dissipating power.
    - Maximum Theoretical Efficiency: For a capacitively coupled (or transformer-coupled) Class A amplifier, the maximum theoretical efficiency is 25% (for resistive load). For an ideal transformer-coupled Class A, it can reach 50%.
    - Reasons for Low Efficiency: Power is continuously dissipated in the collector resistor (R_C) and the transistor itself, even when no signal is applied. When an AC signal is present, power is transferred to the load, but significant power is still wasted as heat.
- Distortion: Generally low if operated within the linear region. However, as the input signal amplitude increases, the amplifier can enter saturation or cutoff, leading to significant clipping distortion.
- Power Calculations:
    - DC Input Power (P_in(DC)): This is the total power supplied by the DC power source.
      P_in(DC)=V_CCtimesI_CQ (for a simple CE Class A with collector resistor)
      Where I_CQ is the quiescent (DC) collector current.
    - AC Output Power (P_out(AC)): This is the power delivered to the load resistor (R_L).
      P_out(AC)=frac(V_out(RMS))2R_L=frac(V_out(peak))22R_L=frac(V_out(p−p))28R_L
      Where V_out(RMS), V_out(peak), V_out(p−p) are the RMS, peak, and peak-to-peak AC output voltages, respectively.
    - Efficiency (eta): The ratio of AC output power to DC input power, expressed as a percentage.
      eta=fracP_out(AC)P_in(DC)times100

Numerical Example (Class A Efficiency):

Consider a Class A amplifier with V_CC=12V, R_C=1kOmega, biased such that I_CQ=5mA. The amplifier is driving an 8Ω load.

P_in(DC)=V_CCtimesI_CQ=12Vtimes5mA=60mW.

If an AC output voltage of V_out(peak)=2V is measured across the 8Ω load.

P_out(AC)=frac(V_out(peak))22R_L=frac(2V)22times8Omega=frac416=0.25W=250mW.

Efficiency eta=frac250mW60mWtimes100 -> This example shows P_out(AC) being larger than P_in(DC), which is impossible for efficiency. This indicates my example output voltage is too high for the given DC conditions or the amplifier circuit assumed. Let's correct this.

For a Class A common emitter with R_C as load, max peak-to-peak output swing is $V_{CC}/2$. So $V_{out}(peak)$ cannot exceed $V_{CC}/2=6V$. Also, R_L is usually coupled, so R_L is the effective AC load.

Let's assume a real scenario: $V_{CC}=12V$, $I_{CQ}=10mA$.
$P_{in}(DC)=12V\times 10mA=120mW$.

If the maximum undistorted peak output voltage is $V_{out}(peak)=3V$ (which is realistic for a capacitively coupled load on a 12V supply with some voltage drop on R_C). And $R_L=8\Omega$.

$P_{out}(AC)=\frac{(3V)^2}{2\times 8\Omega}=\frac{9}{16}=0.5625W=562.5mW$.

This output power is too high for an input DC power of 120mW, highlighting the limits of simple Class A with R_C bias. The actual power delivered to the load cannot exceed the power dissipated by the transistor in AC operation, and total output AC power must be less than $P_{in}(DC)$.

Corrected Example:

For an ideal capacitively coupled Class A amplifier, the max power delivered to the load is $P_{out}(max)=\frac{I_{CQ}V_{CC}}{8}$.

If $V_{CC}=12V$, $I_{CQ}=10mA$. $P_{in}(DC)=12V\times 10mA=120mW$.

$P_{out}(max)=\frac{(10mA)(12V)}{8}=15mW$.

Then, $\eta=\frac{15mW}{120mW}\times 100$. This is within the 25% max for resistive load.

4.1.2 Class B Push-Pull Amplifier

- Operating Principle: In a Class B amplifier, each transistor is biased at cutoff. This means that a transistor only conducts for approximately 180 degrees (half) of the input AC cycle. A push-pull configuration uses two transistors (one NPN, one PNP, or two NPNs with a phase splitter) where one transistor handles the positive half of the output waveform, and the other handles the negative half.
- Efficiency: Class B amplifiers are much more efficient than Class A, with a maximum theoretical efficiency of 78.5%. This is because current is drawn from the power supply only when there is an input signal, reducing quiescent power dissipation.
- Distortion (Crossover Distortion): The major drawback of Class B is crossover distortion. Because each transistor is biased at cutoff, there is a small voltage region around 0V where neither transistor is fully turned on. This creates a "dead zone" in the output waveform, resulting in a distorted (not perfectly smooth) output near the zero-crossing points.

4.1.3 Class AB Power Amplifier (Compromise)

- Operating Principle: Class AB amplifiers are a compromise between Class A and Class B. Each transistor is biased slightly above cutoff, allowing a small quiescent current to flow even with no input signal. This ensures that both transistors are conducting for slightly more than 180 degrees (e.g., 190-200 degrees), overlapping their conduction regions slightly.
- Efficiency: Efficiency is lower than Class B but significantly higher than Class A (typically 50-70%).
- Distortion: The small quiescent current effectively eliminates crossover distortion, resulting in much cleaner output waveforms compared to Class B. This makes Class AB the most common class for audio power amplifiers.
- Biasing for Class AB: Small biasing voltages (e.g., using two forward-biased diodes in series with the base circuit of the push-pull transistors) are used to provide the necessary small quiescent current.

4.2 Negative Feedback: Enhancing Amplifier Performance

Feedback involves feeding a portion of the output signal back to the input. If the fed-back signal is out of phase with the input signal, it's called negative feedback (or degenerative feedback). Negative feedback is widely used to improve amplifier characteristics.

- Principle: A fraction of the output voltage or current is sampled and fed back to the input, where it is summed (subtracted for negative feedback) with the original input signal. This effectively reduces the overall gain but offers significant performance improvements.
- Types of Negative Feedback: There are four basic types based on how the output is sampled (voltage or current) and how it's mixed at the input (series or shunt):
    - Voltage-Series Feedback: Output voltage is sampled, fed back in series with the input. (Often used for Op-Amp non-inverting amplifier).
    - Voltage-Shunt Feedback: Output voltage is sampled, fed back in shunt (parallel) with the input. (Often used for Op-Amp inverting amplifier).
    - Current-Series Feedback: Output current is sampled, fed back in series with the input.
    - Current-Shunt Feedback: Output current is sampled, fed back in shunt with the input.
- Key Feedback Formulas (General for negative feedback):
  Let A be the open-loop gain (gain without feedback) and beta be the feedback factor (fraction of output fed back).
    - Closed-Loop Gain (A_f): The gain with feedback.
      A_f=fracA1+Abeta
      For large Abeta (i.e., Abetagg1), A_fapproxfrac1beta. This means the gain becomes almost entirely dependent on the feedback network, making it very stable and predictable.
    - Input Resistance with Feedback (R_in(f)):

        - For Series Input Feedback (like Voltage-Series or Current-Series): Input resistance increases.
          R_in(f)=R_in(1+Abeta)
        - For Shunt Input Feedback (like Voltage-Shunt or Current-Shunt): Input resistance decreases.
          R_in(f)=fracR_in1+Abeta
    - Output Resistance with Feedback (R_out(f)):
        - For Voltage Output Feedback (like Voltage-Series or Voltage-Shunt): Output resistance decreases.
          R_out(f)=fracR_out1+Abeta
        - For Current Output Feedback (like Current-Series or Current-Shunt): Output resistance increases.
          R_out(f)=R_out(1+Abeta)
    - Bandwidth with Feedback (BW_f): Negative feedback generally increases the bandwidth.
      BW_f=BW(1+Abeta)
    - Distortion and Noise Reduction: Negative feedback significantly reduces non-linear distortion (e.g., harmonic distortion) and noise generated within the amplifier.
      Distortion with feedback = Distortion without feedback / (1+Abeta)
      Noise with feedback = Noise without feedback / (1+Abeta)
    - Stability Improvement: Negative feedback makes the amplifier less sensitive to variations in component parameters and power supply fluctuations, improving overall stability. However, excessive feedback or improper design can lead to instability and oscillation if the loop gain (Abeta) reaches specific conditions at certain frequencies (Nyquist criterion).

Numerical Example (Effects of Negative Feedback):

Consider an amplifier with open-loop gain A=1000, input resistance R_in=1kOmega, output resistance R_out=100Omega, and bandwidth BW=10kHz.

We apply voltage-series negative feedback with a feedback factor beta=0.05.

Loop Gain Abeta=1000times0.05=50.

- Closed-Loop Gain (A_f):
  A_f=fracA1+Abeta=frac10001+50=frac100051approx19.6
  (Note the significant reduction in gain from 1000 to 19.6).
- Input Resistance with Feedback (R_in(f) - Voltage-Series):
  R_in(f)=R_in(1+Abeta)=1kOmegatimes(1+50)=1kOmegatimes51=51kOmega
  (Input resistance dramatically increased).
- Output Resistance with Feedback (R_out(f) - Voltage-Series):
  R_out(f)=fracR_out1+Abeta=frac100Omega1+50=frac100Omega51approx1.96Omega
  (Output resistance significantly decreased).

- **Bandwidth with Feedback (BW_f):**
  BW_f=BW(1+Abeta)=10kHztimes(1+50)=10kHztimes51=510kHz
  (Bandwidth dramatically increased).

This example clearly illustrates the trade-offs and improvements offered by negative feedback.

5.0 CIRCUIT DIAGRAMS:

Figure 5.1: Class A Common-Emitter Power Amplifier (Capacitively Coupled Load)

```
          VCC (+12V or +15V DC)
            |
            R1 (Bias Resistor)
            |
            +----- Base of Q1 (NPN Power BJT, e.g., 2N2222)
            |   /|\
            R2 (Bias Resistor)  |----- Collector of Q1 ----- RC (Collector Resistor) ----- +VCC
            |        |
            GND     \|/
                    Emitter of Q1
                      |
                      RE (Emitter Resistor)
                      |
                      +----- CE (Bypass Capacitor) ----- GND
                      |
                      GND

  Input Side Circuitry:
  AC Function Generator --> Cc1 (Input Coupling Capacitor) --> Base of Q1
  (Measure Vin here with Oscilloscope Ch1)

  Output Side Circuitry:
  Collector of Q1 --- Cc2 (Output Coupling Capacitor) --> RL (Load Resistor, e.g., 8 Ohm)
--> GND
                                          |
                                          V_out (Measure across RL with Oscilloscope Ch2)

  Note: RC in this context acts as a collector load resistor, dissipating power.
```

Figure 5.2: Class B Push-Pull Amplifier (Complementary Symmetry)

```
       VCC (+V)
         |
         D1 (Optional for Class AB)
         |
  Input ---- Rb1 --- Base of Q1 (NPN)
         |
```

```
          | (Signal via coupling capacitor if needed for single supply)
          |
          +--- Emitter of Q1 ---+--- Output (to Load RL)
          |                     |
          |                     |
          |                     |
 Input ---- Rb2 --- Base of Q2 (PNP)
          |
          D2 (Optional for Class AB)
          |
        VEE (-V or GND for single supply)

If single supply: VCC (+V)
                 |
                 Rb (Bias Resistor to common Base)
                 |
    Input ---+--- Base of Q1 (NPN)
             |
             +--- Base of Q2 (PNP)
                 |
                 D1 --+-- D2 (for Class AB bias, across bases)
                      |
                 +---- Emitter of Q1 ---+---- Output (to Load RL)
                 |                      |
                 +---- Emitter of Q2 ----
                 |
                 GND
```

Simpler Single Supply Class B Push-Pull (No Bias Diodes for Class B):

```
              VCC (+V)
                |
                R_bias_NPN
                |
      Input --- Base of Q1 (NPN)
                |
                Emitter of Q1 ---+--- Output to Load RL
                                 |
                                 |
                Emitter of Q2 ---+
                |
      Input --- Base of Q2 (PNP)
                |
                R_bias_PNP
                |
                GND
```

The standard complementary symmetry Class B looks like this (with +/- supplies typically):

```
              +Vcc
```

|
|
Collector of Q1 (NPN)
|
+---- Output (to Load RL)
|
Collector of Q2 (PNP)
|
|
-Vcc

Input is fed to the bases of Q1 and Q2. Biasing resistor networks (e.g., voltage divider) at the bases for Class B (near cutoff) or Class AB (slight forward bias).

For Class AB, two diodes (1N4001 or 1N4148) are typically placed in series between the bases of the NPN and PNP transistors, biased by a resistor from +Vcc and another from -Vcc (or GND).

Example of Push-Pull Biasing (Simplified for single supply, for conceptual drawing):
VCC
|
R_pullup
|
Input Signal --+-- Base of Q1 (NPN)
|
R_pulldown
|
GND (or Vcc/2 if split supply is simulated by caps)

Emitter of Q1 --+-- Output to Load RL
|
Emitter of Q2 --+
|
Input Signal --+-- Base of Q2 (PNP) (often same input signal, just inverse function)
|
R_bias_PNP (to GND or -Vee)

Let's use a standard complementary symmetry Class B (or AB) with input applied to bases via current limiting/coupling.

Figure 5.2 (Revised for clarity): Basic Class B Push-Pull (Complementary Symmetry)
```
+V_SUPPLY
|
|
(Q1 - NPN Transistor)
Collector
|
Emitter ---+
|
```

```
                  +--- OUTPUT (to Load RL)
                  |
         Emitter ---+
              |
         Collector
         (Q2 - PNP Transistor)
              |
              |
           -V_SUPPLY (or GND for single supply, with appropriate input biasing)

   Input is fed to the BASE of Q1 and BASE of Q2.
   For Class B: Bases are biased at approximately 0.7V for NPN and -0.7V for PNP (relative
to emitter) to be at cutoff.
   For Class AB: Small forward bias (e.g., using two diodes in series) is applied between
the bases.

   Simplified Input to Bases:
   AC Function Generator --- Cap_in --- (Biasing Resistor Network) --- Base of Q1
                                                  --- Base of Q2

   Often, a single input signal is applied to both bases, with Q1 amplifying positive half
and Q2 negative half.
```

Figure 5.3: Voltage-Series Negative Feedback Amplifier (Op-Amp Non-Inverting Configuration)

```
      +Vcc (e.g., +15V)
        |
      Op-Amp (e.g., LM741)
   Non-inverting Input (+) --- Input Signal (Vin)
                  |
                  +-- R1 (Feedback Resistor 1)
                  |
   Inverting Input (-) ---+
                  |
                  +-- R2 (Feedback Resistor 2)
                  |
                  GND

   Output of Op-Amp (Vout) --- (Connected to R1)

       -Vcc (e.g., -15V)
```

Note: $A = $ Open Loop Gain (very high, e.g., 10^5 for Op-Amp).
Feedback Factor $\beta = R_2 / (R_1 + R_2)$.
Closed Loop Gain $A_f = 1 + R_1 / R_2$ (for $A\beta \gg 1$).

6.0 PROCEDURE:

Follow these systematic steps to design, build, and characterize the power amplifiers and the feedback amplifier.

Part A: Class A Power Amplifier Characterization

1. **Class A Design (Single Stage Common Emitter):**
    * **Goal:** Design a Class A common-emitter amplifier similar to Experiment 3, but designed to drive a low-impedance load (e.g., 8 Ω or 16 Ω) and deliver measurable power.
    * **DC Bias:** Choose V_{CC} (e.g., 12V). Select a higher quiescent collector current (I_{CQ}) than for small-signal (e.g., 20 mA to 50 mA) to allow for greater output power. Bias the Q-point at roughly $V_{CEQ} \approx V_{CC}/2$.
    * **Component Selection:** Choose appropriate resistors (R_1, R_2, R_C, R_E) based on your I_{CQ} and V_{CEQ} targets. Use a power transistor (e.g., 2N2222, or even BC547 if output power requirement is very low and for educational purpose distortion observation) capable of handling the selected I_{CQ} and power dissipation. Choose suitable coupling capacitors (C_{C1}, C_{C2}) and bypass capacitor (C_E).
    * **Load Resistor (R_L):** Use a low-wattage resistor (e.g., 8 Ω, 16 Ω) as the load, ensuring its power rating is sufficient for the expected output power.
    * **Pre-Calculations:** Calculate expected $P_{in(DC)}$ and estimated maximum $P_{out(AC)}$ and efficiency.
2. **Circuit Construction:**
    * Assemble the Class A common-emitter power amplifier on the breadboard as per Figure 5.1.
    * Double-check all connections, resistor values, and capacitor polarities.
3. **DC Q-point Measurement:**
    * Apply V_{CC}.
    * Measure the DC voltages V_B, V_E, V_C, V_{CE} and DC collector current (I_{CQ}) using the DMM. Record in Table 7.1.
4. **AC Performance and Efficiency Measurement:**
    * Connect the Function Generator to the input (after C_{C1}) and set it to a mid-band frequency (e.g., 1 kHz) and a small sinusoidal amplitude.
    * Connect Oscilloscope Channel 1 to V_{in} (at base) and Channel 2 across the load resistor R_L (V_{out}).
    * **Measure Output Power:** Gradually increase the input signal amplitude until a clear, undistorted output waveform is observed with maximum swing. Measure the peak-to-peak output voltage ($V_{out(p-p)}$) across the load R_L.
    * Calculate $P_{out(AC)} = (V_{out(p-p)})^2 / (8 \times R_L)$.
    * Calculate $P_{in(DC)} = V_{CC} \times I_{CQ}$ (using your measured I_{CQ}).
    * Calculate Efficiency ($\eta = P_{out(AC)} / P_{in(DC)} \times 100\%$). Record in Table 7.1.
5. **Distortion Observation:**
    * Continue increasing the input signal amplitude beyond the point of maximum undistorted output.

* Observe the output waveform on the oscilloscope. Note and sketch the characteristics of clipping distortion as the amplifier is driven into saturation or cutoff. Record your observations in Table 7.1 and discussion section.

Part B: Class B Push-Pull Amplifier Characterization

1. **Class B Design (Complementary Symmetry):**
   * **Goal:** Build a Class B push-pull amplifier using one NPN and one PNP transistor. This typically requires a dual power supply (+V and -V) or a single supply with appropriate DC shifting at the input. For simplicity, we can use a single supply with input capacitor and a biasing network to set the common base point to VCC/2.
   * **Biasing:** For Class B, bias the transistors just at cutoff (e.g., for NPN, $V_{BE} \approx 0V$). No quiescent current should ideally flow.
   * **Component Selection:** Choose NPN and PNP transistors with similar characteristics (e.g., 2N2222 and 2N2907, or BC547 and BC557 for very low power). Use a suitable load resistor (R_L).
2. **Circuit Construction:**
   * Assemble the Class B push-pull amplifier on the breadboard as per Figure 5.2 (simplified complementary symmetry). Pay close attention to transistor types (NPN/PNP) and their pinouts.
3. **Crossover Distortion Observation:**
   * Apply the appropriate dual DC power supply (if used) or single DC supply with biasing.
   * Connect the Function Generator to the input, set to a low frequency (e.g., 1 kHz) and a small sinusoidal amplitude.
   * Connect Oscilloscope Channel 1 to V_{in} and Channel 2 to V_{out} (across R_L).
   * Observe the output waveform, especially at low signal amplitudes. You should clearly see **crossover distortion** (a flat spot or notch around the zero-crossing of the waveform).
   * Increase the input amplitude slightly and observe how the crossover distortion becomes less prominent relative to the total signal swing but is still present.
   * Sketch the observed waveform with crossover distortion in your lab notebook/file. Record your observations in Table 7.2.

Part C: Class AB Power Amplifier (Optional)

1. **Modification from Class B:**
   * **Goal:** Modify the Class B amplifier to a Class AB configuration to eliminate crossover distortion.
   * **Biasing:** The key is to provide a small forward bias to the base-emitter junctions of both transistors so that a small quiescent current flows. This is typically achieved by placing two forward-biased diodes (e.g., 1N4001 or 1N4148) in series between the bases of the NPN and PNP transistors. The voltage drop across these diodes (approximately 1.4V for two silicon diodes) provides the necessary bias.
2. **Circuit Construction:**
   * Implement the diode biasing network into your Class B circuit.
3. **Observation of Distortion Reduction:**
   * Apply power and input signal.

* Observe the output waveform on the oscilloscope, particularly at low signal amplitudes.
* Compare the output waveform with the one from the Class B amplifier. You should see a significant reduction or elimination of crossover distortion, resulting in a smoother waveform around the zero-crossing.
* Record your observations in Table 7.2.

Part D: Voltage-Series Negative Feedback Amplifier Analysis

1. **Design (Op-Amp Configuration is Easiest):**
   * **Goal:** Design a non-inverting amplifier using an Op-Amp (e.g., LM741). This inherently uses voltage-series negative feedback.
   * **Open-Loop Configuration (Conceptual for measurement of 'A'):** An Op-Amp itself has very high open-loop gain. It's difficult to measure A directly. Instead, we typically take a buffer (voltage follower) or a small gain configuration as the "open-loop" or "uncompensated" amplifier for *demonstration* purposes. A common base or common emitter BJT stage can be used as an 'open-loop' amplifier if discrete components are preferred.
   * **Feedback Network:** Choose resistors R_1 and R_2 for the feedback network (as in Figure 5.3) to achieve a desired closed-loop gain A_f.
     * Example: For $A_f = 10$, if $A_f = 1 + R_1/R_2$, then $10 = 1 + R_1/R_2 \implies R_1/R_2 = 9$. So, choose $R_1=9k\Omega$ (e.g., 8.2k + 820 Ohm) and $R_2=1k\Omega$.
   * **Pre-Calculations:** Calculate the theoretical closed-loop gain (A_f), theoretical input resistance ($R_{in(f)}$), and theoretical output resistance ($R_{out(f)}$) using the formulas in Section 4.2.
2. **Circuit Construction:**
   * Assemble the Op-Amp based voltage-series feedback amplifier on the breadboard as per Figure 5.3.
   * Ensure correct power supply connections to the Op-Amp (+Vcc, -Vcc).
3. **Measurement Without Feedback (Conceptual/Reference):**
   * For Op-Amp circuits, directly measuring parameters without feedback (A, R_{in}, R_{out}) is impractical due to very high gain and impedance. Instead, we can conceptually consider the Op-Amp itself as the open-loop amplifier. If using discrete transistors for the base amplifier, you would first measure its parameters without the feedback loop.
   * **If using a discrete BJT stage as the base amplifier (challenging for this lab, but theoretically possible):**
     * Construct the discrete amplifier without the feedback network.
     * Measure its voltage gain (A), input resistance (R_{in}), and output resistance (R_{out}) using methods from Experiment 3. Measure its bandwidth. Record these as 'Without Feedback' values in Table 7.3.
4. **Measurement With Negative Feedback:**
   * Apply the calculated feedback network (R_1, R_2) to your Op-Amp (or discrete) amplifier.
   * Apply a sinusoidal input signal (e.g., 1 kHz, small amplitude).
   * **Measure Closed-Loop Gain (A_f):** Measure V_{in} and V_{out} using the oscilloscope. Calculate $A_f = V_{out}/V_{in}$. Record in Table 7.3.
   * **Measure Input Resistance ($R_{in(f)}$):** Use the source resistance method (similar to Exp. 3, Part B.3). Apply a known series resistor R_S to the input. Adjust R_S until

V_{in} (at Op-Amp input) drops to half its value without R_S. $R_{in(f)} = R_S$. Record in Table 7.3.
    * **Measure Output Resistance ($R_{out(f)}$):** Use the load resistance method (similar to Exp. 3, Part B.4). Measure $V_{out(OC)}$ (output without load). Then connect a variable load R_L' and adjust it until V_{out} drops to half of $V_{out(OC)}$. $R_{out(f)} = R_L'$. Record in Table 7.3.
    * **Measure Bandwidth (BW_f):** Perform a frequency sweep (similar to Exp. 3, Part C). Plot gain vs. frequency (Bode plot). Determine f_L and f_H (where gain drops by 3dB from mid-band closed-loop gain). Calculate $BW_f = f_H - f_L$. Record in Table 7.3.
    * **Distortion Observation:** Qualitatively observe the output waveform for distortion. Compare it to the un-feedbacked amplifier if you had one.
    * **Comparison:** Compare the measured values ($A_f, R_{in(f)}, R_{out(f)}, BW_f$) with your theoretical calculations and with the 'without feedback' values (if discrete amplifier was used).

Part E: Stability Observation (Qualitative, Optional)

1. **Setup for Potential Instability:**
    * This part might be challenging or require specific amplifier designs prone to oscillation (e.g., very high gain discrete stages, or Op-Amp with large capacitive loads or improper compensation).
    * One way to demonstrate is to use a high-gain common-emitter stage (without emitter bypass capacitor or with small R_E for higher gain) and try adding parasitic capacitances or inductive loads.
2. **Observation:**
    * Observe if the amplifier oscillates (produces unwanted output signal even without input, or distorted output).
    * Then, introduce the negative feedback (e.g., by adding R_E and C_E appropriately, or by connecting the Op-Amp feedback loop).
    * Observe if the oscillations cease and the amplifier becomes stable.
    * Record your observations in Table 7.4. *Crucially: Do not attempt to intentionally create oscillations if you are unsure of component safety or damage to equipment.* This is a qualitative observation if the opportunity arises.

7.0 OBSERVATIONS AND READINGS:

7.1 Class A Power Amplifier Data:

Parameter	Designed/Calculated Value	Measured Value	Remarks/Comparison
V_{CC} (Supply Voltage)		___________ V	
I_{CQ} (Quiescent Collector Current)		___________ mA	
V_{CEQ} (Quiescent CE Voltage)		___________ V	
R_L (Load Resistance)		___________ Ω	
$V_{in(p-p)}$ (Max Undistorted Input)	N/A	___________ V	
$V_{out(p-p)}$ (Max Undistorted Output)	N/A	___________ V	
$P_{out(AC)}$ (Calculated)	___________ W	___________ W	

$P_{in(DC)}$ (Calculated)	___________ W	___________ W	
Efficiency (η)	___________ %	___________ %	
Observation of Clipping Distortion at High Input Signal:	(Describe briefly)		

7.2 Class B / Class AB Power Amplifier Data:

Parameter	Observation / Measurement	Remarks
Class B Push-Pull Amplifier		
Supply Voltage (+V / -V)	___________ V / ___________ V	
$V_{in(p-p)}$ (Small Signal)	___________ V	
$V_{out(p-p)}$ (Small Signal)	___________ V	
Observation of Crossover Distortion:	(Describe clearly, e.g., "Distinct flat spot at zero-crossing")	(Include sketch if possible in report)
Class AB Power Amplifier (Optional)		
Bias Diodes Used (Type)		(e.g., 1N4001)
Quiescent Current (Small I_Q)	___________ mA (if measurable)	
Observation of Crossover Distortion (after modification):	(Describe clearly, e.g., "Significantly reduced/eliminated")	

7.3 Voltage Series Negative Feedback Amplifier Data:

* **Feedback Network Resistors:** R_1= ___________ Ω, R_2= ___________ Ω
* **Calculated Feedback Factor (β):** ___________
* **Calculated Theoretical Closed-Loop Gain (A_f):** ___________

Parameter	Without Feedback (Measured, if discrete)	With Feedback (Measured)	With Feedback (Calculated Theoretical)	Remarks/Comparison
Voltage Gain (A)	___________ (or N/A for Op-Amp)	___________	___________	
Gain in dB	___________ dB	___________ dB	___________ dB	
Input Resistance (R_{in})	___________ Ω	___________ Ω	___________ Ω	
Output Resistance (R_{out})	___________ Ω	___________ Ω	___________ Ω	
Bandwidth (BW)	___________ Hz	___________ Hz	___________ Hz	
Distortion	(Qualitative, e.g., "More")	(Qualitative, e.g., "Less")	N/A	

7.4 Stability Observation (Qualitative, Optional):

Observation Condition	Amplifier Behavior

| Without Negative Feedback (unstable scenario, if created) | (Describe oscillations, noise, or instability) |
| With Negative Feedback (same scenario) | (Describe improved stability, reduced oscillations) |

8.0 GRAPHS:

Include relevant graphs based on your experimental data. Use appropriate labels and scales.

* **Graph 5.1: Class A Output Distortion**
    * **Type:** Linear (Time on X-axis, Voltage on Y-axis)
    * **Plot:** Sketch or plot the input and output waveforms of the Class A amplifier when it is driven into clipping distortion. Clearly label input and output and point out the distorted regions.
* **Graph 5.2: Class B Crossover Distortion**
    * **Type:** Linear (Time on X-axis, Voltage on Y-axis)
    * **Plot:** Sketch or plot the input and output waveforms of the Class B amplifier at low signal levels, clearly showing the crossover distortion around the zero-crossing.
* **Graph 5.3: Frequency Response of Feedback Amplifier**
    * **Type:** Semi-log graph (logarithmic X-axis for frequency, linear Y-axis for gain in dB).
    * **Plot:** Plot the gain in dB versus frequency for the amplifier *without feedback* (if discrete) and *with negative feedback* on the same graph for comparison.
    * **Markings:** Clearly mark the -3 dB points for both curves and label f_L, f_H, and BW for each.

9.0 CALCULATIONS:

Provide detailed steps for all calculations performed in this experiment, using your measured values where appropriate.

9.1 Class A Power Amplifier Calculations:
* **DC Input Power ($P_{in(DC)}$):**
    $P_{in(DC)} = V_{CC} \times I_{CQ(\text{measured})}$ = [Your Calculation] W
* **AC Output Power ($P_{out(AC)}$):**
    $P_{out(AC)} = \frac{(V_{out(p-p)})^2}{8 \times R_L}$ = [Your Calculation] W
* **Efficiency (η):**
    $\eta = \frac{P_{out(AC)}}{P_{in(DC)}} \times 100\%$ = [Your Calculation] %

9.2 Negative Feedback Amplifier Calculations (for Voltage-Series Feedback):
* **Calculated Feedback Factor (β):**
    $\beta = \frac{R_2}{R_1 + R_2}$ = [Your Calculation]
* **Assume/State Open-Loop Gain (A):** (If using Op-Amp, state typical A like 10^5. If discrete, use measured A from 7.3).
    A = [Value]

* **Calculated Closed-Loop Gain (A_f):**
   $A_f = \frac{A}{1 + A\beta}$ = [Your Calculation]
* **Calculated Input Resistance with Feedback ($R_{in(f)}$):**
   $R_{in(f)} = R_{in(\text{without feedback})} (1 + A\beta)$ = [Your Calculation] Ω
* **Calculated Output Resistance with Feedback ($R_{out(f)}$):**
   $R_{out(f)} = \frac{R_{out(\text{without feedback})}}{1 + A\beta}$ = [Your Calculation] Ω
* **Calculated Bandwidth with Feedback (BW_f):**
   $BW_f = BW_{(\text{without feedback})} (1 + A\beta)$ = [Your Calculation] Hz

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10.0 RESULTS:

Summarize your key findings from the experiment, presenting both measured and calculated parameters.

* **Class A Power Amplifier:**
   * Measured Max Undistorted Output Power ($P_{out(AC)}$): [Your Value] W
   * Calculated Efficiency (η): [Your Value] %
   * Observation of distortion: [Brief summary, e.g., "Clipping observed at high input amplitudes."]
* **Class B Push-Pull Amplifier:**
   * Observed Crossover Distortion: [Yes/No] and [Brief description, e.g., "Clear notching at zero-crossing."]
* **Class AB Power Amplifier (Optional):**
   * Crossover Distortion Reduction: [Yes/No] and [Brief description, e.g., "Significantly reduced/eliminated crossover distortion."]
* **Voltage-Series Negative Feedback Amplifier:**
   * Measured Closed-Loop Voltage Gain (A_f): [Your Value] (or [Your Value] dB)
   * Measured Input Resistance with Feedback ($R_{in(f)}$): [Your Value] Ω
   * Measured Output Resistance with Feedback ($R_{out(f)}$): [Your Value] Ω
   * Measured Bandwidth with Feedback (BW_f): [Your Value] Hz
   * Qualitative observation of distortion/noise: [Reduced/Increased/No change]
* **Stability Observation (Optional):**
   * Impact of Feedback on Stability: [Brief statement, e.g., "Negative feedback improved stability by reducing oscillations."]

11.0 DISCUSSION AND ANALYSIS:

This is a crucial section for interpreting your results, comparing them with theoretical expectations, explaining observed phenomena, and discussing any discrepancies.

1. **Class A Amplifier Performance:**
   * **Efficiency Analysis:** Discuss your measured efficiency for the Class A amplifier. How does it compare to the theoretical maximum efficiency (25% for capacitively coupled)? Explain the reasons for any discrepancy (e.g., non-ideal components, quiescent power dissipation, transistor saturation voltage). Why are Class A amplifiers generally considered inefficient for power applications?

    * **Distortion:** Explain why clipping distortion occurs in a Class A amplifier when the input signal amplitude is too high. Relate this to the transistor entering cutoff or saturation regions.
2. **Class B and Class AB Amplifier Comparison:**
    * **Crossover Distortion in Class B:** Explain in detail *why* crossover distortion occurs in a Class B push-pull amplifier. Relate it to the transistor biasing at cutoff and the dead zone around the zero-crossing.
    * **Class AB Solution:** Discuss how biasing the Class AB amplifier slightly above cutoff (e.g., using diodes) effectively eliminates or significantly reduces crossover distortion. Explain the trade-off (slight reduction in efficiency compared to Class B, but much better linearity).
    * **Practical Application:** Comment on why Class AB is the most commonly used power amplifier class in audio systems.
3. **Negative Feedback Effects:**
    * **Gain Reduction:** Compare the open-loop gain (if measured, or Op-Amp's inherent high gain) with the closed-loop gain. Explain the fundamental reason why negative feedback reduces overall amplifier gain. Relate this to the formula $A_f = A / (1 + A\beta)$.
    * **Impedance Modification:** Discuss the measured changes in input resistance ($R_{in(f)}$) and output resistance ($R_{out(f)}$) when negative feedback is applied. Explain why voltage-series feedback increases input resistance and decreases output resistance. Relate this to the concepts of current summing and voltage sampling.
    * **Bandwidth Extension:** Compare the bandwidth of the amplifier without feedback (if applicable) and with negative feedback. Explain why negative feedback increases the bandwidth. What is the fundamental trade-off between gain and bandwidth in feedback amplifiers? (The gain-bandwidth product is often constant).
    * **Distortion and Noise Reduction:** Based on your observations, discuss the effect of negative feedback on distortion (and theoretically, noise). Why does negative feedback reduce unwanted signals generated within the amplifier?
    * **Stability:** If you performed the optional stability observation, describe your findings. Explain how negative feedback can improve amplifier stability by reducing sensitivity to component variations and preventing unwanted oscillations.
4. **Sources of Error and Limitations:**
    * Identify potential sources of experimental error in all parts of the experiment (e.g., component tolerances, inaccuracies in DMM/oscilloscope readings, loading effects of measurement instruments, thermal effects on power transistors, breadboard parasitic effects).
    * Discuss how these errors might have contributed to discrepancies between theoretical calculations and experimental results.
    * Comment on the limitations of the simplified theoretical models (e.g., ideal BJT assumptions, simplified feedback formulas assuming ideal Op-Amp).

12.0 CONCLUSION:

Conclude your experiment by summarizing the key learning outcomes and reinforcing the understanding gained.

This experiment provided a comprehensive study of power amplifier classes and the profound effects of negative feedback. We successfully characterized a Class A amplifier,

observing its low efficiency and clipping distortion at high signal levels. The Class B push-pull amplifier demonstrated high efficiency but suffered from inherent crossover distortion, which was effectively mitigated by modifying the circuit to a Class AB configuration. Furthermore, the experiment conclusively demonstrated the significant benefits of negative feedback in amplifier design. We observed and quantified the reduction in gain, the increase in input impedance, the decrease in output impedance, and the extension of bandwidth. These practical observations reinforce the theoretical understanding that negative feedback is a powerful tool for improving amplifier linearity, stability, and overall performance, despite the trade-off in gain. The experiment has provided a strong foundation for understanding the principles and practical applications of power amplifiers and feedback in electronic circuits.
